IAPSO (Physical Oceanography)

P01a - P01 General Topics on the Physical Science of the Oceans

IUGG-0469

Regional sea level variability around the northern Australian coastline from tide gauges and satellite altimetry

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This paper investigates a consistent view of the low frequency sea level variability along the northern Australian coastline using data from both satellite altimetry and tide gauges. The 20 years of sea level observations from multi-satellite altimetry missions and tide gauges are analysed in the time interval 1993–2013. Firstly, the impact of the geophysical corrections applied to the altimetry sea level measurements and the consistency of the altimetric and the tide gauge sea level observations are examined. Both observations are then used to characterize sea level trends and inter-annual variability over the study region. The results show that the basin average of 14 tide-gauge time series is in good agreement with the basin average of the altimeter data, with correlation coefficient 0.95 and root mean square difference 18 mm. The linear rate (6.5782 ± 0.4 mm/yr) estimated from tide gauges is slightly higher than that (6.0975 ± 0.3 mm/yr) from altimetry in the study period, which strongly depend on the length of the time-interval. The different trends are likely related to the higher interannual variability of coastal sea level, caused by the regional sea level. Decomposition of the inter-annual altimeter sea level has the first mode highly correlated (74%) with Multivariate El Nino-Southern Oscillation index (MEI). The results suggest thet the inter-annual sea variability in this region is closely related to the El Niño Southern Oscillation (ENSO), while sea level trends might be linked to longer oceanic variations such as Glacial Isostatic Adjustment (GIA), land motions and accelerated ocean warming.

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IUGG-1451

Inverting Laplacians: a direct method for the determination of the World Ocean Circulation from Argo float displacements and temperature/salinity

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The Eulerian time-mean velocity field obtained from the Ollitrault & Rannou's Argo float displacement data base **Andro** is used to create an absolute geopotential field at 1000 db. This is done by solving a Poisson equation with Neumann boundary conditions, an equation that originates from Charney's balance equation. From thereon the geopotential at all depths can be obtained from hydrostatics. When the geopotential at the surface is subtracted from a mean altimetric surface, we obtain an internally reconstructed geoid from oceanic data.

In such a circulation, however, the barotropic (depth-integrated) transports are divergent and this would prevent for instance to compute heat and fresh water fluxes across basins. By solving a second Poisson equation with Dirichlet boundary conditions, it is possible to obtain the barotropic streamfunction, hence the non divergent barotropic transports. This barotropic solution will be illustrated in the North Atlantic, North Pacific and Southern Oceans and compared to Sverdrup's solution.

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IUGG-2123

Nonlinear shallow-water tides observed with excellent signal-to-noise ratio by two geodetic laser strainmeters at the Canfranc (Spain) Underground Laboratory.

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Comparisons between observed Earth strain tides and ocean models loading predictions can give an independent mean to validate the ocean models themselves and finally the whole modelling process. In particular, the accurate representation of nonlinear tides, such as quater-diurnal and higher-frequency components, and of their effects is a challenging task to be accomplished in the next years.
The Canfranc underground laboratory (LSC), excavated in the rock under the Central Pyrenees (Spain), hosts a geodynamical facility capable to record continuously the whole geodynamic spectrum, from near-field seismicity to tectonic deformation, including Earth tides. Using two near-orthogonally-oriented 70-m-long high-resolution laser strainmeters installed in the LSC, we have obtained continuous precision measurements of local strain in terms of dL/L, where L is the interferometer length and dL its change over time. The laser strainmeters are operational since early 2012.
Spectra show clear tidal peaks whose frequencies range from the diurnal band to at least 8 cicles per day (cpd). Tidal peaks at frequencies higher than 2 cpd are ascribable to ocean loading of linear and nonlinear constituents, mainly from the Bay of Biscay. Strain amplitudes of observed nonlinear tides range from few 10^-12 to 4x10^-10 (M4).
We will show comparisons between observations and predicted strain tides, computed using ocean-tide loading programs included in the SPOTL package (Agnew, 2013) and two ocean tidal models, namely TPXO8-atlas (enriched with the European Shelf 2008 regional solution) and FES2012. In particular, M4, MS4, and MN4 will be compared with predictions by both ocean tidal models, while N4 and the linear M3 and M6 tides will be compared with predictions by FES2012 only.

IAPSO (Physical Oceanography)

P01a - P01 General Topics on the Physical Science of the Oceans

IUGG-3286

Automated ocean front detection: An Earth observation-based validation tool for basin and shelf scale ocean models

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Automated ocean front detection is a well established tool for identifying and visualising dynamic physical processes in Earth observation (EO) products. Incremental improvements in the application of this technique now allow for maximum exploitation of cloud affected scenes and the generation of synoptic maps of mesoscale processes based on front persistence, strength and location. With increased computational availability comes the opportunity for numerical model simulations to run at ever finer scales, capturing the mesoscale and sub-mesoscale in global and regional simulations, respectively. However, in parallel there is a need to validate these models at a comparable scale, one which is increasingly beyond the range of gridded altimetry surface current products.

Here, automated front detection techniques are similarly applied to two models, with the goal of validating their performance based on the expression of coherent surface structures. At the basin scale, quantitative comparison of the positions of the main fronts (Gulf Stream, Kuroshio, Agulhas and Antarctic Circumpolar systems) and lesser known fronts (e.g. Azores front) is performed between EO products and the ORCA025 and ORCA12 global hindcasts. A more regionally-focussed analysis of the processes shelf-edge processes is performed using the 1/60th degree resolution, AMM60 European shelf model, developed under the NERC FASTNEt project. Model fields are compared to 1km and 9km global merged multi-sensor SST products on varying time-scales. Model performance is scored using receiver-operating characteristic (ROC) analysis, with the assessment of physical structures removing the need for limiting, pointwise comparisons.

IAPSO (Physical Oceanography)

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IUGG-5125

Upper ocean variability at the Porcupine Abyssal Plain time series site during 2012-2013 from ocean gliders

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As part of the Ocean Surface Mixing Ocean Submesoscale Interaction Study (OSMOSIS), a year-long Seaglider deployment was undertaken at 48.7°N, 16.2°W in the northeast Atlantic near the Porcupine Abyssal Plain sustained observatory. Two gliders at a time were deployed, collecting a total of 8138 profiles to 1000 m of temperature, salinity, biogeochemical variables and dive-average current. The glider sampling covered 15 km by 15 km, with a vertical resolution of 0.5-1 m, an average time interval between profiles of each glider of 2 hours, to within 2-3 m of the surface. Previous observations are either from shipboard CTDs, giving limited temporal resolution and coverage, or from moorings, covering a limited number of depths and not close to the surface. Thus, the glider data enable a new characterisation of the seasonal cycle and the temporal variability.

The seasonal cycle in temperature weakens with depth from a peak-to-peak amplitude of 6°C near the surface to less than 0.6°C for all depths below 200 m. The phase changes gradually, with the bottom half being 4-5 months out of phase with the mixed layer. Salinity displays a weak seasonal cycle, which is essentially in phase with the seasonal cycle in temperature except in the uppermost 50 m. For both temperature and salinity, variability is lowest at depths around 400 m. The variability of salinity and dissolved oxygen on density surfaces reveal the processes leading to temporal variability. The deep variability is dominated by meddies, which are intermittent on multiple timescales. There is clear evidence of an M2 internal tide, which reduces in amplitude from 1000 m to the surface, consistent with a mode 1 baroclinic tide. Rossby waves are clearly detected as increased variability at periods between 40 and 70 days.

IAPSO (Physical Oceanography)

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IUGG-5372

Revealing the timing of ocean stratification using remotely-sensed ocean fronts

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Stratification is of critical importance to the circulation, mixing and productivity of the ocean, and is expected to be modified by climate change. Hence it would be prudent to monitor the stratification of the global ocean, though this is currently only possible using in situ sampling, profiling buoys or underwater autonomous vehicles. Earth observation (EO) sensors cannot directly detect stratification, but can observe surface features related to the presence of stratification, for example shelf-sea fronts that separate tidally-mixed water from seasonally stratified water. This presentation describes a novel algorithm that accumulates evidence for stratification from a sequence of oceanic front maps, and discusses preliminary results in comparison with in situ data and simulations from 3D hydrodynamic models. In certain regions, this method can reveal the timing of the seasonal onset and breakdown of stratification.

This research is based on the composite front map approach, which is to combine the location, strength and persistence of all fronts detected on EO sea-surface temperature or ocean colour data over several days into a single map, improving interpretation of dynamic mesoscale structures (Miller, 2009). These techniques are robust and generic, and have been applied to many studies of physical oceanography, most recently in the NERC FASTNEt project, and marine animal distribution.

Miller, P.I. (2009) Composite front maps for improved visibility of dynamic sea-surface features on cloudy SeaWiFS and AVHRR data. Journal of Marine Systems, 78(3), 327-336. doi:10.1016/j.jmarsys.2008.11.019

IAPSO (Physical Oceanography)

P01b - P01 General Topics on the Physical Science of the Oceans

IUGG-1043

On the wind mechanical forcing of the ocean general circulation

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The wind mechanical forcing of the ocean general circulation and its seasonal variations are examined using available observational products, focusing on the role of the mean and fluctuating winds. It is found that including wind fluctuations in the stress calculation produces a qualitative change in the estimates of the mean and seasonal wind stress, particularly at mid and high latitudes where the synoptic wind variability is large. This effect of wind fluctuations on air-sea momentum exchange has immediate dynamical consequences for the large-scale ocean circulation. For example, power input to the ocean general circulation and subtropical gyre transport can be underestimated by more than 50% if the fluctuating winds are not taken into account. However, the impact of including wind fluctuations depends strongly on the presence of the mean winds. If the mean winds are ignored in the stress calculation, the net effect of the fluctuating winds is to take energy out of the ocean owing to the skewness of the near-surface wind field. Furthermore, co-variances of wind fluctuations are found to explain most of the effect of the fluctuating winds, while the variable drag coefficient makes a non-negligible contribution in the Southern Ocean. These results imply that paleo and future climate studies need to take into account the changes of the large-scale low-frequency wind field as well as the synoptic weather systems.

IAPSO (Physical Oceanography)

P01b - P01 General Topics on the Physical Science of the Oceans

IUGG-2650

Towards downscaling changes of oceanic dynamics

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The concept of downscaling, according to which smaller scale dynamics may be described as being "conditioned" by the state of larger scale dynamics plus small scale physiographic details, has become very successful in applications dealing with specifying (distributions of) atmospheric (impact) states. A large variety of statistical models and weather generators have been designed; regional atmospheric models as well as large-scale constrained global models have been constructed to this end.

We suggest using this concept also for regional and local oceanographic applications. The concept needs a modification, as not only regional physiographic details but also regional atmospheric forcing plays a major role. In first "fishing expeditions", we screen high-resolution global ocean simulations forced with NCEP atmospheric re-analyses as well as oceanic-reanalysis, to what extent known large-scale features, such as the Kuroshio conditions local current systems in Chinese marginal oceans.

The second task will be to determine to what extent large-scales state variability is consensually described in oceanic re-analyses – this allows the determination of suitable large-scale predictors in empirical and dynamical downscaling exercises for the recent past.

IAPSO (Physical Oceanography)

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IUGG-3302

Inference of vertical velocities in a mid ocean anticyclonic mesoscale eddy

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Ageostrophic secondary circulation (ASC), including vertical velocity (w), in mesoscale eddies may play an important role on modulating biogeochemical fluxes. For example there are growing evidences that point out that mesoscale anticyclonic eddies may enhance primary production. However due to the lack of knowledge of the w-field the mechanisms of such modulation are still under discussion. Obtaining direct measurements of w is, because of its small magnitude, technically very difficult and, consequently, indirect theoretical methods have been conceived to estimate w. It has been proposed three different horizontal patterns for w inside anticyclonic (baroclinic) mesoscale eddies. Martin and Richards (2001) proposed that an upwelling develops at the eddy center due to wind-flow interactions. Alternatively, Mahadevan et al. (2008) proposed that ASC cells develop at the eddy periphery also due to wind-flow interactions. Viúdez and Dritschel (2003) model predicts quadrupole pattern in w associated to horizontal deformation at the vertex of elliptical eddies.

With the aim to study the modulation of the biogeochemical fluxes by the ASC in anticyclonic mesoscale eddies, a typical eddy of the Canary Eddy Corridor was interdisciplinary surveyed on September 2014 in the framework of the PUMP project. Horizontal velocity field as obtained with a 75 kHz SADCP indicates that the eddy is elliptic. For the density field we combined SeaSoar data and CTD data. The mesoscale w is inferred by solving a generalized omega equation using density and horizontal velocity observations. Preliminary observations of the phytoplankton distribution suggest the development of w-cells at the eddy vertex that need to be supported by the ongoing inference of the w-field.

IAPSO (Physical Oceanography)

P01b - P01 General Topics on the Physical Science of the Oceans

IUGG-3448

Enhancement of primary production and deep mixing by a mesoscale mid ocean anticyclonic eddy

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A typical anticyclonic eddy of the Canary Eddy Corridor, located 300 nautical miles southwest of the Canary Islands, was interdisciplinary surveyed on September 2014 in the framework of the PUMP project (ref: CTM2012-33355). This project aims to investigate the modulation of the biogeochemical fluxes by the ageostrophic secondary circulation (SAC) and mixing in anticyclonic mesoscale eddies.

The eddy, 4 month old, was an intrathermocline type eddy characterized by a dome shape of the isopycnals in the sallower layers and bow shape in the deeper layers. It was elliptical, 110 km diameter and 400 m deep. We observed a clear enhancement of microphytoplankton biomass, with respect to the far field, at the eddy periphery coinciding with larger values of vertical mixing parameters such as entrainment rates and diapycnal eddy diffusivities. Minima values of all these properties where observed at the eddy center. Vertical velocity is being inferred by solving a generalized omega equation in order to identify if SAC play also a role on the enhancement of primary production as it is the case observed for vertical mixing.

We also observed trapping of near inertial waves (NIW) at the base of the eddy (400 m) that introduced a shear mixing as intense or even higher than in the upper

mixing layer as indicated by measurements of turbulent kinetic energy dissipation rate. NIW shear was observed form the eddy base until 800 m. These observations point out that mesoscale anticyclonic eddies act as deep mixing structures through NIW trapping. This mechanism has been widely discussed in the literature but to our knowledge our observations provide first evidences of such deep mixing on a typical anticyclonic mesoscale eddy.

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IUGG-4967

A geometric decomposition of eddy-mean flow interactions

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Understanding eddy-mean flow interactions is a long-standing problem in geophysical fluid dynamics with modern relevance to the task of representing eddy effects in coarse resolution models. Eddy momentum fluxes are captured by the eddy covariance matrix, which also encodes information about eddy size, shape, and orientation through its geometric representation in the form of the so-called variance ellipse. Exploiting this recognition suggests a potentially fruitful way forward by offering a description of eddy-mean flow interactions in terms of eddy ellipse geometry.

Here we present a framework that describes eddy-mean flow interactions in terms of ellipse geometry, and illustrate it with an application to an unstable jet. We show that the eddy vorticity flux divergence F, a key dynamical quantity describing the average effect of eddies on the time-mean flow, may be decomposed into two components with distinct geometric interpretations: i) variations in the variance ellipse orientation; and ii) variations in the anisotropic part of the eddy kinetic energy, itself a function of the variance ellipse size and shape. Application of the divergence theorem shows that F integrated over a region is explained entirely by variations in these two quantities around the region's periphery.

This framework has the potential to offer new insights into eddy-mean flow interactions in a number of ways. It identifies the ingredients of the eddy motion that have a mean flow forcing effect; it links eddy effects to spatial patterns of variance ellipse geometry that can potentially suggest mechanisms underpinning these effects; and finally it illustrates the importance of resolving eddy shape and orientation, and not just eddy kinetic energy, for accurately representing eddy effects.

IAPSO (Physical Oceanography)

P01c - P01 General Topics on the Physical Science of the Oceans

IUGG-0894

Fast wind-induced migration of Leddies in the South China Sea

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Eddies off the Strait of Luzon (which we term here “Leddies” in analogy to Teddies originating from the Indonesian Throughflow) are formed rapidly and migrate swiftly. Their migratory rate (~ 10-20 cm/s) is an order of magnitude faster than that of most eddies of the same scale (~ 1 cm/s). On the basis of observations, it has been suggested earlier that the rapid generation process is due to the Southeast Monsoon.

This earlier suggestion is placed on more solid ground by developing both analytical and process oriented numerical models. Because the eddies are formed by the injection of foreign, lighter Kuroshio water into the South China Sea (SCS), we model them as lenses, i.e., “bullets” that completely en-capsule the mass anomaly associated with them. It turns out that the rings migrate at an angle a (between zero and 90°) to the right of the wind direction [i.e., $Tan^{-1}(2-\gamma) f^2 R/ 8 g' C_D$, where, in the conventional notation, g is the vorticity, R the eddy radius and C_D the interfacial friction coefficient along the lens’ lower interface]. Their fast migration speed is given by $2(\tau_S / \rho_w) (\sin \alpha) / fH$, where t_S is the wind stress on the surface, ρ_w the water density and H is the maximum eddy depth. With high interfacial drag (i.e., large C_D) the rings move relatively slowly (but still a lot faster than Rossby waves) in the wind direction, whereas with low drag they move fast at 90° to the right. These analytically predicted values are in good agreement with our isopynic numerical simulations.

IAPSO (Physical Oceanography)

P01c - P01 General Topics on the Physical Science of the Oceans

IUGG-1030

A probabilistic eddying ocean simulation for climate: the global OCCIPUT ensemble.

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Academic models have demonstrated the chaotic behavior of current systems at high Reynolds number, up to decadal timescales. Unlike laminar ocean models used in most current climate projections, eddying OGCMs also spontaneously generate a substantial intrinsic variability from mesoscales to multi-decadal/basin scales, with a stochastic character, and a marked SST signature where air-sea fluxes are maximum in Nature. Whether and how this ocean-driven low-frequency intrinsic variability may ultimately impact climate predictability when eddies are present is an important but unsettled question. A preliminary step toward this question is to better describe the stochastic component of the low-frequency ocean variability, with a focus on climate-relevant indexes.

The goal of the OCCIPUT project is to perform and analyze a 50-member ensemble of 1/4° global ocean/sea-ice hindcasts driven by the same reanalyzed 1958-2014 atmospheric forcing. Reduced-size (10-member 8-year North Atlantic) pilot experiments have validated the integration strategy: after a climatologically-forced spinup, the spread of the ensemble is triggered by applying stochastic perturbations for a couple years; eddy-eddy interactions then take control of the subsequent growth of the ensemble spread and of its cascade toward long space and time scales. The pilot experiments and the 50-member global ensemble will provide a probabilistic description of the ocean state and evolution over the last decades, a measure of the actual constraint exerted by the atmosphere on interannual-to-decadal ocean variability, and characterize the stochastic character of the eddying ocean over a wide range of spatio-temporal scales. We will present our strategy, and first results from these probabilistic simulations.

IAPSO (Physical Oceanography)

P01c - P01 General Topics on the Physical Science of the Oceans

IUGG-1606

Seasonal and interannual upwelling features off the Northwest Africa coast

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Satellite data (altimetry, sea surface temperature and chlorophyll-a), ocean surface wind products, Lagrangian observations (surface drifters) and other ancillary data (upwelling indices, large-scale climatic indices) are used to describe the upwelling seasonal and interannual variability off the Senegal and Mauritania coasts, in the period 2002-2014. The upwelling seasonality depicts a clear meridional trend: the southern sector shows a pronounced fluctuation between upwelling and non-upwelling seasons, with the most favourable upwelling conditions in the period January-June; whereas in the northern sector the upwelling occurs throughout the year, with a maximum in October-November. The marked seasonal periodicity is reproduced by the surface circulation patterns: upwelling seasons are characterized by predominant westward-southwestward currents located north and south of Cape Vert, respectively; non-upwelling seasons show a strong coastal poleward current and several sub-basin eddies located offshore.

Long-term variability of the wind forcing, sea surface temperature and chlorophyll-a patterns and frequency of upwelling events are linked with the interannual atmosphere-ocean teleconnections. Significant interannual variability of the Senegal and Mauritania upwelling system is related with ENSO and NAO. Relaxation/intensification of the upwelling seasons are associated with the weakening/strengthening of Atlantic Trade winds during the El Niño/La Niña and NAO^-/NAO^+ events, respectively.

IAPSO (Physical Oceanography)

P01c - P01 General Topics on the Physical Science of the Oceans

IUGG-3682

Seasonality in sea surface salinity and relating sea surface variables

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With accumulation of salinity observational data by Argo floats, it becomes possible to investigate salinity variability on seasonal to interannual time scales. While we know that there is strong seasonality in sea surface temperature (SST), seasonality in sea surface salinity (SSS) is not known well. Based on gridded Argo and other observational data and atmospheric reanalysis data, we examine global distribution of SSS seasonality using 12-month lagged auto-correlation map. In contrast to SST, which shows clear seasonality except for the tropical oceans especially in the Pacific, seasonality of SSS is not clear in large part of the global ocean except for tropics in the eastern Atlantic, the eastern Pacific, and the western Indian Oceans. Meanwhile the distribution depends on data products to some extent. Consistent with the limited seasonality, forcing field for SSS, i.e., precipitation-evaporation, Ekman transport, and geostrophic current fields also show limited seasonality except for the tropical oceans.

IAPSO (Physical Oceanography)

P01c - P01 General Topics on the Physical Science of the Oceans

IUGG-4691

Intra-seasonal variability of barotropic sea-level in the tropical Indian ocean

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The Barotropic responses are not yet been studied in Tropical Indian Ocean due to the lack of observations. One of the means through which the barotropic signals can be measured is through the measurement of bottom pressures using sensors mounted on the sea bottom . Four such sensors mounted on the sea bottom to measure the bottom pressure, recognized as bottom pressure recorders (BPRs), are now available in the Tropical Indian Ocean. Though they were deployed during the past few years to detect the tsunami wave, they provide an opportunity to study the barotropic sea-level variability in the Tropical Indian Ocean. The data from the four BPRs, when filtered intra-seasonally, reveals that the sea-level at two spatially distant locations, notably at Bay of Bengal and Arabian Sea, oscillates in unison during December-April. We show, for the first time, the existence and consequence of a tropically forced barotropic intraseasonal oscillation in Tropical Indian Ocean. Using the observations and a general circulation model run in barotropic mode, we show that a barotropic response, forced by a patch of wind in the gap region between Australia and Indonesia, dominate the Barotropic Intraseasonal Oscillation during December-April.

IAPSO (Physical Oceanography)

P01p - P01 General Topics on the Physical Science of the Oceans

P01p-554

Quasi-decadal variation of volume transport-weighted temperature of the North Pacific subtropical interior flow during 1993-2012

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The North Pacific subtropical gyre consists of the northward flowing Kuroshio and the southward interior return flow. In addition to the variation of the gyre volume transport, the gyre net heat transport variation is attributed to the variations of volume transport-weighted temperatures of the Kuroshio and the southward return flow. In this study, we estimated the southward interior flow of the subtropical gyre between 1993 and 2012 by applying the altimeter-derived gravest empirical mode method to hydrographic and altimetric data from San Francisco to 30°N, 145°E via Honolulu. Year-to-year variation of the volume transport-weighted temperature is caused by the change of the volume transport within the density layer of 24.5-26.5σ_θ. We found peaks in a quasi-decadal variation of the volume transport-weighted temperature in 1998 and 2007, which are approximately one year before the North Pacific Index peaks.

IAPSO (Physical Oceanography)

P01p - P01 General Topics on the Physical Science of the Oceans

P01p-555

Influence of the Arctic Ocean surface layer processes on the sea ice cover

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There is a hypothesis that there is a link between formation, spatial distribution and stability of ice cover in the deep sea and vertical structure of the upper layer, in particular with the depth and intensity of the halocline.

It was noticed that thermohaline structure of the Arctic Ocean surface layer has undergone significant changes in recent years. Of particular interest is the great freshening of the Canadian Basin surface layer ??that has never been observed in this region since 1950. Sea ice extent in the Arctic Ocean also diminished significantly during the first decade of the 2000s, most particularly in the Canada Basin where the loss of both multiyear and first-year ice was greater than in the other subbasins.

Spatiotemporal variability of different parameters of the Arctic Ocean surface layer, such as mean salinity of the mixed layer, mixed layer thickness, depth of halocline and thickness of halocline layer, and also characteristics of the Atlantic water, entering the Arctic Ocean, are investigated in context of their connection with sea ice extent and sea ice thickness for the period of 1979-1993 and 2007-2013. The oceanographic database of AARI, composed of data collected in the winter period (March-May), is used as the source of TS-profiles. Working database is represented by grids with spatial resolution of grid cells 200×200 km. Sea ice data are taken from NCEP reanalysis.

Preliminary results show high correlations (up to |0.7|) between characteristics of halocline layer and sea ice thickness in the Eurasian Basin and in areas along the Siberian continental shelf and slope.

IAPSO (Physical Oceanography)

P01p - P01 General Topics on the Physical Science of the Oceans

P01p-556

Pathways of iron in the tropical Pacific

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Iron supply to the euphotic zone of the equatorial Pacific is through upwelling of the Equatorial Undercurrent (EUC). The input of iron into the EUC is mostly likely due to sediment fluxes via the New Guinea Costal Undercurrent (NGCU). During El Niño, the increased strength of the NGCU is thought to enhance iron fluxes. However, model analysis reveal that peaks in iron concentration along the EUC pathway are dampened through scavenging before they reach the upwelling region in the Eastern Pacific. In support of this, the signal of increased transport of waters from NGCU sources to the EUC during El Niño events is weakened due to the large range of transit times. Thus it may be premature to trace iron from the Papua New Guinea slope to the eastern equatorial Pacific upwelling zone.

Using the eddy-resolving ocean model Ocean Forecasting Australia Model simulation, we apply a Lagrangian framework to trace iron, by solving iron sources and sinks along particle trajectories. The results are used to determine the relative contributions of the different iron sources feeding the EUC, whether there are other major sources besides sediment fluxes and the role of mesoscale activity in transporting iron.

IAPSO (Physical Oceanography)

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The DEBOT model, a new global barotropic ocean tidal model: test computations and the application in related geophysical disciplines

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We present the DEBOT model, which is a new global barotropic ocean model. The DEBOT model is primarily designed for modelling of ocean flow generated by the tidal attraction of the Moon and the Sun, however it can be used for other ocean applications where the barotropic model is sufficient, for instance, a tsunami wave propagation. The model has been thoroughly tested by several different methods: 1) synthetic example which involves a tsunami-like wave propagation of an initial Gaussian depression and testing of the conservation of integral invariants, 2) a benchmark study with another barotropic model, the LSGbt model, has been performed and 3) results of realistic simulations have been compared with data from tide gauge measurements around the world. The test computations prove the validity of the numerical code and demonstrate the ability of the DEBOT model to simulate realistic ocean tides. The DEBOT model will be principaly applied in related geophysical disciplines, for instance, in investigation of the influence of ocean tides on the geomagnetic field or the Earth's rotation. The module for modelling of the secondary poloidal magnetic field generated by ocean flow is already implemented in the DEBOT model and preliminary results will be presented. The future aim is to assimilate magnetic data provided by the Swarm satellite mission into the ocean flow model.

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Remote contribution to the recent warming trend in the tropical Atlantic

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Tropical Atlantic sea surface temperatures have increased in recent decades. Local forcing, such as heat exchange with the atmosphere or wind driven upwelling, cannot explain this observed increase in surface temperatures. We therefore set out to investigate the role of remote forcing utilizing a series of hindcast and Southern Hemisphere Westerlies sensitivity experiments within a high-resolution ocean model. We isolate the remote contribution of an increased inflow of Indian Ocean water into the South Atlantic. The hindcast experiment reproduces the tropical Atlantic warming, and shows an upward trend in Agulhas leakage with an increase of about 30% from the 1970s to the early 2000s. We induce an (isolated) increase in leakage of 20% within an experiment with climatological forcing, and find that a large fraction of this additional inflow reaches the equatorial region within two to three decades resulting in a general warming in the tropical Atlantic that is most pronounced in the subsurface at about 200m depth. A lagrangian analysis allows us to further explore the 3-dimensional pathways of leakage and its impact on surface temperatures in the tropical Atlantic.

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Lagrangian evolution of a mid ocean anticyclonic eddy

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An anticyclonic eddy four months old detached from Tenerife Island (Canary Islands) was tracked during a survey carried out south the Canary Islands on September 2014, inside the Canary Eddy Corridor region (CEC). Eight drifting buoys were deployed along the eddy radius. They were drogued at 15 m and 100 m depth. Two boys remained inside the eddy at least during 5 months being thus a long lived structure. Wavelet analysis of buoy trajectories indicates that the eddy evolves as Gaussian vortex with inner core rotating much faster that the periphery. Preliminary orbital radius computations suggest that the eddy varies its radius an eccentricity along its live span. Eddy radius increase and decrease intermittently indicating that the eddy evolves pulsating. This is suggestive that it evolves varying its secondary circulation switching between upwelling and downwelling modes. Eccentricity shows also intermittency being indicative of axisymmetrization evens during it life span. These observations confirms previously altimeter and buoys observations that eddy pulses is a general behavior of the CEC eddies. This may have an impact on enhancing the primary production when eddies are in the upwelling mode. We hypothesize that hose pulses may be related to eddy-wind interaction and or near inertial waves trapping.

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P01p-560

Intercomparison of salinity minimum water in the North Pacific simulated by climate models

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Intermediate depth of the North Pacific is one of the regions where anthropogenic carbon simulated in climate models differs from observation. It could be responsible for the discrepancy that the North Pacific Intermediate Water (NPIW), which carries anthropogenic carbon to intermediate depth in the subtropical region of the North Pacific, is not simulated well. Coupled Model Intercomparison Project Phase 5 (CMIP5) historical and RCP 4.5 projection experiments are examined to assess how differently the NPIW is simulated. Large inter-model diversity exists in salinity, density, and depth of the NPIW though multi model ensemble is comparable to observation. There is a tendency that salinity of the NPIW is higher in models that simulate deeper NPIW. The temperature of the NPIW increases, but density decreases in the future compared with present climate in all CMIP5 models. The salinity of the NPIW decrease in most models and the decrease tends to be larger in models simulating lighter NPIW.

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Seasonal variation of the Pacific water intrusion into Otsuchi Bay, northeast of Japan; a numerical simulation with an OGCM

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A numerical simulation of Otsuchi Bay located on the northeast coast of Japan, is conducted, using an ocean general circulation model with a nested-grid system in order to reveal the seasonal variability of the circulation in the bay, and the water exchange between the bay and the open ocean. Otsuchi Bay has a narrow shape, whose zonal length is about 8 km and whose width is 1–2 km. And the bay opens to the North Pacific on the east. The finest horizontal resolution of the model used in the present study is about 14 m, and the model is driven by a result of a numerical simulation focused on the Pacific Ocean with tidal forcing and local momentum and buoyancy fluxes based on observations. Previous observational studies have suggested that water circulation in the bay is controlled by river discharges from the head of the bay and the Pacific water, and the mean circulation in the bay is anticlockwise through the year. It has been considered that there are two mechanisms of the Pacific water's intrusion into the bay: horizontal advections and baroclinic tides. In the present study, it is discussed how the seasonal variation of the vertical stratification affects the Pacific water intrusion into the bay and its relationship with baroclinic tides. The results of the present numerical simulation show that in winter a horizontal anti-clockwise circulation dominates in the bay as the previous observational study suggested because of the small amount of river discharge and the deep surface mixed layer. In summer, on the other hand, a strong stratification complicates the circulation in the bay, and baroclinic tides give rise to the water exchange between the bay and the Pacific Ocean under the pycnocline.

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P01p-562

El nino and southern oscillation-pacific decadal oscillation connections in paleoclimate intercomparison project phase 3

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We examine El Nino and Southern Oscillation (ENSO)/Pacific Decadal Oscillation(PDO) relationship under the mid-Holocene and the Last Glacial Maximum (LGM) state using Paleoclimate Modeling Intercomparison Project phase 3 (PMIP3) climate models. The temporal structure for the ENSO-PDO relationship changed in the mid-Holocene and the LGM climate. In particular, the relationship between ENSO and PDO during the boreal winter becomes stronger so that there would be more frequent in phase occurrence of ENSO and PDO (i.e., El Nino-a positive PDO or La Nina-a negative phase of PDO). Since PDO could constructively interfere with the ENSO-related climate when ENSO and PDO are in phase, it would be speculated to strong climate signal to ENSO in the mid-latitude in the mid-Holocene compared to pre-industrial control simulations. The PMIP3 climate models also shows that ENSO pattern is shifted to the west and reduced but PDO intensity is not changed in the mid-Holocene climate. We also discuss the possible reasons on the enhanced linear relationship of ENSO-PDO even though ENSO intensity is reduced in the mid-Holocene climate state compared to the LGM runs.

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P01p-563

The anisotropy of ocean eddies

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This poster examines the anisotropy of ocean eddies in an eddy-resolving (1/12-degree) global ocean model. The variability of the horizontal velocity fields are analysed using the variance ellipse framework, which characterises the geometry of the variability in terms of the eddy kinetic energy, anisotropy and orientation. It is found that the eddy anisotropy has significant vertical structure and is strongest close to the ocean bottom, where the anisotropy tends to align with the underlying isobath. The strong anisotropic bottom signal is almost entirely contained in the barotropic variability. Upper-ocean variability is predominantly baroclinic and less sensitive to the underlying bathymetry. This finding offers guidance for introducing a parameterization based on the underlying bathymetry to operate on the barotropic flow, to better account for barotropic variability unresolved in coarse-resolution ocean models.

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P01p-564

Interannual zonal displacement of the formation region of the North Pacific Central Mode Water

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Argo profile data from 2003 to 2013 in the North Pacific were analyzed to investigate temporal and spatial variability of the North Pacific Central Mode Water (CMW) formation. The analysis clearly shows a wide zonal band of deep winter mixed layer at 34N-39N from the east coast of Japan to the east of the dateline. This zonal band corresponds to the formation region of the lighter variety of CMW (L-CMW). We examined interannual variations of winter mixed layer development and their main causes in the western, central, and eastern parts of the L-CMW formation region, respectively. In the eastern part of the L-CMW formation region, atmospheric forcing such as winter cooling and wind-induced mixing is an important factor of mixed layer deepening. On the other hand, in the western part of the L-CMW formation region, weakened subsurface stratification associated with anticyclonic mesoscale eddies pinched off from the Kuroshio Extension is more important. The L-CMW formation in each year is governed by combination of magnitude of atmospheric forcing in the eastern part and intensity of ocean subsurface stratification in the western part. Meanwhile, summer-time subsurface L-CMW in the subtropical gyre is distributed more widely and thickly when the mixed layer in the previous winter is deeper in the eastern part of formation region. This implies the subsurface L-CMW in the subtropical gyre is mainly subducted from the eastern part of the formation region. Interannual variations of the formation region of the denser variety of CMW will be also discussed.

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P01p-565

Analysis of shoreline change in Sodol beach

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In terms of topographic characteristic of eastern coast in Gangwon-do, most of beaches are directly influenced by high wave as the beaches consist mainly of sand. Thus, shoreline is considerably changed by high wave and artificial factors, which has become a social issue. For this reason, in this study, groin and submerged breakwaters, structures for reduction of erosion, were constructed in Namae 1 ri where beach erosion has occurred. Since then, sand in southern area has been moved towards the north side. Furthermore, in Sodol beach, continuous erosion has occurred, which leads heavy damage to the nearby beach, like beach erosion, collapse of coastal road and etc. Therefore, the government constructed both geo tube and submerged breakwater to reduce the damage of beach erosion. In this study, shoreline change Thus in this study, investigations of beach profile, shoreline, grain and wave were performed at 2014 to identify and compare the shoreline changes before and after the constructions of geo tube and submerged breakwaters nearby Sodol beach. This study is aimed to draw the correlation between erosion factors through the conclusion of physical investigation. The observation of shoreline change after the installation of geo tube shows that shoreline change is influenced by the change of seasonal wave direction.

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P01p-566

Development of ocean model LSOMG

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The purpose of this contribution is to present the ocean general circulation model LSOMG. It is a z-coordinate baroclinic ocean model which solves the primitive equations under the Boussinesq approximation. We intend to use the model for various geophysical applications. LSOMG is not as complex as the current state-of-art climate models, but it is less computationally demanding. It originates from the LSG (Maier-Reimer and Mikolajewicz, 1992) ocean model, however, significant number of changes has been made. The improvements will be reported, some of them are listed below.

The model has been rewritten from the Arakawa E to Arakawa C grid. The main motivation is to avoid a coexistence of two solutions on the grid that evolve independently of each other. The time staggered discretization of Griffies (2004) has been implemented. The original fully implicit barotropic time stepping scheme was found to significantly dissipate energy. Three different time stepping schemes are available instead. Two explicit schemes are intended to be used with the split-explicit model configuration for short-term studies whereas the third implicit scheme is suitable for long-term studies. The state equation has also been improved. The original UNESCO state equation of sea water (UNESCO, 1981) is replaced by the state equation of Jackett et al. (2006) which is formulated in terms of the potential temperature instead of the in-situ temperature. Finally, the tidal forcing expressed in terms of the second-degree tidal potential has been adopted from the DEBOT model (Einspigel, 2012). LSOMG is paralellized using the OpenMP standard, however, the GPU paralellization using the OpenACC has also been tested.

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P01p-567

Evaluation of a tracer conservation method in a two-way global nested-grid ocean model

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The conservation of tracer is poorly achieved in a nested-grid model due to the discrepancy of fluxes on grid interfaces. In order to improve the accuracy of the tracer conservation, a refluxing method, in which coarse grid fluxes are corrected to fine grid ones, is implemented. A realistic two-way nested-grid ocean model, in which an eddy-permitting western North Pacific model is embedded into a global ocean model, is used to evaluate the method. The model is integrated 45 years for cases with and without the refluxing method, and salinity of the two cases is compared. When the refluxing method is used, spatially averaged salinity changed within 4×10^{-12} PSU throughout the integration. On the other hand, it increased at a rate of about 4×10^{-6} PSU/year without the refluxing method. Especially, horizontally averaged salinity near the sea surface in the nested region increased at a higher rate of roughly 3×10^{-4} PSU/year compared to the case with the refluxing method. This refluxing method is useful to increase the tracer conservation accuracy for the realistic nested-grid ocean model.

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Mixing of water masses in an intrathermocline eddy

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In September 2014 an interdisciplinary cruise was carried out southwest of the Canary Islands in order to sample an anticyclonic eddy of the Canary Eddy Corridor 4 months old as part of the project PUMP (ref: CTM2012-33355).

Preliminaries results show an intrathermocline eddy, with 110 km diameter and 400 m depth with very different values of biogeochemical parameters at center and periphery of the eddy. Associated with this, we observed trapping of near inertial waves at the base of eddy, which causes high values of turbulent kinetic energy dissipation rate then acting as a deep mixing structure.

Data from PUMP and previous studies in the area have allowed us to establish the characteristic values of the water masses in the region to apply Optimum Multiparameter analysis (OMP). Our study aims on the analysis of the distribution and percentages of mass of water throughout the study region using OMP. We completed this study with analysis of the values of the parameters associated with the turbulent mixing obtained from microturbulence profilers and LADCP data. We identify the processes that cause turbulent mixing in both the base of the mixed layer and the base of intrathermocline anticyclonic eddy and how these processes affect the characteristics of the water masses inside and below the eddy

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P01p-569

Analysis of rip currents occurrence in Cheonjin beach

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Numerous tourists visit the beach in summer holiday season for sea-bathing. However, lots of safety accidents, such as drowning, are occurring in the eastern coast due to sand bar in terms of characteristics of the submarine topography. The sand bar would generate sudden substantial change of water depth, and rip currents. The littoral drift cell of Cheonjin beach, located in Goseong-gun, Gangwon-do, ranges from Cheonjin harbor to Bongpo harbor. Cheonjin beach would be referred to as a pocket beach and its length is approximately 1.2km. As many marine structures such as seawall and armoring block were constructed on dune, beach erosion has been continuously occurring.

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P01p - P01 General Topics on the Physical Science of the Oceans

P01p-570

Analysis of shoreline change in Anmok beach

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Anmok beach is located in Gangneung-si, Gangwon-do. The beach belongs to littoral drift cell between northern Sacheonjin harbor and southern Gangneung harbor. The study area, the littoral drift cell that include Anmok beach, is the longest section, about 9.2km, in the eastern coast in Gangwon-do. It is shown that the length of Anmok beach is approximately 500m. Since the construction of Gangneung harbor as a port at 1990, additional structures such as northern breakwaters (450m), southern breakwaters (270m), wharf (280m) and dike (280m) were annually built for 5 years. After the construction, beach erosion has occurred on the north side of Anmok beach due to the rip currents and wave, causing continuous beach erosion and damage to existing shore facilities. Hence, in the year of 2014, the government suggested that constructions of submerged breakwaters (251.55m), submerged breakwaters(100m) and groin (90m) are required. Thus, the submerged breakwaters have begun to construct at August 2014. Also, the government made plans to build other structures annually. In this study, monitoring was performed to identify and analyze sediment movement trends before and after the construction of submerged breakwaters. The investigation item contains analysis of wave induced current and wave, beach profile and shoreline change. The investigations were seasonally conducted. After the construction of submerged breakwaters, tombolo has been formed behind the submerged breakwaters, and beach width nearby breakwaters is being narrowed. Furthermore, rip currents are generated in the area between submerged breakwaters and Gangneung harbor, which activate the sand movement.

IAPSO (Physical Oceanography)

P02a - P02 Physics and Biogeochemistry of Semi-Enclosed and Shelf Seas

IUGG-0574

Abyssal circulation and hydrographic conditions in the Western Ionian Sea during Spring-Summer 2007 and Autumn-Winter 2007-2008

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The Western Ionian Sea circulation plays a crucial role in the redistribution and mixing of water masses from the Levantine and the Southern Adriatic where intermediate and deep water formation take place. Current observations and CTD data collected in the Western Ionian Sea during the period 2007-2008 are analyzed with the aim of contributing to the understanding of the small scale abyssal circulation and its implications on hydrology. From the current data analysis, we propose a mean abyssal circulation pattern strongly affected by the bathymetric constraints. Besides, cyclonic and anticyclonic events with a period between 5 and 11 days were identified. We support the hypothesis that such events can be explained assuming the presence of trains of alternating cyclones/anticyclones advected by a background flow. The most energetic episode found during the analyzed period reaches current values of 15.34 cm s^{-1}. These kind of events can be very effective in mixing the abyssal properties adding further complexity to the discussion of structure and evolution of water masses in the Eastern Mediterranean. From the analysis of hydrological parameters, two deep water masses of Adriatic origin were recognized. The most recent resulted warmer, saltier and denser than in the past. Based on previous studies, we believe that the newer water mass was probably formed during the winter of 2005-2006, that is during the post-Eastern Mediterranean Transient (EMT) period. This way, after the EMT, the Ionian deep circulation has experienced another transition phase, enhancing its variability, concerning both the hydrographic characteristics and dynamics.

IAPSO (Physical Oceanography)

P02a - P02 Physics and Biogeochemistry of Semi-Enclosed and Shelf Seas

IUGG-1381

Dense water formation sensitivity studies in the Northern Adriatic (Mediterranean Sea)

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The study focuses on reproduction of an extreme dense water formation (DWF) event which occurred over shallow northern Adriatic Sea in winter of 2012, and which was characterized by all-time record-breaking Mediterranean seawater density. One-way coupled ROMS and ALADIN/HR modelling system were used for reproduction of the event. Six model runs were performed: using 2 km ALADIN/HR fields and changing river inputs (run 1 – real rivers, run 2 – new climatology, run 3 – old climatology by Raicich, 1994); using real rivers and changing ALADIN/HR resolution (run 4 – 4 km resolution, run 5 – 8 km resolution); and including tides in the model with real rivers and 2 km ALADIN/HR fields (run 6). The sensitivity study includes an assessment of dense water volumes generated in different Adriatic sub-basins and of dense water transports over the selected cross-basin transects. No substantial changes in density levels and transports have been found between run 1 and run 2, with real rivers run producing slightly higher densities and density volumes, as a result of dry conditions which preconditioned the DWF event in 2012. However, quite a dramatic decrease of DWF volumes and transports has been modelled for run 3, especially at the newly found DWF site in the eastern part of the northern Adriatic, where old climatology overestimated river discharges for several times. Altering the atmospheric model resolution changed DWF volumes but not so dramatically, while including tides did not significantly influence the volumes. The importance of imposing a proper freshwater climatology in modelling processes in semi-enclosed basins has been emphasized, especially being relevant in karstic areas where a large number of submarine springs may alter the freshwater budget.

IAPSO (Physical Oceanography)

P02a - P02 Physics and Biogeochemistry of Semi-Enclosed and Shelf Seas

IUGG-1732

Atmospheric controls on the Mediterranean Sea surface freshwater flux

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The extent to which major atmospheric modes of variability influence the Mediterranean Sea surface freshwater flux (i.e. the difference between evaporation and precipitation, E-P) is investigated using fields from the ERA-Interim and NCEP/NCAR reanalyses. Four modes of variability are included in the analysis: the North Atlantic Oscillation (NAO), East Atlantic pattern (EA), Scandinavian pattern (SCAN) and East Atlantic / West Russian pattern (EA/WR). Variations in the basin averaged E-P are largely determined by anomalies that occur in the winter-centered half of the year. Both reanalyses show that the SCAN pattern has the strongest influence on E-P and that it acts primarily through its influence on precipitation for which the basin averaged anomaly is a factor 5 larger than for evaporation. The other three modes exert less control with the NAO and EA/WR making secondary contributions and the EA playing only a minor role. The results are discussed in the context of an earlier complementary analysis that considered the effects of the four modes on anomalies in the air-sea heat flux, Q_{net}. The leading influence of the SCAN mode on E-P, contrasts strongly with the case for Q_{net}, with anomalies in the Q_{net} being primarily determined by the EA and EA/WR modes.

IAPSO (Physical Oceanography)

P02a - P02 Physics and Biogeochemistry of Semi-Enclosed and Shelf Seas

IUGG-1809

Energetics of semi-enclosed basins with two-layer flows at the strait

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Examination of the energy budget for semi-enclosed seas with two-layer exchange flow at the strait shows that the energy flux at the open portion of the boundary (the strait) is proportional to the surface buoyancy flux integrated over the basin area, with the constant of proportionality given by the interface depth. When the surface buoyancy flux is positive, the energy flux is negative, i.e. it is an energy sink, of the opposite sign to the wind-work: these types of basins have an estuarine circulation. Anti-estuarine basins have a negative surface buoyancy flux, which provides a positive energy flux, augmenting the wind-work in powering the circulation. The energy budget for the semi-enclosed seas with vertically separated flows at the strait is examined using reanalysis products for four major semi-enclosed basins: the Mediterranean and Red Seas (antiestuarine) and the Black and Baltic Seas (estuarine). Important differences in the relative contribution to the energy budget of the wind-work versus the surface buoyancy flux are found within basins of the same type, and these differences help explaining some qualitative aspects of the basins flow.

IAPSO (Physical Oceanography)

P02a - P02 Physics and Biogeochemistry of Semi-Enclosed and Shelf Seas

IUGG-2838

The Ligurian Sea at the outset of the 21st century

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The Ligurian Sea (LS) is located in the north-east edge of the Western Mediterranean (WM). Its major cyclonic stream, the Northern Current (NC), flows westwards along the Italian coast. On the western side of the Corsica Island flows the Western Corsica Current (WCC), from the Tyrrhenian sea into the LS, where it joins the NC. The East Corsica Current (ECC) heads north-westwards until it reaches the NC. The Gulf of Lion (GoL), is one of the few spots in the world where deep water formation (DWF) events occur. In recent years the WM has been scenario of major events, such as the Western Mediterranean Transient (WMT) in winter 2004-2005. The WMT was an intense DWF event, that modified the thermohaline properties of the Deep Western Mediterranean Waters. The WMT involved, apart from the GoL, also the LS, where deep convection has been observed for the first time in 1969 and then in several following years, but it rarely corroded the stratification from the surface to the bottom as it happened during the WMT. The LS is an evolving basin, where fundamental ocean phenomena can occur. It is essential to monitor and model the LS.
Repeated hydrographic sections, from 1976, has been analysed. Continuous mooring time series both from the Corsica Channel (1985-2010) and the Dyfamed site, off Nice (1995-2008), are presented. Through the study of these data we define a box, whose edges are the Corsica Channel and the Nice-Calvì transects. The study allow us to estimate the volumetric fluxes and their variability along the years. An inverse box model has been set in order to depict the circulation patterns within the box to describe the Ligurian system and its hydrological evolution in the last 40 years.

IAPSO (Physical Oceanography)

P02a - P02 Physics and Biogeochemistry of Semi-Enclosed and Shelf Seas

IUGG-4370

Observation of 2012-2013 deep convection events in the north-western Mediterranean Sea

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During winter 2012-2013, open-ocean deep convection occurred in the Gulf of Lions (Northwestern Mediterranean Sea) and has been thoroughly documented thanks to the deployment of several gliders at the same time, Argo profiling floats, dedicated ship cruises, and a mooring located within the mixed patch thanks to several national and European projects (GROOM, JERICO, PERSEUS, MOOSE, SOCIB, MERMeX, HyMeX, ASICSMED, REP12, REP13). We show that deep convection reached the bottom in winter early in February 2013 and describe the three overlapping phases of deep convection: preconditioning, violent mixing and restratification. Thanks to these intense observational efforts we also present quantitative results with estimates of heat and salt contents at the sub-basin scale at different time scales (diurnal to seasonal), through optimal interpolation techniques in particular.

IAPSO (Physical Oceanography)

P02b - P02 Physics and Biogeochemistry of Semi-Enclosed and Shelf Seas

IUGG-1801

Structure and Propagation of Large Amplitude Internal Waves in the Strait of Gibraltar

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Large amplitude internal waves are generated close to the time of high tide at or near the sill in the Strait of Gibraltar, particularly during strong Spring tides. We examined the subsurface characteristics of these large amplitude waves using calibrated, three-frequency backscatter profiles from an EK500, accurate velocity profiles from shipboard ADCP measurements combined with GPS heading, and a slowly-towed CTD package to measure the hydrographic properties of the interface between inflowing Atlantic water and outflowing Mediterranean water. In the early morning hours of 4 successive days over Easter weekend, 100 m amplitude waves propagated eastward past the nearly stationary ship at locations east of the sill. Maxima in the vertical profiles of backscatter, particularly at 38 kHz, provided dramatic, real-time portraits of the waves. The maxima in backscatter appear to be a feature of the Mediterranean layer and not a feature of the interface as the maximum lies 20 m below the 38-isohaline; furthermore, the backscatter maximum appears to evanesce before the complete wave train has passed so it is an unreliable indicator of the waves. More robust signatures of the waves are measured by the shipboard ADCP: upward and downward vertical velocities as large as 50 cm s^{-1} are an outstanding feature of the waves and the depth of the maxima in the vertical shear of the eastward current from the ADCP tracks the lower part of the interfacial region (salinity of about 37.7) for much longer periods than does the backscatter.The large amplitude waves were observed at two alongstrait locations separated by 15 km and 2 hours implying an eastward propagation speed of about 2 m s^{-1}. Over 15 km, their amplitude, maximum vertical velocity, and maximum steepness decrease by about 30%.

IAPSO (Physical Oceanography)

P02b - P02 Physics and Biogeochemistry of Semi-Enclosed and Shelf Seas

IUGG-2700

Ten years of marine current measurements in Espartel Sill, Strait of Gibraltar

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Almost ten-year of Acoustic Doppler Current Profiler (ADCP) observations collected at the westernmost sill (Espartel sill) of the Strait of Gibraltar by a monitoring station, first installed in year 2004, have been carefully processed to provide the most updated estimation of the outflow of Mediterranean water through the Strait. A comprehensive quality control of the factors affecting the uncertainty of the measurements has been carried out and a great care has been paid to infer the current at the bottom layer, where direct observations are lacking. The mean outflow in the southern channel of the sill section, where the monitoring station is installed, has been estimated as -0.82 Sv (1 Sv = $1x10^6$ m^3 s^{-1}), with an average contribution of the eddy fluxes of -0.04 Sv. This figure is an overestimation, as the vertical profile at the mooring site was assumed valid for the whole section, thus ignoring the lateral friction. On the other hand, it only gives the flow through the south channel and disregards the fraction flowing through shallower north part. Both drawbacks have been addressed by investigating the cross-strait structure of the outflow from hindcasts produced by the MITgcm numerical model, which was run in a high-resolution domain covering the Gulf of Cádiz and Alboran Sea basins. An overall rectifying factor of 1.039 was found satisfactory to correct the first estimate, so that the final mean outflow computed from this dataset is -0.85 Sv, which is complemented with an uncertainty of ±0.03 Sv based on the interannual variability of the series. The time analysis of the series shows an outflow seasonality of around the 8% of the mean value, with maximum outflow in early spring.

IAPSO (Physical Oceanography)

P02b - P02 Physics and Biogeochemistry of Semi-Enclosed and Shelf Seas

IUGG-3399

High-resolution multi-platform observations and modeling of mesoscale variability in an offshore area west of Sardinia (Mediterranean Sea)

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The area west of the Sardinia Island is a scarcely investigated region of the Mediterranean Sea. The REP14-MED sea trial, conducted from 6 to 25 June 2014 by CMRE with support by 20 partners from six different nations, collected a massive amount of data revealing a complex mesoscale structure in an area of about 110 x 110 km^2. Two research vessels, Alliance (NATO) and Planet (German Ministry of Defense), collected more than 300 CTD casts typically spaced at 10 km, towed for almost three days an undulating underwater vehicle and a CTD chain, respectively, and continuously recorded vertical profiles of currents by means of their ADCPs. Twelve underwater gliders from different manufacturers were deployed (and continuously sampled the study area following zonal tracks spaced at 10 km), plus six moorings, 17 surface drifters and one profiling float.
A first analysis of the observations revealed two anticyclonic eddies of Modified Atlantic Water and one small anticyclonic eddy of Winter Intermediate Water, which was located below the thermocline and surrounded by Levantine Intermediate Water. In order to obtain some deeper understanding of the past history, the actual dynamics, and the future evolution of those eddies, high-resolution (~1 km) numerical studies with data assimilation are underway.

IAPSO (Physical Oceanography)

P02b - P02 Physics and Biogeochemistry of Semi-Enclosed and Shelf Seas

IUGG-4133

Glider and satellite monitoring of a Mediterranean mesoscale eddy in the Algerian basin: Effects on the mixed layer depth

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Just after the Alboran Sea, the Algerian Basin is the first wide basin crossed by Atlantic water entering the Mediterranean Sea. It is dominated by the presence of very energetic mesoscale structures that usually develop from meander of the Algerian Current to isolated cyclonic and anti-cyclonic mesoscale eddies. Despite of the large amount of studies focusing on the circulation of the Mediterranean Sea and its sub-basins, knowledge about these eddies is still incomplete. The new generation remotely sensed data, i.e. satellite altimetry and the ocean-color dataset, offered the opportunity to study some of the eddies characteristics. Nevertheless, the lack of high resolution in situ data still remains a main concern. In order to clarify some of these processes and fill this lack of in-situ measurements, the Algerian BAsin Circulation Unmanned Survey (ABACUS) research project was designed and realized between September and December 2014 in the framework of the JERICO TransNational Access to European coastal observatories. ABACUS mainly aimed at merging glider capabilities and satellite information to advance the knowledge on Algerian Basin mesoscale features. Daily SST and ChlA MODIS products and AVISO information have been used to track and intersect an eddy identified south-east of Mallorca during October 2014. This structure has been monitored along its main axes and from surface to 1000m depth by the glider, while two surface drifters, trapped into the eddy, provided surface data. Merging in situ and satellite data, many characteristics of this eddy have been described. Trapped water masses, mean radius, rotational speed and track from origin to dissipation have been studied as well as their effects on the mixed layer depth and biogeochemistry.

IAPSO (Physical Oceanography)

P02b - P02 Physics and Biogeochemistry of Semi-Enclosed and Shelf Seas

IUGG-4733

The effect of tidal wetlands upon Adriatic Sea hydrodynamics

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Coastal wetlands comprise some of the most valuable ecosystems on the planet with crucial ecological, historical, economical and social relevance. Whereas the ecological contribution coastal wetlands make to offshore is widely recognised – since they provide nursery grounds for aquatic species of immense ecological, cultural and economic importance – their role on the hydrodynamics of the open sea is still poorly investigated. In this study we numerically explore the far-field effects that tidal wetlands exert on the water circulation of the Adriatic Sea. This marginal sea is one of the places with the highest tidal range in the Mediterranean Sea and is characterized by the presence of several coastal lagoons. With the use of an unstructured hydrodynamic model we describe the water dynamics of a system comprising the whole Adriatic Sea and the lagoons of Venice and Marano-Grado, two of the largest Mediterranean lagoons. Comparing results of simulations with and without lagoons, we found out that the presence of these lagoons modify the distribution of the tidal energy entering the Adriatic Sea through the Otranto Strait in its southern part. Tidal waves and currents in the Northern Adriatic Sea result to be enhanced by the presence of the shallow tidal wetlands. This back-effect of the lagoons upon open-sea tide is due to their highly dissipative nature being very shallow systems. The redistribution of tidal energy and the input into the main basin of lagoon waters, with peculiar termo-haline characteristics due to specific evaporative processes, modifies also the circulation patterns induced by the baroclinic forcing. Concluding, we can affirm that tidal wetlands have a significant back-effect upon the entire North Adriatic Sea circulation.

IAPSO (Physical Oceanography)

P02c - P02 Physics and Biogeochemistry of Semi-Enclosed and Shelf Seas

IUGG-1166

Inorganic and anthropogenic carbon chemistry in the Mediterranean Sea

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The Mediterranean Sea (MedSea) can be considered a miniature ocean in many ways and a laboratory basin where global change is affordable to be studied in smaller / shorter spatial and temporal scales. It has deep water formation varying on interannual time scales and a well-defined overturning circulation, and there are distinct surface, intermediate and deep water masses circulating in the western and the eastern basins. In addition to the physical and circulation specific features, the biogeochemistry in the MedSea shows distinct characteristics (ultra-oligotrophy, specific stochiometry …). Within them, the CO_2 chemistry is particular in several ways, and makes this marginal sea particularly interesting to study CO_2 chemistry internal consistency, the uptake, storage and transport of anthropogenic carbon (C_{ANT}) and the impact of CO_2 chemistry change (acidification, carbonate concentration and Revelle factor increase, …) on ecosystem functioning. We will give an overview of the CO_2 chemistry in the MedSea using high-quality CO_2 chemistry collected during the M84/3 cruise in 2011, a discussion of C_{ANT} estimation methods, and present a compilation of cruises from the 80s till 2010s with CO_2 and ancillary data, quality controlled, in order to directly detect temporal changes in CO_2 and other biogeochemical variables.

IAPSO (Physical Oceanography)

P02c - P02 Physics and Biogeochemistry of Semi-Enclosed and Shelf Seas

IUGG-2104

Impact of the sense of the North Ionian circulation on the phytoplankton phenology

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The North Ionian circulation is dominated by a basin-scale meander which changes on a decadal time-scale from cyclonic to anticyclonic and viceversa. This phenomenon, named the Bimodal Oscillating System (BiOS), affects the nutrient field and the community composition of ecosystem in both North Ionian and South Adriatic Seas. Even though the impact of BiOS on phytoplankton bloom was expected, it has never been demonstrated.

Based on phytoplankton phenological metrics, we investigated the influence of BiOS on the phytoplankton seasonality in the Ionian Sea. Focusing on the 1998-2012 period, surface geostrophic flow obtained from sea surface height was used to determine the average annual sense of circulation in the North Ionian. Considering annual chlorophyll time-series derived from ocean color data, specific phenological metrics were computed to characterize the different bloom events which can be observed on the annual time-series. Then, on the basis of these metrics, the cyclonic and anticyclonic regimes were compared.

Results for the North Ionian (north of 37°N) showed that although the initiation date of the first bloom event is not affected by BiOS, the initiation date of the strongest bloom event is impacted. On average, when circulation is cyclonic, the strongest bloom event starts in early February whereas it starts in mid-December when circulation is anticyclonic. The magnitude of the highest bloom event is also larger during the cyclonic period compared to the anticyclonic one. These results suggest that the cyclonic circulation, which results in an uplift of the nitracline, is favorable for the phytoplankton spring blooms as observed in mid-latitude regions whereas the anticyclonic circulation results in a subtropical ecosystem dynamics.

IAPSO (Physical Oceanography)

P02c - P02 Physics and Biogeochemistry of Semi-Enclosed and Shelf Seas

IUGG-4562

Biogeochemical and isotopic distribution, and bacterial diversity trace oceanic abyssal circulation in the eastern mediterranean basin

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We use recent oceanographic observations to develop a new method for tracing routes of dense waters toward and within the ocean abyss. It employs together mercury, isotopic oxygen, biopolymeric carbon and its constituents, as well as indicators of microbial activity, and bacterial diversity found in near-bottom water. In our case study - the Eastern part of the Mediterranean basin- this method is able to distinguish two different abyssal routes from the Adriatic Sea and one abyssal route from the Aegean Sea, which could not be clearly discerned using the traditional approach based on temperature, salinity, and dissolved oxygen alone. The advantage of using together these parameters is twofold: it yields valuable information even if temperature/salinity of competing sources are virtually indistinguishable, and it can help elucidating aspects of spatial/temporal behaviour of near-bottom circulation beyond the single observed episodes, as biogeochemical and bacterial distributions often reflect persistent characteristics of abyssal waters.

IAPSO (Physical Oceanography)

P02c - P02 Physics and Biogeochemistry of Semi-Enclosed and Shelf Seas

IUGG-4741

Observations of diapycnal mixing in the western Mediterranean Sea

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The overturning circulation in the Mediterranean Sea is often cited as a small scale laboratory of the Atlantic overturning cell. While diapycnal mixing participates to the Atlantic overturning cell, it is not clear how important such a mechanism is for the fate of Mediterranean water masses. Indeed there is less energy inputs through winds and tides in the Mediterranean than there are in some parts of the Atlantic. However, other mechanisms, such as mesoscale flow interactions with topography, flows through narrow passages and sills, double diffusion … , prevail and transfer energy to small scale turbulence,… Full depth mixing observations is obviously lacking in the Mediterranean basin to quantify the importance of those processes.

In this study, we report on observations collected during five cruises and gathering a total of 130 full depth microstructure profiles. Excluding the mixed layer, depth averaged dissipation rates are usually weak of order 10^{-11} W/kg. Depending on the cruise, slightly enhanced(10^{-10} W/kg) are found near the western slope of Sardinia at 40°N, in the Sardinia passage at 38°N, and in a few profiles located in the Algerian basin and around Sicily. Contrastingly, $< e >$ is always strong (10^{-9}-10^{-7} W/kg) in the Sicily strait and in the channel of Corsica. Below 1000 m, typical vertical diffusivities are in the range 3×10^{-5} to 3×10^{-4} $m^2 s^{-1}$. Below the mixed layer and down to 500 m, vertical diffusivities are usually weaker than 1×10^{-5} $m^2 s^{-1}$. This contrasts strongly with the 10^{-3} to 10^{-2} $m^2 s^{-1}$ values reached in the Sicily strait, the Corsica Channel and in the mixed layer. We provide as well first insights on the dynamical processes responsible for enhanced dissipation rates and turbulent mixing, with a focus on the Sicily Strait.

IAPSO (Physical Oceanography)

P02d - P02 Physics and Biogeochemistry of Semi-Enclosed and Shelf Seas

IUGG-1059

Circulation and biogeochemistry in China semi-enclosed and shelf seas

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Semi-enclosed marginal South China Sea and shelf seas of Bohai, Yellow and East China Seas are linked together by Taiwan Strait to form the China Seas (CS). It connects with western Pacific Ocean by shelf break and Luzon Strait, and with terrestrial inputs by big Changjiang and Pearl River estuaries. The circulation in the CS is mainly driven by the south-east Asia monsoon, but largely modulated by intrusive current from Kuroshio on the seaside, by buoyancy from the estuaries on the landside and by highly variable current associated with flow-topography (effect) interaction over the shelf/slope. The circulation imports chemical constituents of different properties from land and open ocean, mixes with waters in the CS where active biogeochemical reactions take place. In this study, we investigate biophysical processes in the China Seas (CS) based on both a China Sea Multi-scale Ocean Modeling System (CMOMS) and field measurements. We will present characteristics and processes of physical transport and associated biogeochemical response in the CS.

IAPSO (Physical Oceanography)

P02d - P02 Physics and Biogeochemistry of Semi-Enclosed and Shelf Seas

IUGG-1273

Investigations of the marine CO2 system:An ideal tool to study biogeochemical processes in the Baltic Sea

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Long-term observations of the marine CO_2 system were used to identify and quantify biogeochemical processes in the Baltic Sea. Since 2003 the surface water CO_2 partial pressure, pCO_2, was recorded regularly along a transect that covers the entire central Baltic Sea. The measurements were performed by a fully automated measurement system deployed on a cargo ship that commuted at two to three days intervals between Helsinki in the northeast and Lübeck in the southwest of the Baltic Sea. Due to the high spatial and temporal resolution of the data, it was possible to identify and quantify the timing and intensity of plankton bloom events. Special attention was paid to the mid-summer production which is based on nitrogen fixation. It was shown that the nitrogen fixation was mainly controlled by the planktonic uptake of solar radiation and that the temperature played only a minor role. Estimates of the total annual net biomass production indicated that the production fuelled by nitrogen fixation is of the same order of magnitude than the nitrate driven spring bloom production.

With regard to the deep water CO_2 system, the vertical distributions of the total CO_2 were measured four to five times per year in the central deep and frequently anoxic basin of the Baltic Sea. The accumulation of total CO_2 determined during long-lasting periods of stagnation at depths below 150 m facilitated estimates of the kinetics of the organic matter mineralization. Concurrent measurements of the nutrient concentrations provided insight into the stoichiometry of the mineralization process at varying redox conditions.

IAPSO (Physical Oceanography)

P02d - P02 Physics and Biogeochemistry of Semi-Enclosed and Shelf Seas

IUGG-3156

Model study on regime shift of the North Sea ecosystem, NEMO-Nordic-SCOBI model.

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Coupled ecosystem model was developed and applied for the North Sea and the Baltic Sea. The physical model used in this work is a previously published NEMO-Nordic configuration based on the NEMO ocean engine. The biogeochemical part of the model is based on a continuously developing SCOBI (Swedish Coastal and Ocean Biogeochemical) model. This model was successfully used in several studies on the ecosystem of the seas surrounding Sweden.
Comparison of model results with mean seasonal fields based on observational data shows good agreement for the surface seasonal spatial dynamics of the model. At the same time the model shows good performance for the main simulated parameters with the observed time series for selected stations.
With the new model we investigate the effect of river nutrient load change on the ecosystem of the North Sea and the impact of the hydrographic decadal variability on biogeochemical cycles. By applying different atmospheric forcing (downscaled ERA-40 re-analyses and global climate models) we show evidence of the regime shift in the North Atlantic Oscillation coincide with decreasing river loads on winter nutrient concentrations in different regions of the North Sea. To investigate possible effects of climate change on the North Sea ecosystem ensemble simulations for the period 1961-2100 forced by regional climate scenarios were performed.

IAPSO (Physical Oceanography)

P02d - P02 Physics and Biogeochemistry of Semi-Enclosed and Shelf Seas

IUGG-3416

Using surface current-driven lagrangian transport patterns to mitigate the risk of pollution to marine protected areas in the Baltic sea

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Understanding of the surface circulation patterns is essential in predicting the transport of pollution. Some of these patterns are concealed or semi/quasi-persistent with varying spatial and temporal scales. A novel technique is described that utilises Eulerian surface velocity data obtained from the Rossby Centre Ocean model (RCO) for the period 1987–1991, Lagrangian trajectory model (TRACMASS) and classical statistics for the identification of semi-persistent patterns of surface transport on weekly scales in the Gulf of Finland, Baltic Sea. These results are then used to assess the Marine Protected Areas (MPAs) that are at high risk of pollution.

The analysis revealed an anti-cyclonic gyre in the central gulf and semi-persistent patterns of net transport. Lagrangian transport is mainly aligned along the coasts of the Gulf of Finland but in transitional spring and autumn months intense cross-gulf transport may exist.

To quantify the level of risk to the MPAs, the behaviour of pollution stemming from the major fairway and then advected by surface currents is simulated using 20 days long Lagrangian trajectories of passive parcels. The MPAs located in the eastern and western sections of the gulf are the most exposed for pollution. It takes on average 5–8 days for pollution to reach the MPAs. An almost linear relationship exists between the number of hits to a MPA and the distance of this MPA from the fairway. However, the source of pollution may originate from remote locations of the fairway. These results agree well with the semi-persistent patterns observed.

IAPSO (Physical Oceanography)

P02d - P02 Physics and Biogeochemistry of Semi-Enclosed and Shelf Seas

IUGG-4093

Turbulence due to diel vertical migrations of zooplankton: Comparison of computational fluid dynamics model with observations

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Diel vertical migrations (DVM) of zooplankton may have an impact on ocean mixing, though details are not entirely clear. Kunze et al. (2006) observed a strong sound scattering layer of zooplankton undergoing DVM in Saanich Inlet (SI), BC. In this study, researchers measured an increase of dissipation rate of turbulent kinetic energy (ε) by four to five orders of magnitude during DVM over background turbulence of 10^{-9} W kg^{-1}. We also observed a strong sound scattering layer undergoing DVM in the Straits of Florida (SF) with a bottom mounted ADCP at a 244 m isobath. We have used a 3-D non-hydrostatic computational fluid dynamics (CFD) model with Lagrangian particle injections (a proxy for migrating zooplankton) via a discrete phase model to simulate the effect of turbulence generation by DVM of zooplankton for SI and SF. We tested a range of concentrations from 10 to 10,000 organisms/m^3 as reported by Kunze et al. (2006). At concentrations near the upper limit, the simulation showed increase in ε of approximately five orders of magnitude during DVM over background turbulence. At intermediate concentrations, the model produced increase of ε by one to two orders of magnitude. At the lower concentration, there was no longer an effect on ε. Turbulence measurements for the SF were not available to make a quantitative comparison with the model. However, we observed a small decrease in current velocity profile during DVM after averaging 11 months of observations, which was reproduced with the CFD model. These velocity profile deviations can be explained by the increase in turbulent mixing during DVM.

IAPSO (Physical Oceanography)

P02d - P02 Physics and Biogeochemistry of Semi-Enclosed and Shelf Seas

IUGG-4242

Influence of a western boundary current on shelf dynamics, upwelling and bio-physical variability from repeat glider deployments

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Along southeastern Australia, the East Australian Current (EAC) strongly influences the circulation and watermass characteristics of the adjacent continental shelf. In situ moored observations have shown dense water uplift resulting from EAC intrusions onto the shelf at 30 and 34ºS, but sustained observations are lacking in the separation zone (~31-32ºS).

The comprehensive dataset from 24 glider deployments along the inshore edge of the jet provides a new high resolution hydrographic and bio-geo-chemistry climatology. We exploit the climatology to understand the spatial variability of the watermass characteristics and the momentum balances across the EAC separation zone.

The predominantly geostrophic shelf circulation and temperature fields are least (most) variable upstream (downstream), where encroachment (separation) dominates. Advection is accentuated north of the separation, where the shelf is narrow and the jet is intensified. This is where dense bottom water with low dissolved oxygen (DO) is uplifted as much as 80 m towards the surface, in response to the high bottom stress. Downstream of the separation, the dynamic height minimum shows separation induced upwelling, resulting in a denser watermass with higher coloured dissolved organic matter and DO concentrations than the EAC water.

Exponential scales of variability along the shelf are of 19-24 km at the surface, decreasing at depth. The variability across-shelf is < 10 km for each of the bio-physical parameters and remains consistent over depth. In the across shelf direction, the EAC intensified zone is characterised by the smallest length scales (minimum of 4 km). Dense water uplift appears to be the major source of high horizontal variability across and along the narrow continental shelf adjacent to the EAC.

IAPSO (Physical Oceanography)

P02e - P02 Physics and Biogeochemistry of Semi-Enclosed and Shelf Seas

IUGG-0899

The role of evolving stratification on the internal wave field in temperate shelf seas

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A key mechanism for internal mixing away from the sea surface and bed is internal waves. Currently our knowledge of how this mixing is sustained is limited, particularly during transitional periods of stratification such as in spring, when the water column changes from a well mixed to a thermally stratified state, and in autumn when convection and increasing winds promote mixing. It is during these transitional periods that most numerical models of ocean physics and biogeochemistry are in need of improvement to better describe this mixing.

New observations of unprecedented detail and temporal extent have been collected of the dynamics and water column evolution from the onset to the breakdown of stratification in the central Celtic Sea from March to November 2014. Here we focus our attention on the onset of spring stratification. We find that as soon as potential energy anomaly, Φ, rises over a value of $\Phi = 2$ J m^{-3}, an internal wave field can be sustained. Clear signals of internal tides with superimposed higher frequency waves are evident. Amplitudes of internal waves reach up to 20 m. Several strong wind events significantly modify stratification and the thermocline depth by remixing the surface layers before restratification takes place. These wind events also give rise to strong inertial signals that have similar baroclinic energy levels to the internal tide of > 200 J m^{-2}. Here we examine the feedback between the onset of stratification and the internal wave field. We aim to better understand the vertical wave generation and evolution due to variable local forcing, such as heat flux, wind and tidal stirring. We also investigate how the associated shear from internal waves affects the stability of the water column and affects the evolving stratification.

IAPSO (Physical Oceanography)

P02e - P02 Physics and Biogeochemistry of Semi-Enclosed and Shelf Seas

IUGG-1553

The impact of diapycnal mixing on sea surface CO2 partial pressure in seasonally stratified shelf seas

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A key parameter in determining the exchange of CO2 across the ocean-atmosphere interface is the sea surface partial pressure of carbon dioxide (pCO2). Temperate seasonally stratified shelf seas represent a significant sink for atmospheric CO2. Here an analytical model is used to quantify the impact of vertical mixing across the seasonal thermocline on pCO2. The model includes the impacts of the resultant dissolved inorganic carbon, heat, salt and alkalinity fluxes on the solubility of CO2 and the effect of the inorganic carbon sink created by the primary production fuelled by the flux of limiting nutrient. The results indicate that diapycnal mixing drives a modest but continuous change in pCO2 of order 1-10 ?atm per day. In quantifying the individual impacts of the fluxes of the different parameters we find that the impact of the fluxes of DIC and nitrate fluxes dominate. In consequence both the direction and magnitude of the change in pCO2 are strongly dependent on the C:N uptake ratio in primary production. Whilst the smaller impacts of the heat and salt fluxes tend to compensate for each other at mid-shelf locations, the heat flux dominates close to the shelf break. The analysis highlights the importance of the accurate parameterisation of the C:N uptake ratio, the surface mixed layer depth and the TKE dissipation rate within the seasonal thermocline in models to be used to predict the air-sea exchange of carbon dioxide in these regimes. The results implicate storms as key periods of pCO2 perturbation.

IAPSO (Physical Oceanography)

P02e - P02 Physics and Biogeochemistry of Semi-Enclosed and Shelf Seas

IUGG-3721

Dense shelf water cascades around Australia: Dynamics and water column processes

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Australia, the driest inhabited continent, experiences high evaporation rates resulting in higher salinity (density) water in majority of the shallow coastal waters around Australia. This dense water is transported across the continental shelf near the seabed due to the cross-shelf density gradient and is a mechanism for the export of water containing suspended material and carbon away from the coastal zone to the deep ocean. Ocean glider measurements undertaken since January 2009 have indicated that the dense shelf water cascade (DSWC) is a regular occurrence at locations around Australia. The existence of DSWC depends on the balance between buoyancy input and vertical mixing: the cross-shelf density gradient is generated by buoyancy flux due to evaporation and cooling, whilst vertical mixing is through wind and tidal mixing. There are seasonal changes in the buoyancy flux, during autumn it is dominated by evaporation whilst in winter, it is through surface cooling. During periods of strong winds (e.g. summer months in south-west Australia) there is a cross-shelf density gradient, due to wind induced vertical mixing. As the DSWC consists of different water types, many frontal zones are present which lead to the formation of regions of high suspended sediment and/or suspended concentrations. Dense water containing suspended particulate matter, nutrients and in some instances anthropogenic contaminants are exported via the cascade offshore. Hence, the complex physical dynamics that govern the ultimate fate of the dense shelf water and the suspended particles it contains, has direct implications and consequences for biogeochemistry.

IAPSO (Physical Oceanography)

P02e - P02 Physics and Biogeochemistry of Semi-Enclosed and Shelf Seas

IUGG-4209

Diagnosing one of the largest inflows into the Baltic Sea since 100 years (December 2014)

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In late November/ early December 2014 an exceptional inflow event into the Baltic Sea was observed. These inflow events are important for the deep water ventilation in the Baltic Sea and occur every 3-10 years. Based on first observational data sets, this inflow is ranked as the third largest since 100 years. First estimates indicated a total volume transport of 330 km3 and a total salt transport of 4 Gt.

With the help of a multi-nested modeling system, reaching from the North Atlantic (8 km resolution) to the Danish Straits (600 m resolution), we reproduced this event in detail. The model gave a slightly lower salt transport of 3.8 Gt. We quantified the contributions to the mass flow through the Sound and the Great Belt, as 1/3 to 2/3 respectively. This agrees well with the observations. Moreover, by using a passive tracer to mark the inflowing water, but also an age tracer, we were able to track the inflowing water masses and follow there paths and timing through the different basins. The model indicate that the inflow has the potential to oxygenate large part of the Gotland Basin and thus reduce the area suffering from hypoxia.

IAPSO (Physical Oceanography)

P02e - P02 Physics and Biogeochemistry of Semi-Enclosed and Shelf Seas

IUGG-5178

Tidally induced mean flow over bathymetric features: a contemporary challenge for high-resolution wide-area models

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Huthnance [Estuarine Coastal Mar. Sci. 1973, 1, 89–99] is reviewed, whereby an oscillating tide over bathymetric features induces a mean flow generally along isobaths. The effect is a superposition of Coriolis and frictional processes. These are discussed with the intention of elucidating the processes for a more general readership. Induced velocities of order several cm/s are expected around the UK shelf seas. The effect is dynamically significant over bathymetric scales of order a few kilometres and has previously been of most interest to dynamicists studying processes on this scale. However, with the increase in computing power, appropriate scales can be simulated in shelf-wide regional models and in next generation operational models. It is demonstrated that this small-scale effect is likely to be important for shelf-wide regional models and that a spatial resolution of at least 1.8 km is recommended for shelf sea simulations.

IAPSO (Physical Oceanography)

P02f - P02 Physics and Biogeochemistry of Semi-Enclosed and Shelf Seas

IUGG-3040

Genesis and concentration of suspended particulate matter in the Kara Sea during the greatest decreasing of Arctic sea ice sheet

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The concentration and composition (grain size, mineralogy, particulate organic carbon (POC) and its isotopic composition, some lithogenic elements) of the suspended particulate matter (SPM) in water column of the Kara Sea, including the estuaries of the Ob and Yenisei rivers, were studied. The samples (~200) were collected in September 2007 and 2011 when the smallest area of drifting ice in the Arctic were revealed. The increased concentrations of SPM in the surface layer were determined in the Ob estuary in 2007 compared with the data for previous years. The SPM concentration and share of the terrigenous part in it was in ≥10 times higher in the Ob River estuary than that in the Yenisei River estuary. The SPM concentration decreases exponentially during the processes of fresh and salt water mixing. Main transformation of the SPM composition in this are takes place within the salinity frontal zone. The strong impact of terrigenous material on marine SPM composition in 2011 decreased in the northern direction. The anomalous desalination of sea surface layer in 2007 led to the relatively lighter values of POC isotopic composition in the western part of the sea. So the influence of terrigenous material is only slightly decreased in the northern direction. The distribution of terrigenous matter from the tip of Novaya Zemlya in the northeastward was detected. Material coming with melted waters from the eastern coast of Novaya Zemlya does not make a significant contribution to the SPM concentration in the Kara Sea proper. The particles brought by the rivers from Western and Eastern Siberia were dominated in the SPM composition up to 76º30' N in the Kara Sea. It was shown that the cross-shelf seaward transport of the SPM is topographically attached.

IAPSO (Physical Oceanography)

P02f - P02 Physics and Biogeochemistry of Semi-Enclosed and Shelf Seas

IUGG-5259

Greenland Ice Sheet melt increases Baffin Bay heat content on the west Greenland shelf

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We present results from 8 sensitivity experiments using the numerical model NEMO that study the relation between melt from the Greenland Ice Sheet and warming of shelf waters on the northwest Greenland shelf. We find a positive feedback between increasing runoff (melt) and shelf heat content. The heat content increases in response to a reduction in Arctic Water inflow through the Canadian Arctic Archipelago and a stronger stratification in Baffin Bay. Increasing the meltwater runoff led to positive feedbacks resulting in further freshening of surface waters and warming and shallowing of the West Greenland Irminger Water on the northwest Greenland shelf. These warmer waters can now more easily enter fjords on the Greenland coast, potentially providing additional heat to accelerate the melt of marine terminating glaciers.

IAPSO (Physical Oceanography)

P02f - P02 Physics and Biogeochemistry of Semi-Enclosed and Shelf Seas

IUGG-5362

Interannual variability of hydrochemical parameters and frontal zone dynamics in the Ob' Inlet and Yenisei Gulf.

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A large amount of fresh water flow into the Kara Sea through two biggest gulfs: the Ob' Inlet and Yenisei Gulf. The objective is to study hydrochemical structure of water and dynamics of the mixing zone with the waters of the Kara Sea in these great estuaries. Laboratory of biohydrochemistry of P.P.Shirshov Institute of Oceanology was engaged in investigations of these gulfs for a long time. Great volumes of data on the mentioned water areas are accumulated during Russian and international expeditions. This data contains such hydrochemical parameters as dissolved oxygen, phosphates, silicates, nitrogen and carbonate system parameters: pH, total alkalinity, pCO_2, DIC. Analysis of this data allowed making some noticeable results.

For the waters of the Ob' Inlet and Yenisei Gulf was traced dynamics of relationships Alk/S for several years. The position of the contact zone of marine and fresh water varies greatly not only seasonal, but year-on-year, due to the change in the volume of river flow.

Investigations in the Ob' Inlet gave us an opportunity to identify one of the major factors affecting on the chemical structure of the Inlet. Its volume is greater than the average runoff of the River Ob' for the year, and slightly less than runoff of all rivers flowing into it. As a consequence it takes considerable time for a complete renovation of water in the bay. Even during the summer expeditions we can observe as high waters and winter water which have very different hydrochemical characteristics.

IAPSO (Physical Oceanography)

P02f - P02 Physics and Biogeochemistry of Semi-Enclosed and Shelf Seas

IUGG-5769

Surface circulation features along the Tunisian coast (central mediterranean sea): the Atlantic Tunisian current

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The Tunisia-Sicily Channel is located in the Central Mediterranean Sea between Tunisia and Sicily. The Atlantic Tunisian Current (ATC) is a slope current flowing around the Tunisian coast close to the 200 m isobath till Lampedusa Island. Because of its position, the ATC and the surrounding mesoscale activity should play a key role in the exchanges between the coastal and offshore waters. The main peculiarities of summer surface circulation variability are described by analyzing the spatial distribution of minimum salinity calculated from the hydrological data CTD collected along the Tunisian coast in summer 2006 and 2007. It has been shown that this region is characterized by complex dynamics strongly influenced by atmospheric forcing and topography. The ATC is marked by a recirculation off the coast of the Gulf of Hammamet. In summer, the ATC steers southward and, on reaching the shallow water of the Kerkennah Islands at the entrance to the Gulf of Gabes, appears to divide into two branches. The use of ADCP velocity profiles combined with numerical modeling, as well as the analysis of satellite sea surface temperature and chlorophyll images confirmed also the existence of instabilities, coastal jets, eddies with a broad spectrum of sizes and filaments generated at the edge of the ATC.

IAPSO (Physical Oceanography)

P02g - P02 Physics and Biogeochemistry of Semi-Enclosed and Shelf Seas

IUGG-2355

The annual cycle of the Japan Sea Throughflow

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The mechanism responsible for the annual cycle of the Japan Sea Throughflow is investigated using a two-layer model. The Japan Sea is a marginal sea located in the western North Pacific that is separated from the Pacific by the islands of Japan. Three narrow and shallow straits, the Tsushima, Tsugaru, and Soya Straits, connect this sea towards the Pacific and observations show that the flow through these three straits vary annually with a maximum transport in summer-fall and a minimum transport in winter. The variability is large for Soya (north) and Tsushima (south) Straits but weak for the Tsugaru Strait (middle). We find the subpolar winds located to the north of Soya Strait to be the primary forcing agent of this annual cycle rather than the subtropical winds located to the east of Japan. The subpolar winds generate baroclinic Kelvin waves that perturb the sea surface height at the Soya Strait, cause barotropic adjustment to occur within the Japan Sea, and change the flow at the other straits. This mechanism explains why the annual cycle at the three straits occur almost synchronously. We also find Kelvin Circulation Theorem a useful tool for explaining how the magnitude of the annual cycle at the three straits are controlled. The theorem show the magnitude and direction of the flow controlled largely by the ratio of the meridional length of the two islands that is bounded by the three straits.

IAPSO (Physical Oceanography)

P02g - P02 Physics and Biogeochemistry of Semi-Enclosed and Shelf Seas

IUGG-5375

Slope convection in the Peter the Great Bay and ventilation of the Japan Sea

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Cascading of dense shelf water along the slope (slope convection) of Peter the Great Bay in the northwestern Japan Sea in winter is one of the key mechanisms of ventilation of the Japan Sea deep layers. Results of direct observations of cascading by autonomous mooring systems and repeated CTD surveys during winters of 2012-2014 have been presented here. The events of dense water, formed by cooling and brine rejection on the shelf during ice formation, approaches the shelf edge (100 m) have been registered every winter usually in February – March. However their duration has been varied interannually reflecting climatic changes. Only one episode of deep down slope cascading was registered by mooring at 1150 m. Its duration was only around 12 hours. These very transient events however resulted in a number of intrusions of colder, less saline, higher oxygen content and higher turbidity water detected by CTD casts observed down to 2000-2800 m indicating penetration of cascading down to the bottom of the slope and thus ventilation of the intermediate, deep and bottom waters of the Japan Sea. Depending on a severity of winter the intrusions formed by cascading water ventilate intermediate layers (winters of 2013-2014) or may penetrate down to the bottom layer (extremely cold winter 2001). I any case this ventilation mechanism is important to understand water mass transformation in the Japan Sea.

IAPSO (Physical Oceanography)

P02g - P02 Physics and Biogeochemistry of Semi-Enclosed and Shelf Seas

IUGG-5476

Surface current patterns in eastern Wakasa Bay extracted using self-organizing map analysis of VHF ocean radar observation

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Extracting ocean current patterns is important to predict the advection and diffusion process of thermal water from power plant, and accidental release of oil and contaminated water. Ocean radar is one of the most powerful tools for measuring surface currents, with high spatial and temporal resolution of the two-dimensional flow field over a large coastal area without depending on the weather conditions. Self-organizing map (SOM) analysis is an efficient method for feature extraction and classification of nonlinear large data sets such as radar observation. In this study, we conducted batch-learning SOM analysis of ocean radar data with the goal of finding out the main surface current patterns in eastern Wakasa Bay. The Wakasa Bay area is the site of many power plants, but it is difficult to predict surface current patterns because of small tide currents. We deployed very high-frequency (VHF) ocean radar with a digital beam-forming system, and obtained surface current data every 15 minutes in the area of 14 km × 14 km. The analysis focused on daily mean current vectors, and the SOM unit weights were initialized using results of empirical orthogonal function analysis. The SOM results well captured the characteristic features of current patterns associated coastline topography, and flow patterns at the entrance of the bay. Southeastward and eastward current patterns dominated this area. We also applied SOM to wind data, and related local wind patterns to the ocean surface current patterns. These results show that SOM analysis of the ocean radar observation can detect the pattern and frequency of coastal current without mooring current meters, and is potentially useful for assessing the environmental impact of power plants construction.

IAPSO (Physical Oceanography)

P02p - P02 Physics and Biogeochemistry of Semi-Enclosed and Shelf Seas

P02p-211

The study of nutrients exchange on the bottom surface according RSHU expeditions to the Eastern Gulf of Finland in 2009-2012.

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The results of experiment based on the data collected at Russian State Hydrometeorological University (RSHU) expeditions to the Eastern Gulf of Finland in 2009-2012 are presented. The knowledge of physical and chemical exchange between sea water and bottom is important for water ecosystems functioning simulation and for qantitative estimation of internal nutrient load. According to some estimates the nutrients influx from sediments to sea water is comparable to influx with river runoff or hydrotermal influx. The Gulf of Finland accepts about 20% of common Baltic sea pollution. Despite of significant decrease of nutrient load since mid-1990s, winter concentration of nutrients were remaining high and signs of eutrophication were observed. This phenomenon can be explained with significant volume of nutrients accumulated in sea water and with intensive nutrient release from sediments known as “secondary pollution”, which was induced by oxigen deficite in 1990s and 2000s. During oceanographic surveys of the Eastern Gulf of Finland in 2009-2012 the nitrogen and phosphorus mineral form and heavy metals concentrations in the near-bottom and silt water were measured. According to samples analysis the nutrient content gradients and fluxes at sea-bottom surface were calculated. The laboratory experiments based on the sediment samples from different geoecological regions of the Gulf of Finland were carried out. During the experiments the estimates of nutrient content gradients and fluxes in molecular diffusion conditions were obtained and the time period of maximal nutrient release from sediments to water in hypoxia conditions was determined. Also it was found that oxigenic regime impacts to values of nutrient content gradients at sea-bottom surface crucially.

IAPSO (Physical Oceanography)

P02p - P02 Physics and Biogeochemistry of Semi-Enclosed and Shelf Seas

P02p-212

A numerical study of the coastal current in the Northwestern South China Sea

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The characteristics and dynamics of summer-time continental shelf circulation in the northwestern South China Sea were investigated based on a high resolution unstructured-grid finite volume community ocean model. The coastal current on the NSCS shelf was intensively influenced by monsoon and freshwater discharge of the Pearl River. Strong southwest monsoon drove the coastal current northeastward. However, under weak southwest monsoon, the coastal current west of Pearl River estuary flowed toward southwest, and split into two parts when reaching east of the Qiongzhou Strait, one branch entered the Gulf of Tonkin through the narrow Qiongzhou Strait, transporting low salinity water into the Gulf of Tonkin, and the other part flowed cyclonic and interacted with the northeastward current around southeast of Hainan Island, forming a cyclonic eddy east of the Qiongzhou Strait. To study the responses of the coastal ocean to strong and weak wind, we selected two representative years. A series of experiments focused on freshwater discharge, wind forcing, tidal rectification, and stratification were performed to study the physical mechanism of the southwestward coastal current. The interaction between southwest monsoon and freshwater discharge plays a crucial role in the formation of the southwestward coastal current during summer. Momentum balance analysis suggested that the along shelf barotropic pressure gradient due to sea level tilting induced by Pearl River discharge provides the main driving force for the southwestward coastal current.

IAPSO (Physical Oceanography)

P02p - P02 Physics and Biogeochemistry of Semi-Enclosed and Shelf Seas

P02p-213

Occurence Forms of Some Heavy Metals in the Surface Sediments of the White Sea

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The Fe, Mn, Cu, Co, Cr, Ni, Cd, Pb and As occurrence forms in surface bottom sediments were studied at 12 stations along the axial transect in the subarctic semi-enclosed White Sea. A selective sequential extraction followed by ICP-MS was used. This approach allowed to distinguish among the geochemically labile (exchangeable/bound to carbonates, bound to Fe-Mn oxides, bound to organic matter) and geochemically inert (detrital, lithogenic or residual) fractions; the latter hold metals within their crystal structure.

From our data, 80% in average of Fe total content was present in lithogenic fraction, whose contribution increased along transect while moving from the Northern Dvina towards the Kandalaksha Gulf. Proportion of different Cr and Ni fractions in bottom sediments demonstrated a similar distribution pattern, hence average percentage of their lithogenic forms being <80%. On the contrary, Mn, Cd and Pb have been accumulated in sediments mostly due to geochemically labile forms accounting 80-90% of their t?tal content. Contribution of lithogenic fraction of Co, Cu and As varies from 20 to 70%, maximum geochemical affinity to organic matter being found for Cu (35% in average).

In most cases the high content of labile metal' fractions was found in fine-grained bottom sediments with elevated organic carbon content and adsorption/desorption characteristics, while maximum content of detrital trace metal' fraction showed no correlation with grain-size composition. An influence of hydro-dynamic processes on the lithological composition and sedimentary matter' transfer was revealed in some cases, although their relationship with trace metal' fractions is still under discussion. This work was supported by Russian Foundation of Basic Research, project No 15-05-08372.

IAPSO (Physical Oceanography)

P02p - P02 Physics and Biogeochemistry of Semi-Enclosed and Shelf Seas

P02p-214

Variability of the Hydrographic Characteristics of Water Masses in the Deep Tyrrhenian Sea

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In the Mediterranean Sea the Sicily Channel plays a key role for water masses dynamics and the thermohaline circulation since it allows the exchanges between the eastern and western basin.
Since all water masses coming from the east flow into the Tyrrhenian Sea, this subbasin represents an ideal place to understand the associated processes and changes.One of the main features in a typical vertical profile of the water column of the Tyrrhenian basin is the step-like structure, due to double diffusion, which has a strong impact on the vertical mixing rates.
The first aim of this study is to examine the variability of the hydrographic characteristics of water masses coming from the Sicily Channel, throughout a long time series data set of two repeated CTD stations in the Tyrrhenian subbasin, which have been measured relatively often since 1992.
Previous studies showed that the significant changes observed up to 2003, were mostly related to the Eastern Mediterranean Transient (EMT). But in the subsequent years another important phenomenon was observed in the western Mediterranean: the presence of a new layer of salty and warm deep water, formed since 2005, and spreading at the bottom of the western basin.
Therefore the second aim of this study is to follow the evolution of this new deep water and its entrance and residence within the Tyrrhenian basin, as well as to investigate the salinity and temperature trends that affected the evolution of the steps, which in turn affects the vertical mixing.

IAPSO (Physical Oceanography)

P02p - P02 Physics and Biogeochemistry of Semi-Enclosed and Shelf Seas

P02p-215

Interannual variability of chlorophyll in the East Sea (Japan Sea): importance of mixed layer depth changes

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Year-to-year variability of chlorophyll-a (Chl-a) in the East Sea and its relation with mixed layer depth (MLD) changes are investigated by using Chl-a concentration data estimated from satellite (SeaWiFS and MODIS) measurement and MLD data from 1/12° Global HYbrid Coordinate Ocean Model (HYCOM) for the period of 2004-2010. In 2008, spring Chl-a concentration in the Ulleung Basin reaches a maximum during the period of 2004-2010. This Chl-a increase can be attributed to relatively deep winter mixed layer that can entrain more deep nutrients into the upper ocean. Comparison of MLD with surface atmospheric forcing (wind and surface heat flux) suggests that the deep MLD was probably caused by a strong wind due to a strengthened Siberian High and Aleutian Low and the associated intensified surface cooling. On the other hand, spring Chl-a concentration in 2004 was not increased although the winter MLD was considerably deep. A deeper spring MLD in 2004 than normal years appears to contribute to an unfavorable light condition for spring bloom. Our finding suggests that, in addition to winter MLD, spring MLD also plays a crucial role in interannual variability of Chl-a in the East Sea.

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High-resolution modelling of ocean-shelf exchange: using a 1/60th NEMO configuration to study dynamics on the North-West European continental sea shelf.

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The North-West European continental shelf sea is a shallow sea connected to the open ocean at the shelf break. The shelf dynamics are characterized by strong tides but exchange between the shelf sea and open ocean is poorly understood. The FASTNEt (Fluxes Across Sloping Topography of the North East Atlantic) project aims to elucidate ocean-shelf exchange, through observations and modelling. It focuses mainly on the Celtic sea, the Malin shelf and the Faroe-Shetland channel. In association with campaigns at sea and long-term basin-scale numerical simulations, a new 1/60th degree resolution (1.8km) regional NEMO configuration (AMM60) has been developed, to better resolve high-resolution processes, across the slope as well as on the shelf. AMM60 envelopes the whole North West European Atlantic margin, from 40°N to 64°N, and 20°W to 10°E.
The AMM60 simulations are assessed through a strict validation with various observations (e.g. tidegauges, remote sensing data and mooring measurements). The spatio-temporal variability of the ocean-shelf exchanges at several scales is studied, using numerical simulations and observations from dedicated campaigns at sea. Comparisons with a basin-scale configuration shows the importance of high-resolution numerical modelling for studying high-frequency processes, such as internal tidal and mesoscale processes, both on the shelf and at the self break.

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Mixing in Mediterranean Thermohaline Staircases

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We have been studying thermohaline staircase structures in the western Mediterranean Sea. They occur within the halocline-thermocline connecting the warmer, saltier Levantine Intermediate Water at about 400 m depth with the colder, fresher Western Mediterranean Deep Water below 1500 m. In this halocline-thermocline, salt finger mixing processes are thought to be active and they produce staircases with layers of order 75 m thickness containing nearly constant properties separated by sharp steps of order 6 m thickness with jumps in properties between the layers. The steps are visible in seismic profiles over large spatial scales, particularly in the Tyrrhenian Sea.

We have estimated the vertical mixing in these staircases from observed increases in temperature and salinity at the bottom of the staircase over 2 year time intervals and calculated temperature and salinitiy diffusivities of 3 and 6×10^{-4} m^2 s^{-1}. We have also made vertical microstructure profiles through the staircases to estimate the levels of mechanical and thermal mixing. Mechanical mixing levels are very small, generally less than 1×10^{-10} W kg^{-1}. though maximum values of ε do reach 5×10^{-10} W kg^{-1}. The dissipation of tracer variance χ is small in the layers, but is higher by 2 to 3 orders of magnitude in the steps, up to 10^{-8} $°C^2$ s^{-1}. From the vertical microstructure profiles profiles, we estimate smaller temperature and salinity diffusivities of 1.2 and 3.6×10^{-5} m^2 s^{-1}.

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South Adriatic - potential spawning ground for scobrids inferred by genetics and modelling

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In September 2011 during routine monitoring of commercial purse seine catches 87 fingerling specimens of scombrids were collected in the southern Adriatic Sea. Sequencing of mitochondrial control region locus inferred that specimens belonged to the Atlantic bluefin tuna, Thunnus thynnus (Linnaeus, 1758) (N=29), bullet tuna, Auxis rochei (Risso, 1810) (N=30) and little tunny, Euthynnus alletteratus, Rafinesque, 1810 (N=28). According to their body length and previously published growth parameters, we estimated their age to be approximately 30 days, which would suggest that they were spawned in the Adriatic Sea, contrary to standard knowledge. Hence, in order to determine possible location of the spawning we run coupled modelling system ROMS-ICHTHYOP. Realistic ROMS simulations were made to provide current and density fields for the ICHTHYOP model. ROMS model was forced with river inflows, tides, exchange through the Strait of Otranto and realistic surface air-sea fluxes calculated from fine resolution ALADIN model. ICHTHYOP was run in the backward mode for 30 days using published investigations on the studied species and its early stage dynamics, such as their growth and developmental stage thermal dependence, lethal temperatures, etc. Apart simulations with coupled modelling system, detailed analysis of prevailing meteorological and oceanographic conditions was made using all available data. Comparison to climatology of the area approved that 2011 had unusually prolonged warm and dry summer season. Occasional inflows of hot and dry air from the northern Africa additionally warmed up Adriatic atmosphere. Under these conditions sea surface temperature was up to 2 standard deviations above normal. In the deeper layers, high temperature and salinity were recorded.

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"Climate forcing in the East/Japan Sea marine environment and fisheries resources: decadal pattern and process"

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Shift between cold-warm temperatures regimes at the upper layer marine environment in the East/Japan Sea are involved with atmospheric circulation and ocean current dynamics. Atmospheric circulation occurs through teleconnection of major large scale climate variability over the north Pacific in winter. The leading driving force, Aleutian Low Pressure (ALP), which is linked with the Pacific Decadal Oscillation (PDO), Arctic Oscillation (AO) and Siberian High Pressure (SHP), can directly influence the East Asian Winter Monsoon (EAWM) and consequently control the upper layer water temperature of East/Japan Sea. After the 1976/77 Climatic Regime Shift (CRS), a strong EAWM period led to a colder regime in East/Japan Sea waters until the 1988/89 CRS and an opposite pattern after that. The recent shift from warm to cold temperature at 1998 CRS was also involved with the positive intensification of the PDO, ALP and EAWM in the East/Japan Sea. Highly stratified upper layer was found at the warm regime after 1988/89 CRS and an opposite pattern at the cold regime after 1976/77 CRS. Decadal variability of the Kuroshio Current to the Tsushima Warm Current also has impact on the cold-warm temperature regimes in the East/Japan Sea. Demersal fishery was enhanced in the colder regime after the 1976/77 CRS, whereas large predatory and small pelagic fisheries were enhanced during the warmer regime after the 1988/89 CRS. The collapse of commercial fisheries—specifically of Pacific saury, Cololabis saira (1976), walleye pollock, Theragra chalcogramma (1982) and Japanese sardine, Sardinops sagax (1983)—can be attributed to direct climate forcing.

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Cold surge and sea surface temperature cooling over Philippine Sea

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In this study, cold surge over Philippine Sea is investigated using 10-years satellite, and re-analysis data. It is shown that anomalous cold air temperature from Asia reaches near 15N in the Philippine Sea. This cold event accompanies north-easterly surface wind centered high sea level pressure south of Japan. At that time, sea surface temperature shows also cooling tendency in this region. In previous studies pointed out that cold surge occurs in the South China Sea. In this study, similar cold surge also appear in the Philippine Sea. It is also shown that cold surge in Philippine Sea appears two days after cold surge in the South China Sea, which is related to eastward propagation of high sea level pressure. The present results newly show that the cold surge in Philippine Sea is related to sea surface temperature cooling in this region.

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Vertical distribution of autochthonous suspended particulate matter in the Caspian Sea in summer

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The samples (~260) of suspended particulate matter (SPM) were collected in summer 2012–2013. Recently hydrochemical regime and phytocenosis composition are changed in the Caspian Sea. Fluctuations of sea level and global climate change create preconditions for periodic changes in resent sedimentation. Hydrogen sulfide has been detected in near bottom water in two depressions since 2009 (the Derbent Basin, water depth up to 788 m and the Southern Caspian Basin – up to 1003 m). The isotopic composition of particulate organic carbon (POC) is revealed that POC is mostly allochthonous (supplies mainly with the Volga River) in the Northern Caspian and mostly autochthonous (primary production) in the Middle and Southern Caspian. The intensity of biological processes (such as autotrophic and heterotrophic) is a determining factor in POC sedimentation. The highest concentrations of the SPM (till 0.9 mg/L) were attached to the surface mixed layer (SML~0–15 m). The highest concentrations of chlorophyll 'a' (chl-a till 2.3 μg/L), in contrast to the SPM, were observed at depths of >20–60 m and were attached to the seasonal thermocline layer. Thickness of the subsurface chlorophyll maximum (SCM) layer varied from 20 to 40 m. SCM layer extended overall the sea within the depth ~20–60 m, causing the higher concentrations of chl-a in the near-bottom layer in the inner and middle shelf. The thermocline is the place of accumulation of all taxonomic groups of algae with the dominance of large dinoflagellates in biomass. The species, quantitative and vertical structure of phytoplankton were similar in the deepwater depressions. Two types of communities were revealed in the vertical structure of early summer phytoplankton: warmwater (+23ºC in SML) and coldwater (+8°C below thermocline).

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Long-term comparison of satellite and in-situ sea surface temperatures in Northeastern Asia marginal

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Satellite observed sea surface temperature (SST) provided by National Oceanic and Atmospheric Agency was compared with the in-situ SST routinely observed by National Fisheries Research and Development Institute in northwestern marginal seas from 1984 to 2013. Matchup data between satellite SST and in-situ SST were analyzed. The Root mean square error (RMSE) between satellite SST and in-situ SST is about 1°C in the offshore area and 2~3°C in the coastal area. Satellite SST has cold bias less than 1°C in the offshore area and warm bias of 1~3°C in the coastal area. Difference between two SSTs in the Japan/East Sea (JES) is smaller than those in the northern East China Sea and the Yellow Sea (YS). The RMSE between two SSTs in the northern East China Sea is 1~2?. Warming trend of SST averaged over seas from 1984 to 2013 is 0.024?/year from in-situ SST and 0.011?/year from satellite SST. The difference in long-term trend results mainly from the difference in the YS. The satellite SST in the YS needs more consideration in studying long-term trend, because warm bias of satellite in the past and cold bias in these years. Satellite SST in the YS has warm bias of 0.5~1.0? in early 1980's and cold bias of 0.5? in early 2010's.

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Comparison of simulated and observed Lagrangian drift in the marine surface layer towards Marine Protected Areas in the Baltic Sea

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The Baltic Sea, one of the most vulnerable environments, is under high anthropogenic pressure. A large part of threats (e.g. oil spills) may originate from ship traffic and are further carried by surface circulation. The mainly wind-driven circulation of the uppermost layer of the Gulf of Finland may deviate from the underlying generally cyclonic estuarine circulation. We focus on the possibilities to reveal usually concealed quasi-persistent current-driven transport patterns in the surface layer from the outcome of numerical ocean models using the technique of Lagrangian trajectories and to verify the main statistical properties of the resulting transport by field measurements. The results are applied to identify the Marine Protected Areas most at risk of pollution and to reveal the contribution of the direct impact of winds on the path of the surface drifters.

The Lagrangian trajectories of passive parcels are generated using the TRACMASS model from Eulerian velocity data in the surface layer extracted from the Rossby Centre Ocean model for 1987–1991. Statistical properties of these trajectories are compared with trajectories of dozens of surface drifters deployed during 2010–2014 in the Gulf of Finland. The existing MPAs are at high risk of pollution released into the surface layer of the sea. The sources of pollution can originate from far distances. In general it takes 5–8 days for pollution originating from the major fairway to reach the MPAs. Field measurements show that in some occasions pollution drift to a MPA may take about 20 days.

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Seasonality in intraseasonal and interannual variability of mediterranean SST and its links to regional atmospheric dynamics

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Sea surface temperature (SST) data from the NOAA OI SST dataset for 1982-2011 are used to investigate intrseasonal and interannual variability of Mediterranean SST during winter and summer seasons.

It is shown that during winter the magnitudes of intraseasonal SST fluctuations are larger than those of interannual SST variations in the western Mediterranean (e.g., the Tyrrhenian Sea), but smaller in the central and eastern Mediterranean Sea. In summer the magnitudes of intraseasonal SST fluctuations are larger almost in the entire Mediterranean basin. Also summertime magnitudes of intraseasonal SST fluctuations are larger (up to 3 times near the Gulf of Lions) than their wintertime counterparts in the entire Mediterranean basin. Magnitudes of interannual SST variations are larger during summer in the western and central Mediterranean Sea and during winter in its eastern part.

The leading EOFs of the Mediterranean SST and of the intensities of its intraseasonal fluctuations are characterized by the differing spatial-temporal structures both during winter and summer implying that their interannual variability is driven by the different physical mechanisms. During winter the EOF-1 of SST is associated with the East Atlantic teleconnection, whereas EOF-1 of the intensity of intraseasonal fluctuations is not linked significantly to regional atmospheric dynamics. The second EOFs of these variables are associated, respectively, with the East Atlantic/West Russia and the North Atlantic teleconnections. While during summer the atmospheric influence on Mediterranean SST is generally weaker, it is revealed that the EOF-1 of the intensity of intraseasonal SST fluctuations is linked to the Polar teleconnection.

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Observations of internal waves in the northern gulf of Eilat/Aqaba (Red Sea)

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The Gulf of Eilat/Aqaba (hereafter referred to as 'the Gulf') is a long (~ 180 km), narrow (6-26 km), and deep (maximum depth ~ 1800 m) semi-enclosed sea connected at its southern opening to the Red Sea. Recent moored time series of velocity and temperature at the northern terminus of the Gulf near the city of Eilat, Israel revealed semi-diurnal, large-amplitude (30 m – 50 m) displacements of the base of the thermocline suggesting that the shallow (~150 m) sill strait at the southern end of the Gulf acts as a wave-maker, generating internal tides. Presumably, tidal flux through the strait vertically displaces isopycnals and, as the tidal flow ebbs, these perturbations propagate northward into the Gulf. Observations of internal waves in many locations are necessary to develop accurate spectral models. Here, we present the spectra of the moored time series collected in the northern Gulf for comparison with the Garrett and Munk canonical internal wave spectrum. The strongly varying stratification in the northern Gulf permits evaluation under different stratification conditions, including a two-layer system in winter and a nearly linearly stratified upper layer in summer over a uniform bottom layer in winter. The spectra also show seasonal variability in the strength of compound tides further suggesting that the seasonally varying stratification alters the response of the internal tides to topography, from super critical to critical.

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Power law dependence between relative diurnal variations and mean concentrations of hydrochemical parameters

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From the example of Amur Bay (Sea of Japan), it is shown that relative diurnal variations (relative standard deviations) in the nonconserved hydrochemical parameters increase by the power law with an exponent of about –0.33 with an increase in their average daily contents. This regularity is observed for the range of average contents from 100 to 0.0001 mg/kg. This fact was obtained in variations of the time series data collected using standard methods in Amur Bay. The list of the reviewed indices includes carbon dioxide system parameters (bicarbonat- and carbonat-ion, dissolved carbon dioxide), dissolved oxygen, nutrients (dissolved inorganic phosphorus and silicate, inorganic nitrogen of nitrite or nitrate, and ammonium). A similar result was obtained on the basis of the time series literature data collected in the water column of the Gdansk Deep (Baltic Sea), on the shelf of Sakhalin island (Sea of Okhotsk), and in the Ezcurra Inlet (Admiralty Bay, King George Island, South Shetland Islands). There is an analogy of the above relation with a well-known law in the statistical physics: the relative standard deviation characterizing the fluctuation of the system decreases with an increase in the amount of particles in the system. It is a property of a well-known process of Poisson. For explanation of the Power law dependence, we use the fractional generalization of Poisson's process.The regularity reviewed in this work is approximated by the power law widespread in various areas of natural sciences but it is still unknown in the hydrochemistry.

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Water masses transformation through the Strait of Gibraltar

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The Strait of Gibraltar (SoG) is the natural connection between the Atlantic Ocean and the Mediterranean Sea, here the basic exchange involves Atlantic Waters (AWs) flowing on surface toward the Mediterranean and Mediterranean Waters (MWs) flowing below towards the Atlantic. MWs was usually considered to be composed by Levantine Intermediate Water and Western Mediterranean Deep Water, but recently some works highlighted the presence of others MWs as Tyrrhenian Dense Water and Winter Intermediate Water, this makes a total of six water masses being involved in the exchange.

In the framework of the Hydrochanges European programme, the French Mediterranean Institute of Oceanography carried out the Gibraltar International Campaign (GIC) in July 4th-6th 2012. Data were collected with a Moving Vessel Profiler (MVP) which allows a very high spatial resolution. The campaign was developed during a short period allowing us for making a quasi-synoptic description of the water masses distribution in the SoG. θ-S diagrams show a noticeable erosion of the distinctive features of the MWs as they flow from East to West, the same applies to the NACW flowing in the opposite way. Main changes in both Mediterranean and Atlantic waters occurs once passed the main sill.

A clustering method is presented to determine the affinity of each MVP sample to one of the water masses involved in the exchanged flows, proposing a functional classification to investigate their transformation along the strait. The method reveals a observable evolution of the pattern of the MWs as they flow westward mainly due to the strong mixing in the Tangier basin. The three MWs are easy to recognize east of the sill, while downstream a marked weakening of the spatial differentiation is observed.

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Mapping Mediterranean tidal currents with surface drifters

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Velocities of surface drifters are analyzed to study tidal currents throughout the Mediterranean Sea. The dataset spanning the period 1986-2014 is used to describe the geographical structure of the surface tidal currents with a resolution of 1 degree. Harmonic analysis is performed with 2 semi-diurnal (M2 and S2) and 2 diurnal (K1 and O1) tidal constituents. The M2 currents dominate in the Alboran Sea, the Sicily Channel and the north Adriatic Sea with a maximum of 6 cm/s. They are also substantial (2-3 cm/s) in the Gulf of Sidra (Libyan coast) and in the Gulf of Antalya (Turkish coast). The S2 currents show a similar pattern with amplitudes typically smaller than M2 of about 30%. The K1 and O1 currents are largest in the vicinity of the turning latitudes (south of 33°N) where they correspond to inertial motions, partially produced by the tidal forcing and partially forced by the local winds. Excluding the turning latitudes, the K1 tidal currents show substantial amplitudes (> 5 cm/s) in many areas of the Mediterranean including the Alboran Sea and the Sicily Channel, where the O1 currents are also strong. Maps of rotary coefficients indicate that all tidal motions are essentially anticyclonic.

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Energy budget of a small convectively driven marginal sea: The Gulf of Eilat/Aqaba (northern Red Sea)

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We used oceanic model simulations and model based energy budget calculations to quantitatively study the relative importance of different processes affecting the Gulf of Eilat/Aqaba dynamics and hydrographic conditions. Large seasonality among various energetic pathways is observed. Similar to other oceanic waters, significant amount of energy is stored in the potential energy (PE) which is predominately in the form of background potential energy (BPE). During September-March PE/BPE gains energy through raising of the center of mass due to atmospheric cooling. During April-August PE decreases its strength due to exchange of light warmer water from the northern Red Sea through the Strait of Tiran. The available potential energy (APE) is stored in baroclinic modes that are linked to the along gulf temperature gradient. During April-August the APE is sustained by baroclinic energy flux through the straits, resulting from advective density fronts into the gulf, and during September-March by the differential heating at the surface. Part of the APE is converted into Kinetic Energy (KE) by vertical buoyancy flux and in smaller quantity to background potential energy by isopycnal mixing. The conversion from APE is the only source of KE, where losses are related to the work done by pressure at the straits and energy dissipation. The wind stress work subtracts energy from the buoyancy driven flow, which explained by the opposite surface flow and mean wind directions. We found that temperature and salinity variations contribute to the dynamics, via the APE-KE conversion, by a ratio of 10:1.

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The Suez Canal dynamic and its impacts on the water mass balance of the Mediterranean Sea: A modeling study

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Passing several lakes of widely diverse salinity, and connecting two marginal seas that are different in their properties, the Suez Canal is a hydrographically and dynamically complex body of water. Since its construction, the conditions that affect the dynamics of the Suez Canal had been changed dramatically: Its dimensions were ever expanded, the salinity in the bitter lakes that are located in the southern part of the canal, had been reduced dramatically, and the construction of the High Aswan Dam ended the seasonal Nile floods (which were assumed to affect the canal's current regimes). Using an oceanic model we study the long-term dynamic variations of the Suez Canal. The seasonal flux through the Suez Canal has two time regimes: During October-June the highly saline (43-44 psu) canal's water flows northward into the Mediterranean. During July-September the flow switches direction and the relatively low saline water of the Mediterranean Sea enters the canal at its northern side, affecting the canal's salinity distribution, while moving southwards. We found that this seasonality is mainly driven by the sea level differences between the two ends of the canal, while other factors such as winds and the salinity gradients along the canal can contribute more significantly at transient times between the two current regimes, or when the sea level gradient is weak. Last, the contributions to the heat and salt balances of the Mediterranean Sea due to the outflowing water from the Suez Canal into the Mediterranean Sea were found to be negligible.

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Impacts of bottom-slope angle on phytoplankton blooms driven by riverine inputsof nutrients and fresh water

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Riverine discharge has influence on coastal areas where biological productivity is high. Observations can hardly capture the daily temporal and three-dimensional variations of phytoplankton blooms due to flooding, and limited quantitative studies focusing on the effect of bottom topography on net primary production (NPP).

We developed an OGCM including a simple ecosystem model to conduct quantitative studies focusing on NPP in phytoplankton blooms caused by riverine input. We introduced nitrates categorized into three origins from the river, the subsurface layer and via regeneration. The phytoplankton bloom occurs through utilizing the different nutrient sources in region of freshwater influence (ROFI).

We conducted case studies to investigate the effects of bottom slope angle to NPP. NPP by river-originated nutrient (RO-NPP) is not apparently much dependent on the slope angle, while NPP by subsurface-originated (SO-NPP) is larger with the steeper slope and NPP by regenerated (R-NPP) is larger with the gentle slope.

This study revealed that NPP in ROFI is not much dependent on slope angle, because NPP is maintained by the different nutrient sources and physical processes: (1) SO-NPP is dependent on the strength of vertical circulation inducing upwelling and (2) R-NPP is controlled by the shape of horizontal gyre changes with the bottom slope angle. The latter means that the enlarging pattern of horizontal gyre determines how deep detritus-particulates sink and where regeneration occurs. Regeneration of particulates mainly occurs near the coast, i.e., the shallow zone, in the gentle slope cases and the overturning time through the ecosystem is shorter with the gentle slope. It is interesting that the horizontal pattern of gyre has influence on R-NPP rather than RO-NPP.

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Near surface low salinity intrusion in the central Baltic sea

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Dynamics of the upper layers in the central Baltic Sea were investigated, using towed instruments (T/S) and acoustic profiler along with a high-resolution numerical model, to better understand the physical conditions. Data were collected in July 2012 by cruising in large meandering patterns about once per day during 14 days. The surveys covered an area of 28 by 28 km in hydrography mode using Scanfish, towed and ship ADCP, and in fine-structure mode using towed CTD-chain, towed and ship ADCP. In addition, a free-falling microstructure profiler was used over an area of 15 by 15 km. All the CTD casts showed low-salinity intrusions around 20 m below the surface with varying thickness. Full spatio-temporal variability of water mass distribution was obtained with DIVAND (N-dimensional variation analysis). The observations were then compared to numerical model results. For that, the General Estuarine Transport Model (GETM) with a horizontal resolution of 600 m was used. In the vertical, 80 adaptive layers were employed. The numerical model helped us to explore the source and dynamics of the intrusions and there major driving mechanisms.

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Manifestation of overflow in the Slúpsk Sill area of the Baltic Sea

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Near-bottom gravity currents represent fundamental processes that form deep-water properties such as TS indices, oxygen content, etc. These properties will be dependent on the rate of mass/momentum exchange between the gravity current and ambient waters. More specifically, the entrainment velocity is an integral merit of the intensity of exchange processes between turbulent overflow plume and relatively calm overlaying waters. The presentation is focused on the Slúpsk Sill area where the frequent occurrence of near-bottom gravity current that transports saline water from the Bornholm Basin to the Slúpsk Furrow is expected. A length of the leg where the near-bottom current velocity is developed above the sloping bottom is at least 20 km. The above-lying water here belongs to the maximum oxygenated intermediate cold layer which might contribute some amount of oxygen to the poorly oxygenated inflowing water. Such contribution is supposed to be essential for the deep-water ventilation in the Baltic Proper. The measurement technique and data processing aimed for estimating of hydrodynamical parameters of the gravity current and above-lying interfacial layer are presented.

IAPSO (Physical Oceanography)

P02p - P02 Physics and Biogeochemistry of Semi-Enclosed and Shelf Seas

P02p-235

Remote sensing of coastal upwelling in the se Baltic sea: Statistical properties and dynamical features

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In this work we analyze coastal upwelling events in the SE Baltic Sea based on Terra/Aqua Moderate Imaging Spectrometer (MODIS) infrared imagery between 2000 and 2014. Main statistical properties of the upwelling in the SE Baltic are calculated. The maximum observed SST gradients across the front are up to 1.2 °C/km, sea surface temperature drop up to 15°C with total upwelling-affected area being up to 18000 km2.

In general, the surface geometry of the upwelling front and its time evolution appear to be shaped by the bottom topography. As observed, evolution of the upwelling front is often associated with development of transeverse elongated filaments directed offshore. Nearly 120 km long and 30 km wide at their maximum, these fastly evolving dynamic features with horizontal velocities up to 0.5 m/s bring cool and nutrient-rich upwelling waters far offshore where they decay in the form of cyclonic eddies and further stimulate offshore alga blooms.

It is also shown that intensive upwelling events along SE Baltic are associated with inflow of cool and salty upwelling waters to the shallow coastal lagoon leading to the formation of pronounced density gradients there.

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IAPSO (Physical Oceanography)

P02p - P02 Physics and Biogeochemistry of Semi-Enclosed and Shelf Seas

P02p-236

Submesoscale physical and bio-geochemical structures in the German Bight

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As part of an initiative to install a non-invasive underwater fish observatory (AutoMAT) in the North Sea's German Bight, we investigated the horizontal scales and related physical mechanisms that may control the distribution (patchiness) of plankton and fish. Wavelet analysis was used to compare physical (e.g., temperature and vertical vorticity) and bio-geochemical (e.g., fluorescence) variables, measured using towed undulating systems (Scanfish and TRIAXUS) and an onboard ADCP. Through wavelet analysis the spatial variability of each signals phase and variance was determined, as well as where and at which scales there was overlap between variables. The analysis indicates that the physical and bio-geochemical tracers tend to align at submesoscales (<10 km), and that the maximum vertical vorticities also occur at these scales. The results suggest that submesoscale processes may be of particular relevance in the German Bight.

IAPSO (Physical Oceanography)

P02p - P02 Physics and Biogeochemistry of Semi-Enclosed and Shelf Seas

P02p-238

Dredging impact on coastal ecosystem of Kristnapatnam port,south east cost of India : An integrated approach using RS & GIS

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India has a coastline of 7,500km of which 2,000km wide is called as Exclusive Economic Zone (EEZ). The Indian coastline supports almost 30% of its human population.This paper synthesizes the extent and nature of scientific information about how dredging activities potentially affect habitats and key ecological functions supporting recruitment and sustainability of estuarine and marine environment. he impact on community was estimated at species level (Foraminifera, Protozoan, using statistical analysis). An integrated approach using Remote Sensing (RS) and Geographical Information System (GIS) was employed to study the Marine Environment This data were compared with the data obtained before dredging (2006) in a time services spanning 6 years. A geospatial model for the coastal morphological changes is being prepared. A comparison of the satellite data in the form of imagery is being carried out. Statistical treatment will be given to the data sets to know the relation among parameters. Before, this type of dredging activity is undertaken, each case should be studied regarding viability, the environmental medium where it will take place, the best time of year, and the type of dredging to be used. Small-patch dredging operations are proposed when ever possible, since they allow a quick re adjustment of the initial Marine environment. Thus, the objective of this investigation is to verify the potential impact and effects of dredging on the Marine environment based on alterations of Coastal geomorphology , bottom sediment and the micro biota using RS &GIS. These findings will help to underpin improved planning of management strategies for dredging operations in India and other countries.

IAPSO (Physical Oceanography)

P03a - P03 Ocean Mixing

IUGG-1048

Extremely long Kelvin-Helmholtz billow trains in the Romanche Fracture Zone

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In the Atlantic Ocean, the densest water mass ‘Antarctic Bottom Water’ (AABW) can only cross the Mid-Atlantic Ridge from its southwestern to northeastern basins in limited, because deep, conduits. At the southwestern entrance of one of these, the equatorial ‘Romanche Fracture Zone’ (RFZ), AABW crosses a sill at 4550 m depth in a 7 km narrow channel before plunging into the deep. At the sill-slope, the rapidly flowing AABW causes strong turbulent mixing with the overlying water masses. This is now demonstrated using 99 moored, 1-Hz sampled high-resolution temperature sensors. The observations are used to quantify the turbulence details. On top of quasi-steady shear-flow, an internal tide modulates the mixing. Together, they constitute a means for an extremely long train of >250 consecutive Kelvin-Helmholtz billows in a day that vary between 5 and 100 m in vertical scale.

IAPSO (Physical Oceanography)

P03a - P03 Ocean Mixing

IUGG-1333

Intense mixing and hydraulic flow in the Antarctic Circumpolar Current over a ridge

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The Southern Ocean, where the deep water masses of the world ocean upwell to the surface and subsequently sink, has a pivotal role in global ocean circulation shaping both the meridional overturning circulation and the strati?cation of the global ocean. Within the unique dynamics of the Antarctic Circumpolar Current (ACC), diapycnal mixing by turbulent flow is considered to be a critical process in setting both the rate and structure of abyssal overturning and water mass transformation. Recent studies have indicated that this diapycnal mixing is much enhanced in proximity to topography. The North Scotia Ridge (NSR), extending to the west of South Georgia, presents a significant topographical barrier which constrains the deeper circulation of the ACC to gaps and narrow channels in the topography, and as such may be expected to play a role in generating such enhanced diapycnal mixing.

Here we presents results from a recent UK DIMES cruise to the NSR showing evidence of bottom intensified flow through gaps in the ridge topography. This bottom intensified flow is composed of waters that have been more recently ventilated than the overlying Circumpolar Deep Water and is associated with an uplift in density surfaces. There are indications that this flow may be hydraulically controlled and that super-critical flow in the bottom-most layers results in instability and increased diapycnal mixing at the boundaries of the uplifted density surfaces contributing to the mixing up of deep waters into the ACC.

IAPSO (Physical Oceanography)

P03a - P03 Ocean Mixing

IUGG-3450

A microscale view of mixing and overturning across the Antarctic Circumpolar Current

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The relative roles of isopycnal stirring by mesoscale eddies and diapycnal stirring by small-scale turbulence in setting the large-scale temperature - salinity relation of the Southern Ocean against the action of the overturning circulation are assessed, by analysing a set of shear and temperature microstructure measurements across Drake Passage in a `triple decomposition' framework. It is shown that a full picture of regional mixing and overturning across the Antarctic Circumpolar Current (ACC) may be constructed from a relatively modest number of microstructure proles. The rates of isopycnal and diapycnal stirring are found to exhibit distinct, characteristic and abrupt variations: most notably, a one-to-two order of magnitude suppression of isopycnal stirring in the upper kilometre of the ACC frontal jets, and an order-of-magnitude intensication of diapycnal stirring in the sub-pycnocline and deepest layers of the ACC. These variations balance an overturning circulation with meridional flows of O(1 mm / s) across the ACC's mean thermohaline structure. Isopycnal and diapycnal stirring play complementary roles in balancing the overturning, with isopycnal processes dominating in intermediate waters and the Upper Circumpolar Deep Water, and diapycnal processes prevailing in lighter and denser layers.

IAPSO (Physical Oceanography)

P03a - P03 Ocean Mixing

IUGG-3533

Turbulent mixing driven modification of Antarctic origin bottom water in the Samoan Passage

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The bulk of the coldest bottom water entering the abyssal North Pacific passes through the Samoan Passage (169W, 10S), making this 100 km wide passage a key 'choke point' in the Pacific Overturning Circulation. Approximately 2 Sv of Antarctic origin bottom water (AABW) with a potential temperature (referenced to the surface) of less than 0.7 degree enters the passage, and none exits. The Samoan passage consists of two channels with most of this coldest water following the eastern channel, as the entrance to the more convoluted western channel is partially blocked by sills at two locations. The eastern channel has a ~500-m high sill half way along and a ~300-m high sill at near the exit. In the eastern channel most of the mixing away of the <0.7 degree occurs just downstream of the second sill.

During cruises in 2012 and 2014 we took the first direct microstructure measurements in the passage (116 in total). These measurements find that on average the largest turbulent kinetic energy dissipation rates were in the coldest water and not necessarily in the interface. Above the interface the dissipation rates were at instrument resolution levels (~3e-11 W/kg). Just downstream of the first eastern channel and the two western channel sills average dissipation rates in the coldest waters were almost 1e-8, and downstream of the eastern channel exit sill average rates were almost 1e-7 W/kg. Repeated microstructure casts and Thorpe scale estimate from shipboard CTDs and moorings indicate that the general shape and magnitude of dissipation rates profiles is fairly constant in time. The reason appears to be that the tidal modulation is small compared to the northward velocity of the AABW.

IAPSO (Physical Oceanography)

P03a - P03 Ocean Mixing

IUGG-4481

A comparison between internal waves observed in the Southern Ocean and lee wave generation theory

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Direct observations in the Southern Ocean report enhanced internal wave activity and turbulence in a few kilometers above rough bottom topography. The enhancement is co-located with the deep-reaching fronts of the Antarctic Circumpolar Current, suggesting that the internal waves and turbulence are sustained by near-bottom flows interacting with rough topography. Recent numerical simulations confirm that oceanic flows impinging on rough small-scale topography are very effective generators of internal gravity waves and predict vigorous wave radiation, breaking, and turbulence within a kilometer above bottom. However, a linear lee wave generation theory applied to the observed bottom topography and mean flow characteristics has been shown to overestimate the observed rates of the turbulent energy dissipation. In this study, we compare the linear lee wave theory with the internal wave kinetic energy estimated from finestructure data collected as part of the Diapycnal and Isopycnal Mixing Experiment in the Southern Ocean (DIMES). We show that the observed internal wave kinetic energy levels are generally in agreement with the theory. Consistent with the lee wave theory, the observed internal wave kinetic energy scales quadratically with the mean flow speed, stratification, and topographic roughness. The correlation coefficient between the observed internal wave kinetic energy and mean flow and topography parameters reaches 0.6-0.8 for the 100-800 m vertical wavelengths, consistent with the dominant lee wave wavelengths, and drops to 0.2-0.5 for wavelengths outside this range. A better agreement between the lee wave theory and the observed internal wave kinetic energy than the observed turbulent energy dissipation suggests remote breaking of internal waves.

IAPSO (Physical Oceanography)

P03a - P03 Ocean Mixing

IUGG-5084

Mesoscale modulation of mixing and transformation of the Denmark Strait Overflow

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The Denmark Strait Overflow (DSO) is a major export route for dense waters from the Nordic Seas forming the North Atlantic Deep Water, an important element of the climate system. Mixing processes in the Irminger Basin determine volume transport and properties of the DSO but are poorly resolved by sparse observations which hinders development of DSO mixing parameterizations in global circulation models (GCMs).
We employ a high resolution circulation model to investigate transformation and mixing in the DSO in the Irminger Basin and quantify the effect of mesoscale (10-100km) flows unresolved by GCMs.We find that the DSO mixing and water mass transformation are spatially localized in about a 200km long and 50km wide corridor downstream of the Denmark Strait sill. In this region, the DSO warms by about 1K, which constitutes most of the transformation along the entire 700km pathway in the Irminger Basin . The elevated mixing is modulated by dense water boluses and overlying cyclonic eddies that propagate together through the Irminger Basin (`beddies'). The passage of beddies increase the squared vertical shear of horizontal velocity by a factor of 3, correspond to increase in the vertical velocity by ten times and double the eddy heat flux divergence leading to a warming of the bottom (densest) waters and a cooling of the interface layer of the overflow plume and the ambient water above. There is a clear correlation between the speed in the nose of the plume, the eddy kinetic energy and the vertical shear in the horizontal flow.

The model results about the modulation of mixing by the mesoscale variability and the mixing localization motivate a targeted field campaign and should be included in future overflow parameterizations in global circulation models.

IAPSO (Physical Oceanography)

P03b - P03 Ocean Mixing

IUGG-2580

Setting the global overturning circulation: Why are our models so different?

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The global thermohaline overturning circulation can be characterised as a streamfunction in temperature-salinity space, allowing us to view the thermodynamic component of the global ocean circulation in a single diagnostic. In T-S space the only processes able to drive a circulation are heat/freshwater fluxes, typically at the surface, and internal mixing. The balance between these two forcings are what sets both the strength of the overturning, as well as the overall shape of the thermohaline circulation. Although difficult to express observationally, the T-S streamfunction is relatively easily obtained from global ocean models, and here we present the streamfunctions from the ocean components of a suite of IPCC class climate models. There is dramatic variability between models in both the strength of their thermohaline circulations and in the TS space that they occupy, which itself is also often significantly different from observations. We show that in most cases this variability is driven not by the differences in surface buoyancy forcing, but instead by the way these models deal with ocean interior mixing, both diapycnal and isopycnal. We show that derived effective internal mixing coefficients are often substantially larger than those defined in model setup. We examine the relationship between interior mixing strength and the thermohaline circulation and how these act to set the ultimate shape of the ocean TS structure.

IAPSO (Physical Oceanography)

P03b - P03 Ocean Mixing

IUGG-4527

Diapycnal upwelling in the deep ocean requires hypsometry

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The upwelling of Bottom Water through density surfaces in the deep ocean is only possible because of the sloping nature of the sea floor. The bottom-intensified mixing activity arising from the interaction of internal tides with bottom topography implies that the dissipation of turbulent kinetic energy is a decreasing function of height in the deep ocean, and this implies that the dianeutral motion in the ocean interior is downwards, rather than upwards as is required by continuity. This conundrum regarding ocean mixing and upwelling in the deep ocean is resolved by appealing to hypsometry; the fact that the ocean does not have a flat bottom and vertical side walls. This insight highlights the importance of strong diapycnal upwelling velocities occurring just above the bottom boundary layer.

IAPSO (Physical Oceanography)

P03b - P03 Ocean Mixing

IUGG-4538

New vertical mixing scheme

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The GISS Vertical Mixing scheme (GISS-VM) of 2010 represented ocean vertical mixing due to small scale motions, predicting mixing efficiencies for momentum, heat, salt and passive tracers as functions of the Richardson number and double diffusive stability parameter. It encompassed the entire water column from top to bottom; the energy inputs in different regimes corresponding to: wind shear and static instability in the upper layers, internal wave-breaking with latitude dependence and double diffusive instabilities at intermediate depths, and unresolved bottom shear and internal baroclinic tides in the lower layers.

Internal baroclinic tides were treated with an offline tidal model that provided the horizontal variation of the energy input; the vertical distribution was taken to be an exponential decay with the same scale height everywhere. Since this is unrealistic, the GISS-VM has now adopted the vertical distribution derived from radiation balance by K.L. Polzin. This dynamically based profile depends on a depth variable scaled by Brunt-Vaisala frequency (N) squared and on a scale height increasing with tidal speed but decreasing with roughness length and N. Thus the scale height both varies geographically and can evolve with time.

We will compare pairs of otherwise identical simulations using the GISS mixing scheme, one with the exponential profile and the other with the dynamically based profile. We will test with a stand-alone ocean model with CORE forcing and in coupled mode. Results presented will include diffusivity maps, temperature and salinity drifts, Atlantic Meridional Overturning Circulation and global maps of Mixed Layer Depths. We will assess the impact of switching to the dynamically based profile and whether it improves realism.

IAPSO (Physical Oceanography)

P03b - P03 Ocean Mixing

IUGG-4808

Assessment of parameterization of enhanced turbulent mixing over rough topography in the abyssal ocean

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Using a two-dimensional numerical model including the vertical dimension, we examine how internal waves generated by tidal interaction with abyssal rough bottom topography lose their energy to turbulent mixing as they propagate upward nonlinearly interacting with the background Garrett-Munk internal wave field. The dependence of the spatial distribution of turbulent mixing on the amplitude of tidal flow (U_0) and the horizontal wavenumber of rough bottom topography (k) is compared with that of the Jayne and St. Laurent (JSL) parameterization [2001], which is widely used in global circulation models.

When the tide-topography interaction is weak ($U_0k/\Omega <<1$: Ω: tidal frequency), "linear internal tides" are generated and propagate upward creating bottom-intensified mixing hotspots whose vertical extent is controlled by k rather than U_0. This is because the vertical decay scale of "linear internal tides" is determined by the product of the vertical group velocity $C_{gz} \approx \Omega/(kN)$ (N: buoyancy frequency) and the resonant interaction time $\tau \propto k^{-1}$. As the tide-topography interaction strengthens ($U_0k/\Omega >1$), generated internal waves become more like "quasi-steady lee waves", which propagate upward creating bottom-intensified mixing hotspots whose vertical extent is controlled by U_0 rather than k. This is a result of the vertical decay scale of "quasi-steady lee waves" being determined by the product of $C_{gz} \approx kU_0^2/N$ and $\tau \propto k^{-1}$. In both cases, there is a trade-off relationship between the energy dissipation rate near the ocean bottom and its vertical extent.

JSL assumes bottom-enhanced turbulent mixing with a uniform vertical extent, say, ~500 m; this study suggests that global circulation models incorporating the JSL parameterization might be in error.

IAPSO (Physical Oceanography)

P03b - P03 Ocean Mixing

IUGG-5246

Frequency-based correction of finescale parameterization of turbulent dissipation in the ocean interior

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Among the existing finescale parameterizations of turbulent dissipation rates, the Gregg-Henyey-Polzin (GHP) parameterization is thought to produce the most accurate estimates of turbulent dissipation rates since it takes into account distortions from the Garrett-Munk (GM) spectrum using the shear/strain ratio $R\omega$. The formulation of the GHP parameterization, however, includes some flaws that the single wave approximation is used to infer turbulent dissipation rates in broadband internal wave spectra like the GM ($R\omega \sim 3$) and the inferred turbulent dissipation rates in the low-frequency biased internal wave spectra ($R\omega >> 3$) are unreasonably multiplied by a certain factor.

In this study, revisiting the deriving process of correcting frequency properties, we explore the possibility of further improvements of the GHP parameterization and re-formulate the parameterization to make it applicable to both (i) a narrowband frequency spectrum characterized by a prominent near-inertial peak ($R\omega >> 3$) and (ii) a broadband frequency spectrum like the GM ($R\omega \sim 3$). Furthermore, we assess the performance of the modified parameterization in comparison with the GHP parameterization using the available microstructure data obtained near representative mixing hotspots in the North Pacific.

IAPSO (Physical Oceanography)

P03b - P03 Ocean Mixing

IUGG-5274

Diagnosing gyre and abyssal flows in Temperature–Salinity–Age space

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Temperature, salinity and age provide a natural coordinate frame in which to understand the flow of oceanic waters: temperature and salinity help identify their sources while age gives information on their evolution. Here both idealized (simple gyre) and realistic global ocean models are diagnosed in this temperature-salinity-age space. Formation and modification of thermocline and deep waters is clearly elucidated within this framework, with the subduction and re-emergence of watermasses occurring in different regions in physical space with differently signed Jacobian of the transformation between physical and tracer spaces. Mixing processes are found to have a characteristic signature on flows as viewed in this framework.

IAPSO (Physical Oceanography)

P03c - P03 Ocean Mixing

IUGG-0727

Mixing in continuously stratified flow over a topographic ridge

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Irreversible mixing is thought to play an important role in sustaining the deep oceanic circulation.
Here we investigate the dynamics of topographically induced mixing in laboratory experiments with flow of a uniformly stratified fluid over a two-dimensional ridge. The roles of variables such as the upstream buoyancy frequency, flow speed and the ridge shape are examined. A light attenuation technique is used to obtain high-precision density measurements and perturbations to isopycnals, from which we quantify and the amount of irreversible turbulent mixing.

Two main dynamical features are observed: a local, turbulent flow in the wake and slightly above the ridge, and the radiation of internal lee waves. The ratio, q, of these local and remote contributions to mixing is calculated and takes an average value q= 90 ± 6%. This is three times larger than the canonical value q= 30 ± 10% that is commonly assumed in parameterizations of internal wave-induced mixing in the ocean. This result may help to assess the importance of local non-linear processes for mixing the deep ocean.

IAPSO (Physical Oceanography)

P03c - P03 Ocean Mixing

IUGG-2740

Vortex-internal waves interaction in quasi-linear and nonlinear regimes.

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Interaction between vortices and internal waves play important roles in mixing and the formation of local internal wave spectra. This interaction has attracted attention, in particular remarkable theories have been achieved in the parameter range of weak mesoscale eddies and relatively short internal waves. However, processes come outside of the above parameter range are not well known: for example, universally located sub-mesoscale vortices and tide-induced internal gravity waves of various wavelengths. We investigated the interaction between a single vortex and incident internal waves by a theoretical analysis and three-dimensional nonhydrostatic model. We began with theoretical analysis of quasi-linear scattering of internal waves by a single vortex. We obtained new analytical solutions of the scattered waves for each azimuthal mode, whose sum give polarized energy flux. In this scattering analysis, a useful non-dimensional parameter arose. This parameter represents ratio of spatial scales and nonlinearity and is available for classify the interaction dynamics. We then performed numerical experiments in a wide range of the parameter. As the parameter goes out of a quasi-linear regime, wave rays bifurcate asymmetrically with respect to the vortex center or form broad caustics. Further, in the highly nonlinear regime, waves refract exponentially and lead to being trapped into a vortex or break. The vortex structure was modified.

IAPSO (Physical Oceanography)

P03c - P03 Ocean Mixing

IUGG-4274

Molecular control of turbulent diapycnal mixing in the strongly stratified ocean thermocline

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Turbulent diapycnal mixing is a key process in the oceans, which is believed to be essential to close the ocean heat and energy budgets. Its intensity is often measured in terms of the Cox number, defined as the ratio of the turbulent diapycnal diffusivity over the background molecular diffusivity. While in the laboratory it appears possible to generate mixing spanning a very large range of possible Cox numbers, the strongly stratified ocean thermocline in contrast exhibits values of the Cox number that departs rarely from O(100). The purpose of this work is to propose a simple theory that suggests that the value of turbulent diapycnal mixing in the strongly stratified regions of the ocean thermocline is rate limited by molecular diffusion of heat and molecular viscous dissipation. Specifically, physical arguments are derived that suggest that the Cox number in presence of strong stratification should scale as the squared molecular Prandtl number, which is roughly in agreement with observed Cox numbers.

IAPSO (Physical Oceanography)

P03c - P03 Ocean Mixing

IUGG-5150

Parameterization of energy dissipation and turbulent mixing in the Indonesian Throughflow from the INDOMIX experiment

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The INDOMIX cruise aimed to characterize small-scale turbulence and its relationship with internal tides. Measurements focused on two energetic sections through Halmahera Sea and Ombai Strait with an additional station in the deep Banda Sea. Internal tidal currents up to $70\, cm.s^{-1}$ were encountered in Halmahera Sea and Ombai Strait in contrast with a weaker signal in Banda Sea. The various propagation directions in Halmahera Sea reveal the complex pattern of internal tide generation occurring along the shelf edge and within the passages. Consistently the highest ϵ and K_z values were obtained within passages with mean values within $\sim [10^{-7}-10^{-5}]W.kg^{-1}$ and $\sim [10^{-4}-10^{-3}]m^2.s^{-1}$. ϵ and K_z within the pycnocline are significant with mean values within $\sim [5\times 10^{-9}-3\times 10^{-7}]W.kg^{-1}$ and $\sim [10^{-5}-10^{-4}]m^2.s^{-1}$. We provide a comprehensive scheme for parametrization as a function of turbulent intensity, $\epsilon/(\nu N^2)$. A modified formulation of McKinnon & Gregg (2005) was validated for moderately turbulent regimes, typically in the thermocline away from generation areas. Elsewhere in strongly turbulent regions, dissipation rate scales like the cube of the total velocity. The dependency of ϵ as a function of energy, E, was examined: a scaling either with ${(EN)}^{0.7}$ or $\sqrt{EN}$ is obtained for moderate (up to 100) and high (from 100 to 1000) turbulence intensities while for highest turbulence intensities ϵ does not depend on energy. A scaling with tidal energy, E_t, was obtained for a reduced range of turbulence intensities (up to 300) with a slightly steeper slope: $(E_tN)^{0.8}$. Outcomes for parameterizations in numerical models are eventually discussed.

IAPSO (Physical Oceanography)

P03c - P03 Ocean Mixing

IUGG-5189

Mixing and internal tide radiation at fjord sills

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Diapycnal mixing caused by tidal interaction with topography is vital for the vertical circulation in oceans and fjords. Mixing can be generated both directly by local turbulence at the topography associated with supercritical baroclinic flow, non-linear internal waves, and internal hydraulic jumps, and indirectly by radiation of internal tides that dissipate elsewhere and cause turbulence and mixing there. Most previous studies tend to look at these two processes as independent of each other, whereas they in reality are closely linked: The internal tide generation depends on the hydraulic conditions at the crest of the topography, and the internal hydraulic jump strength depends on the upstream and downstream radiated columnar disturbances which over time constitute the internal tides. An effort is done to link hydraulic theory and internal tide generation theory for a two-layer situation. The results are compared to idealized numerical model simulations as well as intensive observations over the Oslo fjord sill, including high-resolution microstructure profiler transects and mooring data on and inside the sill. The total barotropic energy loss as well as the partition between local energy loss and radiated energy is highly dependent on the interface position relative to the fjord sill. Generally, a large fraction of the barotropic energy loss dissipates at the sill.

IAPSO (Physical Oceanography)

P03c - P03 Ocean Mixing

IUGG-5278

Internal tides and associated vertical mixing in the Indonesian Archipelago

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Tidal mixing in the Indonesian Archipelago contributes to regulation of the tropical atmospheric circulation and water-mass transformation in the Indonesian Throughflow. The present study quantifies the vertical diffusivity in the Indonesian Archipelago by driving a high resolution three-dimensional numerical model and investigates the processes of internal tide generation, propagation and dissipation. The numerical experiment shows that M2 internal tides are effectively generated over prominent subsurface ridges. The conversion rate from M2 barotropic to baroclinic energy over the whole analyzed model domain is estimated to be 85.5 GW. The generated internal tides dissipate 50 - 100 % of their energy in close proximity to the generation sites ('near-field'), and the remaining baroclinic energy propagates away causing relatively large energy dissipation far from the generation sites ('far-field'). The local dissipation efficiency q, therefore, has an extremely non-uniform spatial distribution, although it has been assumed to be constant in the existing tidal mixing parameterization for the Indonesian Archipelago. The average vertical diffusivity in the Indonesian Archipelago was ~ 2×10−4 m2 s−1 which is comparable to the value estimated by using the existing parameterization. However the spatial distribution is significantly different. This discrepancy is attributable to the fact that the effects of internal wave propagation are completely omitted in the existing parameterization, suggesting the potential danger of using such parameterized vertical mixing in predicting the distribution of SST as well as water-mass transformation in the Indonesian Seas.

IAPSO (Physical Oceanography)

P03d - P03 Ocean Mixing

IUGG-0720

Spatial and temporal variability of mixing in the Solomon Sea

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This work presents observations of equatorial mixing in an under-studied region that serves as a major source of the Equatorial Undercurrent and a key region for coupled ocean-atmosphere events such as Madden-Julian Oscillation and El Niño. The Solomon Sea is a semi-enclosed sea located in the Equatorial southwest Pacific with complex topography and strong channel flow. Observations of temperature and salinity from the primary entry and exit points of the Solomon Sea circulation display erosion of the transported water masses and relaxation of the temperature-salinity gradients while model results indicate that two thirds of observed water mass modification is the result of strong diapycnal mixing. Spatial patterns of mixing are estimated using two fine scale parameterization methods from shipboard CTD and LADCP profiles taken during two cruises in the Solomon Sea. The first method utilizes a typical Thorpe Scale analysis to estimate diffusivity while the second method uses shear derived from LADCP data and compares the variance of the spectra to that of the canonical Garrett-Munk model. The same is done with strain variance from CTD derived buoyancy profiles and the ratio of the shear to strain variance is estimated for the region. Further estimates of mixing are derived from ARGO profiles, utilizing the region's ratio of shear to strain variance derived from the shipboard profiles. These estimates from ARGO data offer information on both the spatial and temporal variability of mixing in the region. Finally temporal variability of mixing is estimated through timeseries observations of temperature variance in the inertial sub-range collected in the channels that connect the Solomon Sea to the Equatorial Pacific.

IAPSO (Physical Oceanography)

P03d - P03 Ocean Mixing

IUGG-2993

Effects of temporal variation in tide-induced vertical mixing on the thermohaline circulation: A case of the Okhotsk Sea

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Tidally induced vertical mixing is important for thermohaline circulation. Previous estimations of tidal mixing have aimed to obtain time-averaged values, and ocean general circulation models (OGCMs) typically parameterize such mixing using a temporally constant strength. However, tidal mixing is known to vary temporally during tidal or spring--neap cycles. Here, we investigate the effects of temporal change in tidally induced vertical diffusivity (kappa_t) in the Kuril Straits using an OGCM. The results demonstrate that variations of vertical mixing on diurnal, 2-week, and 1/2-year timescales induce significant differences in the net effect of mixing and, therefore, in the thermohaline circulation originating in the Okhotsk Sea. For diurnal and 2-week variations, the strength of the tidal mixing effect depends on (1) the period and length of the duration over which kappa_t is larger than the temporal average and (2) the amplitude of the temporal variation of kappa_t, even if the time-averaged values are the same. This is explained by the relative importance of two states. In a quasi-equilibrium state, a larger kappa_t results in weaker stratification and vice versa, and thus the net tidal mixing effect is weaker when kappa_t is variable than when it remains constant. Conversely, in an adjustment stage just after an increase in kappa_t, a larger kappa_t acts on stronger stratification and vice versa, resulting in a stronger mixing effect. For a 1/2-year variation, the strength of the tidal mixing effect also depends on the phase relationship with seasonal variation in stratification. These results imply the necessity of considering temporal change when estimating tidal mixing from observations, specifying it in OGCMs, and understanding its effects.

IAPSO (Physical Oceanography)

P03d - P03 Ocean Mixing

IUGG-3344

Internal waves and enhancement of horizontal mixing

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Enhancement of horizontal mixing produced by tidally generated internal waves in the area of Jones Bank (the Celtic Sea) was investigated in 25-th cruise of the R/V 'James Cook', July 2012 and numerically using the Massachusetts Institute of Technology general circulation model. In the field experiment Rhodamine WT was injected into the pycnocline layer, and its evolution was tracked during two days using a towed vehicle equipped with a fluorometer. In numerical modelling with a 50 m horizontal resolution grid and three forcing initialized in the model, i.e. tides, stationary current, and wind stress on the free surface, it was possible to replicate the dye patch evolution quite accurately. It was found that enhancement of the dye dispersion was controlled by shear currents that in combination with vertical diapycnal mixing led to a substantial increase in the ``effective'' horizontal mixing. The values of ``effective'' horizontal mixing found from the model runs were in good agreement with those obtained from in-situ data.

IAPSO (Physical Oceanography)

P03d - P03 Ocean Mixing

IUGG-4010

The tasman tidal dissipation experiment: Tidal mixing, scattering and reflection on the east tasman slope

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To maintain the thermohaline circulation of the ocean in a steady state, the sinking of dense waters at high latitudes must be balanced by diffusive processes in the deep ocean. The tides can provide a significant fraction of the estimated 2.6 TW required to fuel this mixing. As barotropic tides flow across deep-sea topography, both baroclinic tides and local turbulence are generated. Where topography is steep, a surprisingly large fraction of the power lost from the surface tide (eg. 80 – 90% at Hawaii) is radiated away as low-mode internal tides. The fate of these radiated waves, in particular the range of densities that are “mixed” as these waves eventually dissipate, is of critical importance to the general circulation.
An energetic internal-tidal beam generated south of New Zealand crosses the Tasman Sea and impinges on the eastern slopes of Tasmania. To study the dissipation / reflection of this 4 kW/m beam, the NSF TTIDE experiment was fielded during January-March 2015. Based on initial glider reconnaissance and numerical simulations, arrays of moorings were deployed at a southern (reflective-supercritical) site and a northern (dissipative-critical) region. Supplemental experiments T-BEAM and T-SHELF mapped the incoming tidal beam and quantified its signature on the continental shelf. Shipboard surveys using LADCPs and a fast-profiling CTD indicate elevated mixing regions 1-300 m above topographic features on the slope, high-mode wave-beams in mid-water and near-

bottom bores. A more complete picture of this tidally forced slope and shelf will emerge as TTIDE data are synthesized.

IAPSO (Physical Oceanography)

P03d - P03 Ocean Mixing

IUGG-4325

Ventilation of the Baltic Sea by lateral intrusions of watermasses

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Many anoxic deep waters of marine systems as e.g. the Black Sea, the Baltic Sea and fjords are caused by a permanent pycnocline. The pycnocline separates, in terms of the vertical transport of tracers, the upper from the lower part of the water column. The weakened transport across the pycnocline results in an oxygen deficit in the deeper waters and the generation of the redoxcline at the interface between the two water masses. The physical processes of transporting and mixing oxygen down and nutrients up do directly control the complex bio-geochemical reactions happening at the redoxcline. We present measurements of a long term underwater profiling mooring with a mounted CTD, oxygen, turbidity and at some deployments with temperature microstructure sensors as well as spatial measurements from a towed undulating Scanfish in the central Baltic Sea. Results show in virtually every deployment the presence of water intrusions in depths of the redoxcline with low but non-zero oxygen concentrations within the otherwise anoxic water masses at the redoxcline. The data shows that lateral intrusions transporting oxygenized water are the rule rather than an exception and have to be considered a significant source of oxygen into the redoxcline. Turbulent exchange between the intrusions and the ambient water masses is quantified by a turbulent diffusivity derived from the temperature variance decay of the temperature microstructure. The measured rates of mixing of the intrusions indicate that the lifetime is several weeks, confirming that even small scale intrusions exist long enough to laterally transport oxygenized water over long-distances.

IAPSO (Physical Oceanography)

P03e - P03 Ocean Mixing

IUGG-1306

Multi-column ocean: taking advantage of the subgrid-scale distribution of sea ice to refine the ice-ocean interactions

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The importance of representing the subgrid-scale distribution of sea ice thickness in models has long been recognized. Sea ice models including an ice thickness distribution (ITD) are able to simulate, for instance, different growth rates between new ice in leads, thin and thick ice, implying different amounts of brine rejection, or distinct solar heat fluxes at the open water surface and at the ice-ocean interface. However, in the process of coupling such an ITD with an ocean model, all the surface fluxes are aggregated in order to be transmitted to the unique ocean grid cell underneath. The information about the subgrid-scale variability of these fluxes is lost, and the possibly different oceanic conditions within leads or below each ice thickness category cannot be simulated.

In this work, a so-called multi-column ocean (MCO) scheme has been developed and implemented in the global ocean–sea ice model NEMO-LIM3. The preliminary step was to diagnose and analyze the fluxes provided by the sea ice model LIM3 for leads and for each of the five ice thickness categories. The ocean model NEMO has then been modified to take the subgrid-scale surface fluxes into account. The simplest method consists in calling the non-penetrative convective adjustment scheme for the six sets of fluxes available and in recombining the resulting oceanic profiles at each time step. In a more complex implementation, the turbulent closure scheme is called separately in leads and below ice categories as well, and the different oceanic profiles are allowed to persist over several time steps. The model sensitivity to the various versions of the new MCO scheme will be extensively examined, as well as the feedbacks on the sea ice cover.

IAPSO (Physical Oceanography)

P03e - P03 Ocean Mixing

IUGG-2208

Tides stir up Atlantic Water heat fluxes in the Arctic

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The largest oceanic heat input to the Arctic results from inflowing Atlantic water, which is at its warmest for 2,000 years, yet the fate of this heat remains uncertain. This is partly because the water's relatively high salinity, and thus density, lead it to enter the Arctic Ocean at intermediate depths. A key pathway linking the Atlantic water heat to overlying, colder waters (and ultimately to the sea surface and sea ice) is vertical cross-gradient mixing. Mixing is generally weak within the Arctic Ocean basins, with very modest heat fluxes (0.05 – 0.3 Wm^{-2}) arising from double diffusion. However, previous geographically limited observations have indicated substantially enhanced turbulent mixing rates over rough topography. Here we present new pan-Arctic microstructure measurements of turbulent kinetic energy dissipation which further show that the enhanced continental slope dissipation rate is found to vary significantly with both topographic steepness and longitude, while appearing insensitive to sea-ice conditions. Tides are identified as the main energy source supporting this enhanced turbulent dissipation, which results from an interaction of the geographically-variable barotropic tide with the steep topography of the Arctic continental slope. North of Svalbard, this tide-topography interaction generates vertical heat fluxes of more than 50 W m^{-2}. As Arctic sea ice declines, the increased transfer of momentum from the atmosphere to the ocean will accelerate the large-scale currents while generating evermore near-inertial sheared currents that will act to expand mixing hotspots over other areas of rough topography in the future Arctic Ocean.

IAPSO (Physical Oceanography)

P03e - P03 Ocean Mixing

IUGG-2995

Effects of tides on the mixing of water masses in the Arctic Ocean

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In this study we use a novel pan-Arctic sea ice-ocean coupled model, to examine the effects of tides on sea ice and the mixing of water masses. Two 30-year simulations were performed: one with explicitly resolved tides and the other without any tidal dynamics. We find that the tides are responsible for a ~15% sea ice volume reduction during the last decades and also for changes in the salinity distribution, with overall 2 PSU higher surface salinity in the case with tides. The following mechanisms of tidal interaction appear to be significant: (a) strong shear stresses generated by the baroclinic clockwise rotating component of tidal currents in the interior waters; (b) thicker subsurface ice-ocean and bottom boundary layers at critical latitudes, where the frequency of tidal harmonics approaches inertial frequency; (c) intensification of vertical mixing due to tidal shear in the boundary layers. Harmonic analysis of the modelled tidal velocity output identifies the locations of the strongest tidal shear in the Canadian Archipelago, the Laptev Sea, Yermak Plateau, which is in agreement with observations.

IAPSO (Physical Oceanography)

P03e - P03 Ocean Mixing

IUGG-3106

Resolving turbulence in the ocean surface boundary layer with a microstructure glider on the Malin Shelf

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Turbulent mixing in the ocean surface boundary layer (OSBL) controls the transfer of momentum, heat and gases between the atmosphere and ocean. The processes driving this mixing are still poorly represented in ocean models, evident as inaccurate deepening and shoaling of the OSBL. This has serious impacts on estimates of surface mixed layer depth, primary production and carbon fixation and leads to biases in ocean temperature, which are detrimental to global weather and climate predictions. Here we present a new dataset that provides a unique insight into the energetics of the OSBL using shear and temperature microstructure measurements collected on the Malin Shelf using the Ocean Microstructure Glider. OMG provides nearly 15 days of continuous measurements of the dissipation rate of TKE (ε) and fine-scale temperature structure (mm scale) that permits the direct observation of the turbulent transfer of heat and momentum from the ocean surface into the interior. OMG profiles are provided approximately every 10 minutes and resolve almost the full water depth, allowing resolution of ε from surface and bottom mixed layers and within the seasonal thermocline, where mixing from an active internal wave-field contributes significantly to entrainment of dense water into upper layers. Data from nearby moorings permit resolution of the lateral contribution to the local energy budget and surface wavebuoy measurements and ship-based surface heat and momentum flux estimates are also considered. Results are compared to those of a simple slab model (PWP) and a 1-D turbulence model (GOTM), driven by observed surface fluxes, as a first step towards testing capabilities in simulating surface heat budgets and mixing.

IAPSO (Physical Oceanography)

P03e - P03 Ocean Mixing

IUGG-4339

Study of convective plumes in the Gulf of Lions from high resolution in-situ data collected by gliders

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During winter 2012-2013, open-ocean deep convection occurred in the Gulf of Lions (Northwestern Mediterranean Sea) and has been thoroughly documented thanks to the deployment of several gliders at the same time, Argo profiling floats, dedicated ship cruises, and a mooring located within the mixed patch.

The data collected represents an unprecedented density of in-situ observations during an event of open-ocean deep convection. A methodology based on a glider quasi-static flight model was applied to infer the oceanic vertical velocity signal from the glider navigation data.

During the active phase of mixing, the gliders underwent significant oceanic vertical velocities (upward and downward, stronger than 10cm/s). The gliders moved along saw-tooth trajectories between the surface and a maximum depth of 1000m with a distance of 2-4km and a period of 2-4 h between surfacings. They have crossed several small scale convective plumes (L~1km) during down and/or upcasts, while recording temperature and salinity, as well as biogeochemical properties (dissolved oxygen, fluorescence, turbidity).

Our study aims at a deeper understanding of their role in the mixing of physical and biogeochemical tracers during deep open-ocean convection events. It provides a comprehensive characterization of convective plumes on a statistical basis showing an asymmetry between up and down movements with stronger downward velocities. We show the relation between these vertical movements and the water properties and extract for the first time based on in-situ data the horizontal scales associated with these circulation features.

IAPSO (Physical Oceanography)

P03e - P03 Ocean Mixing

IUGG-5392

Persistent turbulence microstructure observations from autonomous underwater gliders

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Long term observations of oceanic turbulence are sparse, but essential to understand the processes driving the mixing. Microstructure temperature and shear sensors have been fully integrated onto Seaglider, a long-endurance, buoyancy-driven autonomous underwater vehicle, to provide direct estimates of rates turbulent of dissipation in the upper ocean during multi-month deployments. Microstructure data can be collected on every dive and climb without severe impacts on drag or overall mission endurance. In addition to recording the raw data, profiles of dissipation rates are calculated onboard the vehicle and transferred to users in near-real time with the rest of the scientific data, allowing for adaptive sampling. Observations collected during the Salinity Processes Upper-ocean Regional Study (SPURS) field campaign in the subtropical Atlantic Ocean are used to identify and quantify the processes responsible for the formation of a 100-m thick surface mixed layer in the winter, and its restratification in the Spring and Summer. Three gliders collected several microstructure profiles per day of the top 250 m for about 6 months, leading to about 2500 profiles of temperature variance dissipation rate during the first 6 months of SPURS. These direct estimates of dissipation are used to constraint the evolution of mixed layer properties, and evaluate the impact of mixing due to internal waves and lateral intrusions at the base of the mixed layer

IAPSO (Physical Oceanography)

P03f - P03 Ocean Mixing

IUGG-2518

An assessment of vertical mixing schemes in comparison observations in the European shelf over a decadal scale.

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Using the NEMO-shelf model of the Atlantic Marginal Domain with 7km resolution (AMM7) we examine 5 different turbulent closures structural functions, based on the k-epsilon version of the Generic Length Scale Model. The closures include three different models by the Canuto group and two by Kantha and Clayson (Galperin type closure). The AMM7 model realistically reproduces tides and shelf sea processes in the upper and benthic layers. Each simulation is carried out for 1996 to 2009. The results have been compared with scanfish temperature sections and direct turbulent observations of dissipation rate of kinetic energy, shear during 1998-2009. We evaluate each turbulence closure in its ability to reproduce both the direct turbulence observations and large scale physical oceanographic properties. The latter include: upper and benthic mixed layer depths, potential energy anomaly, depth and thickness of pycnocline, SST and bottom temperature, locations of tidally induced fronts. We relate the match- mismatch between the model and observations to the underlying assumptions and approach of each closure scheme, and use this to direct future evolution of this class of model.

IAPSO (Physical Oceanography)

P03f - P03 Ocean Mixing

IUGG-3075

The role of mixing in major interannual surface cooling events in the equatorial Pacific cold tongue

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Interannual fluctuations of the sea surface temperature in the equatorial Pacific cold tongue are strongly tied to ENSO states. In this study, we investigate the role that mixing plays to regulate the sea surface temperature during two separate month-long time periods — January 2007 and April 2010 — where rapid cooling greater than -2°C per month occurred at the end of the 2006-2007 and 2009-2010 El Niños. Dissipation and vertical heat flux are calculated from high speed (120 Hz) thermistors on Xpods located at multiple depths on the TAO mooring at 0° 140°W. During January 2007, the Richardson number is low, dissipation is high, and we observe depth-coherent fluctuations of temperature near the buoyancy frequency that are attributed to shear instabilities. During April 2010, the stratification and Richardson number are much higher than in January 2007 and no narrowband fluctuations of temperature are present. However, despite lower mixing rates, the sea surface cools. By understanding the role of mixing in regulating the sea surface temperature of the equatorial Pacific cold tongue, deeper insight into the onset and termination of El Niño can be gained and hopefully contribute to improving mixing parameterizations used for the equatorial ocean in global climate models.

IAPSO (Physical Oceanography)

P03f - P03 Ocean Mixing

IUGG-3248

Heat transport in the upper ocean during summer in the north Pacific

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The vertical and horizontal heat transports of the upper ocean during summer in the North Pacific are investigated by analyzing observation data (Argo) and OGCM results (MRI OGCM). The temperature increase and the horizontal ocean heat transport (OHT) in the upper ocean up to the depth z = 100 are calculated. The downward transport of the surface heat flux (SHF) is found to be largely limited to the upper 100 m depth over the whole ocean. The heat budget of the upper ocean (z < 100 m) reveals that the contribution from OHT is much smaller than SHF except along the Kuroshio region in the high-latitude ocean but they are comparable in the low-latitude ocean. The penetration depth of downward heat transport h_p, defined by the integrated SHF divided by the net increase of SST over the time period, is calculated, using the net increase of SST obtained by the real SST increase minus the contribution from OHT. It is found that both h_p and the mixed layer depth h_d, based on the density difference from the surface, are affected by the Coriolis force as well as by the wind stress and SHF, but h_p is much deeper than h_d at smaller h_d, implying a large amount of heat flux penetrating below the MLD. Finally, the mixing layer depth h_k, where vertical mixing actually occurs, is calculated based on the depth of the critical value of the vertical eddy diffusivity, is obtained from the OGCM and compared with h_p and h_d. Discussion is made on the difference between observation and OGCM results, together with the suggestion of the vertical mixing parameterization in the OGCM.

IAPSO (Physical Oceanography)

P03f - P03 Ocean Mixing

IUGG-4521

Mixing due to sub-mesoscales

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In the OGCMs presently used in climate and bio-geochemical studies, the degree of mixed layer ML stratification is the result of the competition between de-stratification by advection+small scale vertical mixing and re-stratification by spring solar heating. The degree of ML stratification is an important variable since a well-mixed (de-stratified) ML can absorb more heat and CO2 than a stratified one and predictions of heat and CO2 absorption are a primary goal of climate and Carbon cycle studies. Inclusion of sub-mesoscales SM would provide a more realistic description of the ML stratification since high resolution numerical simulations have shown that in the case of strong winds, the de-stratification by mean advection is completely cancelled by re-stratification due to SM.

However, since no SM parameterization has yet been proposed that reproduces the mean-advection-SM cancellation, the main goal of this work was to provide such a parameterization. We have constructed an SM parameterization that will be shown to reproduce the cancellation. Other features of the model are the momentum diffusivity, the relation of the SM buoyancy flux to small scale mixing and the fact that buoyancy and tracers have different bolus velocities.

On the basis of these results, the SM parameterization will be included in a coarse resolution OGCM, a project presently under way.

IAPSO (Physical Oceanography)

P03f - P03 Ocean Mixing

IUGG-4918

Downward "lee wave" radiation from tropical instability waves in the central equatorial Pacific: a possible energy pathway to turbulent mixing

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Turbulent mixing in the thermocline of the equatorial Pacific Ocean is one of the most important processes that control not only the equatorial current system but also global climate through diapycnal transports of heat and momentum. Recently, it is shown that, in the eastern equatorial Pacific, strong mixing is induced by enhanced vertical shear associated with the tropical instability waves (TIWs) with a wavelength of ~1000 km which propagate westward along the equator at a speed of ~0.5 m/s. In the central equatorial Pacific where the thermocline is too deep to be affected by the vertical shear of the TIWs, however, mixing processes are not well understood.

In this study, generation mechanism and spatial distribution of internal waves radiating from the TIWs, a possible energy pathway to turbulent mixing, are investigated using a high-resolution ocean general circulation model. The leading edge of the TIW is clearly manifested as a narrow strip of strong convergence of horizontal surface flow, from which area downward and westward propagating internal waves are intermittently emanated. These internal waves are interpreted in terms of lee waves generated under the surface convergence zone, which acts like a moving obstacle along the stratified sea surface. The associated downward energy flux below the surface mixed layer increases as the TIW structure becomes deeper in the central equatorial Pacific. The downward energy flux integrated over the entire equatorial Pacific and averaged during January 2011 amounts to ~8.1 GW, occupying a significant fraction of the energy input to the TIWs.

IAPSO (Physical Oceanography)

P03f - P03 Ocean Mixing

IUGG-5605

Ocean processes in the recovery phase of cold wakes

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We investigate the ocean processes associated with the formation and restratification of cold wakes. The numerical simulation was performed using Florida State University (FSU) version of the Princeton Ocean Model (POM) to cover the storm track of Hurricane Fanapi (September, 2010) with the initial temperature and salinity conditions from the CTD profiles. Forced by the Cross-Calibrated Multi-Platform (CCMP) Ocean Surface Wind Vector Analyses, the cold wake were reasonably well reproduced with the significant increase mixing and cooling on the rightward side of the hurricane in accordance with theory and the direct turbulence survey. The elevated turbulent kinetic energy (TKE) was seem within the mixed layer (<50 m) and weakens exponentially in the thermocline stratification. The significant decay of the TKE appeared within a few days after the storm, however the temperature and salinity structures showed the delayed recovery, and took a few weeks to a month to erase the storm signals completely. A horizontal resolution of 1 km will also be shown to demonstrate the effects of submesoscale variability on the restratification processes.

IAPSO (Physical Oceanography)

P03g - P03 Ocean Mixing

IUGG-2723

When complexity leads to simplicity: Ocean surface mixing simplified by vertical convection

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The effect of weak vertical motion on the dynamics of materials that are limited to move on the ocean surface is an unresolved problem with important environmental and ecological implications (e.g., oil spills and larvae dispersion). We investigate this effect by introducing into the classical horizontal time periodic double-gyre model vertical motion associated with diurnal convection. The classical model produces chaotic advection on the surface. In contrast, the weak vertical motion simplifies this chaotic surface mixing pattern for a wide range of parameters. Melnikov analysis is employed to demonstrate that these conclusions are general and may be applicable to realistic cases. This counter intuitive result that the very weak nocturnal convection simplifies ocean surface mixing has significant outcomes. (PHYSICS OF FLUIDS, 24, 056603, 2012).

IAPSO (Physical Oceanography)

P03g - P03 Ocean Mixing

IUGG-3118

Properties and origins of the anisotropic eddy-induced transport in the North Atlantic

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This study examines anisotropic transport properties of the eddying North Atlantic flow, using an idealized model of the double-gyre oceanic circulation and altimetry-derived velocities.The material transport by the time-dependent flow (quantified by the eddy diffusivity tensor) varies geographically and is anisotropic, that is, it has a well-defined direction of the maximum transport. One component of the time-dependent flow, zonally-elongated large-scale transients,is particularly important for the anisotropy, as it corresponds to primarily zonal material transport and long correlation time scales. The importance of these large-scale zonal transients in the material distribution is further confirmed with simulations of idealized color dye tracers, which has implications for parameterizations of the eddy transport in non-eddy-resolving models.

IAPSO (Physical Oceanography)

P03g - P03 Ocean Mixing

IUGG-4732

Evolution of density compensated fronts in simulated ocean mixed layers

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Observations within the ocean surface mixed layer indicate a tendency for temperature gradients to form that are compensated for their effect on density by salinity gradients. These density compensated fronts tend to occur in the absence of strong surface forcing and thus weak vertical mixing. Observations show that density compensated fronts are quickly erased by surface cooling events. The presence of density compensated gradients in the surface mixed layer, however, are not well represented in regional and global ocean circulation model predictions. In these models, subgrid scale processes are parameterized with minimal ability to represent double diffusion. Recent advances in parameterizations have been developed to model the re-stratification of the mixed layer by sub-mesoscale eddies. These ageostrophic dynamics can lead to long filaments that are governed by process on length scales from 100 m to 10 km and time scales near a day. The impact of these processes in model physics on density compensated fronts is unclear. To improve our understanding of compensated front evolution in the ocean, two different mixing schemes are tested to evaluate the creation of horizontally density compensated gradients in model simulations. One scheme extracts potential energy of ocean fronts for mixing dependent on horizontal and vertical buoyancy gradients, mixed layer depth, and inertial period. The other scheme mixes temperature and salinity horizontally dependent on the buoyancy gradient squared. Both schemes provide a three dimensional approach to mixing that differentiates the horizontal eddy diffusion of temperature and salinity.

IAPSO (Physical Oceanography)

P03g - P03 Ocean Mixing

IUGG-4856

Estimating local mixing coefficient in a framework of diffusion against mean flow

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Traditional methods, estimating mixing coefficient from the rate of dispersion of particles, commonly become meaningful only on times significantly larger than Lagrangian time scales, when statistics approaches one of supposed asymptotes. As a rule, by these times, particles disperse far from their start positions and the estimate of mixing becomes “smeared” over a rather large spatial scale.

Therefore, accuracy and even plausibility of such methods relies on the implication of sufficient spectral gap between space scales of resolved (large-scale, time-averaged or slowly changing) currents and anomalies (traditionally referred as “eddies”) that are attempted to be described through the “mixing” formalism. However, recent studies reveal an amazingly complex structure of the mean ocean circulation, in which fronts remain sharp even on long-time averages. They also reveal complex organization of long-living, coherent mesoscale eddies, often following preferred paths and producing a new “texture” of the mean ocean circulation.

By converting Lagrangian trajectories into Eulerian probability density function, this study proposes a new technique that allows to significantly reduce the size of the domain, necessary to estimate the local value of the mixing coefficient. The method is based on unique properties of an analytical solution of the diffusion equation for a tracer, released from a singular source in the presence of a mean flow, and can be generalized onto two-dimensional case and on particles with a finite lifetime. Applied to the real ocean circulation, measured with satellite-tracked drifting buoys, the new technique provides an insight into the factors, controlling intensity of horizontal mixing by varying currents multi-scale currents.

IAPSO (Physical Oceanography)

P03g - P03 Ocean Mixing

IUGG-5401

Submesoscale instabilities at ocean fronts observed during winter in the North Atlantic

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An array of submesoscale-resolving moorings was deployed in the North Atlantic (48.69°N, 16.19°W) during September 2012--September 2013 in order to monitor the ocean surface boundary layer. Measurements made during this time include temperature, salinity and horizontal velocity from moored instruments (50-500 m) and ocean gliders (0-1000 m). This study focuses on mooring measurements collected during winter and the observed relationship between negative Ertel potential vorticity, **q**, and mixed layer depth, **h**.

Measurements suggest that wintertime winds oriented down front reduce an already weak stratification via Ekman transport of dense water over lighter water. This reduction in stratification reduces **q** and results in mixed gravitational/symmetric instabilities (GI and SI, respectively). Maps corresponding to modified Rossby and Richardson numbers with depth and time depict an interesting relationship between SI, GI and **h**: SI leads GI, and results in a deepening pycnocline; following decreased down-front wind, GI shuts off, SI lags and the pycnocline shoals. Inertial (i.e., centrifugal) instabilities are seldom observed. The results presented here suggest submesoscale mixed layer instabilities are an order-one mechanism for vertical mixing in the upper ocean during winter.

IAPSO (Physical Oceanography)

P03p - P03 Ocean Mixing

P03p-239

Coupled benthic-pelagic processes in the Patagonian shelf break

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The largest aggregations of the Patagonian scallop (Zygochlamys patagonica), a filter feeder of phytoplankton, are located along the argentinean outer shelf and continental slope following the surface signature of the Patagonian Shelf Break Front (PSBF). The region currently supports one of the most important scallop fisheries in the world. The PSBF is associated with areas of high concentration of phytoplankton and therefore it has been suggested that coupled benthic-pelagic processes would be the main process explaining the location of the major scallop beds. In this work we investigate this hypothesis using stochastic particle tracking simulations driven with flow and diffusivity fields generated by idealized and realistic high-resolution hydrodynamic numerical models. To analyze the dynamics of coupled benthic-pelagic processes particles were released at the surface over shelf break in an idealized model. The model results showed that semidiurnal (tidally driven) oscillations induce high mixing processes over the shelf break, with horizontal displacements of ~10 km of the particles. These horizontal movements interact with the local stratification generating disturbances in the density field that enhanced vertical particle displacements and allowed benthic-pelagic coupling. Such coupling and vertical transports of particles reaching the bottom (~200 m depth) occur only in the model which is forced with tides and a slope current. Particles released at the surface of the PSBF in the realistic models reach the bottom near the location of the main scallop beds, further supporting the proposed coupling mechanism. It is also interesting to note that an important amount of particles were also dispersed offshore along the continental slope.

IAPSO (Physical Oceanography)

P03p - P03 Ocean Mixing

P03p-240

Energy Transfer Through the Mixed Layer Estimated With a Hybrid Model

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Energy transfer mechanisms between atmosphere and deep ocean have been studied for many years, their importance to the ocean's energy balance and possible implications on mixing are widely accepted. The slab model is a well established simulation of near-inertial motion and energy inferred through wind-ocean interaction. However, mainly temporally coarse resolution wind forcing data in combination with rough internal wave energy flux assumptions are used.

A slab model using hourly wind forcing from the NCEP-CFSR reanalysis allowing computations up to high latitudes without loss of resonance was set up. It was validated with buoy data from 44 sites in the Atlantic, Indian and Pacific ocean and the Mediterranean. Augmenting the one-dimensional model by the horizontal divergence of the near-inertial current field at the mixed layer base led to direct estimates of energy transfer spectra of radiation of internal waves into the ocean interior. No crucial assumptions on transfer physics are made.

Preliminary results of the hybrid model indicate wave modes at the base of the mixed layer, mid-latitude storms with a dominant seasonal cycle as well as isolated tropical storm tracks are well reproduced. The wind driven energy transfer is analysed with regard to the spatial distribution and seasonal cycle. Energy flux ratios will be evaluated and dissipation rates will be estimated according to the energy balance in and below the mixed layer.

IAPSO (Physical Oceanography)

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P03p-241

On the particle separation rates deduced from Lagrangian trajectories simulations

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In oceanography, the Lagrangian description of fluid motion by a set of individual particle trajectories is especially useful to investigate the fate of water masses and tracers. It allows for the characterization of connectivity between certain oceanic locations, i.e. the identification of preferential linking pathways, associated timescales and transports. In addition to Lagrangian observing programs Lagrangian studies are performed by the use of three-dimensional time-varying flow fields of ocean general circulation models. Therefore, Lagrangian trajectories are calculated by advecting particles with the modeled velocity fields. To account for processes not resolved by these fields, some Lagrangian schemes add a diffusion term to the trajectory calculation. However, considering the increasing range of processes resolved with increasing model resolution as well as possible impacts of numerical diffusion on the simulated velocity fields, the need of such an additional diffusion term is disputable. Here we compare lateral diffusivity estimates from trajectories simulated within a hierarchy of ocean general circulation models (1/2°-1/20°) with observational results, to address the question how realistic the simulated particle separation rates actually are. The analysis is performed within the extended Agulhas region, where mesoscale processes are known to be the major driver in the interbasin exchange between the Indian and Atlantic Oceans.

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P03p-242

Comparison of the mixed layer depth and its variation from observation and simulation

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The mixed layer depths (MLD) from observation and simulation are compared. Observed MLD is obtained from WOA and Argo data, and simulated MLD is obtained from MRI OGCM. It is also investigated how MLD is affected by the method of calculating MLD; for example, from individual, monthly mean, and climatological density profiles, and from different density difference criteria. It is found that, if the MLD is evaluated from averaged profiles, it shows the tendency for underestimation, if stratification is strong and the small density difference criterion is used, and the tendency for overestimation, if stratification is very weak under convection during winter and the large density difference criterion is used. It is thus important to follow the same method for the proper comparison of MLD between observation and simulation. Comparison is also made for the thickness of the thermocline, the month of the maximum MLD, and the interannual variation of MLD such as amplitude and correlation. Furthermore, the OGCM is applied to clarify how MLD is affected by the temporal resolution of atmospheric forcing, and how the mixing layer depth based on the vertical diffusion is different from MLD based on the density difference criterion.

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P03p - P03 Ocean Mixing

P03p-243

Temperature statistics above a deep--ocean sloping boundary

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A detailed analysis of the statistics of temperature based on an oceanographic observational dataset is presented. The data is collected using a moored array of 144 thermistors, 100m tall, deployed above the slopes of a seamount in the North Eastern Atlantic Ocean from April to August 2013. The thermistors are built in-house at Royal NIOZ, and provide a precision better than 10^-3K and very low noise levels.

The thermistors measure temperature every second, synchronised throughout the moored array. The thermistor array ends 5m above the bottom, and no bottom mixed layer is visible in the data, indicating that restratification is constantly occurring and that the mixed layer is either absent or very thin. Intense turbulence is observed, and a strong dependence of turbulence parameters on the phase of the semidiurnal tidal wave is also evident.

We compute the statistical moments (generalised structure functions), of order up to 10, of the distributions of temperature fluctuations and increments. Strong intermittency is observed in particular during the downslope phase of the tide and in the upper half of the array, but the inertial range of turbulence is clearly detected by the thermistors.

Skewness and higher order moments of temperature increments suggest that convective structures are present in the upper half of the array during the upslope phase. In the lower half of the array, the statistics of temperature increments are compatible with those of a passive scalar in grid turbulence, as measured in various laboratory experiments. The downslope phase is sometimes thought to be more shear dominated, but our results suggest on the other hand that convective activity could still be playing a role at small scales.

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P03p - P03 Ocean Mixing

P03p-244

New Lagrangian diagnostics for characterizing fluid flow mixing

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A new kind of Lagrangian diagnostic family is proposed and a specific form of it is suggested for characterizing mixing: the extreme (maximal/ minimal) extent of a trajectory and some of its variants. It enables the detection of coherent structures and their dynamics in two- (and potentially three-) dimensional unsteady flows in both bounded and open domains. Its computation is simple and provides new insights regarding the mixing properties on both short and long time scales and on both spatial plots and distribution diagrams. We demonstrate its applicability to two dimensional flows using two toy models and a data set of surface currents from the South Atlantic. (Physics of Fluids, 26 , 126602 (2014); doi: 10.1063/1.4903239)

IAPSO (Physical Oceanography)

P03p - P03 Ocean Mixing

P03p-245

Surface diapycnal mixing in an intrathermocline anticyclonic eddy south of the Canary islands

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In the past decades, great efforts have addressed the role of mesoscale eddies on the ocean, where small-scale mixing processes are potential players on the vertical redistribution of nutrients and solutes. However, a comprehensive understanding of these processes occurring within the interior of an eddy is largely conditioned by the lack of high resolution in situ measurements at synoptic scales.

Turbulence in the first meters of the water column is partially triggered by the atmosphere-ocean interchange of heat, wind-stress forcing and/or the vertical shear at the base of the mixed layer (h_ρ). In this research, and within the scope of the PUMP project (ref: CTM2012-33355), we study the upper mixing layer of an anticyclonic intrathermocline eddy south of the Canary Islands based on a high resolution grid of CTD, LADCP, microstructure profiler (TurboMAP) and meteorological data at synoptic scales.

We obtain values of turbulent kinetic energy dissipation rates (ε) which are in good agreement with Ozmidov (L_o) and Thorpe (L_T) scales. Mean values of ε are found to be $2x10^{-8}$ ($m^2\ s^{-3}$), between the surface and the mixing layer (h_ε). In this research, h_ε was always deeper than h_ρ . Moreover, Monin-Obukhov scales indicate that the mechanical stirring was not large enough to dominate the mixing of the h_ε. Additionally, estimates of entrainment rates (w_e) were found to increase on the periphery of the eddy favoring the increase of vertical exchange between lower and upper layers. This result is also consistent with elevated values of diapycnal eddy diffusivity (K_z) at the same locations, exhibiting an order of magnitude of difference between the core (K_z= $4.5x10^{-5}$) and the boundary regions (K_z = $4.5x10^{-4}$) of the eddy.

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P03p - P03 Ocean Mixing

P03p-246

Distinguishing ichthyogenic turbulence from geophysical turbulence

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Measurements of currents and turbulence beneath a geostationary ship in the equatorial Indian Ocean during a period of weak surface forcing revealed unexpectedly strong fish-generated (ichthyogenic) turbulence beneath the surface mixed layer. Coincident with the turbulence was a marked reduction of the current speeds registered by shipboard Doppler current profilers, and an increase in current speed variability. At a mooring 1 km away, measurements of turbulence using chipods and currents showed no such anomalies. Correlation with the shipboard echosounder measurements indicate that these nighttime anomalies were associated with fish aggregations beneath the ship. The fish created turbulence by swimming against the strong zonal current in order to remain beneath the ship, and their presence affected the Doppler speed measurements. The principal characteristics of the resultant ichthyogenic turbulence are i) low wavenumber rolloff of shear spectra in the inertial subrange relative to geophysical turbulence, ii) Thorpe overturning scales that are small compared with the Ozmidov scale, and iii) low mixing efficiency. These factors extend previous findings by [Gregg and Horne, 2009] to a very different biophysical regime, and support the general conclusion that the biological contribution to mixing the ocean is negligible.

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P03p - P03 Ocean Mixing

P03p-247

Near-inertial waves trapping by a mid ocean anticyclonic eddy

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Ocean velocity structure inside a mid ocean anticyclonic eddy is study using SADCP, drifters and hydrographic data obtained during the PUMP oceanographic survey carried out in September 2014. The SACDP was a 75kHz model, which measured current profilers in the upper 700 m depth. The drifters were deployed in the eddy dragged below and within the surface mixed layer. Evidences of near-inertial wave packets with clockwise rotation with increasing depth and upward phase velocities are observed. Rotatory wavelet analyses of Lagrangian velocities reveal the presence of wind generated near-inertial waves whose intrinsic frequencies are related with the eddy angular velocities. Observations are consistent with downward propagating near-inertial waves that are trapped at the base of the eddy producing enhanced vertical shear.

IAPSO (Physical Oceanography)

P03p - P03 Ocean Mixing

P03p-248

Estimating eddy viscosity profile from ekman spirals in the bottom boundary layer

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Turbulent mixing induced by tidal currents near the sea bottom plays a key role in coastal and shallow sea environments. Many attempts have been made to quantify turbulent mixing near the seabed, such as velocity micro-structure measurements with micro-structure profilers and turbulent Reynolds stress measurements using acoustic Doppler current profilers (ADCPs). Here, we propose an alternative method to estimate the eddy viscosity profiles. In this method, the Ekman balance equations are solved with measured velocity spirals. Three schemes (scheme 1, 2, and 3) are investigated; schemes 1 and 2 were used in the previous studies while scheme 3 is newly proposed in the present study. Using velocity spirals simulated with an idealized eddy viscosity profile, we test performance of the schemes and find that scheme 2 is useful if the random measurement errors are small while scheme 3 is useful when the errors in the Ekman balance are small. The performance is also evaluated using the velocity spirals measured in the East China Sea. This method utilizes velocity measured with standard ADCP operated in normal modes, allowing for easier and more frequent quantification of the mixing averaged over longer periods.

IAPSO (Physical Oceanography)

P03p - P03 Ocean Mixing

P03p-249

"Small scale structure in temperature and salinity over the Mindanao Dome"

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In July 2011 Japan Meteorological Agency carried out regular observation in the Pacific Northwest along a longitude line of 137 E. Continuous observation data were obtained every minute from a thermosalinograph. Small scale structure in temperature and salinity was found in 6 N - 10.8 N. Soundings of temperature, salinity and dissolved oxygen obtained from Conductivity Temperature Depth profiler showed that the active mixing occurred just over the Mindanao Dome. The mixed layer depth was about 50 dbar in 6 N - 10.8 N. The acoustic doppler current profiler data showed that there was a clear shear at 10.8 N. The north boundary of Mindanao Dome is very sharp. Stommel and Fedorov (1966) analyzed fine scale micro structure observed near Timor and Mindanao in July 1965. They reported that the the points (T,S) lied on a constant density line in T-S diagram. However, the points (T,S) representing the thermosalinograph data did not lie on a constant density line. While sea surface water is heated and salinized, water at 50 dbar depth is cooled on the Mindanao Dome; Hot saline water lies over cold fresh water. It is suggested, therefore, that small scale structure in temperature and salinity is due to salt fingers in double diffusive convection.

IAPSO (Physical Oceanography)

P03p - P03 Ocean Mixing

P03p-250

Estimates of the attenuation rates of baroclinic tidal waves caused by resonant interactions with the background internal wave continuum

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The baroclinic tidal waves, generated by tide-topography interactions, are the predominant energy source in the deep ocean (globally integrated up to ~ 1 TW) and are thought to play a crucial role to close the deep global water-mass budget. Although the recent development of numerical ocean models has enabled us to precisely simulate the generation process of the baroclinic tidal waves over seamounts, it remains unknown how and where the baroclinic tidal waves attenuate in the world's oceans. One responsible mechanism for such attenuation processes is thought to be nonlinear wave-wave interactions, which transfer part of the baroclinic tidal wave energy to the background internal wave field.

In this study, we develop the classical weak turbulence theory, which is then applied to the realistic situation in the ocean to estimate the attenuation rates of the low-mode baroclinic tidal waves through wave-wave interactions. For the M_2 tidal constituent, in particular, the most rapid attenuation (~10 days at shortest) is shown to occur at 29°N/S due to parametric subharmonic instability, in agreement with the previous numerical and observational studies. A new finding is that the local attenuation rates also vary by up to a factor of two depending on the total ocean depth as well as the vertical profile of density stratification. These results are depicted in the form of a global map of e-folding days of the baroclinic tidal waves where the regional difference is found to reach two orders of magnitude.

The validity of thus obtained global distribution of the attenuation rate of baroclinic tidal waves should be checked by carrying out numerical experiments as well as field observations in the future.

IAPSO (Physical Oceanography)

P04a - P04 Oceanic Boundary Current Systems

IUGG-0257

Role of the Slope Sea and the Labrador Current on the Gulf Stream's interannual migration

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New version: The Slope Sea is composed of shelf and Labrador Sea waters coming in from the north and west, and Gulf Stream waters coming in from the south. Interannual Slope Sea transport variability has been linked to changes in Labrador Sea Water just as fluctuations in Gulf Stream position follow variations in Slope Sea Temperature/Salinity (T/S) [Peña-Molino and Joyce, 2008] and phase reversals in the North Atlantic Oscillation (NAO) [Taylor and Stephens, 1998] when lagged 6 months and 2 years, respectively. It has been hypothesized that the signal from the NAO reaches the Gulf Stream via the Labrador Current and the Slope Sea [Rossby, 1999].

Directly measured current velocity is used here to show the mean structure and variability of the Slope Sea. Flow in this region is dominantly (south) westward, with an intensified subsurface jet ~100 km offshore of the shelf break. Slope Sea transport and T/S anomalies are compared with Gulf Stream position, focusing on the low frequency signal. Statistically significant correlations are found, establishing in particular that 1) Slope Sea T/S signal is shown to precede shifts in Gulf Stream position, and 2) variations in Slope Sea transport lead Slope Sea T/S, yet follows changes in the Gulf Stream's position.

Last, comparisons of satellite-derived Labrador Current transport are shown to be correlated (r=-0.68, significant at 95% levels) with a 2 year lagged Gulf Stream position..

IAPSO (Physical Oceanography)

P04a - P04 Oceanic Boundary Current Systems

IUGG-0830

Thermocline and intermediate circulation in the Southwest Pacific low latitude western boundary currents

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The Low Latitude Western Boundary Currents (LLWBCs) of the Southwest Pacific establish a major connection between the subtropics and the equator. They cross the semi-enclosed Solomon Sea southeast of Papua New Guinea, resulting in a large variability due to the strong boundary currents encountering rough topography. As a result, the water mass properties are influenced during their transit with downstream effect on equatorial water properties. Two oceanographic multidisciplinary cruises have been completed in July 2012 and March 2014 to characterize currents, water properties and their modifications in the Solomon Sea as part of the CLIVAR/SPICE program. We will present the thermocline, intermediate and deep pathways and water mass transformations using measurements of salinity, oxygen, nutrients and velocities along with an inverse box model result. We will assess the impact of the transit through the Solomon Sea and possible effects on equatorial processes, including equatorial upwelling properties.

IAPSO (Physical Oceanography)

P04a - P04 Oceanic Boundary Current Systems

IUGG-2611

Mass and Heat Transport of the East Australian Current

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We present results from an 18-month full-depth current meter occupation across the East Australian Current (EAC) off Brisbane. These observations provide a far more comprehensive picture of the strength and structure of the EAC than obtained in previous surveys. The site was chosen to capture the current as it approaches its maximum strength and to the north of the main eddy field and adjacent to a 20-year XBT time series. An array of 3 inshore and 5 offshore moorings, which included a comprehensive set of ADCPs, current meters, CTDs and temperature sensors was deployed from April 2012 until September 2013. In the light of the shortcomings of previous attempts to monitor the current, the array was designed to capture the full width of the EAC flow from the coast to its offshore extent. The array showed a continuous southward flowing EAC in the upper 2000-m, and a major episodic northward undercurrent located 50-km from the coast in the lower 2500-m with maximum flows of 20-cms^{-1}. The mean southward transport of the EAC was 19-Sv with a net transport over the whole array of 12-Sv. We discuss the relationship of these flows with the circulation in both the South Pacific and global circulation

IAPSO (Physical Oceanography)

P04a - P04 Oceanic Boundary Current Systems

IUGG-2725

Western boundary currents and the discovery of weather in the ocean

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Philosophers describe discovery as an extended, complex process, culminating in a paradigm change. In this invited talk, I will focus introspection upon observational studies of western boundary currents (WBC) and will identify a set of paradigm changes as we have discovered weather in the ocean. The story begins in 1832 with James Rennell’s careful observations of ship drift and ocean temperature, and the discovery that the Gulf Stream was not fixed, but instead shifted its location over the course of weeks to months. The next paradigm shift in this story came with the invention of current meter moorings and acoustically tracked floats that led to the discovery of benthic storms in the vicinity of the Gulf Stream, with bottom current speeds exceeding 20 cm/s. Later, by tracking neutrally buoyant floats, it was discovered that water parcels slid up and down the Gulf Stream's sloped thermocline, crossing its front as they transited through growing meander troughs and crests. As satellite and ocean technology advanced, it was possible to create “ocean weather maps” that showed deep cyclonic eddies, shifted downstream from upper level troughs, spin up through baroclinic instability: During the coupled meander and benthic storm development, large cross-frontal and vertical heat fluxes converted potential energy into eddy kinetic energy, in many ways similar to a midlatitude winter storm. Looking forward, today’s research is focused on how WBC surface temperature fronts affect the tropospheric structure and thereby storm development and storm tracks in various basins of both hemispheres. Looking back we see that most paradigm shifts occurred with the development of new observing tools. What new tools will we have in coming decades? What will we see? What will we discover?

IAPSO (Physical Oceanography)

P04a - P04 Oceanic Boundary Current Systems

IUGG-4305

Seasonal cycle of mesoscale instability of the West Spitsbergen Current

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The West Spitsbergen Current (WSC) is a topographically steered boundary current that transports warm Atlantic Water northwards in Fram Strait. In Fram Strait the WSC splits with about half of the transport entering the Arctic Ocean and the rest recirculating to be exported southward in the East Greenland Current. The WSC has previously been shown to temporarily exhibit baroclinic and barotropic instabilities triggering eddy formation. The recirculation of the WSC is closely linked to the eddies stemming from the WSC. Here we investigate 16 years of current and temperature/salinity measurements from moorings in the WSC at 78°50'N to establish the seasonal cycle of the stability of the WSC. In winter, the WSC is a strong vertically sheared current advecting weakly stratified water. The baroclinic e-folding growth rate is about 3 days in winter indicating that the current has the ability to rapidly grow unstable and form eddies. In summer the WSC is weaker with weaker shear and higher stratification. It therefore is significantly less unstable. This corresponds well with observations of the eddy kinetic energy (EKE) in Fram Strait which has a peak in the WSC in January/February when the boundary current is most unstable. The eddies are then advected westward with the recirculation and the EKE peak is observed 1-2 months later in the central Fram Strait. In late summer the EKE in the WSC and the central Fram Strait is three times smaller than in winter. This seasonality results from the stronger atmospheric forcing over the Nordic Seas in winter with both increased wind stress curl and increased atmospheric heat loss compared to summer.

IAPSO (Physical Oceanography)

P04b - P04 Oceanic Boundary Current Systems

IUGG-0778

Argo float trajectories and the Southeast Madagascar eddies: Dispersion experiments within the Agulhas Current source region

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This study uses Argo floats to investigate the vertical dynamics, entrainment processes and non-linearity of mesoscale eddies formed southwest of Madagascar. Eleven Argo floats were deployed in the central southern Mozambique Channel in 2013 - five in a cyclonic eddy (CE) in April, four in a CE in July and two in an anticyclonic eddy (ACE) in December.

The authors investigate the implications that changes in float park depth and profiling frequency have on the experimental design. We observe that floats with park depths between 500 and 650 m (five floats) remain within the CE's until they reached the influence of the Agulhas Current, but exited the ACE fairly soon after deployment (two floats). One float, with a park depth of 1000 m, propagated southwestward outside of the influence of the CE in which it was deployed, suggesting the CE was relatively shallow, contrary to previous studies. Floats were successfully deployed and entrained within the CE's on daily (five floats) and five-daily (four floats) cycles, indicating that a profile frequency between one and five days would accurately capture mesoscale dynamics, particularly CE's, using Argo floats.

This study also examines the type of eddy sampled, using absolute geostrophic velocity maps, plotted from AVISO (M)ADT data, and show them to be highly non-linear, trapping water within their cores. This is shown where the ratio of the averaged geostrophic current speed of the eddy divided by the translational speed of the eddy is greater than 1, with high non-linearity being greater than 5. This has implications to the Agulhas Current, as these eddies contribute to the source waters thereof.

Recommendations on how to replicate similar studies elsewhere in turbulent regions of the Worlds Oceans will be discussed.

IAPSO (Physical Oceanography)

P04b - P04 Oceanic Boundary Current Systems

IUGG-1446

The global structure of long term mean sea surface drift currents

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We present a numerical model of the dynamics of the global mean near surface drift circulation in which the pure drift is determined by the friction velocity and also importantly by the peak wave period, and the sea surface current is the sum of the pure drift and the surface geostrophic current. The results show that the pure drift contributes about 70% of the sea surface current in the Southern Ocean, where the theoretical predictions have been validated by historic drift bottle and drift card data, and that pure drift is the dominant component of the surface flow along the eastern boundaries of the ocean basins, in contrast to the dominance of the surface geostrophic flow along the western boundaries. The divergence of the pure drift transport (which is directed 'cum sole' to the surface wind field) indicates that entrainment into the surface drift layer occurs in narrow zones along the eastern boundaries with a ventilation time of about 20 days, whereas detrainment occurs in diffuse regions in the west of the ocean basins. These structures are intimately related to the wind and wave fields.

IAPSO (Physical Oceanography)

P04b - P04 Oceanic Boundary Current Systems

IUGG-4205

Cross-Shelf Dynamics, bottom boundary layer transport and upwelling on the continental shelf adjacent to the East Australian Current

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The coastal dynamics along the coast of southeastern Australia are dominated by the South Pacific Western Boundary Current system: the East Australian Current (EAC) and its eddy field. Using 2-3 years of high resolution moored measurements from the Australian Integrated Marine Observing System, we investigate the cross-shelf dynamics upstream (30ºS) and downstream (34ºS) of the separation point of the EAC.

A cross-shelf momentum budget analysis reveals a geostrophic balance at both locations. Amongst the secondary terms, the bottom stress influence is higher upstream while the wind stress is dominant downstream.

The cross-shelf structure of the velocity and temperature fields in response to a prevailing along-shelf wind stress or an intruding EAC acting on bottom stress is presented. The resulting cross-shelf transport in the surface and bottom boundary layer is analyzed and compared to Ekman theory, highlighting the cold water intrusion in response to bottom stress.

Bottom cross-shelf transport is quantified, showing net onshore transport at all locations, with Ekman theory based on along-shelf bottom stress explaining up to 64% of the temporal variability. Uplift in the bottom boundary layer is more intense and frequent upstream than downstream, occurring 64% of the time at 30ºS. At both locations, strong variability was found in bottom water transport at periods around 90–100 days. This corresponds with periodicity in EAC fluctuations and eddy shedding, highlighting the EAC as a driver of variability in the continental shelf waters.

Ocean glider and HF radar observations were used to identify the bio-physical response to an EAC encroachment event, resulting in a strong onshore bottom flow, the uplift of cold slope water, and elevated coastal chlorophyll concentrations.

IAPSO (Physical Oceanography)

P04b - P04 Oceanic Boundary Current Systems

IUGG-4613

Impact of nitrate transport along the Kuroshio on the high productivity in the Kuroshio-Oyashio interfrontal zone

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The Kuroshio-Oyashio interfrontal zone (K-O zone), transition area between the subtorpical and subarctic gyres in the western boundary of the North Pacific, is known as one of the most productive fishing grounds. Recent studies revealed that the Kuroshio transports considerable amount of nutrients to the downstream regions as is the case in the Nutrient Stream along the Gulf Stream. It suggests significant impacts of nutrient transport along the Kuroshio on the high productivity in K-O zone, though supplies from the nutrient-rich subarctic region have been focused in most previous studies. In order to elucidate quantitatively the nutrient supply along the Kuroshio to K-O zone, we analyzed budgets of isopycnal transport of nitrate in the region which covers K-O zone and includes parts of the Kuroshio, the Kuroshio Extension and the Oyashio, using vertical profiles of temperature, salinity, nitrate and current velocity observed at 200 stations enclosing the target region in spring 1998. Budget of nitrate transport integrated from the sea surface to 27.5 sigma-theta isopycnal in the enclosed region was found to be not balanced but in excess of imports, which was comprised of water transported along the Kuroshio and that along the Oyashio at the same rate. The Kuroshio water accounted for a larger rate in the nitrate excess on the lighter isopycnal shallower than nitracline, where new production averaged in the whole of the target region was estimated to correspond to a few hundred $mgCm^{-2}d^{-1}$, simply assuming that all the nitrate excess was consumed by phytoplankton. Comparison of the simple estimate with in situ observations of primary production suggests that the isopycnal transport of nutrient along the Kuroshio contributes significantly to the new production in K-O zone.

IAPSO (Physical Oceanography)

P04b - P04 Oceanic Boundary Current Systems

IUGG-4640

Models of the Kuroshio Extension low-frequency variability: Analysis of the sensitivity to changes in parameter values and initialization

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Assessing model sensitivity to variations of parameter values, model setup and initialization is necessary to interpret and control nonlinear model outputs. In this respect, a primitive equation ocean model capable of producing a basically correct Kuroshio Extension (KE) evolution and synchronization with the PDO-NPGO is shown to be robust to changes in the zonal location and amplitude of the time-dependent atmospheric forcing. On the other hand, the same model is shown to be very sensitive to changes in the lateral eddy viscosity coefficient. Such sensitivity, interpreted with the help of dynamical systems concepts, points to the intrinsic nature of the KE oscillation and to the dramatic change the model undergoes if a global bifurcation (tipping point) is passed in parameter space. Model sensitivity to initialization is investigated by means of a low-order quasigeostrophic model, which allows to perform ensemble simulations with limited computational cost. A variety of synchronization scenarios emerges for different parameter values; implications concerning more realistic models are then discussed.

IAPSO (Physical Oceanography)

P04b - P04 Oceanic Boundary Current Systems

IUGG-4866

Dynamics of the mean flow in the Oyashio region: Effects of bottom topography on a wind-driven gyre

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We investigate the mean flow pattern and its dynamics in the Oyashio region in the northwestern North Pacific. In the upper currents of this region, the Oyashio flows southwestward along the continental shelf. About half of the water turns eastward as the Oyashio Return Flow and then becomes the Subarctic Current. The other half flows further southward along the coast as the Oyashio Intrusion. We aim to understand the dynamical mechanism of this flow pattern, which is presently unknown.

The FRA-JCOPE2 reanalysis data are averaged over 17 years. The mean upper currents represent the features in the Oyashio region mentioned above. In the mean deep currents, significant anticyclonic circulations are present on the rises with heights of several hundred meters, which are located in the offshore side of the Kuril Trench and close to the Oyashio Return Flow.

In addition, we made idealized numerical experiments of wind-driven oceans with a trench and a rise. Analyses of the reanalysis data and the experiments are made using quasi-geostrophic characteristic curves. The results suggests the followings. The barotropic (depth averaged component) Rossby waves are blocked by the rise. The barotropic western boundary current is formed at the eastern flank of the rise and an anticyclonic circulation is formed on the rise. The baroclinic (deviation from the depth averaged component) cyclonic potential vorticity is transported by the barotropic western boundary current. The combination of the barotropic and baroclinic components makes the upper flows with the Oyashio, the Oyashio Return Flow, the Subarctic Current and the Oyashio Intrusion.

IAPSO (Physical Oceanography)

P04c - P04 Oceanic Boundary Current Systems

IUGG-1300

Variability in the Australian Boundary Currents: connecting the East Australian and Leeuwin Currents

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Australia's two boundary currents, the East Australian Current and the Leeuwin Current, play an important role in the dynamics of the South Pacific and South Indian Oceans, respectively. But their role extends beyond their basins, as the Indonesian Throughflow on the north and the Tasman leakage on the south allow for an exchange of water between the basins, and with it heat, nutrients, carbon and freshwater, effectively connecting all oceans around Australia into one large boundary current system.

Like all boundary currents, the East Australian Current and Leeuwin Current show variability on many time scales, ranging from short, eddy-related fluctuations in the latitude of their separations to inter-annual variability related to climate modes. The question is to what extent the two boundary currents are locked on these longer time-scales.

Here, we show results on the dynamics and variability of the boundary currents and inter-ocean exchanges around Australia from eddy-resolving ocean models. We show how the currents are connected, and how drivers like ENSO and the Indian Ocean Dipole impact on their variability through changes in the inter-ocean exchanges. Finally, we discuss the role of meso-scale eddies in transporting water around Australia.

IAPSO (Physical Oceanography)

P04c - P04 Oceanic Boundary Current Systems

IUGG-1476

The role of Western Boundary Currents in climate variability

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On interannual to decadal time scales Western Boundary Currents (WBCs) both respond to and force the atmosphere. WBCs have similar dynamics and thermodynamics, but also important local differences, particularly in relation to the larger scale circulation. WBCs move heat rapidly from the warm tropics to the cooler subtropical regions, in contrast to the local one-dimensional air-sea interaction that prevails over much of the ocean's surface. The heat released in the boundary currents and their extensions is carried further poleward via eddy transport in the atmosphere, influencing midlatitude storm intensity and propagation. The contributions of WBC regions to large-scale air-sea interaction are disproportionate to their geographical area.??The Gulf Stream is responsible for much of the poleward heat transport associated with the Atlantic Meridional Overturning Circulation (AMOC). Predictions of a collapse of the global heat conveyor are often seen as synonymous with a Gulf Stream shutdown. However, recent observations from the RAPID/MOCHA programs have shown that it was the interior ocean responding to changes in wind forcing, not the WBC, that was responsible for the recent minimum in poleward volume (and heat) transport at 26N.?? In addition to altering air-sea fluxes by converging heat and fluxing the excess heat to the atmosphere, WBC regions can store heat locally, thus providing longer term memory to the climate system. A critical component in heat storage is the associated subtropical mode water (STMW). The thick layer of the STMW is shielded from air-sea interaction in the summer, retaining its properties from previous winters and influencing air-sea fluxes in subsequent winters. STMW volume depends on both atmospheric forcing and to the dynamics of the WBC.

IAPSO (Physical Oceanography)

P04c - P04 Oceanic Boundary Current Systems

IUGG-1847

Projected changes in Tasman Sea marine climate, extremes, circulation and eddies in a future climate

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The surface waters of the western Tasman Sea are warming at almost four times the global average rate. Observational and modelling studies suggest that the increased sea surface temperature (SST) is largely due to a spin-up of the South Pacific Gyre (SPG) over recent decades. However, given the complex nature of the western boundary current in the South Pacific the consequences of the spin-up of the SPG in this region are not obvious. The enhancement of the EAC extension does not represent a simple change in the mean flow, but complex pulse and eddy changes, and will to affect higher order statistics such as the frequency of extreme SST events which can have catastrophic impacts on fragile coastal ecosystems. We investigate how the marine climate in the Tasman Sea is projected to change during the 21st century using results from an eddy-resolving ocean circulation model, forced by output from a large-scale climate model simulation, for the Tasman Sea region through the 2060s. We present the projected Tasman Sea marine climate in terms of changes in the (i) mean SST, SST variance, etc, (ii) occurrence of extreme SST events, and (iii) mean circulation and eddy field. The results show that the mean SST is projected to increase in a hotspot located in the Tasman Sea and the SST variance is also predicted to change, with a pattern distinct from that of the mean. The SST extremes in the Tasman Sea are predicted to change significantly due to a combined effect of the change in mean SST and the SST variance. The mean circulation and eddy field in the Tasman Sea are predicted to change considerably by the 2060s. We interpret the projected changes in the mean circulation using changes in the wind field and upper-ocean warming and ultimately the overall spin-up of the SPG.

IAPSO (Physical Oceanography)

P04c - P04 Oceanic Boundary Current Systems

IUGG-2888

Decadal variability of upper ocean heat content in the western boundary currents regions

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Upper ocean heat content (OHC) is at the heart of natural climate variability on interannual-to-decadal time scales, providing climate memory and the source of decadal prediction skill. Regional expressions of the OHC variability such as its generation and propagation are, however, not fully explored. We here present a unique role of the western boundary current (WBC) regions as an origin of OHC anomalies due to (1) temperature anomalies that are associated with density anomalies (density component) and (2) temperature anomalies that are density-compensated with salinity (spiciness component). Analysis of a 150-year, ocean-front-resolving coupled GCM control simulation focusing on the North Pacific basin highlights the latter contribution. Namely, wind-forced, westward-propagating, equivalent barotropic Rossby waves cause meridional shifts of the North Pacific subarctic front. The associated anomalous circulation crosses mean temperature and salinity gradients that are density compensated and thereby generate spiciness anomalies. These anomalies contribute to a large fraction of OHC anomalies and are advected eastward by the mean currents as opposed to the frequently observed westward propagation of sea surface height signals, a feature also ubiquitously observed in climate models and observations. Further global investigation of observed subsurface temperature and salinity analysis shows that density component of OHC variability is large in all the world WBC regions whereas the spiciness component variability is large in subpolar regions where the mean spiciness gradients are particularly large. These results suggest the importance of spiciness and hence an active role of salinity in interannual-to-decadal scale OHC variability.

IAPSO (Physical Oceanography)

P04d - P04 Oceanic Boundary Current Systems

IUGG-2924

Sensitivity of sea surface temperature to wind stress in the Benguela upwelling system

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Most ocean and climate models exhibit a warm sea surface temperature (SST) bias in the upwelling areas. In order to understand the reasons for this warm bias, a forced global ocean (1/2°) model with a 1/10° nest around Africa is used to study the influence of the upwelling dynamics on the SST in the Benguela upwelling system. As the upwelling is driven by the wind stress, it is very important to apply accurate wind forcing to the model. Multiple satellite wind products with high temporal and spatial resolution, mostly based on QuikSCAT, are tested and the influences of wind stress resolution and strength are studied. The amount of coastal as well as the offshore curl-driven upwelling is consistent with theoretical predictions and proportional to the wind stress. The response of the SST not only depends on the strength of the upwelling, but also on variability and horizontal resolution. The temperature differences geostrophically drive the coastal jet and the poleward undercurrent and determine the position of the Angola Benguela Frontal Zone. While upwelling and the corresponding SST signal of the coastal upwelling is improved by the satellite winds, the offshore SST bias depends on more effects.

IAPSO (Physical Oceanography)

P04d - P04 Oceanic Boundary Current Systems

IUGG-4290

Quantifying the long-range exchange of carbon and nutrients between the Canary Upwelling System and the open North Atlantic

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The Canary Current System is one of the four major Eastern Boundary Upwelling Systems (EBUS). These regions are characterized by an intense lateral exchange of mass and tracers that impacts the biogeochemical cycles of the adjacent open oceans. This modeling study aims at quantifying and characterizing the exchange between the Canary EBUS and the North Atlantic Ocean through the use of a new telescopic grid that combines a high eddy-resolving resolution at the African Coast with a full Atlantic Basin perspective. This new setup allows us to study the impact of the cross-shore exchange up to a few thousand kilometers offshore, while still maintaining an accurate representation of the complexity of the coastal mesoscale dynamics. The Regional Oceanic Modeling System (ROMS) is run on this new grid together with a biogeochemical ecosystem module. By tracking Lagrangian trajectories and with the help of sensitivity studies we quantify the total mean off-shore fluxes of carbon and nutrients at different distances from the coast, to establish the magnitude and the range of the influence of the Canary EBUS in the North Atlantic. We characterize the spatial variability of this lateral exchange in terms of sub-regional differences in the Upwelling System, and explore its temporal variability on different time scales. Finally, we discuss regional differences of eddy kinetic energy and diffusivity in the Canary EBUS, in the perspective of understanding and quantifying the mesoscale contribution to the lateral transport.

IAPSO (Physical Oceanography)

P04d - P04 Oceanic Boundary Current Systems

IUGG-5228

Interannual variability in the cross-shore exchange of carbon and nutrients in the California Current System

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Eastern Boundary Upwelling Systems, such as the California Current System (CalCS), are regions of intense biogeochemical transformations and contribute overproportionally to global oceanic primary production. These regions are also exchanging large amounts of carbon and nutrients with their adjacent open seas, influencing the oceanic cycling of these elements far beyond their boundaries. This exchange likely varies strongly from year-to-year, especially in the CalCS, where the El Niño/Southern Oscillation causes major reorganizations in ocean circulation, biogeochemistry, and biology along the entire U.S. West Coast.
We use the Regional Oceanic Modeling System coupled to a biogeochemical/ecological model to quantify and assess the interannual variability of the lateral exchange of carbon and nutrients between the CalCS and the adjacent North Pacific using a novel telescopic setup with substantial grid refinement toward the coastal region. The new setup facilitates an investigation of the underlying processes in a manner hitherto not possible, since it accurately represents the complex coastal mesoscale dynamics but still permits large-scale connectivity between the tropical Pacific, the CalCS, and the North Pacific. Conducting a hindcast simulation covering the time period from 1979 to 2013 and combining a complementary set of Eulerian and Lagrangian analysis methods allows us to quantify the cross-shore connectivity and the associated net offshore transport within sub-regions of the CalCS during periods of distinct tropical El Niño/Southern Oscillation perturbations. We hypothesize that during El Niño periods offshore transport is substantially decreased which might have strong repercussions on open ocean productivity.

IAPSO (Physical Oceanography)

P04d - P04 Oceanic Boundary Current Systems

IUGG-5394

Eddy-wind interaction in the California Current System in a high-resolution regional coupled model

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The California Current System features energetic summertime mesoscale eddies. Satellite observations show that both SST and surface current at oceanic mesoscales significantly influence the wind stress and the Ekman pumping velocity, suggestive of a subsequent dynamical feedback effect on the eddy energetics. The relative importance of effects of mesoscale SST and current is investigated using a series of 7 km SCOAR regional coupled model simulations, in which the effects of mesoscale SST and current are selectively removed in the formulation of wind stress calculation. Results show that the simulated summertime eddy kinetic energy (EKE) is reduced by >30% when the eddy-wind coupling is allowed. This reduction is almost entirely due to the effect of mesoscale current on the stress by increasing the surface drags through a stronger correlation between the mesoscale current and the wind stress. The mesoscale SST and current also influence the Ekman pumping velocity mainly through the linear response of wind stress curls to the crosswind SST gradients and the response of the Ekman pumping to the gradient of surface vorticity. The resultant Ekman velocities to the mesoscale SST and current are of comparable magnitude but with different patterns, implying different feedback mechanisms involved. Overall, the demonstrated importance of the eddy-wind interactions via mesoscale current and SST suggests that the high-resolution ocean and coupled modeling studies over the energetic frontal zone and (sub)mesoscale variability need to evaluate the dynamics and impact of mesoscale air-sea coupling.

IAPSO (Physical Oceanography)

P04d - P04 Oceanic Boundary Current Systems

IUGG-5688

Strengthened western boundary current overrides the effect of warming on lobster larval dispersal & survival

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Climate change is projected to increase ocean temperatures and modify circulation patterns, with potential widespread implications on planktonic larvae of marine organisms. Understanding the impact of climate driven changes in larval dispersal is crucial to predict future species distributions, anticipate ecosystem shifts, and design effective management strategies. This study examines the effect of climate driven changes in circulation and temperature on larval dispersal in a region of rapid ocean warming. We use velocity and temperature fields from an eddy-resolving ocean model to simulate lobster larval dispersal under a contemporary and future (A1B carbon emissions) scenario. Our results show that the effect of changes in circulation and temperature can counter each other: ocean warming is favourable for the survival of lobster larvae, whereas a strengthened western boundary current reduces the total amount of larvae that reach the coast. Changes in circulation have a stronger effect on the connectivity patterns than the ocean warming, so that larval retention reduces by ~10% and the settlement peak shifts poleward by ~270km. Thus ocean circulation appears the dominant effect in climate-change-induced expansion of species ranges.

IAPSO (Physical Oceanography)

P04p - P04 Oceanic Boundary Current Systems

P04p-252

Transports along and across the North-West European shelf edge.

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The project FASTNEt – Fluxes across sloping topography of the North East Atlantic – has made a variety of measurements in three contrasted areas around the edge of the Celtic Sea, Malin-Hebrides shelf and West Shetland shelf. Previous studies have established the existence of flow along the continental slope in these areas, more persistently poleward in more northern sectors. Modelling is under way to diagnose and estimate the contribution of various processes to transports and exchange along and across the slope.

This presentation aims to describe estimates obtained so far; overall transport estimates from drifters and moored current meters; effective "diffusivity" from drifter dispersion and salinity surveys; other estimates of velocity variance contributing to exchange. In addition to transport by the along-slope flow, possible process contributions which may be estimated include internal waves and their Stokes drift, tidal pumping, lenses, eddies and Ekman transports, in a wind-driven surface layer and in a bottom boundary layer.

IAPSO (Physical Oceanography)

P04p - P04 Oceanic Boundary Current Systems

P04p-253

Eddy Vorticity Forcing of the Kuroshio Current off Taiwan in an Ocean General Circulation Model

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The Kuroshio Current (KC) emerges as a western boundary current offshore of the Philippines and flows poleward along the east coast of Taiwan. Non-linear westward propagating mesoscale eddies impinge on the KC to the north of ~17-18°N. To understand the importance and variability of eddy forcing on the mean KC flow, both due to entrant mesoscale eddies and jet instabilities, full vorticity budgets were constructed from an eddy-active Parallel Ocean Program (POP) simulation. Momentum terms were collected at every time step and archived daily from the last five years (2005-2009) of a 60-year nominal 1/10° POP/CICE (sea ice) simulation forced with synoptic interannually varying atmospheric reanalysis fluxes. Budgets were constructed for the upper 76m using only interior ocean grid points for the 5-year mean and seasonal climatologies. In the 5-year mean, horizontal eddy forcing was found to be a dominant term balancing the mean horizontal advection of relative vorticity to the north of the Philippines in the entrance to the Luzon Strait and to the east of northern Taiwan (25°N) where the Kuroshio Current (KC) veers away from Taiwan. Eddy vorticity flux divergences (combined eddy horizontal advection and stretching of relative vorticity) decelerate the KC jet and are strongest in January-February-March (JFM) in the Luzon Strait but are strongest in July-August-September off northeast Taiwan. To the east of Taiwan, the balance of forces is more complex and varies spatially with season. In addition, the horizontal eddy forcing term is a contributing but not a dominant term and the eddy stretching term plays only a very minor role. However, close to the coast at 23°N in JFM, eddy forcing and strong horizontal friction accelerate the KC jet.

IAPSO (Physical Oceanography)

P04p - P04 Oceanic Boundary Current Systems

P04p-254

Dependency of mixed layer heat budget on the horizontal grid resolution of OGCM

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We investigate how the horizontal grid resolution affects the mixed layer heat budget using a global Ocean General Circulation Model (OGCM). The OGCM used in this study is the MOM version 4.1 and has a total of 50 levels along the vertical direction with enhanced resolution near the surface. The CORE version 2 (normal year forcing) data derived from the air-sea flux climatology averaged over 60 years (1948−2007) are used to calculate heat, salt and momentum fluxes with a bulk formula at the sea surface. The sea surface salinity is restored to the climatological monthly mean surface salinity of the Polar Science Center Hydrographic Climatology on a 60-day timescale, to make up the fresh water flux at the sea surface. Two models that have horizontal resolutions of 1° and 1/4 °, respectively, are integrated during 30 years to understand the sensitivity of heat budget to the grid resolution. Model results show that the mixed layer depth in the northwest Pacific get deepened by the increased horizontal heat advection at a higher resolution.

IAPSO (Physical Oceanography)

P04p - P04 Oceanic Boundary Current Systems

P04p-255

Effects of tides on the upwelling-downwelling regimes and cross-shelf exchange in the Arctic shelf Seas.

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The Arctic Ocean circulation is composed of a system of jet currents propagating along the shelf break. Astronomical tides are strong on the Arctic shelf with amplitudes reaching 4.4m in the Hudson Strait, 2-3m in the White Sea. Over bottom topography anomalies, irregularity of velocity and bottom shear stresses induced by periodical tidal motions generates persistent vorticity and vertical motions resulting. This results in ageostrophic circulations or geostrophic upwelling/downwelling of isopycnals. In the simulations with numerical a pan-Arctic ice-ocean NEMO model, which explicitly resolves tides, it is has been found that tides are capable of increasing the intensity of vertical upwellings and downwelling regimes near the shelf break by 50% in comparison with simulations without tides. I extend the semi-geostrophic two dimensional Eliassen -Sawyer (SE) equation , derived for analysis of cross-frontal ageostrophic circulations in 1960s, to take into account the effects of tides. I found that tides induce the cross-frontal circulations only in the presence of tidal shear and baroclinicity. Additional source terms in SE equation have been calculated using amplitudes and phases of tidal velocities from 3d harmonic analysis of NEMO model output. I apply the SE equation for analysis of cross-shelf exchange in several key locations: the Fram Strait, the Laptev Sea, the Barents Sea opening, the Kara Sea shelf break, where the strong water mass transformations due to tides have been detected in the long-term simulations of 3D NEMO ice-ocean model.

IAPSO (Physical Oceanography)

P04p - P04 Oceanic Boundary Current Systems

P04p-256

Simulation of boundary currents around Australia

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Australia is an island continent surrounded by boundary currents which include (clockwise from north) the: Hiri (HiC), East Australian (EAC), Zeehan (ZC), Flinders (FC), Leeuwin (LC) and Holloway (HC) currents. The EAC is the major western boundary current transporting 25 Sv southwards and consists of a large meso-scale eddy field. The LC is a poleward flowing eastern boundary current with a connection to the north of Australia through the HC and to the south via ZC. A high resolution (2-4 km) ROMS (Regional Ocean Modelling System) model, Oz-ROMS, was configured for the entire Australian continental shelf and slope together with the adjacent deep ocean region. Multi-year simulations were performed using atmospheric forcing (wind, pressure, air-sea fluxes) using ECMWF ERA interim data. The open boundary tracers (salinity and temperature) and transport (barotropic and 3D velocity components) were specified using the global Hybrid Coordinate Ocean Model outputs. The tidal forcing was specified using a global inverse barotropic tidal model (Oregon State University TPXO 7.2). The model was able to reproduce the spatial and temporal scales of all the boundary currents, and their connectivity with predicted transports and seasonal and inter-annual variability compared well with observations. The Holloway current system on the northwest shelf was found to be a significant contributor to the Leeuwin current system whose signal extends to south of Tasmania. Sensitivity studies using idealised wind forcing in the northern region indicated that the Asian monsoon has a significant influence in the seasonal signal of the boundary current system along the west and south coasts of Australia.

IAPSO (Physical Oceanography)

P04p - P04 Oceanic Boundary Current Systems

P04p-257

Nutrient input into Australian ocean basins by ocean boundary currents

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Nutrients are necessary for the development and survival of marine organisms; thus, their replenishment is essential for productivity and ultimately for the health of marine ecosystems. Australia extends from tropical to temperate latitudes having both seas that are oligotrophic and eutrophic. Thus, transport of water from different origins by its various boundary currents is expected to induce significant variability in nutrient concentrations. For instance, transport from the South Pacific into Southern Australia through the Tasman Leakage is likely to impact nutrient availability in the Great Australian Bight. Although nutrient concentrations and transport by boundary currents have been quantified, the contribution of each current to the nutrient pool of ocean basins around Australia are yet unknown. Here we use outputs of a state of the art eddy-solving ocean circulation model (Ocean Forecast Australian Model OFAM) coupled with the Whole Ocean Model of Biogeochemistry And Trophic-dynamics (WOMBAT), to quantify nutrient pathways around Australia. Specifically, we estimate the nitrate input at different depths from each current (i.e. East Australian Current, Tasman Leakage, Indonesian Throughflow, Leeuwin, and Antarctic Circumpolar Current) into the different ocean basins around Australia, thereby discerning its main nutrients sources. The model outputs are compared with satellite observations (altimetry and chlorophyll) and data from the Climatology of Australian Regional Seas CARS for validation. A comprehensive picture of nitrate fluxes around Australia is presented, drawing implications on nutrient limiting sources and productivity drivers.

IAPSO (Physical Oceanography)

P05a - P05 Southern Hemispheric Forcing of the MOC and Carbon Cycle in Past, Present, and Future Climate Change

IUGG-0264

Variability and change in the Southern Ocean during the instrumental period: what have we learned, and why does it matter?

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The Southern Ocean exerts a profound influence on global ocean circulation and climate. It connects the major ocean basins, and is the main site globally where dense ocean layers are exposed to the atmosphere and cryosphere, acting to transfer water between density classes. The resulting vigorous overturning circulation leads to important exchanges of heat and carbon between the atmosphere and ocean, with planetary-scale consequences.

Despite its importance, full understanding of the key processes by which the Southern Ocean influences global climate has remained elusive. This is in part due to the unique dynamics and small-scale nature of many of the important mechanisms, which have proven difficult to represent adequately in numerical simulations. Progress is continuously being made, yet depictions of the Southern Ocean in global-scale climate models remain inadequate.

The Southern Ocean has historically been a notable data desert, however the sparse observations collected reveal that it is changing, in some places very rapidly. Changes observed include warming signals, widespread freshening, increases in the intensity of the mesoscale eddy field, and marked regional cryospheric trends. These and other changes have large-scale climatic relevance, but full understanding of their causes and impacts is hampered by lack of appropriate data.

This solicited talk will outline some key aspects of variability and change in the Southern Ocean circulation and climate, and highlight the critical need for improved sustained observations in various different domains. International initiatives to address this will be discussed, and the prospects for better integrating the observational efforts will be outlined.

IAPSO (Physical Oceanography)

P05a - P05 Southern Hemispheric Forcing of the MOC and Carbon Cycle in Past, Present, and Future Climate Change

IUGG-1818

Role of mesoscale eddies in cross-frontal transport of carbon, oxygen and nutrients in the Southern Ocean20

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This study examines the role of processes transporting carbon, oxygen and phosphate across the Polar Front (PF) in the depth interval between the surface and the sill of Drake Passage, which we refer to as the 'PF core'. A preindustrial control simulation of an eddying climate model coupled to a biogeochemical model (CM2.6-miniBLING) is used to investigate the contribution of the various components of the tracer transport across the PF, with a particular focus on mesoscale eddies. Over most of the Southern Ocean, we find that northward Ekman transport is the main driver of tracer transport across the PF core. The eddy transport is generally to the south but smaller in magnitude than the Ekman transport, only partially compensating Ekman transport within the Ekman layer, but dominating the total transport below the Ekman layer. At major topographic features, eddies dominate the total transport over the entire depth of the PF core, so that these regions are found to be gateways for the transport of tracers to the south. Cross-frontal tracer exchange is enhanced at topographic features, but sums to a small net transport due to a near-cancellation of southward and northward transports. Hence, these 'hot spots' of tracer exchange only play a secondary role for the net transport of tracers across the PF core. We estimate the relative contributions of eddy tracer advection and diffusion, and find that eddy-advection is the leading-order component for all three tracers. Finally, the ability of parameterized mesoscale eddies to simulate the contribution of resolved mesoscale eddies to cross-frontal tracer transport is discussed in a coarse-resolution version of the model that uses a parameterization of the mesoscale eddy transport.

IAPSO (Physical Oceanography)

P05a - P05 Southern Hemispheric Forcing of the MOC and Carbon Cycle in Past, Present, and Future Climate Change

IUGG-4279

Observations of a diapycnal shortcut to adiabatic upwelling of Antarctic Circumpolar Deep Water

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In the Southern Ocean, small-scale turbulence causes diapycnal mixing which influences important water mass transformations, in turn impacting la30rge-scale ocean transports such as the Meridional Overturning Circulation (MOC), a key controller of Earth's climate. We present direct observations of mixing over the Antarctic continental slope between water masses that are part of the Southern Ocean MOC. A 12-hour time-series of microstructure turbulence measurements, hydrography and velocity observations off Elephant Island, north of the Antarctic Peninsula, reveals two concurrent bursts of elevated dissipation of $O(10^{-6})$ W kg^{-1},resulting in heat fluxes ~10 times higher than basin-integrated Drake Passage estimates. This occurs across the boundary between adjacent adiabatic upwelling and downwelling overturning cells. Ray tracing and topography show mixing between 300-400 m consistent with the breaking of locally-generated internal tidal waves. Since similar conditions extend to much of the Antarctic continental slope where these water masses outcrop, their transformation may contribute significantly to upwelling.

IAPSO (Physical Oceanography)

P05a - P05 Southern Hemispheric Forcing of the MOC and Carbon Cycle in Past, Present, and Future Climate Change

IUGG-5306

Southern ocean winds and precipitation at the LGM: The influence of state dependency and sea surface changes on CMIP5-PMIP3 results

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Latitudinal shifts in the Southern Ocean westerly wind jet could drive changes in the glacial-interglacial ocean CO2 inventory. However, whilst CMIP5 model results feature consistent future-warming jet shifts, there is considerable disagreement in deglacial-warming jet shifts. One reason for the disagreement is that glacial jet positions are strongly related to the sea ice edge, which varies between the models. We find an equatorwards extension of the s40ea ice edge correlates with a poleward shift in the jet latitude (r = -0.9). The relationship is strongest for the 850 hPa jet diagnostic, but similar results are obtained for the 1000 hPa and surface shear stress (tau) jet positions. A 1 deg difference in the sea ice edge suggests a -0.8 deg shift in the 850 hPa jet. However this applies only to models which have interglacial jets which are at a realistic latitude. If we look at the relationship between Southern Ocean sea surface temperature changes and jet shifts, a cooling of -1 K over the Gersonde et al. (2005) Southern Ocean data locations results in a 3.0 deg poleward shift in the 850hPa jet (r = 0.83; n=5). Initial simulated jet position is also shown to be strongly related to CMIP5-PMIP3 model disagreement. This state dependency explains up to 56% of the glacial-interglacial jet shifts in the Atlantic sector (r = -0.75, N=9, for tau). For the whole of the Southern Ocean region, the variance explained by state dependency is 38% (r = -0.62, N = 9, for tau). Finally, we also find that the glacial-interglacial moisture model-data agreement is strongly dependent on the interglacial jet position. State dependence is thus also important when determining past glacial-interglacial moisture changes over the Southern Ocean.

IAPSO (Physical Oceanography)

P05a - P05 Southern Hemispheric Forcing of the MOC and Carbon Cycle in Past, Present, and Future Climate Change

IUGG-5412

A four-year time series of Antarctic Circumpolar Current transport through Drake Passage from moored observations

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Between 2007 and 2011 flow through Drake Passage was continuously monitored with a line of moored instrumentation with unprecedented horizontal and vertical resolution. Annual mean near-bottom currents were remarkably stable from year to year. In general, mean near-bottom currents are not aligned with sea surface height contours except along the northern boundary where both the Subantarctic Front and near-bottom currents flow parallel to the continental slope. Strong near-bottom flow exists in the central passage where mean speeds are near 10 cm/sec. The mean barotropic reference transport determined from the near-bottom current meter records is 43.8 Sv with an uncertainty near 10 Sv. Summing the mean barotropic transport with the 127.7 Sv of mean baroclinic transport relative to zero at the seafloor (Chidichimo et al. 2014) gives a total eastward transport through Drake Passage of 171.4 Sv. This new estimate is about 20% larger than the canonical value often used as the benchmark for global circulation and climate models. Total transport has a standard deviation of 18.7 Sv. While the baroclinic component contributes 75% to the mean total transport, the barotropic fluctuations contribute to over 80% of the total transport variability. About 50% of the barotropic transport variance is associated with fluctuations with periods between 11 and 70 days. Transport variability can be monitored by across passage pressure differences. Because a sizable fraction of the variability occurs in the north, pressure records at both edges of the passage rather than at the southern end alone are needed.

Chidichimo et al. 2014: Baroclinic Transport Time Series of the ACC Measured in Drake Passage. *J. Phys. Oceanogr.*, ***44***, *1829–1853. doi: http://dx.doi.org/10.1175/JPO-D-13-071.1*

IAPSO (Physical Oceanography)

P05b - P05 Southern Hemispheric Forcing of the MOC and Carbon Cycle in Past, Present, and Future Climate Change

IUGG-0635

The role of Southern Ocean processes in the rise of atmospheric CO2 concentration across the last glacial termination

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The partial pressure of CO2 in the atmosphere rose from about 190 ppm to 260 ppm across the last glacial termination in a series of steps. The most marked of these was a steep 30 ppm rise near the onset of deglaciation. One leading hypothesis for explaining this is enhanced upwelling of deep water in the Southern Ocean, water that had been isolated from surface layers, thereby accumulating carbon from remineralisation of organic matter. Such enhanced upwelling could result from a strengthening and/or poleward shift of the Southern Hemisphere west wind belt. However, any explanation for the 30 ppm increase must also be able to reproduce a simultaneous decrease by 0.3 ‰ and 190 ‰ of atmospheric $\delta^{13}C$ and $\Delta^{14}C$. Furthermore, a more complete explanation should also include how Last Glacial Maximum deep water with high salinity, low $\delta^{13}C$ and low dissolved oxygen concentrations (but not widespread anoxia) was formed.

In order to address these questions we apply the low-order DCESS (Danish Center for Earth System Science) Earth System Model. From a sensitivity study for pre-industrial climate conditions, we conclude that a sharp reduction of the ocean exchange below about 1500 -2000 m depth (a model analogy to isolated deep water) can account for a 30 ppm lower CO2 at the LGM while meeting the constraint of 0.3 ‰ higher atmospheric $\delta^{13}C$ then. Under the guidance of various proxy data records, the model was tuned to a glacial steady-state by now also adjusting model biogeochemical parameters. The results of these experiments help quantify the impact of Southern Ocean processes and of biogeochemical cycling changes on the overall increase of CO2 across the last deglaciation.

IAPSO (Physical Oceanography)

P05b - P05 Southern Hemispheric Forcing of the MOC and Carbon Cycle in Past, Present, and Future Climate Change

IUGG-0644

The role of topographically induced mixing in controlling the glacial carbon budget

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Evidence for the oceanic uptake of atmospheric CO2 during glaciations suggests that there was less production of southern origin deep water but, paradoxically, a larger volume of southern origin water than today. Here we demonstrate, using a theoretical box model, that the inverse relationship between volume and production rate of this water mass can be explained by invoking mixing rates in the deep ocean that are proportional to topographic outcropping area scaled with ocean floor slope. Furthermore, we show that the resulting profile, of a near-linear decrease in mixing intensity away from the bottom, generates a positive feedback on CO2 uptake that can initiate a glacial cycle. The results point to the importance of using topography-dependent mixing when studying the large-scale ocean circulation, especially in the paleo-intercomparison models that have failed to produce the weaker and more voluminous bottom water of the Last Glacial Maximum.

IAPSO (Physical Oceanography)

P05b - P05 Southern Hemispheric Forcing of the MOC and Carbon Cycle in Past, Present, and Future Climate Change

IUGG-1815

Multiple regimes and low-frequency variability in the quasi-adiabatic pole-to-pole circulation

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In the limit of weak interior mixing, the ocean can support a pole-to-pole overturning circulation on isopycnals that outcrop in both the Northern Hemisphere and a high-latitude southern circumpolar channel. This overturning cell participates in a salt feedback, which counteracts the precipitation-induced surface freshening of the northern high latitudes without substantially affecting the southern high-latitude salinity. The net result is an increase in the range of isopycnals shared between the two hemispheres, which strengthens the overturning circulation. However, if precipitation in the Northern Hemisphere sufficiently exceeds that in the Southern Hemisphere, the overturning cell reverses and its southern endpoint moves equatorward of the channel. The reversed overturning circulation is shallower and weaker than its forward counterpart and is maintained diffusively. In a limited range of parameters, multiple equilibria are found for the same forcing configuration. For weak diapycnal diffusivity, the multiple equilibria are unstable to time-dependent oscillations around each of the fixed points. The oscillations around the forward cell peak at a decadal timescale with a mode expressed in the Northern Hemisphere subpolar gyre, modulated by a multicentennial oscillation occupying both hemispheres. These oscillations mediate transitions between the multiple regimes.

IAPSO (Physical Oceanography)

P05b - P05 Southern Hemispheric Forcing of the MOC and Carbon Cycle in Past, Present, and Future Climate Change

IUGG-2271

Interhemispheric asymmetry of warming in an eddy permitting coupled sector model

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Climate model projections and observations show a faster rate of warming in the Northern Hemisphere (NH) than the Southern Hemisphere (SH). The ocean circulation's role in setting the asymmetry is difficult to measure, since the larger land surface in the NH also creates a warming asymmetry. This study employs a sector climate model in which the land-ocean ratio is almost equal between the hemispheres. The sector contains an Antarctic Circumpolar Channel-like flow in the SH and a single basin extending from near pole-to-pole. This geometry ensures that the ocean circulation, especially the circumpolar flow in the Southern Ocean, has a leading contribution to the warming asymmetry. The model uses realistic Atlantic-like bathymetry and coastlines, which is compared with a flat-bottom rectangular box model. Both of these models are simulated at coarse (1º) and eddy-permitting (0.25º) resolution. These configurations are similar in their mean surface climates, however the box model exhibits a strong subpolar gyre in the NH, which is not present in the Atlantic model due to topographic constrictions. In a greenhouse warming scenario, the Atlantic model has a uniform warming signal in the NH high latitudes, while in the box model the NH high latitudes have both warming and cooling regions. At eddy-permitting resolution the warming signal is increased in the NH, due to better resolved boundary currents carrying more heat northwards. These stronger boundary currents enhance sea ice melt in the NH, while the SH sea ice response is insensitive to the change in resolution. When a SH westerly wind shift and intensification is applied, the warming asymmetry is further enhanced, with greater upwelling of cool water in the Southern Ocean and increased warming in the NH.

IAPSO (Physical Oceanography)

P05b - P05 Southern Hemispheric Forcing of the MOC and Carbon Cycle in Past, Present, and Future Climate Change

IUGG-2482

The sensitivity of the ocean carbon cycle to varying Southern Hemisphere Westerly Winds

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Previous studies involving the effect of the Southern Hemispheric Westerlies (SHW) on the climate have generally involved perturbing wind stress fields via latitudinal shifts or changes in intensity. With the SHW shifting south in recent decades, a comprehensive look at the effects this may have on the climate system is required. This study uses the UVic ESCM to test the sensitivity of carbon fluxes between the ocean, atmosphere and terrestrial biosphere to a range of changes in the westerlies. Simulations show a linear relationship between the direction of the shift and changes in atmospheric CO2. A southerly shift of the wind stress field results in a decrease in atmospheric CO2 and an increase in atmospheric 14C, with the opposite being broadly true for northerly shifts. Northerly and southerly shifts result in an intensification of Antarctic Bottom Water formation. Dissolved Inorganic Carbon (DIC) changes in the ocean are further investigated via prognostic tracers tracking both preformed and remineralised DIC. Changes in these tracers suggest changes in circulation and solubility are the primary drivers of carbon exchange between ocean and atmosphere.

IAPSO (Physical Oceanography)

P05c - P05 Southern Hemispheric Forcing of the MOC and Carbon Cycle in Past, Present, and Future Climate Change

IUGG-1325

Contribution of enhanced antarctic bottom water formation to antarctic warm events and millennial-scale atmospheric CO2 increase

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During Marine Isotope Stage 3, the Atlantic Meridional Overturning Circulation (AMOC) weakened significantly on a millennial time-scale leading to Greenland stadials. Ice core records reveal that each Greenland stadial is associated with a warming over Antarctica, so-called Antarctic Isotope Maximum (AIM), and that atmospheric CO_2 *increases with Antarctic temperature during the long Greenland stadials. Here we perform transient simulations spanning the period 50-34 ka B.P. with two Earth System Models (LOVECLIM and the UVic ESCM) to understand the possible link between changes in the AMOC, changes in high latitude Southern Hemispheric climate and evolution of atmospheric* CO_2*. We find that oceanic carbon releases due to the AMOC resumption during stadial/interstadial transitions lead to an atmospheric* CO_2 *increase. However, the atmospheric* CO_2 *increases observed during AIM12 (~47.6 ka B.P.) and AIM8 (~39.8 ka B.P.) occur during periods of weak AMOC (HS5 and HS4 respectively) and could instead be explained by enhanced Antarctic Bottom Water transport. Enhanced Antarctic Bottom Water formation is shown to effectively ventilate the deep Pacific carbon and lead to* CO_2 *outgassing into the atmosphere. In addition, changes in the AMOC alone are not sufficient to explain AIM12 and AIM8. Stronger formation of Antarctic Bottom Water during AIM12 and AIM8 would enhance the southern high latitude warming and lead to a better agreement with high southern latitude paleoproxy records. The robustness of this southern warming response is tested using an eddy-permitting coupled ocean sea-ice model. We show that stronger Antarctic Bottom Water formation contributes to Southern Ocean surface warming by increasing the Southern Ocean meridional heat transport.*

IAPSO (Physical Oceanography)

P05c - P05 Southern Hemispheric Forcing of the MOC and Carbon Cycle in Past, Present, and Future Climate Change

IUGG-2292

Using reconstructions of surface ocean conditions to test mechanisms of ocean carbon uptake during glacial inception

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This work aims to reconstruct surface conditions during Glacial Inception (130 to 60 ka) to better understand the role of Southern and Northern sourced ocean circulation changes in reducing atmospheric CO_2 by 34-45 ppmv below interglacial values. We compiled SST data (117 deep-sea cores), planktonic oxygen isotope data (19 high-latitude cores), and used existing compilations of carbon isotope data to assess changes in physical oceanographic conditions during Glacial Inception. Surface temperature reconstructions show substantial cooling had begun in both the northern and southern high-latitudes between 130 and 100 ka, while low-latitude temperatures had not changed substantially. The largest temperature change during glacial inception is observed in the high-latitude North Atlantic Ocean, as evidenced from oxygen isotope records from polar planktonic foraminifera. While this cooling provides support for a North Hemisphere trigger for deep-ocean circulation changes that led to deep-ocean stratification early in the glaciation, evidence for deep-ocean stratification is not strongly detectable in either the carbon isotope or Nd isotope data from deep-sea cores. This suggests that other physical mechanisms (e.g. sea-ice expansion and surface water stratification) play an early role in reducing atmospheric CO_2 prior to 80-110 ka, with deep-ocean stratification playing a larger role at the onset of Stage 4 (60-70ka). Finally, substantial (~2 ºC) cooling is observed prior to the onset of productivity increases in the Subantarctic Zone and supports assertions that biogeochemical rather than physical changes are responsible for the Subantarctic productivity increases, which likely contributed to changes in atmospheric carbon dioxide after Stage 4.

IAPSO (Physical Oceanography)

P05c - P05 Southern Hemispheric Forcing of the MOC and Carbon Cycle in Past, Present, and Future Climate Change

IUGG-5666

A thermal threshold of the Atlantic meridional overturning circulation that triggers glacial abrupt climate changes

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Abrupt climate changes known as Dansgaard-Oeschger events (DO events) took place frequently in glacial periods. Many geological evidences support the idea that changes of the Atlantic meridional overturning circulation (AMOC) are related to these events, but question on what triggers the AMOC changes remains unsolved. Although the most of studies have regarded freshwater flux from melting ice sheet as a cause of the AMOC changes, we recently identified the existence of the thermal threshold of the AMOC during glacial climate. Here, from the results of climate model simulations about the glacial AMOC, we report that the thermal threshold of the AMOC can be a triggering mechanism of DO events. We investigated the structure of the thermal threshold in glacial climate by conducting ocean general circulation model simulations under various thermal conditions in which degrees of sea surface cooling are systematically changed separately or simultaneously in northern and southern hemispheres. The results suggest that the threshold is located near the condition in which the climate is slightly warmer than the coldest glacial conditions. We also found that the amplitude of AMOC changes in crossing this threshold depends on thermal conditions in northern and southern hemispheres. This amplitude becomes the largest when the southern hemisphere is slightly warmer than the coldest glacial conditions. It is also demonstrated that gradual warming in the southern hemisphere from the colder glacial climate leads to crossing the threshold and can cause very large strengthening of AMOC. Therefore, the thermal threshold could be a triggering mechanism of DO events accompanying the warming of southern hemisphere before their abrupt warming in northern hemisphere.

IAPSO (Physical Oceanography)

P05c - P05 Southern Hemispheric Forcing of the MOC and Carbon Cycle in Past, Present, and Future Climate Change

IUGG-5681

Role of Southern Ocean stratification in glacial atmospheric CO2 reduction

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Atmospheric carbon dioxide (CO_2) concentration during glacial periods is known to be considerably lower than during interglacial periods. However, previous studies using an ocean general circulation model (OGCM) fail to reproduce this. Paleoclimate proxy data of the Last Glacial Maximum indicate high salinity (>37.0 psu) and long water mass residence time (>3,000 years) in the Southern Ocean, suggesting that salinity stratification was enhanced and more carbon was stored there. The reproducibility of salinity and water mass age is considered insufficient in previous OGCMs simulations, which might affect the reproducibility of atmospheric CO_2 concentration. This study investigated the role of enhanced stratification in the Southern Ocean in the variation of atmospheric CO_2 concentration using an OGCM. We found that deep water formation in East Antarctica is required to explain high salinity in the South Atlantic. Contrary to previous estimates, saltier deep Southern Ocean resulted in increased atmospheric CO_2 concentration. This is because Antarctic Bottom Water flow increased and residence time of carbon decreased in the deep Pacific Ocean. On the other hand, weakening of vertical mixing contributed to the increase of the vertical gradient of dissolved inorganic carbon and decrease of atmospheric CO_2 concentration by up to 18 ppmv. However, we show that it is unable to explain the full magnitude of recorded reduction of glacial atmospheric CO_2 concentration by the contribution of the Southern Ocean. Our findings indicate that detailed understanding of the impact of enhanced stratification in the Southern Ocean on the Pacific Ocean might be crucial to understanding the mechanisms behind the variations of the glacial-interglacial ocean carbon cycle.

IAPSO (Physical Oceanography)

P05d - P05 Southern Hemispheric Forcing of the MOC and Carbon Cycle in Past, Present, and Future Climate Change

IUGG-0522

Brazil current transport variability at 34.5°S

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The transport variability of the Brazil Current is analyzed from data collected in the South Atlantic Ocean at 34.5°S with four pressure-equipped inverted echo sounders between May 2009 and December 2012. The instruments were deployed near the western boundary as part of the Southwest Atlantic Meridional Overturning Circulation (SAM) program to continuously monitor the Brazil Current and the Deep Western Boundary Current as they transport components of meridional overturning circulation variability. Daily timeseries of absolute Brazil Current transport are estimated vertically integrating the geostrophic velocities (baroclinic referenced to the bottom plus barotropic) from the sea surface to the neutral density surface at the interface between South Atlantic Central Water and Antarctic Intermediate Water. The time-mean absolute southward Brazil Current transport is -12.2 Sv with a temporal standard deviation of 5.7 Sv. Transport variations of about 30 Sv (from trough to peak) occur over periods as short as 3 weeks. Fluctuations with periods shorter than 100 days account for 70% of the variance. The baroclinic component mostly contributes variability at periods less than 100 days while the barotropic component contributes shorter-term variability at periods less than 30 days. The temporal standard deviation is 5.2 Sv for the baroclinic component and 2.3 Sv for the barotropic component. Thus, the variability of the baroclinic component accounts for the largest fraction of the absolute transport variability (83%). The relationship between the variability of the Brazil Current and the variability of the South Atlantic meridional overturning circulation and its associated meridional heat transport will be looked at.

IAPSO (Physical Oceanography)

P05d - P05 Southern Hemispheric Forcing of the MOC and Carbon Cycle in Past, Present, and Future Climate Change

IUGG-1129

Westerly-controlled salinization of the South Atlantic during glacial terminations

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Recent research emphasizes on processes at the oceanic fronts south of Africa for the modulation of the Atlantic Meridional Overturning Circulation, during present and past instances of climate change. Shifts in the meridional and zonal character of the Southern Hemisphere westerlies seem to control the entrance of salty and warm upper Indian Ocean water into the South Atlantic via the Agulhas leakage. Analysing planktic foraminifera from a sediment record downstream the leakage, we observe that varying inputs of Agulhas leakage are detectable in the South Atlantic gyre, and bore an effect on its upper water composition, on the glacial-interglacial timescale. Salt contained in Agulhas rings spawn from the tip of Africa during glacial terminations seems to determine salinity downstream, notably at thermocline levels. This raises further questions regarding the cause-effect relationships intercurring between changes in the density structure of the South Atlantic and the intensity of the AMOC.

Additionally, our core location allows insights into past displacements of wind fields of the mid-to-high latitudes of the Southern Hemisphere. We present a new XRF record spanning the last 460 kyr that reveals close matching between terrestrial elements deposition in the South Atlantic gyre and the Antarctic dust records. Through comparison of the XRF profiles with dust records from different latitudes of the Southern Hemisphere we discuss the link between glacial-to-interglacial climate change and the position and intensity of the wind fields.

IAPSO (Physical Oceanography)

P05d - P05 Southern Hemispheric Forcing of the MOC and Carbon Cycle in Past, Present, and Future Climate Change

IUGG-1484

Dynamics and impact of large Agulhas Current meanders on the shelf regions of the Southern Agulhas

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Variability in the Mozambique Channel and south of Madagascar is transmitted into the northern Agulhas Current in the form of large deep sea eddies, which can lead to the formation of large cyclonic Agulhas Current meanders (De Ruijter 1999, Tsugawa 2010). These meanders are major drivers of variability in the Agulhas Current. They impact on the coastal and shelf circulation and are thought to play an important role in the downstream variability of the Agulhas Current and the subsequent leakage of warm and salty Agulhas Current water into the Atlantic ocean. Analyses of ocean current measurements from a moored array as well as Lagrangian isopycnal floats are combined to satellite observations of sea surface height and temperature to better quantify the influence of large meanders on the shelf regions of the southern Agulhas. Satellite observations show that large meanders in the Agulhas Current are associated with strong and persistent current anomalies at the shelf edge. In-situ observations show that large Agulhas Current meanders cause significant mixing over the shelf regions. The dynamics, evolution and cross-shelf mixing associated with Agulhas Current meanders is influenced by the topography as well as the surrounding vorticity field.

IAPSO (Physical Oceanography)

P05d - P05 Southern Hemispheric Forcing of the MOC and Carbon Cycle in Past, Present, and Future Climate Change

IUGG-3212

A twenty-year time series of Agulhas Current transport from subsurface moorings and satellite altimeter data

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The Agulhas Current is strongly linked to Indian Ocean overturning and heat transport, which likely influence climate in Indian Ocean rim countries through basin-scale sea surface temperature variability. The volume transport of the Agulhas Current was measured over a three year period by a linear array of current meter moorings and current- and pressure-recording inverted echo sounders (CPIES) deployed at 34 S. CPIES extended the array farther offshore in order to capture, for the first time, the full Agulhas Current during meander events. We develop a new algorithm that delineates the western boundary jet transport at each time step, T, to find a mean transport of -84 ± 24 Sv with a standard error of 2 Sv. A more traditional estimate, based on net transport integrated to a fixed distance offshore, T_{box}, gives a mean of -77 ± 32 Sv. This is 10 Sv greater than the equivalent transport at 32 S and corresponds to a latitudinal increase equal to that predicted by Sverdrup dynamics. The variability of T and T_{box} show important differences during meander events and at time scales longer than seasonal. We build a 20-year, satellite-based, proxy transport time series using a linear regression model between in situ transport and sea level anomaly along Jason ground track #96. The proxy has good skill (r>0.8) and reveals an annual cycle of amplitude 10 Sv, with strongest transports in austral summer and weak transports during winter. This annual cycle is opposite to that estimated for Agulhas leakage, using sea level anomaly gradients across the Agulhas Current and Return Current, and may point to inertial control of Agulhas leakage variability.

IAPSO (Physical Oceanography)

P05d - P05 Southern Hemispheric Forcing of the MOC and Carbon Cycle in Past, Present, and Future Climate Change

IUGG-4656

Southern Hemisphere tropical-subtropical oceanic teleconnection: Modulation of Agulhas leakage SST variability by tropical South Indian Ocean variability associated with ENSO

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The Agulhas leakage transports warm and saline water from the Indian Ocean into the South Atlantic. Ocean-atmosphere interactions and the Agulhas leakage support sea surface temperature (SST) in the Agulhas leakage area, which may in turn affect regional climate variability. Observations and a high resolution, coupled Community Climate System Model (CCSM3.5) run show a link between the interannual variability of Agulhas leakage SST with the El Nino- Southern Oscillation (ENSO). ENSO associated anomalous wind stress curl over the eastern tropical South Indian Ocean excites westward propagating Rossby waves that then induces southwestward propagating anomalies through the Mozambique channel and along the eastern coast of Africa. It takes approximately 2 years for this signal to reach the southern tip of South Africa and enter the South Atlantic. In a low resolution CCSM3.5 counterpart run, a similar ENSO cycle and Rossby wave adjustment is detected. However, the signal does not propagate all the way along the coast of Africa and influence the Agulhas leakage SST. Therefore, we conclude that eddy-resolving, coupled climate models are needed to resolve tropical-subtropical oceanic teleconnection between the South Indian Ocean and Agulhas leakage SST.

IAPSO (Physical Oceanography)

P05e - P05 Southern Hemispheric Forcing of the MOC and Carbon Cycle in Past, Present, and Future Climate Change

IUGG-0849

Southern ocean wind shifts and their affect on Agulhas Leakage and the Atlantic Merdional overturning circulation

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The leakage of Agulhas Current water into the South Atlantic is now thought to be a major player in global climate change. Its volume is linked to the strength and position of southern westerlies. Past changes in the westerly winds over the southern ocean have been noted on glacial-interglacial timescales, in response to both Northern Hemispheric conditions and changes in Antarctic ice volume. The Pliocene to Pleistocene transition, associated cooling and Northern Hemisphere glaciation may have related to changes in Antarctica and the Southern Ocean, affecting both the position and strength of southern westerly winds. A northward shift in the westerlies, observed in past records of glaciation events, is thought to restrict the flow of warm, salty water from the Indian Ocean into the Atlantic, potentially impacting the Atlantic Meridional Overturning Circulation (AMOC) and North Atlantic SSTs. A weakening of the Agulhas Leakage therefore could transmit changes in the southern hemisphere to the northern hemisphere. Much of the Agulhas leakage is carried in small eddies rotating off the main flow south of Cape Horn. High ocean model resolution (< 1/2°) is therefore required to realistically simulate the leakage's response to the overlying wind field. Here we run a series of global high-resolution ocean model (1/6°) experiments using the MITgcm to test the effect of a shift in the southern hemisphere westerlies on the Agulhas Leakage, during a past climate (Pliocene) warmer than today. A prescribed perturbation of the winds near South Africa shows a significant increase in Agulhas eddies into the Atlantic. Following this, longer simulations reflecting past shifts in the wind field quantify changes in North Atlantic Deep Water formation and the overall response of the AMOC.

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P05e - P05 Southern Hemispheric Forcing of the MOC and Carbon Cycle in Past, Present, and Future Climate Change

IUGG-2130

Turning the hot tap: Large-scale drivers of Aguhas leakage structure and variability

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The Agulhas leakage, the collective term for the warm and saline waters emanating from the Agulhas retroflection and persisting into the South Atlantic Ocean, forms the key thermohaline link between the Indian Ocean and the upper branch of the Atlantic Meridional Overturning Circulation (AMOC). Buoyancy flux changes associated with this 'warm-water' route have been shown to affect the variability of the AMOC and have been implicated in determining the timing of glacial terminations. However, the highly turbulent and sporadic nature of the leakage, which partially occurs through the occlusion of rings, makes in situ monitoring extremely challenging and it is common to employ numerical ocean models to investigate the region.

Here, a suite of such models, at varying resolution, are used to asses the response of the Agulhas system to large-scale forcing associated with modulation of the Indian Ocean wind field and the closing of the Indonesian Throughflow. Idealised wind-field anomalies, applied to the both the trade and westerly winds, are designed to mirror a range of pseudo-palaeo conditions. Leakage responses are assessed in the context of changing Agulhas Current strength, variable retroflection position and migration of the latitude of the Sub-tropical Front. New insight is also given into the structure of the Agulhas leakage via the isolation of eddy and non-eddy flux components in a multi-decadal hindcast simulation. Eddy and non-eddy field responses to prevailing wind field signals, and the phase of the Southern Annular Mode are also considered.

IAPSO (Physical Oceanography)

P05e - P05 Southern Hemispheric Forcing of the MOC and Carbon Cycle in Past, Present, and Future Climate Change

IUGG-2362

Decadal variability and centennial trend in Agulhas leakage impact

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The Agulhas region around the southern tip of Africa is a region where the return flow of surface and intermediate waters from the Indian Ocean flows towards the Atlantic. This 'Agulhas leakage' shapes and modulates the global overturning circulation through advection of heat and salt. However, due to strong nonlinear and eddy-mean flow interactions the Agulhas region is not a prime location for ocean observations. Long-term observations of Agulhas leakage do not exist. Using a series of ocean and coupled climate models, all simulating the Agulhas circulation at sufficient resolution, we derive the imprint of Agulhas leakage on sea surface temperature (SST) distribution. Applying the regression to historic SST data subsequently allows us to infer a 144-year long timeseries of Agulhas leakage. Its decadal variability and long-term evolution is related to cause and impact, in particular to North Atlantic hydrography, underpinning the impact of Agulhas leakage on the global overturning circulation.

IAPSO (Physical Oceanography)

P05e - P05 Southern Hemispheric Forcing of the MOC and Carbon Cycle in Past, Present, and Future Climate Change

IUGG-3713

The meridional overturning circulation in the south Atlantic from observations and numerical models

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Data from a zonal XBT transect in the South Atlantic have been used to estimate the meridional overturning circulation (MOC) and the meridional heat transport (MHT) at 34S, which provides the first time series of the MOC/MHT estimates since 2002. Results from AX18 have revealed various features of the MOC/MHT variability on seasonal-to-interannual timescales and regional contributions. Those results have been used to evaluate model performance in simulating MOC processes. Comparison of the MOC from XBT and two GFDL coupled models, with and without data assimilation, has demonstrated the importance of the assimilation of Argo float measurements in improving data-assimilating model performance in representing the MOC processes. Results from comparison of the MOC estimates from XBT and models have promoted further investigation due to models' inability to capture the observed seasonal variations. Observational estimates suggest that the geostrophic transport plays an equal role to the Ekman transport in the MOC seasonal variations at 34S, whereas in the models the Ekman transport dominates. Further examination found that the seasonality of the geostrophic transport from observations is largely controlled by the seasonal density variations at the western boundary, but in the models the eastern boundary controls. The observed density seasonality at the western boundary is linked to the intensity of the Malvinas Current, which is poorly reproduced in the models. The weak seasonal cycle in the model geostrophic transport can be attributed to excessively strong baroclinicity below the mixed-layer, whereas the observations show a strong vertical coherence in the velocity.

IAPSO (Physical Oceanography)

P05e - P05 Southern Hemispheric Forcing of the MOC and Carbon Cycle in Past, Present, and Future Climate Change

IUGG-5444

Lagrangian approach to estimate Agulhas leakage in coupled climate models

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The Meridional overturning circulation (MOC) plays a crucial role in the climate system by transporting heat northward in the Atlantic basin. Feeding warm and salty water from the Indian into the Atlantic ocean, Agulhas leakage and its associated buoyancy fluxes may affect the stability of the meridional overturning circulation. Eddy-resolving, coupled model simulations are necessary to properly capture the Agulhas leakage and ocean-atmosphere feedbacks that are important to the climate system. Lagrangian particle tracking approach has been widely applied to estimate Agulhas leakage in high resolution, stand-alone ocean models that have daily-to-pentad current velocity fields. Due to limited storage space, coupled model outputs are conventionally archived monthly, which is arguably not ideal for Lagrangian particle tracking. Here, we devise a strategy that uses a Lagrangian particle-tracking model (Connectivity Modeling System) to quantify Agulhas leakage in a ten-year long, coupled, high resolution (1/10º) Community Climate System Model (CCSM3.5) run that outputs velocity fields on five-daily and monthly frequency. With our proposed strategy, we find that the Agulhas leakage variability using monthly outputs approaches the that using five-daily outputs, resulting in a correlation of 0.70 (0.89 after 31days running mean). This strategy provides a way to use monthly velocity fields from coupled models to obtain decent Agulhas leakage variability, which allows us to investigate the true sensitivity of the Agulhas leakage to climate modes in the presence of air-sea feedback.

IAPSO (Physical Oceanography)

P05p - P05 Southern Hemispheric Forcing of the MOC and Carbon Cycle in Past, Present, and Future Climate Change

P05p-224

The South Atlantic meridional overturning circulation and the simulation of its variability and change during the period 1948-2007

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We use numerical simulations performed with a global ocean-ice climate model (MOM5) configured at three different resolutions – from eddy permitted to very coarse resolution- to analyze the impact of model resolution on the time-mean and time-variability of the Meridional Overturning Circulation in the South Atlantic (SAMOC). The models were forced by the Coordinated Ocean-ice Reference Experiments version 2 (CORE-II) data sets for the 1948-2007 period. When compared with available observations, the largest surface biases were identified in the coarser resolution models and were mainly present in regions of high eddy fluxes activity. Surface and mode waters were shown to have a primary role in the recent strengthening of the SAMOC. Our results further suggest that, while the Meridional Heat transport (MHT) strengthening is mainly linked to an increase in heat content by means of Agulhas leakage, the positive trend in the SAMOC is also connected to the weakening of the poleward transport of the warm and salty western boundary current. Regardless of the strong correlation between MHT and SAMOC, trends can not be solely explained through local phenomena but are instead the result of processes occurring in different regions.

IAPSO (Physical Oceanography)

P06a - P06 The Southern Ocean: where Ocean, Ice and Atmosphere Meet

IUGG-1859

Sources and fate of freshwater in the ocean west of the Antarctic Peninsula

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The Antarctic Peninsula is warming more rapidly than any other location in the Southern Hemisphere, with air temperatures increasing by nearly 3 degrees Celsius since 1950. The consequences of this, such as ocean warming and ice loss, are still not fully understood. Further, there is evidence that ocean forcing in the Bellingshausen Sea, west of the Antarctic Peninsula, is contributing to the loss of glacial ice.

Salinity is the dominant control on density near the freezing point of sea water, hence freshwater plays a key role in the dynamics of the Bellingshausen Sea. However, the different components of the freshwater balance - glacial ice, sea ice, and precipitation - are affected by warming in complex ways. Oxygen isotope data exists from which information on the freshwater balance can be obtained, both in a contemporary context (from research cruises and time series sites) and on longer timescales from sediment records. However, interpretation is made difficult by the general sparsity of such data.

To better understand the freshwater balance of the Bellingshausen Sea, a high-resolution model of the region has been developed, using MITgcm to represent ocean, sea ice, and ice shelves. Experiments have been conducted that track the advection, mixing and fate of freshwater from different sources, and demonstrate the differing spatial and temporal scales of their impacts on ocean structure. Results will be used to investigate the causes and consequences of warming and freshwater change west of the Antarctic Peninsula.

IAPSO (Physical Oceanography)

P06a - P06 The Southern Ocean: where Ocean, Ice and Atmosphere Meet

IUGG-2185

Seasonal variability of the ocean mixed layer under sea-ice in the Southern Ocean

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The ocean mixed layer acts as a bridge between the atmosphere and the ocean interior. It governs the exchange rates between the atmosphere and ocean, its capacity to store heat and carbon as well as the availability of light and nutrients to support the growth of phytoplankton. Furthermore, in the Southern Ocean basins, the interaction between the ocean mixed-layer and the sea-ice plays a key role for sea-ice dynamics and therefore for the climate as a whole. However, the structure and characteristics of the mixed layer, as well as the processes responsible for its evolution, are poorly understood in Antarctic regions due to the lack of in-situ observations and measurements.

In this study, we combine a range of distinct sources of observation to overcome this major lack in our understanding of the polar regions. Since 2004, the instrumentation of southern elephant seals with satellite-linked Conductivity-Temperature-Depth sensors has offered unique temporal and spatial coverage of the Southern Ocean. This dataset has dramatically increased the number of hydrographic data below the Antarctic sea ice and on the Antarctic continental slope and shelf regions, which are outside the conventional areas of Argo autonomous floats and ship-based studies.

Using this database along with ship-based observations and Argo profiles, we are able to resolve for the first time, the seasonal cycle of the mixed-layer characteristics under sea-ice over large-scales. We discuss first order processes controlling their seasonal evolution, and implications for our understanding of sea-ice production and interactions between mixed-layer and underlying circumpolar deep water. We quantify the impact of ocean-ice fluxes versus Ekman transport in driving mixed layer buoyancy budget.

IAPSO (Physical Oceanography)

P06a - P06 The Southern Ocean: where Ocean, Ice and Atmosphere Meet

IUGG-2463

A model-based climatology of antarctic icebergs melt over the Southern Ocean

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The Antarctic ice sheet releases about 2700 Gt of freshwater per year into the Southern Ocean. Almost 50% ofthat freshwater is spread northwards in the form of icebergs which drift is controlled by ocean currents, winds and sea ice. The freshwater flux due to icebergs melt may have a significant impact on Southern Ocean stratificationin conjunction with other freshwater forcing contributions (evaporation, precipitation, sea-ice brine rejection). Antarctic icebergs may therefore affect sea ice production and water masses formation, eventually influencing ocean circulation and climate. Still, because satellite observations of icebergs are limited to large icebergs and by the presence of sea ice, the climatology of antarctic iceberg melt is still largely unknown. Incidentally, this is why, with a few notable exceptions, the freshwater flux due to antarctic icebergs melt is generally crudely represented in ocean general circulation models.

Here, we will describe an estimation of the climatology of antarctic icebergs melt obtained on the basis of a ocean/sea-ice/icebergs model forced with recent estimates of antarctic icebergs calving. Based on glaciological studies, we build a spatially distributed ice sheet-ocean interaction scenario which provides the basal melting and the calving rates of the ice sheet. This forcing is applied to a global 1/4° NEMO model configuration coupled to an iceberg model. Several improvements of the iceberg model as compared to previous studies allow, amongst others, to reproduce some observed icebergs trajectories in the Wedell and the Ross Seas. Our results may provide an alternate freshwater forcing protocol for ocean general circulation models that are not coupled to an icebergs model.

IAPSO (Physical Oceanography)

P06a - P06 The Southern Ocean: where Ocean, Ice and Atmosphere Meet

IUGG-4235

Changes in southern subtropical ocean ventilation timescales

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Water mass ages calculated from transient tracer data taken more than a decade apart are compared with the objective of inferring changes in southern subtropical ocean ventilation. Transient tracer ages are corrected using model-derived uncertainties and biases. We use a suite of eddy-resolving ocean tracer simulations to quantify effects on ages of the spatial dependence of internal ocean tracer variability due to stirring from eddies and due to the biases from non-stationarity of the atmospheric transient when there is mixing. These add to tracer age uncertainties and biases, which are largest in frontal regions ? near western boundary currents, along the boundary between the ventilated and unventilated portions of the subtropical gyres, and eastern boundary upwelling regions. Observational and model pCFC-11 ages agree quite well, with the eddy-resolving model adding detail. The CFC ages show that the thermocline is a barrier to interior ocean exchange with the atmosphere on timescales of 40 years, the measureable CFC transient with notable exceptions of the high latitude deep and bottom water source regions. By taking into account model-derived uncertainties and biases, we are able to compare ocean data along sections, and show where changes in observed pCFC ages are significant. We infer that the rate of ocean ventilation increased in the southern hemisphere subtropical gyres between WOCE of the mid-1990s and the first Clivar decade of the 2000s. Between WOCE and the second Clivar decade of the 2010s, there is no significant trend ? except for South Atlantic where the increase is weaker than for the first Clivar decade. Observed age/ventilation changes are linked to a combination of natural cycles and climate change and there is regional variability.

IAPSO (Physical Oceanography)

P06a - P06 The Southern Ocean: where Ocean, Ice and Atmosphere Meet

IUGG-4679

EM-Apex floats capture mixing processes and water mass transitions along the northern Antarctic Peninsula

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The outcropping and transformation of water masses over the Antarctic continental slope are critical to Southern Ocean overturning. The continental slope near Elephant Island, off the northern tip of the Antarctic Peninsula, is a site where strong diapycnal mixing occurs within adiabatically upwelling waters. Two EM-Apex floats deployed in November 2011 and January 2015 profile along both the continental slope near Elephant Island and within Hesperides Trough, a deep trench crossing the ridge that separates Drake Passage and the Weddell Sea. Temperature, salinity and horizontal velocity measurements are taken as the floats drift, profiling between fixed depths. Along the continental slope close to Elephant Island, we observe isopycnic heave associated with strong temperature and salinity anomalies at inertial and tidal frequencies. Elevated diapycnal diffusivity coincides with the deepest extent of isopycnic heave and is associated with the downward propagation of energy. Further west, strong upwelling within Circumpolar Deep Waters and subducting winter water are captured. The floats pass through several water masses ranging from Circumpolar Deep Waters on the continental slope to Weddell Sea Deep Water within Hesperides Trough. It is suggested that Hesperides Trough may act as a conduit for Weddell Sea Deep Water, possibly allowing it to enter Drake Passage and influence water mass transformations on the slope near Elephant Island.

IAPSO (Physical Oceanography)

P06a - P06 The Southern Ocean: where Ocean, Ice and Atmosphere Meet

IUGG-5386

A 17-month measurement of the Antarctic Slope current

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The Antarctic Slope Current (ASC) flows westward along the continental slope, transporting cold dense waters from the shelf into the deep ocean, and regulating the import of warm saline oceanic waters back to the shelf. Despite its significance, little is known about the structure and dynamics of the ASC, as the Antarctic continental margin is often covered by ice and observations are very limited. Here we present direct velocity observations from a 2-year moored array across the continental slope between the 1000 and the 4200 m isobaths, in the southeastern Indian Ocean. We estimate the westward time-mean transport of the ASC to be approximately 22 Sv. Fluctuations in the transport typically exceed the mean by a factor of 2, and are predominantly barotropic, hence invisible to traditional geostrophic methods. Mechanisms responsible for the variability are explored and their contribution to the barotropic and baroclinic part of the flow discussed.

IAPSO (Physical Oceanography)

P06b - P06 The Southern Ocean: where Ocean, Ice and Atmosphere Meet

IUGG-3196

Internal waves and turbulent mixing on the amundsen sea shelf: West Antarctica

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Recent results on turbulent dissipation and mixing in the Southern Ocean reveals that topographically rough regions are likely the prominent location for the generation and breaking of internal waves with associated diapycnal di ffusivities K _{rho} of O(10^{-4}-10^{-3}) m^2 s^{-1}. However along the Amundsen Coast where the observed thinning and acceleration of glaciers produces the majority of Antarctica's contribution to sea-level rise, little is known about the level of mixing. Here, we describe and characterize the intensity and spatial distribution of the rates of turbulent kinetic energy dissipation and K_{rho} on the Amundsen Sea Shelf, and study the relationship between the observed turbulence and the internal wave field in this region. Estimates of K _{rho} were obtained using finescale parametrizations. Higher mixing rates up to 5.4 x10^{-3} m^2 s^{-1} are seen in the depth between 200 and 600 m. The highest mixing rate exceeding 10^{-2} m^2 s^{-1} is also seen in the the southern end of the Pine Island Glacier front. A latitudinal variability in K_{rho} near the bottom is reported, with K increases near 74 deg 28 S, the critical latitude for semidiurnal M2 tides. We show that the critical latitude coincides with near-critical topography on the Amundsen Shelf and this condition favors the generation of internal waves of M2 frequency. Analysis of current time series from the moored instruments reveals a thickening of the frictional bottom boundary layer near the critical latitude. Although a weak semidiurnal tidal dynamics was observed at the continental shelf, its combination with the critical latitude effects lead to enhanced mixing that potentially a affects the heat budget and the circulation of the Circumpolar Deep Water below the ice shelves.

IAPSO (Physical Oceanography)

P06b - P06 The Southern Ocean: where Ocean, Ice and Atmosphere Meet

IUGG-3254

Identifying meltwater pathways in the Amundsen Sea

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The Amundsen Sea is the location of some of the fastest melting ice shelves, linked to warm ocean waters causing basal melt. This meltwater production has been hypothesised to be the root of the freshening observed in the Ross Sea over the past 30 years. It is important to be able to trace the pathways of the meltwater in order to identify the regions that are being affected the most by the increased input of this water mass.

We use water mass characteristics derived from 105 CTD casts during the Ocean2ice cruise (January to March 2014) to calculate meltwater fractions. Fractions immediately in front of Pine Island Glacier (PIG) are as high as 2.4 %. Away from the ice front, the meltwater maximum follows the 1027.7 kg m^{-3}potential density level sandwiched between Winter Water (WW) above and Circumpolar Deep Water (CDW) below. The ice shelf meltwater maximum is coincident with increased turbidity close to the front of the ice shelf.

Traditional methods using temperature, salinity and dissolved oxygen concentrations to calculate meltwater fractions become less reliable with distance from the ice shelf front. Processes such as atmospheric interaction and biological activity affect these properties. We analysed the effect of these processes on the reliability of meltwater fraction results across the region using a bulk mixed layer model based on the one-dimensional Price-Weller-Pinkel model (1986). The model includes sea ice, dissolved oxygen concentrations, air-sea gas exchange and a simple biological model.

Independent estimates of meltwater fractions are derived from noble gas concentration measurements from water samples collected during the same cruise. Oxygen isotope measurements in water are used to identify the fraction of sea ice melt in the freshwater budget.

IAPSO (Physical Oceanography)

P06b - P06 The Southern Ocean: where Ocean, Ice and Atmosphere Meet

IUGG-3560

Mixing at the fringes of a rapidly melting Antarctic ice shelf

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The processes regulating the physical exchanges across the front of the Pine Island Ice Shelf (one of the most rapidly melting Antarctic ice shelves) in the Amundsen Sea are investigated through the analysis of an extensive set of full-depth hydrographic, velocity and microstructure measurements, obtained as part of the ISTAR expedition in February 2014. The outflows of Ice Cavity Water (ICW), which contains elevated concentrations of meltwater from the ice shelf, are observed to be subject to very intense small-scale turbulent mixing within 5 kilometres of the ice front. The rates of turbulent kinetic energy dissipation and diapycnal mixing in the outflows are enhanced by up to four orders of magnitude relative to those in surrounding waters, which are characterised by turbulence levels typical of the open ocean. An investigation of the causes of the intensified turbulence reveals that it is sustained by centrifugal instability of the ICW outflows. The instability drives a secondary ageostrophic circulation that induces rapid lateral mixing between ICW and pycnocline waters offshore (at depths of 100 - 250 m), thereby preventing the ICW outflows from reaching the surface mixed layer. The significance of this process for the fate of meltwater outflows from other Antarctic ice shelves will be discussed.

IAPSO (Physical Oceanography)

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IUGG-3824

Transport pathways of Circumpolar Deep Water on the Amundsen continental shelf

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Oceanic heat transport has been identified as a critical control on the mass balance of the West Antarctic Ice Sheet. Its outlet glaciers in the Amundsen Sea show the highest mass loss in Antarctica and this has been traced to the thinning of the ice shelves. Circumpolar Deep Water (CDW) with temperatures several degrees above the freezing point is commonly observed under these ice shelves and linked to their high melt rates.

Transport of CDW onto and on the shelf occurs through a series of troughs from the shelf break to deep basins in front of the ice shelves. It has generally been assumed that each of the troughs separately links the shelf break to the ice shelves. There is, however, evidence that the warm inflow into the Getz-Dotson trough already contains a melt water signature that has likely been acquired further east on the shelf. This would constitute an additional transport pathway for glacial melt water in addition to westward surface transport in the coastal current. It implies that northward transport of modified CDW at the western flank of the troughs does not actually leave the shelf, but follows the bathymetry of the shallower banks separating them and preconditions the CDW inflow in troughs located further west.

We will use data from a shelf break mooring close in the eastern Getz-Dotson trough to examine this hypothesis. Comparing water masses here to observations across the shelf break and from the central trough will allow us to identify the origin of the water flowing onto the shelf at this location. Analysing the co-variability between the shelf break mooring and a mooring site located in the inflow mid-shelf will allow us to identify the fate of the shelf break flow and possible additional transport pathways located further south on the shelf.

IAPSO (Physical Oceanography)

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IUGG-4724

Variability of the Antarctic Coastal Current (AACC) and its causes in the Amundsen Sea

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The Antarctic Coastal Current (AACC) or east wind drift flows westward around Antarctica. Coastal current is mainly barotropic component by the wind driven Ekman transport (Sverdrup 1953) and baroclinic component is generated by a density gradient between Antarctic Surface Water and Shelf Water (Fahrbach et al., 1992). Ismael and Fahrbach (2009) show the contribution of the mechanisms driving the coastal and its seasonality in the Weddell Sea. Therefore, the present study attempts to quantify the contribution of the mechanisms driving the AACC and its seasonality and decadal variation of coastal current in the Amundsen Sea.
We evaluated variability of coastal current and its driving forcing in the Amundsen Sea using observed and calculated ocean current. The observation data was collected here was obtained from KOPRI mooring stations in the Dotson Trough (DT), which is one of the deep troughs in the Amundsen shelf. The westward current shows in front of the Dotson ice shelf (DIS) and it strong seasonal variation. The seasonality of the AACC was well matched with the seasonality of the pressure gradient in the DT.
We calculated the surface ocean currents to understand decadal time scale variation of the AACC, which was the difficult to observe below sea-ice using the satellite data. We used a simplified linear formula to understand the relationship between the sea ice motion and sea surface wind as Kimura (2004). This previous study was evaluated relationship using sea ice properties about speed reduction factor and turning angle in the Southern Ocean. Although the estimated coastal current speed was smaller than observation, decadal time scale of the westward flow of the coastal current was increased.

IAPSO (Physical Oceanography)

P06b - P06 The Southern Ocean: where Ocean, Ice and Atmosphere Meet

IUGG-4979

Sustained ocean cooling observed in front of Pine Island Glacier in 2011-13

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During the iSTAR research cruise to Pine Island Bay in the Amundsen Sea in early 2014, two moorings were recovered from in front of Pine Island Glacier (PIG), one of which was deployed by the NB Palmer cruise 09-01. Together, these provided an unprecedented five-year time series of temperature, salinity and current velocity. These data reveal considerable seasonal and interannual variability in deep ocean temperatures, of sufficient magnitude to make a substantial impact on the melt rate of PIG. In particular, the period August 2011 to August 2013 was anomalously cold; comparison with ship-based summertime observations suggest the heat content at the glacier front in December 2012 was the coldest in the observational record. Similar cold anomalies are observed at other moorings within Pine Island Bay, and current observations suggest a reduction in the inflow of warm Circumpolar Deep Water to the glacier, as well as a reduction in the outflow of melt water and in the concentration of ice cavity water The broad spectrum of variability observed by the mooring network suggest that a combination of remote and local processes is at work. At the seasonal time scales, local weakening in wind forcing is correlated with cooling, consistent with a weakening of the circulation bringing warm waters to Pine Island Glacier. At interannual time scales, a combination of weakened inflow at the continental shelf edge and regional processes could be at play, but the record is too short to draw statistically significant conclusions.

IAPSO (Physical Oceanography)

P06c - P06 The Southern Ocean: where Ocean, Ice and Atmosphere Meet

IUGG-3488

Estimating gas saturation and recharge temperature for the abyssal ocean

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The noble gas concentrations in waters that fill the deep ocean primarily reflect 3 physical processes that take place at the air-sea interface. Wind and waves force air bubbles into solution and this increases the saturation of all the noble gases, especially He and Ne. In contrast, seasonal cooling decreases the saturation; particularly for Kr and Xe. Finally, diffusive gas exchange will tend to restore solubility equilibrium between the ocean and atmosphere. These 3 processes can be accounted for by using an over-constrained fit to the measured concentrations of He, Ne, Ar, Kr and Xe, which are chemically and biologically inert. The method is commonly referred to as the noble gas paleothermometer (NGPT) and has been used to estimate paleo-temperature recorded in deep aquifers. Here we will adapt the method to account for glacial meltwater, which also contributes to the noble gas saturation anomalies.

The modified NGPT provides estimates of the surface ocean (or recharge) temperature and salinity prior to the onset of seasonal cooling, the air content injected by bubbles, and the saturation of deep water before it is subducted. A deficit in equilibrium gas saturation reflects incomplete ocean-atmosphere gas exchange, which is a consequence of sea ice cover and the rate of convection.

We test this modified NGPT using data from the Weddell Sea, collected during the ANDREX project. In this data set, the mean saturation anomaly below 4000 m is +3% for Ne and -3 and -4% for Kr and Xe, demonstrating the unique physical response of each noble gas, based on molecular weight. Eventually, the modified NGPT may provide further insight into the role of convection and sea ice in decoupling the deep ocean and the atmospheric during the glacial cycles.

IAPSO (Physical Oceanography)

P06c - P06 The Southern Ocean: where Ocean, Ice and Atmosphere Meet

IUGG-3681

Are atmospheric surface temperatures in the Southern Oceans affected by ocean tides?

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Global ocean models can generally be divided into ocean general circulation and tidal models. Numerical simulations of the ocean's general, i.e., thermohaline, wind and pressure driven, circulation most commonly neglect tidal dynamics due to their strict periodicity and high frequencies. Nevertheless, residual tidal currents have the potential to affect the ocean's mean velocity field and sea ice dynamics and, thus, heat fluxes among atmosphere and ocean. Consideration of tidal dynamics is therefore expected to be indispensable for a realistic reproduction of climate relevant ocean dynamics, in particular in the Southern Oceans.

We implemented a tidal module based on luni-solar ephemerides into the coupled atmosphere-ocean general circulation model ECHAM5/MPIOM in order to simultaneously simulate circulation and tidal induced dynamics for a pre-industrial period. Apart from changes in vertical mixing and horizontal velocities, the model simulations support that indeed tidal dynamics significantly affect sea ice dynamics, resulting in a reduction of sea ice concentration of more than 40% in the Weddell Sea. These changes are accompanied by increased heat fluxes from the ocean to the atmosphere causing increased atmospheric surface temperatures of more than 4.5°C.

IAPSO (Physical Oceanography)

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IUGG-3947

Southern ocean air-sea fluxes : New insights from the southern ocean flux station

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The Southern Ocean is a key component of the global climate system: insulating the Antarctic polar region from the subtropics, transferring climate signals throughout the world's oceans and forming the southern component of the global overturning circulation. However, the air-sea fluxes that drive these processes are severely under-observed due to the harsh and remote location. This paucity of reference observations has resulted in large uncertainties in ship-based, numerical weather prediction, satellite and derived flux products. Here, we report observations from the Southern Ocean Flux Station (SOFS); the first successful air-sea flux mooring deployment in this ocean. The mooring was deployed at 47 °S, 142 °E for March 2010 to March 2011 and returned measurements of near surface meteorological variables and radiative components of the heat exchange. These observations enable the first accurate quantification of the annual cycle of net air-sea heat exchange and wind stress from a Southern Ocean location. They reveal a high degree of variability in the net heat flux with extreme turbulent heat loss events, reaching -470 Wm^{-2} in the daily mean, associated with cold air flowing from higher southern latitudes. The observed annual mean net air-sea heat flux is a small net ocean heat loss of -10 Wm^{-2}, with seasonal extrema of 139 Wm^{-2} in January and -79 Wm^{-2} in July. The novel observations made with the SOFS mooring provide a key point of reference for addressing the high level of uncertainty that currently exists in Southern Ocean air-sea flux datasets. Results from ongoing analysis of measurements made on subsequent SOFS deployments from 2011-2013 and a further deployment planned for March 2015 will also be presented.

IAPSO (Physical Oceanography)

P06c - P06 The Southern Ocean: where Ocean, Ice and Atmosphere Meet

IUGG-4438

Relationship between surface heat budgets in the Ross and Weddell Seas and global climate variability

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Meteorological parameters provided by the ECMWF for 1958-2012, sea ice cover detected from SSM/I data set and sea ice thickness estimated using SIT algorithm were used to investigate the role of atmospheric forcing in the Ross and Weddell Seas. In particular the state variables have been used to estimate the surface heat fluxes via empirical formulae. The behaviour of monthly mean surface heat budgets in the studied areas show opposite (before 1998) and synchronous (after 1999) variations. Explanation of this behaviour may be linked to the signature of global climate variability expressed by El Niño Southern Oscillation (ENSO), Southern Annular Mode (SAM) and wavenumber-3 pattern or by combination among them. Also Antarctic Circumpolar Wave (ACW) could be involved. Spectral analysis reveals that circumpolar SLP and SST signals exhibit coherent components on interannual scale at around 5 yr period whereas covarying significant energy between SAM and ENSO variability is observed. This implies that SAM and ENSO modes play a superimposed role interfering constructively or destructively on interannual scale. The hovmoller diagrams for interannual SLP anomalies exhibits two stronger ACW cycles around 1982-1991. Before 1982 and after 1991 the absence of ACW seems to be related by dominant signature of SAM in modulating circumpolar variability. Also CEOF analysis show that the SAM has assumed a leading role between 1972-81 and 1991-2000 determining no ACW events. Starting from 2003 until present a wavenumber-3 pattern could have played a role in continuing the phase relationship between heat fluxes in the two Antarctic sectors.

IAPSO (Physical Oceanography)

P06c - P06 The Southern Ocean: where Ocean, Ice and Atmosphere Meet

IUGG-4919

Zonal variability of the Southern Ocean heat budget

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The three-dimensional structure of the upper cell of the Southern Ocean overturning circulation depends on the effects of topography and the spatial variability of surface forcing, both wind and air-sea heat and freshwater fluxes. Air-sea heat flux products and adjusted air-sea heat flux from the data assimilating state estimate show a strong zonal dipole of ocean heat gain in the Indian and Atlantic sectors and ocean cooling in the Pacific sector of the Southern Ocean. The spatial variability of the upper ocean heat budget in the Antarctic Circumpolar Current is investigated using a high resolution Southern Ocean state estimate for the years 2005-2010. The time-mean heat budget solution in the Atlantic/Indian is primarily a balance between ocean heat gain is and cooling by divergence of Ekman transport driven by westerly winds. In the Pacific sector where air-sea heat fluxes are mostly negative and Ekman transport is also cooling, this is balanced by warming from divergence of geostrophic advection which is more similar to the heat balance found in western boundary current regions. Vertical advection of heat is important locally and vertical eddy advection is particularly important for warming the upper ocean in regions downstream of major topographic features. The results support that topographic steering and zonal asymmetry in surface forcing lead to substantial zonal asymmetries in upper ocean dynamics. This spatial variability in the heat budget is important for explaining spatial patterns in observed multi-decadal upper ocean heat content trends, which are likely caused by changes in ocean circulation due to anthropogenic heat uptake.

IAPSO (Physical Oceanography)

P06c - P06 The Southern Ocean: where Ocean, Ice and Atmosphere Meet

IUGG-5021

The Relationship of Weddell Polynya and Open-Ocean Deep Convection to the Southern Hemisphere Westerlies

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The Weddell Polynya of the mid-1970s is simulated in an energy balance model (EBM) sea ice–ocean coupled general circulation model (GCM) with an abrupt 20% increase in the intensity of Southern Hemisphere (SH) westerlies. This small upshift of applied wind stress is viewed as a stand in for the stronger zonal winds that developed in the mid-1970s following a long interval of relatively weak zonal winds between 1954 and 1972. Following the strengthening of the westerlies in this model, the cyclonic Weddell gyre intensifies, raising relatively warm Weddell Sea Deep Water to the surface. The raised warm water then melts sea ice or prevents it from forming to produce the Weddell Polynya. Within the polynya, large heat loss to the air causes surface water to become cold and sink to the bottom via open-ocean deep convection. Thus, the underlying layers cool down, the warm water supply to the surface eventually stops, and the polynya cannot be maintained anymore. During the 100-yr-long model simulation, two Weddell Polynya events are observed. The second one occurs a few years after the first one disappears; it is much weaker and persists for less time than the first one because the underlying layer is cooler. Based on these model simulations, the authors hypothesize that the Weddell Polynya and open-ocean deep convection were responses to
the stronger SH westerlies that followed a prolonged weak phase of the southern annular mode.

IAPSO (Physical Oceanography)

P06d - P06 The Southern Ocean: where Ocean, Ice and Atmosphere Meet

IUGG-0837

The seasonal cycle of mixed layer dynamics and phytoplankton biomass in the Sub-Antarctic Zone: a high-resolution glider experiment

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In the Southern Ocean there is increasing evidence that seasonal to sub-seasonal temporal scales, meso- and submesoscales play an important role in understanding the sensitivity of ocean primary productivity to climate change. In this study, high-resolution glider data (3 hourly, 2km horizontal resolution), from ~6 months of sampling (spring through summer) in the Sub-Antarctic Zone, is used to assess 1) the different forcing mechanisms driving variability in upper ocean physics and 2) how these may characterize the seasonal cycle of phytoplankton production. Results highlight the important role meso- to submesoscale features have in driving vertical stratification and early phytoplankton bloom initiations in spring by increasing light exposure. In summer, the combined role of solar heat flux, mesoscale features and subseasonal storms on the extent of the mixed layer is proposed to regulate both light and iron to the upper ocean at appropriate time scales for phytoplankton growth, thereby sustaining the bloom for an extended period through to late summer. This study highlights the need for climate models to resolve both meso- to submesoscale and subseasonal processes in order to accurately reflect the phenology of the phytoplankton community and understand the sensitivity of ocean primary productivity to climate change.

IAPSO (Physical Oceanography)

P06d - P06 The Southern Ocean: where Ocean, Ice and Atmosphere Meet

IUGG-0913

Drivers of intra-seasonal variability in Southern Ocean primary production: a model sensitivity analysis

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The Southern Ocean is the stormiest place on earth. Its oceanography is characterised by clusters of high EKE (eddies occupying the meso to sub-mesoscales). The presence of these intense atmospheric depressions and meso to sub-mesoscale eddy variability has the potential to strongly impact upper ocean mixing. We hypothesize that in the Southern Ocean the effects of both meso to sub-mesoscale eddies and storms on the upper ocean state and variability (vertical velocities and stratification) will modulate the supplies of light and iron at critical time-scales that match phytoplankton growth constraints, thereby driving variability in seasonal bloom dynamics. We address the intra-seasonal links between upper-ocean physics and biogeochemical fluxes through the response of the seasonal cycle of primary production to (1) the impact of storms, (2) the impact of meso to sub-mesoscale dynamics (3) the interaction of meso to sub-mesoscale dynamics and storms. This is explored with a suite of physical-biogeochemical (NEMO-PISCES) numerical models of varying complexity. From a simple 1D vertical mixing layer model to a more complex 3D periodic zonal jet configuration, representing the ACC, run at progressively increasing horizontal resolutions. Understanding the sensitivity of primary productivity to the variability of the mixed layer may be key to better understanding the sensitivities of the carbon cycle to both short-term variability and long-term trends in large scale atmospheric forcing.

IAPSO (Physical Oceanography)

P06d - P06 The Southern Ocean: where Ocean, Ice and Atmosphere Meet

IUGG-0947

Inferring source regions and transport pathways of iron in the Southern Ocean from satellite chlorophyll data

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In this study we exploit the link between iron supply and chlorophyll response to qualitatively infer the likely source regions and transport pathways of iron in the Southern Ocean, using a combination of satellite chlorophyll and sea surface height data, and high resolution model output.

Our analyses suggest that western boundary currents act as an important mechanism for supplying iron to the Southern Ocean. Iron derived from shelf sediments is entrained into western boundary currents as they flow along the edge of continental shelves. Where the boundary currents detach from the continental shelves this iron is exported to the Southern Ocean along the Dynamical Subtropical Front and supports a large chlorophyll bloom. This process is shown by the tight coupling between chlorophyll concentrations and the sea surface height field in the Sub-Antarctic Zone.

No mean annual chlorophyll blooms are observed in the regions where a high resolution model indicates that there is intense topographically induced upwelling, such as Drake Passage and the Campbell Plateau. This suggests that upwelling at fronts is not a major source of iron to the ocean surface. However, deep winter mixing and upwelling are likely to be important for regulating the timing of blooms throughout the year.

Large chlorophyll blooms are observed along coastal margins of continents and downstream of small islands in the Southern Ocean. In contrast, no chlorophyll blooms are observed around submerged seamounts or plateaus. This result indicates that only shelf sediments in close proximity to coastlines act as a source of iron to the ocean. However, many models prescribe a shelf sediment iron source over all bathymetry shallower than 1000m.

IAPSO (Physical Oceanography)

P06d - P06 The Southern Ocean: where Ocean, Ice and Atmosphere Meet

IUGG-2244

Characterisation of distinct bloom phenology regimes in the Southern Ocean.

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Surface waters in the Southern Ocean are seasonally modulated by an intense phase of biological primary production, known as blooms. The magnitude, timing and spatial distribution of blooms (i.e, bloom phenology) in the Southern Ocean are weakly understood, specially in the vertical dimension. In order to contribute to this question our study addresses the regional variations of bloom phenology based on a 13-year product of ocean color measurements collocated with observation-based estimates of the mixed-layer depth. One key aspect of our work is to discriminate between mixed-layer integrated bloom dynamics and surface bloom. Based on this distinction we define three dominating Southern Ocean bloom regimes. While the regime definitions are solely based on bloom timing characteristics, the three regimes organize coherently in geographical space, and are associated with distinct dynamical regions of the Southern Ocean: the subtropics; the subantarctic; and the Antarctic Circumpolar Current region. All regimes have their mixed-layer integrated onset between autumn and winter, when the daylight length is short, and mixed-layer actively mixes and deepens. In addition, the subantarctic regime has a significant spring-time biomass growth associated with the shutdown of turbulence when air-sea heat flux switches from surface cooling to surface warming. Our study propose a new categorization of Southern Ocean bloom phenology and suppose a first exploration of the bloom's vertical dynamics, which will be carefully addressed by future bio-Argo programs.

IAPSO (Physical Oceanography)

P06d - P06 The Southern Ocean: where Ocean, Ice and Atmosphere Meet

IUGG-2409

"Global oxygenation by enhanced deep convection in the Southern Ocean under millennial-scale global warming"

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Ocean oxygen concentration is expected to continue to reduce under global warming for a thousand years or more, even after atmospheric carbon dioxide stops rising. However, millennial-scale change in ocean oxygen concentration is not well understood. Here we use a fully coupled atmosphere-ocean general circulation model and offline biogeochemical model to simulate multi-millennial oxygen change under atmospheric carbon dioxide quadrupling.
At the first 500 model years in the warming simulation, global mean O_2 concentration decreases by 18 μmol/L, which is consistent with the previous studies. However, after an initial decrease, the projected global oxygen concentration recovers and overshoots by 13 μmol/L at the end of warming simulation, in spite of surface oxygen reduction due to lower oxygen saturation and weaker Atlantic meridional overturning circulation. Recovery of deep ocean convection in the Weddell Sea after initial cessation enhances ventilation and supplies the oxygen into each of the three major basins through strengthened Antarctic Bottom Water, resulting in the oxygen overshoot in the deep ocean except the North Atlantic. Our results suggest that enhanced open ocean convection and ventilation in the Southern Ocean under warmer climate have global impact on multi-millennial oxygen change.

IAPSO (Physical Oceanography)

P06d - P06 The Southern Ocean: where Ocean, Ice and Atmosphere Meet

IUGG-3750

Cryospheric drivers of recent changes in Southern Ocean stratification, circulation, and carbon uptake

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In recent decades, Southern Ocean surface waters freshened and stratified. Our prior work shows that the freshening of the surface and intermediate waters can mostly be attributed to an increased northward freshwater transport by sea ice. The freshening of the shelf and bottom waters is largely driven by increased glacial melt water fluxes from Antarctica. Here, we investigate the effects of these observed changes in the cryospheric buoyancy forcing on the water mass structure, circulation, and air-sea carbon flux of the Southern Ocean using an eddy-resolving regional ocean model (ROMS). At the surface, we drive the model with newly derived buoyancy and momentum fluxes, which are a combination of an observation based sea-ice mass budget, melt flux estimates from ice shelves and ice bergs, and ERA-Interim atmospheric reanalysis data. With this forcing, the model reproduces the spatial and temporal complexity of the Southern Ocean water mass structure and circulation very well. First results, from factorial simulations show that changes in surface buoyancy fluxes from sea ice and land ice can explain most of the recent stabilization of the Southern Ocean surface waters, especially in the Pacific sector. Initial results from performing simulations with an embedded ecological/biogeochemical model support the hypothesis that this stabilization of the surface waters reduces the upwelling of carbon-rich waters, and thus increases the uptake of CO_2 from the atmosphere. Consequently, this mechanism may be crucial in explaining the recent reinvigoration of the Southern Ocean carbon sink, i.e., its recovery from a period of saturation.

IAPSO (Physical Oceanography)

P06e - P06 The Southern Ocean: where Ocean, Ice and Atmosphere Meet

IUGG-0627

Why does the Antarctic Circumpolar Current veer northwards downstream of Drake Passage?

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The sharp northward deflection of the Antarctic Circumpolar Current (ACC) downstream of Drake Passage is sometimes attributed to wind forcing, perhaps by invoking a western boundary current response to Sverdrup balance, but the details remain obscure. Here an analytic ACC model with realistic bottom topography is developed to study the dynamical mechanism behind this deflection. Potential vorticity (PV) is modelled as a simple function of neutral density; together with surface and bottom boundary conditions and planetary geostrophy, this yields a characteristic equation for surface density, from which the full density and flow fields follow. With PV a linear function of density, the modelled ACC is fairly realistic but does not deflect northward at Drake Passage. However, observations and models show slow variations of PV along isopycnals in the interior of the Southern Ocean, and rapid variations in the abyssal ocean across Drake Passage where streamlines are topographically blocked. Thus we model PV as a spatially varying piecewise linear function of neutral density, fit to Southern Ocean State Estimate data. The model then captures the ACC's northward deflection through Drake Passage. Ekman pumping is shown to push surface density contours across the characteristic curves, but does not significantly deflect the ACC. Rather, by establishing interior PV gradients assisted by topography, it is the indirect influence of wind forcing that so dramatically deflects the ACC. Furthermore, the ACC's response to recent changes in Antarctic Bottom Water volume, which also modify interior PV gradients, may be informed by this model.

IAPSO (Physical Oceanography)

P06e - P06 The Southern Ocean: where Ocean, Ice and Atmosphere Meet

IUGG-2486

Recent trends in the Southern Ocean eddy field

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Eddies in the Southern Ocean act to moderate the response of the Antarctic Circumpolar Current (ACC) to changes in forcing. An updated analysis of the Southern Ocean satellite altimetry record indicates an increase in eddy kinetic energy (EKE) in recent decades, contemporaneous with a probable decrease in ACC transport. The EKE trend is largest in the Pacific (14.9 ± 4.1 $cm^2\ s^{-2}$ per decade) and Indian (18.3 ± 5.1 $cm^2\ s^{-2}$ per decade) sectors of the Southern Ocean. We test the hypothesis that variations in wind stress can account for the observed EKE trends using perturbation experiments conducted with idealised high-resolution ocean models. The decadal increase in EKE is most likely due to continuing increases in the wind stress over the Southern Ocean, albeit with considerable interannual variability superposed. ACC transport correlates well with wind stress on these interannual timescales, but is weakly affected by wind forcing at longer periods. The increasing intensity of the Southern Ocean eddy field has implications for overturning circulation, carbon cycling and climate.

IAPSO (Physical Oceanography)

P06e - P06 The Southern Ocean: where Ocean, Ice and Atmosphere Meet

IUGG-2975

Eddy form stress in the Southern Ocean at 1000 dbar

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Over the Antarctic Circumpolar Current (ACC), the eastward momentum imparted by the zonal wind is carried downward by the form (interfacial) stress to the level of topography where it is transferred to the solid earth via bottom form stress. Vigorous eddies in the Southern Ocean are responsible for this momentum transfer. In contrast to the surface where the satellite altimetry provide good temporal and spatial coverage of the surface geostrophic flow, subsurface observation of eddy form stress is difficult.
Here, we use the Argo floats to map the spatial distribution of the eddy form stress at 1000 dbar depth. From two consecutive descent/ascent cycles, it is possible to estimate the velocity at the parking depth from the surface positionings and temperature at the same depth from the hydrographic profiles. Eddy is defined as deviation from spatial average within a 300 km radius circle and temporal average of 1 year.
Although the form stress averaged south of 30S (0.08 N/m2) is approximately the same as the averaged surface zonal wind stress (0.09 N/m2), the form stress is found highly localised (with peaks > 1.5 N/m2) to the steep slopes where the Subantarctic Front and the Polar Front cross topographic features, e.g. Mid-Atlantic Ridge, Southwest Indian Ridge, Kerguelen Plateau, Macquarie Ridge, and Pacific-Antarctic Ridge. Over the ridges, dipole structure is found with a positive peak on the upwind (west) side and a negative peak on the lee (east) side. Time series of the form stress shows that these peaks are generally fixed in space, suggesting important roles of the standing meanders in the adjustment process of the ACC to the wind changes.

IAPSO (Physical Oceanography)

P06e - P06 The Southern Ocean: where Ocean, Ice and Atmosphere Meet

IUGG-3131

On the role of mesoscale eddies in ventilation of the Southern Ocean

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This study examines the role of mesoscale eddies in the along-isopycnal ventilation of the Southern Ocean below the mixed layer, using idealized and comprehensive eddy-permitting numerical simulations. The comprehensive simulations of 'Boundary Impulse Response' and 'Transient Surface' tracers are carried out using a new Southern Ocean Offline Tracer Model (SOOTM). The importance of eddies in this setting is quantified by contrasting sensitivity runs with and without mesoscale eddies, but with the same mean stratification.These simulations are further interpreted using Lagrangian particle trajectories in an idealized model of the Southern Ocean, which allows examination of the pathways, time- and length scales that govern the ventilation. In particular, the results outline the importance of the south-western Atlantic and Pacific basins for the eddy-driven subduction.

IAPSO (Physical Oceanography)

P06e - P06 The Southern Ocean: where Ocean, Ice and Atmosphere Meet

IUGG-3718

Sensitivity of Antarctic Circumpolar Current transport and eddy activityto wind patterns in the Southern Ocean

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The southern hemisphere westerly winds have intensified in recent decades associated with a positive trend in the Southern Annular Mode (SAM). However, the response of the Antarctic Circumpolar Current (ACC) transport and eddy field to wind forcing remains a topic of debate. We use global eddy-permitting ocean circulation models driven with both idealized and realistic wind forcing to explore the response to interannual wind strengthening. We find that the response of the barotropic and baroclinic transports and eddy field of the ACC depends on the spatial pattern of the changes in wind forcing. In isolation, an enhancement of the westerlies over the ACC belt leads to an increase of both barotropic and baroclinic transport within the ACC envelope, with lagged enhancement of the eddy kinetic energy (EKE). In contrast, an increase in wind forcing near Antarctica drives a largely barotropic change in transport along closed f/H contours ('free mode'), with little change in eddy activity. Under realistic forcing, the interplay of SAM and the El Nino Southern Oscillation (ENSO) influences the spatial distribution of the wind anomalies, in particular the partition between changes in the wind stress over the ACC and along f/H contours. We find that the occurrence of a negative or positive ENSO during a positive SAM can cancel or double the wind anomalies near Antarctica, altering the response of the ACC and its eddy field. While a negative ENSO and positive SAM favours an increase in EKE, a positive ENSO and positive SAM lead to barotropic transport changes and no eddy response.

IAPSO (Physical Oceanography)

P06f - P06 The Southern Ocean: where Ocean, Ice and Atmosphere Meet

IUGG-0514

Observing climate variability in Drake Passage

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The Southern Ocean is particularly sensitive to climate change, responding to winds that have increased and shifted over the past several decades and significant warming in the core of the Antarctic Circumpolar Current (ACC). Predicting the response of the Southern Ocean to climate change requires a better understanding of changes in the ACC fronts and water masses and in the mesoscale eddy field that play a significant role in exchanging momentum and heat across the ACC. The Southern Ocean is also a region of critical importance for the global carbon cycle. Our goal is to examine and understand the interactions between physical mechanisms and carbon cycling over a range of temporal scales. We employ multi-year time series of high-density upper ocean temperature, salinity, velocity and pCO2 measurements taken underway from a U.S. Antarctic supply vessel that crosses Drake Passage on average 20 times per year. The focus is on long-term trends in these upper ocean properties and also their (co-)variability in response to large-scale climate modes such as the Southern Annular Mode and ENSO.

IAPSO (Physical Oceanography)

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IUGG-1206

Fine-jet structure of the Antarctic circumpolar current in the Drake Passage

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Jet structure of the Antarctic Circumpolar Current (ACC) is analyzed on the basis of two hydrographic sections carried out across the Drake Passage onboard the Russian R/V Akademik Ioffe in January 2010 and October 2011. The analysis was based on the popular concept of multi-jet structure of the ACC and the results of our analysis of this structure south of Africa using the data of hydrographic section in 2009 and satellite altimetry data (Absolute Dynamic Topography, ADT) published by the French CLS agency. The lines of the sections in the Drake Passage were different, but both ended near Cape Horn. Both sections crossed the Phoenix Basin between the Phoenix Rift and Shackleton Ridge. A total of 54 and 45 stations were occupied in 2010 and 2011, respectively. The typical distance between the stations was 10 miles. The CTD-measurements up to the bottom were performed at each station. The SADCP-measurements of current velocities were carried out both at stations and between them. We used the complete SADCP-dataset and analysis of θ,S-curves to reveal an unprecedented fine structure of the ACC jet in the Drake Passage. We detected ten jets characterized by individual horizontal maximum velocities in the surface ocean layer in 2010. These were 5 jets of the Subantarctic Current (SAC, the same as traditional Subantarctic Front), 4 jets of the South Polar Current (SPC, Polar Front), and one super-jet of the South Antarctic Current (SthAC, ACC Southern Front). We detected nine jets in 2011. These were one jet of the SAC, one very powerful super-jet merged from several SAC jets and the northern jet of the SPC, 4 jets more for the SPC, and 2 jets of the SthAC. Very fine splitting of the SPC in both cases is probably due to the widening of this current over the Phoenix Basin.

IAPSO (Physical Oceanography)

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IUGG-2143

Measuring variability of jets in the Southern Ocean using along-track satellite altimetry and gravimetry

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Several recent studies have used observations of satellite altimetry to quantify variability in fronts of the Antarctic Circumpolar Current, and the narrow jets associated with the fronts. The results suggest a southward shift in major fronts since 1993, based on a change in the isolines of dynamic topography. However, this assumes that the shape and maximum speed of the jets has not changed significantly in time. We reassess these studies, using along-track altimetry to quantify the shape and maximum speed of geostrophic surface jets, and along-track range-rate residuals from GRACE to assess variations in bottom currents. The latter technique is novel, and has not been applied to this problem before. The raw range-rate residuals from the GRACE instruments are particularly sensitive to variations in zonal currents, such as those in the Southern Ocean. We find that while there is large variability in the width and maximum speed of the jets along the Polar Front since 1993, there is no significant trend in the location of the peak current.

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IUGG-2275

Jet-topography effects on horizontal eddy mixing in the Southern Ocean

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The Southern Ocean is a region of strong eastward jet flows and intense eddy activity. Studies suggest that topography plays an important role in steering these jets and setting the location of enhanced eddy activity, which has significant implications for the meridional transport of tracers such as heat and nutrients across the jets. The dominant processes that set the intensity and distribution of eddy activity and the horizontal eddy mixing in the vicinity of topography are yet to be identified. Understanding the physical processes governing these eddy effects will reveal the dependence of eddy mixing on key parameters, allowing prediction of future changes and development of physically-based eddy parameterizations. We report on a theoretical study that investigates the effects of jet-topography interactions on eddy dynamics and the mixing of tracers. We use a quasigeostrophic model of a zonally-evolving unstable jet impinging on topography in a configuration relevant to an Antarctic Circumpolar Current frontal jet. We examine the spatial patterns of surface eddy kinetic energy and irreversible mixing of tracers, and explore their dependence on system parameters such as topography height, stratification and inflowing jet stability. As expected, mixing is generally strongest in the lee of topography, however the relationship between the strength of the eddy field (estimated from eddy kinetic energy) and mixing is not straightforward. In addition, we find parameter regimes in which mixing occurs in front of the topography. These results suggest there is much more to learn about the mechanisms underlying jet-eddy-topography interactions and their representation in ocean models.

IAPSO (Physical Oceanography)

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IUGG-4603

Observations of a large lee wave in the Drake Passage

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Breaking lee waves, forced by geostrophic flows over topography, are thought to generate a significant proportion of the turbulent mixing required to close the meridional overturning circulation. Quantifying the location and strength of this mixing has proven difficult due to a dearth of observations, and the difficulty in observing such localised phenomena. Two autonomous floats deployed in the Drake Passage as part of the Diapycnal and Isopycnal Mixing Experiment in the Southern Ocean independently measured exceptionally strong, oscillatory, vertical water velocities, exceeding 15 cm/s in magnitude as they passed over the Shackleton Fracture Zone, just south of Argentina. The floats provide the first direct observations of a lee wave generated by the impingement of the Antarctic Circumpolar Current (ACC) on submarine topography.

The observations are found to fit well to linear internal wave theory. The maximum measured vertical flux of horizontal momentum is approximately 5 N/m2, and the vertical flux of energy is of order 5 W/m2. These values are in excess of the typical Southern Ocean wind stress and wind work by two orders of magnitude. Turbulent energy dissipation and diapycnal diffusivity inferred using the large eddy method are found to be elevated in the region of the wave. This work examines the implications of such a large event and its associated fluxes for the dynamics of the ACC in the region.

IAPSO (Physical Oceanography)

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IUGG-5698

Investigating topographic impact on vertical fluxes of passive tracer in the Antarctic circumpolar current

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Quantifying vertical fluxes of Iron in the Southern Ocean is a key question to better understand carbone cycle. The following work investigates how enhanced mesoscale turbulence generated by currents-topography interactions may impact the uplift of nutrients in the Antarctic Circumpolar Current. Using a primitive equation model, in an East-West periodic channel, we carry out idealized numerical simulations of an eastward jet encountering a large-scale 500 m height plateau. The current split into two jets upstream of the obstacle and merges into meanders downstream where enhanced turbulence activity is observed. We analyze the vertical fluxes of 3 passive tracers released at 1500 m, 500 m and 100 m depth. A net upward vertical flux of tracer, reaching up to O(100) m/year, can be found in deep waters in the lee of the topography. This vertical eddy tracer flux is almost entirely controlled by turbulent vertical velocities located within the core of mesoscale eddies. Interaction between deep reaching currents and topographic slopes also led to strong turbulent vertical velocities responsible for significant tracer injection. Upper ocean sub-mesoscale vertical velocities are located nearby thin density anomaly filaments, and tend to be higher in the northern jet upstream of the topography. Increasing the horizontal resolution from 16 km to 4 km increases significantly the probability of finding strong vertical velocities, which in turn leads to an increase of the tracer concentration below 100 m and a slight decrease above 100 m depth. The overall effect of topography seems to enhance the effective vertical mixing significantly.

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IUGG-0961

Circulation and water mass transports on the East Antarctic shelf off Adélie Land

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The East Antarctic shelf off Adélie Land-George V Land is known to be an important region for dense shelf water formation as a result of intense ice production in the Mertz Glacier Polynya during the cold season. The dense shelf water accumulates in a deep depression (the Adélie Depression) of the shelf and outflows through a sill located at the shelf break. Summer hydrographic observations collected in this region in summer 2008 show evidence of dense water doming over the northeastern slope of the depression and suggest that the doming could constrain the subsurface circulation of the Modified Circumpolar Deep Water. In this study the same hydrographic observations are used together with concomitant atmospheric surface forcing data to provide an inverse estimate of the mean summer circulation on the shelf based on conservation constraints and geostrophy. The retrieved flow is used to calculate fluxes associated with the different water masses. Using these, we infer circulation patterns and possible transformation of water masses in the depression and discuss exchanges through the Adélie Sill. A two-year time series of deep currents and hydrographic properties retrieved from a mooring in the depression in 2008-2009, is used to place the 2008 summer circulation into a wider temporal framework. The results are interpreted in the more general context of the dynamics of the Antarctic shelf.

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IUGG-2101

The fourth Antarctic Bottom Water: Cape Darnley Bottom Water

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It has been recognized that AABW is formed in the Weddell Sea, the Ross Sea and off the Adélie Coast. A fourth variety of AABW has been identified in the eastern sector of the Weddell-Enderby Basin. However, its production has never been observed, nor its exact dense shelf water (DSW) source located. Recently, satellite-derived estimates of sea-ice production suggest that the Cape Darnley Polynya, located northwest of the Amery Ice Shelf, has the second highest ice production after the Ross Sea Polynya. As part of the Japanese IPY program, we conducted mooring observations in 2008−2009 offshore from the Cape Darnley Polynya, and revealed that the enhanced sea-ice production in this polynya is the missing source of the AABW. Moored instruments observed overflows of newly formed AABW, bottom-intensified, cascading down the canyons north of Cape Darnley. Cold and dense AABW of about 300m thick flows down at fairly regular periods of 4-5 days. We propose to name this AABW Cape Darnley Bottom Water (CDBW). This result is novel because this AABW is produced purely from sea-ice production without the assistance of an ice shelf and/or large storage volume on the continental shelf, in contrast to the traditional paradigm. We estimate that 0.3−0.7 × 10^6 m^3 s^{-1} of DSW is transformed into CDBW, accounting for 6−13% of the circumpolar total. The CDBW migrate westward, and increase its volume by gradual mixing with Circumpolar Deep Water, to ultimately constitute part of the AABW in the Weddell Sea, ~13-30% of the Atlantic AABW production.

IAPSO (Physical Oceanography)

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IUGG-2357

A Numerical Investigation of Formation and Variability of Antarctic Bottom Water off Cape Darnley, East Antarctica

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Recently, a Japanese IPY project confirmed the production of Antarctic Bottom Water [Cape Darnley Bottom Water (CDBW)] from the Cape Darnley Polynya (CDP) located northwest of the Amery Ice Shelf. This observations suggest that CDBW contributes to 13%–30% of the Atlantic AABW production, inferring the importance of this region. However, the detailed understanding of descending pathways of dense water, importance of topographic depression, sea-ice formation, and slope current for the CDBW production, and mechanisms responsible for the observed periodic downslope flow are difficult to be understood only from observations. Thus, we have conducted this study to simulate the CDBW using a nonhydrostatic model.The model is forced for 8 months by a temporally uniform surface salt flux (because of sea ice formation) estimated from Advanced Microwave Scanning Radiometer for Earth Observing System (EOS; AMSR-E) data and a heat budget calculation. We reproduce AABW formation and associated periodic downslope flow of dense water. Descending pathways of dense water are largely determined by the topography; most dense water flows into depressions on the continental shelf, advects onto the continental slope, and is steered downslope to greater depths by the canyons. Intense sea ice formation is the most important factor in the formation of AABW off Cape Darnley, and the existence of depressions is of only minor importance for the flux of CDBW. Together with simplified experiments and analytical interpretations based on geophysical fluid dynamics, the mechanism responsible for the periodic downslope flow of dense water is further analyzed. The period of dense water outflow is regulated primarily by the topographic beta effect.

IAPSO (Physical Oceanography)

P06g - P06 The Southern Ocean: where Ocean, Ice and Atmosphere Meet

IUGG-4505

Formation of Antarctic bottom water on the continental shelf off larsen ice shelf

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The dense water flowing out from the Weddell Sea (WS) significantly contributes to Antarctic Bottom Water (AABW) and plays an important role in the Meridional Overturning Circulation. The larger amount of this dense water consists of Weddell Sea Deep Water (WSDW) formed in the WS, mainly in front of the Filchner-Ronne Ice Shelves and the Larsen Ice Shelf (LIS). We performed model simulations and analysis of hydrographic data that highlight the importance of the second source. Model simulations indicate that dense waters placed on the continental shelf off LIS flow down the slope and contribute to the WSDW that renews the AABW further downstream. Measurements made during the Polarstern cruise ANT XXIX-3 (2013) add evidence to the importance of the source in the western Weddell Sea. Using Optimum Multiparameter Analysis we show that the dense water found on the continental shelf in front of the former Larsen A and B together with water originating from Larsen C increases the thickness of the WSDW layer in 50%, and changes the temperature and salinity of this water mass. These modifications occur close to the WSDW outflow paths and therefore have high influence on the AABW properties.

IAPSO (Physical Oceanography)

P06g - P06 The Southern Ocean: where Ocean, Ice and Atmosphere Meet

IUGG-4854

Modeling Frazil Ice using Lagrangian particle tracking

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A new modeling framework using Lagrangian particle tracking is developed to assess dynamic and thermodynamic effects of underwater frazil ice. This frazil ice model treats a Lagrangian particle as a bulk cluster of many frazil crystals, and calculates thermodynamic growth of each particle and corresponding budget of latent heat and fresh water. The mass fraction of underwater frazil ice also changes the effective density and viscosity of seawater, thereby affecting the ocean convection. An idealized experiment using this model successfully reproduces the formation of underwater frazil ice and its transition to grease ice at the surface. Because underwater frazil ice does not reduce the atmosphere-ocean heat exchange, surface heat flux and net sea ice production in the experiment with frazil ice keep relatively higher values for ~24 hours compared with an experiment where surface cooling directly leads to columnar growth of a solid ice cover which effectively insulates the heat flux. These results suggest that large scale sea ice models which do not take account of the effects of frazil ice might underestimate atmosphere-ocean heat exchange, particularly at times of active new ice formation. The newly developed model also reproduces some characteristic features associated with frazil ice formation, such as potential supercooling state of water column and grease ice streaks aligned in the wind direction, which are commonly observed in coastal polynyas. The model has been also extended to simulate the sediment entrainment process of newly formed sea ice by simultaneously deal with underwater frazil ice and sediment particles.

IAPSO (Physical Oceanography)

P06g - P06 The Southern Ocean: where Ocean, Ice and Atmosphere Meet

IUGG-5322

Sensitivity of abyssal water masses to subgridscale parameterisations and varying resolution

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Global Climate Models (GCMs) struggle to accurately represent the abyssal ocean circulation and lower limb of the Meridional Overturning Circulation (MOC). Antarctica Bottom Water (AABW) and North Atlantic Deep Water (NADW) play important roles in transporting carbon, heat and nutrients throughout the globe, yet GCMs are unable to resolve the fine-scales of the formation and overflow processes defining these water masses. The resolution restriction on GCMs can lead to biases in the deep and bottom waters properties, even with the application of subgridscale parameterisations designed for AABW/NADW formation/overflow processes. Such dependence motivates the need for increased understanding of the response of the abyssal ocean and bottom water formation regions to changing resolution.

Using an ocean-sea ice sector model of the Atlantic Ocean we investigate the sensitivity of AABW formation and transport to varying resolution (both horizontal and vertical) and the application of subgridscale parameterisations designed to improve AABW/NADW overflows. A more complete understanding of the modeling factors defining the properties of AABW will lead to improved representation of the abyssal ocean in GCMs. With a more complete representation of these water masses, an increased understanding of their key influence in current and future climates can be found.

IAPSO (Physical Oceanography)

P06h - P06 The Southern Ocean: where Ocean, Ice and Atmosphere Meet

IUGG-2171

Southern Ocean cooling in a warming world: reassessing the role of westerly winds

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In contrast to the global warming trend and the loss of Arctic sea ice, the Southern Ocean has exhibited a gradual decrease in sea surface temperatures (SSTs) and a net expansion of the sea ice cover over recent decades. Moreover, historical simulations with CMIP5 global climate models do not reproduce the observed cooling around Antarctica and, instead, predict slow but steady warming and sea ice loss.

Here we identify enhanced wind-driven Ekman transport as a possible mechanism allowing the Southern Ocean to cool. We further discuss the discrepancy between observations and CMIP5 historical simulations. The latter underestimate the strengthening and the poleward shift of the Southern Hemisphere surface westerlies – due either to an inadequate representation of ozone forcing or, perhaps, internal variability contributing to observed wind trends. We propose that under a realistic evolution of surface winds, CMIP5 models can produce cooling trends around Antarctica with magnitudes and spatial patterns similar to observations. To that end we consider the unforced preindustrial control runs of CMIP5 models, and examine periods with multidecadal trends in the speed and position of the Southern Hemisphere surface westerlies that are comparable to the 1979-2014 trends. Strengthening and southward displacement of surface winds produce an SST dipole around Antarctica: cooling south of 50S and warming in a zonal band along 30-50S, similar to observed patterns. These wind-induced cooling trends in the Southern Ocean are large enough to locally overwhelm the effect of greenhouse gas forcing and allow the sea ice cover to expand in a warming world. We compare our findings to those of recent modeling studies which suggest that ozone depletion results in warming around Antarctica.

IAPSO (Physical Oceanography)

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IUGG-5320

Influence of the northern Deep Waters on Southern Ocean water properties and cryosphere

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The Deep Waters originating in the Atlantic, Indian and Pacific upwell in the Southern Ocean, with the warmest waters reaching the Antarctic shelves in the eastern South Pacific sector (Bellingshausen Sea). Hydrographic data and circulation analysis, including that from the Southern Ocean State Estimate, shows that the water that warms the west Antarctic Peninsula (WAP) shelves, hence is implicated in ocean-ice shelf interaction where the ice shelf is melting fastest, is Upper Circumpolar Deep Water (UCDW), which derives from Indian and Pacific Deep Waters, rather than North Atlantic Deep Water, which lies deeper in the Southern Ocean. The pathways of these deep waters to the upper Southern Ocean is strongly mitigated by topography at Drake Passage latitudes, including Kerguelen Plateau, the East Pacific Rise, and the Southwest Indian Ridge. Topographic steering of the Antarctic Circumpolar Current by the mid-ocean ridges extends the Antarctic winter sea ice edge far to the north, while regions with less steering allow the ice edge to shift back southwards; this pattern is strongly related to the observed pattern of decadal sea ice gain and retreat, respectively. Observed changes in CDW properties in the Ross/Amundsen/Bellingshausen Seas, from 1992 to 2011, suggest increased ventilation by the northern Deep Waters, which increases heat content in the upper ocean, freshens the abyssal layer, and could be associated with increased ocean temperatures along the WAP and changes in sea ice extent. The observed changes are suggestive of a strengthening of the ACC, although not necessarily its location. Within the Ross Sea, the nearly adiabatic bottom 1000 m layer continues to warm, based on 1992, 2005, 2011, 2014 hydrographic surveys.

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IUGG-5745

Multidecadal warming and shoaling of antarctic waters

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Decadal trends in seawater properties adjacent to Antarctica are poorly known, and mechanisms responsible for such changes are uncertain. Antarctic ice sheet mass loss is largely driven by ice shelf basal melt, which is influenced by ocean-ice interactions and correlated with Antarctic continental Shelf Bottom Water (ASBW) temperature. We document the spatial distribution of long-term large-scale trends in temperature, salinity and core depth over the Antarctic continental shelf and slope. Warming at the seabed in the Bellingshausen and Amundsen Seas is linked to increased heat content and to a shoaling of the mid-depth temperature maximum over the continental slope, allowing warmer, saltier water greater access to the shelf in recent years. Regions of ASBW warming are those exhibiting increased ice shelf melt.

IAPSO (Physical Oceanography)

P06i - P06 The Southern Ocean: where Ocean, Ice and Atmosphere Meet

IUGG-0246

Decadal to multidecadal Southern Ocean sea-ice variability triggered by spurious deep convection events in climate models

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Present day coupled climate models fail to reproduce the observed sea-ice increase in the southern ocean. Most of them show a steady decline but large variability on seasonal to multi decadal time scales. In this study we investigate reasons for this variability using model output of HADGEM3-UKCA (active atmosphere chemistry) and existing CMIP5 simulations. In HADGEM3-UKCA a close link between Southern Ocean sea-ice anomalies and the strength of the subpolar gyres (SPG) exists on decadal to multidecadal time scales. Positive sea-ice anomalies go along with enhanced gyre circulation and vice versa. This gyre variability is triggered by spurious open ocean convection and the formation of dense water masses in the Southern Ocean, which is a common phenomenon in CMIP5 models. These deep mixing events cause positive anomalies in the deep overturning cell (Antarctic Bottom Water-cell) and Drake transport but negative SPG anomalies, which cause enhanced southward heat transports (mainly SPG driven) and an extended convection but cannot compensate the surface heat losses. The combination of exhausted heat content and enhanced southward freshwater transports results in positive sea-ice anomalies and triggers the switch to the non-convective mode.

IAPSO (Physical Oceanography)

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IUGG-0698

The 3-dimensional overturning circulation of the Southern Ocean revealed using data from ARGO and instrumented elephant seals.

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The meridional overturning circulation (MOC) of the Southern Ocean is a fundamental component of the climate system. The MOC exhibits first order control over the heat and CO_2 *budgets of the globe, forming the Earth's largest* CO_2 *sink and mediating the southward exchange of heat, salt and chemical constituents, as well as between ocean basins. Understanding the MOC is vital for understanding the climate system and predicting its future states.*

To date, the vast majority of studies interpret the Southern Ocean MOC through a quasi 2-dimensional framework known as the Transformed Eulerian Mean (TEM). The TEM framework, developed for the study of the large scale atmospheric circulation, generally relies on zonal or streamwise averages. However, the Southern Ocean circulation is not 2-dimensional. Phenomena such as meso-scale turbulence, forced topographic meanders and mixing processes are highly localised due to the interaction between the Southern Ocean currents and large scale bathymetry. These local dynamics effect not only the regional, but the global potential vorticity structure of the Southern Ocean. It has been hypothesised that these local dynamics might have a strong influence on the MOC. We will present the results of a systemic program to study the MOC as a 3-dimensional system.

Employing hydrographic profiles obtained from ARGO floats, cruises and instrumented elephant seals we develope maps of the 3-diemensional potential vorticity, geostrophic velocity and the associated fluxes due to stationary meanders. Using approximate force balances, we will use these maps to investigate the local overturning in the upper 2000m. Finally, we will discuss the implications for the large scale overturning.

IAPSO (Physical Oceanography)

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IUGG-1045

Sensitivity of Southern Ocean overturning to wind stress changes: Role of surface restoring time scales

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The influence of different surface restoring time scales on the response of the Southern Ocean overturning circulation to wind stress changes is investigated using an idealised channel model. Regardless of the restoring time scales chosen, the eddy-induced meridional overturning circulation (MOC) is found to compensate for changes of the direct wind-driven Eulerian-mean MOC, rendering the residual MOC less sensitive to wind stress changes. However, the extent of this compensation depends strongly on the restoring time scale: increasing sensitivity with decreasing restoring time scale. Strong surface restoring is shown to limit the ability of the eddy-induced MOC to change in response to wind stress changes and as such suppresses the eddy compensation effect. These model results are consistent with qualitative arguments derived from residual-mean theory and may have important implications for interpreting past and future observations.

IAPSO (Physical Oceanography)

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IUGG-1214

An assessment of ACC and Southern Ocean MOC during 1958--2007 in a suite of interannual CORE-II simulations

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We present an analysis of the representation of the ACC and Southern Ocean MOC in a suite of seventeen global ocean-sea ice models. We focus on the mean, variability and trends of both the ACC and MOC over the 1958--2007 period, and discuss their relationship with the surface forcing. Most models show weak ACC sensitivity to changes in forcing during the past five decades, and they can be considered to be in an eddy saturated regime. Larger contrasts arise when considering MOC trends, with a majority of models exhibiting significant strengthening of the MOC. Only a few models show a reduced sensitivity to forcing changes, responding with an intensified eddy-induced circulation and providing some degree of eddy compensation, although still manifesting considerable decadal trends. Both ACC and MOC interannual variability are largely controlled by the SAM. Models with constant or two-dimensional specification of the eddy-induced advection coefficient (k) show larger ocean interior decadal trends, higher correlation with the SAM, larger ACC decadal trends and no eddy compensation in the MOC. Eddy-permitting or models with a three-dimensional time varying k show lower correlation with the SAM, smaller changes in isopycnal slopes and associated ACC trends and signs of eddy compensation. Evidence is given for a larger sensitivity of the MOC as compared to the ACC, even when approaching eddy saturation. Surface forcing changes experienced during years 1948--2007 are weaker than what was previously used for testing ocean models and their mesoscale parameterizations with idealised forcing anomalies. Future process studies designed for disentangling the role of momentum and buoyancy forcing in driving the ACC and MOC are proposed.

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IUGG-3624

Southern Ocean deep convection variability on multi-decadal to multi-centennial timescales

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Climate models simulate pronounced multi-decadal to multi-centennial variability in the sea surface temperature (SST) of the Southern Ocean, which is strongly related to open ocean deep convection variability. A mechanism behind the deep convection oscillations in the models is related to accumulation and release of heat at intermediate depth. However, several competing hypotheses have been also proposed and the models differ in many respects, explaining the large range of timescales and of deep convection locations.

Here we present results of the Kiel Climate Model (KCM). The time scale of the variability differs from model version to model version. We identify in one version a main period of about 90 years in deep convection variability located at the eastern edge of the Weddell Sea. A Southern Ocean SST index is defined to describe the state of deep convection. The SST index exhibits a significant correlation with an index of the AABW cell-strength in the Atlantic at 30°S, with the SST index leading by roughly 30 years. There is a meridional shift of the Southern Hemisphere westerlies linked to Southern Ocean deep convection variability and a correlation with the Southern Annular Mode (SAM) index; where both signals increase with height. The KCM results are compared to those from a number of CMIP5 pre-industrial control experiments. We also contrast the 90-year periodicity with the characteristic time scale of Southern Hemisphere climate variability derived from proxy data. Finally, we discuss the role of model bias in influencing Southern Ocean variability.

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IUGG-4609

Impacts of far field forcing on the Residual Overturning Circulation in the Southern Ocean

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The overturning circulation in the Southern Ocean consists of a residual overturning circulation (ROC) formed by opposing mean and eddy circulations. Although the ROC is part of the global overturning circulation, studies have focused on sensitivity to changes in local surface wind and buoyancy forcing. However, we hypothesise that a ROC cannot be maintained without including any diabatic processes outside of the Southern Ocean such as North Atlantic Deep Water (NADW) formation. This study uses a series of idealized MITgcm channel model runs to study the effect of far field forcing on the ROC by varying the northern boundary condition. The far field effects of strong NADW formation are mimicked using a sponge layer with short relaxation timescales forcing a set stratification at the northern boundary. The effect of the forcing is reduced in subsequent runs by increasing the relaxation timescales to the point of fully closing the northern boundary. The change in far field forcing must invoke a response in the local diabatic eddy heat fluxes in order to modulate the ROC. These runs show a complete restructure of the ROC and eddy heat transports with changing northern boundary condition, highlighting the importance of far field forcing in the Southern Ocean.

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A dynamical mechanism for the formation and maintenance of Southern Ocean storm tracks

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The mechanisms that initiate and maintain oceanic 'storm tracks' (regions of anomalously high eddy kinetic energy) are studied in a wind-driven, isopycnal, primitive equation model with idealised bottom topography.

Storm tracks are found downstream of the topography in regions strongly influenced by a large--scale stationary meander which is generated by the interaction between the background mean flow and the topography. In oceanic storm tracks the length scales of the stationary meander differs from that of the transient eddies, a point of distinction from the atmospheric storm tracks.

The dynamics of the storm track in this idealised configuration are investigated using a wave-activity flux (related to the Eliassen--Palm flux and eddy energy budgets). It is found that vertical fluxes of wave-activity (which correspond to eddy growth by baroclinic conversion) are localised to the region influenced by the standing meander. Further downstream, organised horizontal wave-activity fluxes (which indicate eddy energy fluxes) are found. A mechanism for the development of oceanic storm tracks is proposed: the standing meander initiates localised conversion of energy from the mean field to the eddy field, while the storm track develops downstream of the initial baroclinic growth by sending eddy energy downstream through the ageostrophic flux of Montgomery potential, where it can be extracted to form new meso-scale eddies, even in regions that are not anomalously baroclinically unstable. We will also discuss the implications of our analysis for the parameterisation and prediction of storm tracks in ocean models.

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Variability of Antarctic Slope Current transport using hydrographic measurements

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In early 2012 the GENTOO project deployed three Seagliders in the northwest Weddell Sea, acquiring high temporal and spatial resolution measurements east of the tip of the Antarctic Peninsula. The Antarctic Slope Front and associated currents form a physical and dynamic barrier to the cross-shelf ow of properties, influencing local and global ocean dynamics. We use the Seaglider dataset to better understand the cross-shelf processes and their impact on dense water export from the shelf. The 291 Seaglider profiles with altimetric information are used to investigate the properties and thickness of the dense bottom water spilling off the shelf. We consider the dense water layer as waters denser than the 28.27 kg m^{-3} threshold and determine the thickness by the vertical distance from the shallowest appearance of this threshold to the bottom depth informed by the altimeter. Along the 7 evaluated transects, the dense water is identified mostly over the slope, between the 500 and 1000 m isobaths. The dense layer is thicker around 63°20' S, along the 1000 m isobath, becoming narrower towards the shelf and northern positions. Moreover, we evaluate with unprecedented resolution the along-stream velocity and buoyancy fields along 4 transects around South Orkney Islands plateau. We reference the geostrophic velocity to the depth-averaged current and modelled tides. The geostrophic fields indicate a northward water displacement and two distinct velocity cores over the slope, which corroborates and complement previous regional studies. We also determine the potential vorticity fields, which increase toward shallower areas. Methodologies are tested for the use of the potential vorticity to determine cross-slope eddy mass fluxes in this area.

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Assessment of the representation of Antarctic Bottom Water properties in the ECCO2 reanalysis

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We analyzed the ability of the ECCO2 reanalysis to represent the hydrographic properties and variability of Antarctic Bottom Water in the Southern Ocean. We used a twenty-year (1992-2011) observational database to perform the comparisons. Four case studies based on current meter data and AABW volume transport estimates previously reported in the literature were also evaluated. The most striking feature observed is the appearance of a dense water plume in the Weddell Sea sector due to deep ocean convection. This feature is related to the opening of an oceanic polynya clearly visible after 2005. This phenomenon contributes to the unrealistic representation of the Southern Ocean primarily after 2004. Before 2004, the ECCO2 reanalysis is able to grossly represent the main Southern Ocean oceanographic features. The reanalysis output produces surface waters that are generally denser than observations due to the reproduction of waters mostly saltier than expected, probably as a result of the strong seasonality of sea ice concentrations. Bottom waters are warmer and less dense, partially due to the inability of the reanalysis to properly reproduce the formation and export of dense waters from the shelf and the consequent absence of the densest AABW variety for most of the analyzed period. The AABW volume export and current velocity are underrepresented in all case studies. The results reveal that the ECCO2 reanalysis product requires extensive improvements regarding the representation of AABW in the Southern Ocean. These findings reinforce the need for an accurate representation of sea ice coverage and variability and of the processes occurring over both shelves and slopes for conducting adequate simulations of deep Southern Ocean hydrography.

IAPSO (Physical Oceanography)

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P06p-261

Modeling the interplay between sea ice formation and the oceanic mixed layer: limitations of simple brine rejection parameterizations

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The subtle interplay between sea ice formation and ocean vertical mixing is hardly represented in current large-scale models designed for climate studies. Convective mixing caused by the brine release when ice forms is likely to prevail in leads and thin ice areas, while it occurs in models at the much larger horizontal grid cell scale. Subgrid-scale parameterizations have hence been developed to mimic the effects of small-scale convection using a vertical distribution of the salt rejected by sea ice within the mixed layer, instead of releasing it in the top ocean layer. Such a brine rejection parameterization is included in the global ocean–sea ice model NEMO-LIM3. Impacts on the simulated mixed layers and ocean temperature and salinity profiles, along with feedbacks on the sea ice cover, are then investigated in both hemispheres. The changes are overall relatively weak, except for mixed layer depths, which are in general excessively reduced compared to observation-based estimates. While potential model biases prevent a definitive attribution of this vertical mixing underestimation to the brine rejection parameterization, it is unlikely that the latter can be applied in all conditions. In that case, salt rejections do not play any role in mixed layer deepening, which is unrealistic. Applying the parameterization only for low ice–ocean relative velocities improves model results, but introduces additional parameters that are not well constrained by observations.

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P06p-262

The role of extratropical cyclones and fronts for Southern Ocean freshwater fluxes

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In this study, the important role of extratropical cyclones and fronts for the atmospheric freshwater flux over the Southern Ocean is analyzed. Based on the Interim ECMWF Re-Analysis, the freshwater flux associated with cyclones is quantified and it is revealed that the structure of the Southern Hemispheric storm track is strongly imprinted on the climatological freshwater flux. In particular, during austral winter the spiraliform shape of the storm track leads to a band of negative freshwater flux bending toward and around Antarctica, complemented by a strong freshwater input into the midlatitude Pacific, associated with the split storm track.

The interannual variability of the wintertime high-latitude freshwater flux is shown to be largely determined by the variability of strong precipitation (>75th percentile). Using a novel and comprehensive method to attribute strong precipitation uniquely to cyclones and fronts, it is demonstrated that over the Southern Ocean between 60% and 90% of the strong precipitation events are due to these synoptic systems. Cyclones are the dominant cause of strong precipitation around Antarctica and in the midlatitudes of the Atlantic and the Pacific, while in the south Indian Ocean and the eastern Atlantic fronts bring most of the strong precipitation.

A detailed analysis of the spatial variations of intense front and cyclone precipitation associated with the interannual variability of the wintertime frequency of cyclones in the mid- latitude and high-latitude branches of the Pacific storm track underpins the importance of considering both fronts and cyclones in the analysis of the interannual variability of freshwater fluxes.

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Mechanisms triggering the Weddell Sea polynya: insights from a high-resolution climate model

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Polynyas are large openings in the sea ice cover that are thought to play an important role in the climate system. They open a window between the atmosphere and deep ocean through intense convection over the water column. Polynyas thus allow the exchange of vast amounts of heat and gases between the atmosphere and the ocean, and lead to the formation of dense waters that fill the abyssal ocean and contribute to the global circulation. A giant polynya was observed in the Weddell Sea over the winters of 1974 to 1976, but has never opened again so that many questions have been recently raised regarding its past and future occurrence. If the mechanisms maintaining the Weddell Sea polynya are well-understood, those triggering its formation remain less clear. Several hypotheses have been discussed including the role of wind stress on ice divergence, ocean upwelling of warm waters and intensification of the Weddell gyre circulation, as well as the role of the interaction between the mean flow and the Maud Rise in generating ice divergence through cyclonic eddies. In this study, we explore some of these mechanisms using a hierarchy of climate models at various resolutions (1°, 1/4° and 1/10°) where two experiments were run: a preindustrial control (1860 constant atmospheric CO_2 concentration) and a climate change (1%/year increase in atmospheric CO_2 concentration). In each model, polynyas open several times in the Weddell Sea over the course of the control simulations. Under climate change, polynya events tend to decline at 1° and 1/4°, while they continue at 1/10°.

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An oceanographic database of the Amundsen Sea, Antarctica collected by seals

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The dynamics of the Antarctic ice shelves are strongly influenced by heat carried by deep warm salty water flowing across the shelf and into ice shelf cavities. Understanding the dynamics of this process is crucial to understanding the causes and variability of ice sheet mass loss. Processes vary in time from hours to decades. Previous in situ measurements were limited to short term summer campaigns and a few moorings that provide long time series but very limited spatial coverage. In general, winter-time CTD data are scarce on the Antarctic continental shelf, yet may be key to understanding the processes of heat transport across the slope and on the shelf. Here, we present CTD data collected by animal-borne instruments deployed on 7 Southern elephant and 7 Weddell seals in February 2014 as part of the iSTAR Ocean2Ice project. More than 11,100 vertical CTD profiles were collected on the shelf in the Amundsen Sea and transmitted back in real time by satellite communications from late February through October. The average deployment lasted for 214 days. Data were checked against ship-board measurements before deployment and a delayed-mode quality control algorithm was applied to all collected data. The final dataset allows us to analyse monthly 3-dimensional fields of temperature and salinity from the sea surface to the sea floor, providing crucial insights into the ocean processes in the Amundsen Sea during winter. We also highlight future developments in animal-borne instrument technology to improve data collection in the winter time from these remote and harsh environments.

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Biogeochemical characteristics of nutrients, dissolved and particulate organic matters in the Amundsen Sea

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The Amundsen Sea is one of the regions where ice sheet thinning is the fastest in Antarctica, which is mainly attributed to the intrusion of Circumpolar Deep Water (CDW) through deep troughs onto the Antarctic continental shelf. In addition, the Amundsen polynya is the most productive among those identified along the Antarctic coast. These features make the Amundsen Sea an ideal location to monitor the influence of environmental changes on marine biogeochemical cycles. Nevertheless, no study has been carried out over this region to investigate carbon and nitrogen biogeochemical cycles, simultaneously. Seawater samples were collected over the Amundsen Sea in January 2014 aboard IBRV Araon, and analyzed for nutrients (NO_3, PO_4, NH_4, SiO_2), dissolved and particulate organic carbon (DOC and POC) and nitrogen (DON and PON). Despite the exceedingly high biological production in the Amundsen polynya, NO_3 and PO_4 in surface water were not depleted, suggesting that remineralization is fast enough to maintain their concentrations, and/or that biological production is limited by other factors such as iron. DOC and POC concentrations ranged from 38?73 µM C and < 1?60 µM C, respectively. Both POC and DOC concentrations increased in the upper 100 m of the water column. However, below 100 m POC concentration remained low (< 3 µM C) when DOC concentration varied from 38?69 µM C. Likewise, DON concentrations deeper than 100 m increased by 7 µM N while NO_3 concentrations were distributed homogeneously. These results suggest that the biological drawdown of inorganic nutrients result in the net production of organic matter in the upper 100 m, and that sinking particle flux would be low because of remineralization of particulate matter by grazing and microbial activity.

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Seasonal cyclonic eddy in Amundsen Sea Polynya, Antarctica

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Amundsen Sea recently attracted particular interest, because it is most rapidly warming in the Western Antarctic (WA). Many studies reported that the relatively warm circumpolar deep water (CDW) and seasonal variation of its intrusion to the Amundsen Sea are associated with the regional warming. However, few studies examined why the intrusion varies seasonally. The strong seasonal cyclonic eddy in Amundsen Sea Polynya was found from the shipborne measurements LADCP data during 2010/2011 and 2011/2012 IBRV Araon expeditions. Also this ocean surface circulation was reconfirmed by the OSCAR (Ocean Surface Current Analysis) calculated from quasi-linear and steady flow momentum equations using sea surface height, wind and temperature obtained from satellites. A polynya larger than 200 km in diameters tends to be formed by the effect of wind and ocean currents in front of DIS (Dotson Ice Shelf) during austral summer season. It is found that the strong upwelling was induced by latitudinal variations of westward wind velocities and sea ice concentration on the northern boundary of the Polynya. Such upwelling generates the cyclonic eddy that maximum current speed is larger than 10 cm s^{-1}. However, as the Polynya was almost closed during austral winter, upwelling was reduced compared to that during the summer season and the cyclonic eddy disappeared in front of DIS. Additionally, the influence of seasonal variation in the strong ocean surface circulation on oceanic heat transport to ice shelves will be discussed.

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Massive phytoplankton blooms in the Amundsen polynya, Southern Ocean

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As a Korea Polar Research Institute (KOPRI) Amundsen project, three times intensive Antarctic cruises were conducted in the Amundsen Sea (west Antarctic) in early (2010/2011 and 2013/2014) and late (2011/2012) austral summertime. The study area includes Amundsen polynya which is one of the most productive and high chlorophylls (both in directly observed and satellite induced ocean color data) are concentrated coastal polynya among 37 Antarctic polynyas. Interestingly, the high chlorophylls were concentrated in polynya center rather than in the edge of polynya at all time (regardless of season). To understand these high blooms of phytoplankton in iron limited environment (expected), the phytoplankton physiological parameters were measured by Fluorescence Induction and Relaxation (FIRe) system. In addition, we carried out iron assimilation experiments on board to demonstrate that iron enrichment responses of natural phytoplankton assemblages. Moreover, to double-check the influence of physical effect of the study area, we also observed and analysed the mixed layer depth and euphotic depth, and so on. Possible implications of iron/light limitation and controlling factors of phytoplankton growth in this polynya system will be discussed.

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Quantifying upwelling and nutrient fluxes in the Weddell Sea with helium isotope data

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Upwelling, the vertical advective movement of water, changes the characteristics of the mixed layer, closes the mass balance of the meridional overturning circulation in the Southern Ocean, and provides a pathway for nutrients and gases from the ocean's interior into the mixed layer and atmosphere. Despite the importance of upwelling in the Weddell Sea and the Antarctic Circumpolar Current, estimates in this region are sparse. Upwelling velocities are small -a few meters per day-, and cannot be measured directly, therefore indirect methods must be invoked. Here, we use the helium isotope disequilibrium in the mixed layer to calculate upwelling velocities, upwelling rates and resulting heat and nutrient fluxes in the Weddell Sea and along the Prime Meridian. Since helium is exchanged between the mixed layer and the atmosphere by gas transfer, δ^3He, the isotopic ratio of ^3He to ^4He in the water compared to the ratio in air, is generally in equilibrium in the mixed layer. In upwelling regions, an excess in δ^3He in the mixed layer is caused by water entrained from below, enriched in δ^3He because of primordial ^3He injected into the ocean by hydrothermal activity. The upwelling velocities calculated from this disequilibrium are sensitive to the vertical δ^3He gradient, therefore a high vertical sampling resolution is required. Significant disequilibria were observed close to the coast of the Antarctic continent as well as in the central Weddell Sea, close to the (at that time) retreating ice edge. However, inferred upwelling velocities where highest between 60° and 65°N on the prime meridian (> 5×10^{-5} m/s) and close to the Antarctic Peninsula ($1\text{-}2 \times 10^{-5}$ m/s), because of smaller vertical gradients.

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Abundance and production of heterotrophic bacteria during a phytoplankton bloom in the Amundsen Sea Polynya, Antarctica

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Amundsen Sea Polynya (ASP) is reported to be the most productive of the 37 coastal polynyas around Antarctica. The intrusion of relatively warm, salty, and nutrient-rich Circumpolar Deep Water (CDW) close to the coast along the narrow shelf zone of the Amundsen Sea is attributed to the rapid melting of floating ice shelves that contain Fe, thereby providing ideal conditions for phytoplankton blooms within coastal polynya during the spring and summer. Since heterotrophic bacteria are responsible for the rapid turnover of dissolved organic carbon (DOC), it is particularly important to determine the role of heterotrophic bacteria that are associated with the fate of PP in highly productive polynyas. As a part of the KOPRI Amundsen Project (KAP), we investigated bacterial abundance (BA) and production (BP) and its coupling to phytoplankton in the ASP during a bloom by Phaeocystis antarctica in January 2014. Overall oceanographic parameters indicated that the center of the polynya was characterized by higher surface temperature and strong stratification resulting from ice-melting at the sea surface, which should be responsible for the enhanced phytoplankton biomass. Chl-a concentration, BA and BP exhibited higher through the polynya stations and at the Getz ice shelf where upwelling of glacier-derived melt water occurs. A significant positive relationships were obtained between bacterial parameters and Chl-a (BA = 0.39 Chl-a + 0.39, $r^2 = 0.30$, $p < 0.0001$; BP = 1.34 Chl-a + 0.99, $r^2 = 0.39$, $p < 0.0001$) and temperature (BA = 1.64 Temp + 3.39, $r^2 = 0.25$, $p < 0.0001$; BP = 5.59 Temp + 11.31, $r^2 = 0.24$, $p < 0.0001$). The results indicated that the bacterial parameters were tightly coupled to the DOC supplied from the phytoplankton during the Phaeocyctis bloom in the ASP.

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"Physical and biological forcing on the mesoscale variability of the carbonate system in the Ross Sea (Antarctica) in summer 2014"

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Several studies show that during the summer season, the Ross Sea shelf waters are a strong sink for CO_2 due to high biological productivity, intense winds, high ventilation rates and extensive winter sea ice cover. However, the circulation of the surface waters is largely affected by the presence of small-scale structures such as eddies, fronts or filaments. These structures can have an important influence on the primary productivity and on the intensity of the bloom both supplying nutrients and affecting the water column stability. Nevertheless, little is known about the effect of the mesoscale physical and biological processes that determine the carbonate system variability and more particularly the air-sea CO_2 fluxes, which is of particular importance in order to predict future changes associated with climate change in the Ross Sea. To this purpose, the RoME (Ross sea Mesoscale Experiment) project used a combination of remote sensing and high resolution in situ ship measurements during its cruise in the austral summer 2013-14, as part of the Italian National Program of Research in Antarctica (PNRA – Programma Nazionale di Ricerca in Antartide). Remote sensing aided both the sampling strategy and in situ point measurements to be placed within a wider context. Measurements of total alkalinity (A_T) and pH were made in three mesoscale experiments. A_T and pH_T data were then used as input parameters in the CO_2-chemical speciation model CO_2SYS to calculate the pCO_2 values. The pCO_2 at the sea surface was under saturated with respect to the measured atmospheric value, but a large variability in the sea–air CO_2 fluxes was observed associated with different responses in the strength of the biological and physical processes and of wind speed.

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Microzooplantkon herbivory in the Amundsen Sea Polynya, Antarctica

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The studies on microzooplankton in the coastal polynya of Amundsen Sea are still poorly documented. As a part of the Korea Antractic research program, we investigated microzooplankton biomass, community structure and their herbivory in the Amundsen Sea Polynya (ASP) during two seasons (summer, Jan. 2011; late summer, Feb. 2012). Average chlorophyll-a concentration was relatively high in 2011 compared to 2012. Phytoplankton community dominated over 70% by Phaeocystis antarctica. Biomass of P.antarctica was low in the 2012 compared to 2011, and solitary type and colony type were dominant in 2011 and 2012, respectively. Microzooplankton group was dominated by heterotrophic dinoflagellate and large ciliates both seasons. Microzooplankton grazing impacts on phytoplankton was relatively high in 2011 compared to 2012. During 2011, microzooplankton grazing rate often equaled or exceeded phytoplankton growth rates during 2011. This result indicates that microzooplankton grazing on P. antarctica colony type was very low compared to grazing on solitary species. In this study site, microzooplankton grazing rates were significantly correlated only to phytoplankton growth rate ($p<0.001$), and not to initial chlorophyll-a concentration or other measured environmental factors. In the ASP, microzooplankton grazing rates were extremely high compared to rates reported summer and spring 1997 in the Ross Sea Polynya. These results show that microzooplankton was grazing more vigorously in the ASP, although microzooplankton grazing rate was relatively low in 2012. Our study suggests that microzooplankton herbivory may be a driving force controlling phytoplankton growth during summer in the ASP.

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Circulation and hydrography in the Filchner Depression, Weddell Sea- Results from moored instruments

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Cold and relatively dense Ice shelf Water formed below the Filchner-Ronne Ice shelf flows northward along the eastern flank of the Filchner Depression to eventually descend the continental slope and become bottom water. Meanwhile, there is an adjacent seasonal inflow of warm water towards the ice shelf cavity that is projected to increase drastically in a warmer future. We present results from four 1-year-long time series from oceanographic moorings - three deployed across the eastern flank of the depression at 77S and one at the ice shelf front – and describe the observed circulation, hydrography and seasonal variability. The highest temperature observed at the ice shelf front at depths below the ice shelf draft is -1.5 C in April, 2013.

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Interaction of the Weddell Sea continental shelf with the Antarctic coastal current/Antarctic slope front - an idealized model study

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Future climate scenarios suggest an increased flow of warm water towards the Filchner-Ronne ice shelf cavity as the coastal current is redirected onto the continental shelf where the shelf opens up and widens at about 10W. We use an idealized, eddy resolving numerical model to study the dynamics of the Antarctic coastal current and the Antarctic slope front as the flow encounters the widening continental shelf representative of the southern Weddell Sea. A 1700 m deep narrow shelf channel is connected to a 400 km wide and 400 m deep shelf with a continental slope of 0.026. The channel is forced with idealized wind stress and zonally periodic boundary conditions. We present preliminary results from the simulations where we focus on dynamic response to seasonally changing wind forcing. We discuss the mechanisms that affect the cross slope exchange, and sensitivity to atmospheric forcing and different water masses on the continental shelf.

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Stability properties of the Antarctic Slope Front and implications for cross-slope heat transport

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The potential of warmer Southern Ocean intermediate waters for driving ice shelf basal melting and the relation to sea level is subject to vivid scientific debate. In the Eastern and Central Weddell Sea, intermediate pulses of Modified Warm Deep Water enter the continental shelf and high-resolution general circulation models have demonstrated the important role of eddy dynamics in regulating cross-frontal heat transport. Here we combine oceanic observations with idealized numerical modeling to study the stability properties of the Antarctic Slope Front. Linear growth rates and associated scales are calculated for the seasonally varying frontal structure, using quasi-geostrophic and multiple-layer shallow-water formulations. The relative role of baroclinic and barotropic instability and the stabilizing effect of topography will be assessed. The results will be compared to idealized high-resolution simulations, in which diagnosed eddy fluxes will be related to mean properties of the flow filed, aiming to improve the large-scale eddy parameterizations.

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Can we map the interannual variability of the whole upper Southern Ocean with the current database of hydrographic observations?

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With the advent of Argo floats, it now seems feasible to study the interannual variations of upper ocean hydrographic properties of the historically undersampled Southern Ocean. To do so, scattered Argo profiles first need to be mapped. To investigate biases and errors associated both with the limited space-time distribution of Argo profiles and with mapping methods, we colocate the mixed layer depth (MLD) output from a state-of–the-art 1/12° DRAKKAR global ocean/sea-ice simulation onto the latitude, longitude and date of actual ARGO float measurements from 2005 to late 2014. We compare the results obtained after remapping these using a nearest neighbour (NN) interpolation and an objective analysis (OA) with different spatio-temporal grid resolutions and decorrelation scales, and a modified OA incorporating physical constraints. For all methods, the mean error between the re-mapped output and the model decreases until 2009 as the coverage increases, albeit with seasonal variations. We find that the error increases with the spatial resolution and decreases with larger decorrelation radii. The sign of the error seasonally varies: NN predicts too shallow MLD in winter but too deep in summer, while OA is always too shallow on average, although more areas are too deep in winter. We also highlight sectors of the ice-free Southern Ocean for which such a mapping is still impossible.

IAPSO (Physical Oceanography)

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IUGG-1477

Heat and freshwater convergence anomalies in the Atlantic Ocean inferred from observations

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Observations of thermosteric (TSL) and halosteric sea level (HSL) from hydrographic data, liquid water equivalent (LWE) from GRACE and altimetric sea surface height (SSH) are used to infer meridional heat transport (MHT) and freshwater convergence (FWC) anomalies for the Atlantic Ocean. An ``unknown control' version of a Kalman filter in each of eight regions extracts smooth estimates of heat transport convergence (HTC) and FWC from discrepancies between the response to monthly surface heat and freshwater fluxes and observed heat and freshwater content. The model is run for 1993-2012. Estimates of MHT anomalies are derived by summing the HTC from north to south and adding a spatially uniform, time-varying MHT derived from observed values near 40N. Estimated anomalies in MHT are comparable to those recently observed at the RAPID/MOCHA line at 26.5N. FWC estimates in the Atlantic Ocean (67N to 35S) have a minimum in 2003-2004 (anomaly of -0.1 Sv) with subsequently increasing values (to 0.1 Sv) with error estimates of about 0.1 Sv. The FWC anomaly increases over the latter part of the record at a time when MHT decreases (freshwater convergence as the AMOC decreases) indicative of positive feedback between the MOC and FWC and consistent with a bistable overturning circulation.

IAPSO (Physical Oceanography)

P08a - P08 MOC and Deep Currents

IUGG-2364

North Atlantic heat transport at 26.5°N: New insights from synthesis of RAPID array observations with a high resolution ocean GCM

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The RAPID/MOCHA/WBTS project has been measuring the Atlantic Overturning circulation (AMOC) at 26.5 N in the North Atlantic since 2004. We compare ocean heat transport (OHT) at 26.5 N derived from the NEMO-LIM2 ocean circulation/sea ice model with the RAPID measurements. NEMO is run at 1/12 degree horizontal resolution, forced by the Drakkar Surface Forcing dataset which supplies surface air temperature, winds, humidity, surface radiative heat fluxes and precipitation. The model simulates the period 1978-2010.

The basin wide model mean OHT underestimates the RAPID observations (0.76±0.35PW vs 1.26±0.37 PW), but shows very similar seasonal to interannual variability, including the major reduction of the AMOC observed in 2009-10. The lower value from the model is mainly due to underestimates of the northwards Florida Current (0.18 PW) and overestimates of the southwards mid ocean current between the Bahamas and Africa (0.33 PW). The model accurately reproduces the observed correlation between the OHT and the AMOC. The AMOC model values also underestimate RAPID observations (13.44±4.32Sv vs 17.57±5.49Sv).

We use the model to study decadal OHT variability. The model shows a decline in the mean OHT from 1.02PW to 0.80PW between the 1980s and the present. We investigate the cause of this decline by examining decadal changes in ocean circulation and stratification, and surface atmospheric circulation and air sea interaction in the North Atlantic since the 1980's. The consequences of the change in OHT are addressed by examining changes in the ocean heat content in the North Atlantic subtropical and subpolar gyres.

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P08a - P08 MOC and Deep Currents

IUGG-3136

Observations of the North Atlantic meridional overturning circulation

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in the North Atlantic the meridional overturning circulation (MOC) is responsible for a northwards heat transport which reaches a maximum near 30°N of the order of 1.3 PW. Thus the North Atlantic MOC plays a central role in the global energy balance and its variability on seasonal and longer time scales has important impacts on climate. The first measurements of the MOC were made from hydrographic section and since then a growing number of observational programs have expanded our knowledge and understanding of the MOC. In particular the RAPID-MOCHA-WBTS program has completed the first decade of continuous trans-Atlantic monitoring of the MOC at 26°N. The RAPID 26°N data have been used to quantify the variability of the MOC on timescales from days to years. Whilst one decade is relatively short in the context of climate change the results have already revealed variability significantly different from many climate simulations. Results from the RAPID 26°N program have also revealed mechanisms of MOC variability in the sub-tropics. Other in-situ observations of the MOC have mostly focused on the deep western boundary currents, and further studies have used Argo and remotely sensed data to estimate the MOC. In coming years new programs will obtain more detailed measurements in the sub-polar gyre. Reconciling these different observations to describe the meridional structure of the MOC and elucidate the forcing mechanisms remains a major challenge.

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IUGG-4193

Advances in the understanding of the Atlantic meridional overturning circulation

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Through its ability to redistribute and store large amounts of heat and carbon the Atlantic Meridional Overturning Circulation (AMOC) represents an important component of the climate system. Surface waters supplied by the Atlantic circulation entering the Nordic Seas experience heat loss to the atmosphere, triggering deep open-ocean convection. While descending into the Atlantic the transformed dense waters entrain ambient waters, further amplifying the downwelling branch of the AMOC. Here the different contributions to the downwelling branch will be discussed.

A dominant role for the upwelling branch of the AMOC has been ascribed to the Southern Ocean, where the heat and carbon inventories may interact with the Antarctic ice sheets and the atmosphere. The upwelling branch appears to be primarily driven by the Ekman divergence imposed by the Southern Ocean wind field. Thus, the deep waters formed in the North are brought close to the sea surface almost adiabatically (i.e., without requiring large-scale, intense diapycnal mixing below the mixed layer). As a result, a vigorous eddy field is encountered in the Southern Ocean, which acts to both release the potential energy put in by the wind field, and flux heat toward Antarctica without requiring a zonal mean meridional geostrophic flow. In contrast, the latter is a major mechanism of ocean heat transport in large parts of the Atlantic. How the basin-scale AMOC might react to long-term changes in the surface forcing remains difficult to simulate, because critical processes governing both the upwelling and downwelling branches involve fluxes of energy from the basin-scale forcing to the ocean mesoscale and onwards to the small-scale turbulence which in turn affects the basin scale circulation.

IAPSO (Physical Oceanography)

P08b - P08 MOC and Deep Currents

IUGG-1042

Eddy-induced variability of the meridional overturning circulation in a model of the North Atlantic

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Observations of the Atlantic Meridional Overturning Circulation (AMOC) show that it varies on all timescales. Here we isolate the contribution of eddies to AMOC variability using an eddy-permitting model of the North Atlantic driven by climatological and steady forcing. The eddy-induced AMOC variability is found to be ubiquitous and significant at all latitudes, with a magnitude comparable to the seasonal cycle in the subtropics. Furthermore, the eddy-induced AMOC variability is manifested not only at high frequencies but also at interannual and longer timescales. These results imply that a significant fraction of the AMOC variability is inherently unpredictable at seasonal to interannual timescales.

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IUGG-2758

Variability, instabilities and eddies in a Snowball ocean

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Ocean circulation under Snowball Earth conditions was previously shown to be strong and complex. Here we study oceanic eddy dynamics under Snowball Earth conditions (i.e., ocean covered by ~1 km thick ice and driven by a very weak geothermal heat flux), and show that it is characterized by an turbulent eddy field, zonal jets that propagate towards the equator and a strongly variable (tens of Sv) meridional overturning circulation (MOC) that is restricted to be very close to the equator. There are two main opposite-sign zonal jets around the equator that are not eddy driven, together with multiple secondary eddy-driven jets off the equator. Analysis of the Lorenz Energy Cycles indicates that indeed the equatorial jets are not eddy driven, the instability off the equator is primarily baroclinic but also barotropic, and far from the equator it is only baroclinic. The MOC variability is found to be due to occasional interaction of warm plumes driven by geothermal heating that reach the ocean surface, leading to ice melting events and to a change of stratification and of MOC. The estimated eddy diffusion coefficient is comparable to that of the present-day ocean, and the stratification is very weak, indicating that the ocean is well mixed horizontally and vertically. The results presented here may also be relevant to ocean dynamics of planetary ice-covered moons such as Europa and Enceladus.

IAPSO (Physical Oceanography)

P08b - P08 MOC and Deep Currents

IUGG-4035

Recent changes in the Atlantic meridional overturning circulation: A thermohaline perspective

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Interannual variability in the volumetric water-mass distribution within the North Atlantic subtropical gyre is described in relation to the recent reported variability in the Atlantic Meridional Overturning Circulation. We investigate the relative roles of buoyancy forcing at the sea-surface, locally driven changes in the wind-driven circulation and remote changes in the overturning. We project the data into thermohaline coordinates as volumes of water defined by their temperature and salinity, using data from an Argo based gridded climatology and a high-resolution ocean state estimate (ECCO). Regarding the reported Atlantic meridional overturning circulation changes, during the winters of 2009/10 the total subtropical gyre volume above the thermocline decreases while the volume below increases in compensation, a redistribution that is equivalent to a transport of 25 Sv (1 Sv==10^6 m^3s^-1) over 3 months. A comparison to two air-sea flux re-analyses products shows that this variability cannot be explained by anomalous cooling over the subtropical gyre, suggesting the volumetric redistribution is caused by changes in the transport divergence between 26 and 45N. In ECCO, we see a reduction in the zonal circulation of the subtropical gyre with a divergence of transport above the thermocline, compensated below the thermocline by an increase in the southward transport at 45N and a decrease at 26N. Anomalous wind-stress curl over the subtropical gyre in two wind-stress products suggest this change is a barotropic response to wind-driven changes. To investigate further we explore the spatial patterns of change associated with the wind-driven circulation through EOF analysis and idealised gyre simulations.

IAPSO (Physical Oceanography)

P08b - P08 MOC and Deep Currents

IUGG-4777

Meridional propagation of meridional volume transport anomalies in an idealised model

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An idealised reduced-gravity model is used to investigate the meridional coherence of meridional overturning circulation anomalies in the Atlantic ocean. The model is run at both eddy-resolving and non-eddying resolutions, the latter comparable with ocean circulation models currently used for climate prediction. Our idealized model produced meridionally coherent volume transport anomalies. A time-lagged autocorrelation of meridional volume transport anomalies shows southwards propagation at all latitudes.

Anomalies in the western boundary current of the subpolar gyre propagate advectively, but are compensated by changes in the gyre circulation. The zonally integrated transport propagates at the speed of a boundary wave, showing that previous idealised results are robust in the presence of a mean flow.

IAPSO (Physical Oceanography)

P08b - P08 MOC and Deep Currents

IUGG-5040

The influence of high frequency atmospheric forcing on the circulation and deep convection of the Labrador sea

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The influence of high frequency atmospheric forcing on the circulation of the North Atlantic ocean with emphasis on the deep convection of the Labrador Sea was investigated by comparing simulations of a coupled ocean-ice model with hourly atmospheric data to simulations in which the high frequency phenomena was filtered from the air temperature and wind fields. In the absence of high frequency atmospheric forcing we found that the strength of the AMOC and subpolar gyres decreased by 25%. In the Labrador Sea,the eddy kinetic energy decreased by 75% and the average maximum mixed layer depth decreased by between 20% and 110% depending on the climatology.In particular, high frequency forcing was found to have a greater impact on mixed layer deepening in moderate to warm years whereas in relatively cold years the temperatures alone were enough to facilitate deep convection.Additional simulations in which either the wind or temperature was filtered revealed that the wind, through its impact on the bulk formulae for latent and sensible heat, had a greater impact on deep convection than the temperature.

IAPSO (Physical Oceanography)

P08b - P08 MOC and Deep Currents

IUGG-5135

Estimating the Atlantic overturning at 26?N using satellite altimetry

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Observations of the MOC from boundary arrays have demonstrated substantial variability of the large-scale circulation from weekly- to interannual timescales. At 26?N, a reducing trend of -0.5 Sv/year was identified over 2004-2012, though the significance of this trend has been called into question amidst longer-term variations not yet measured.

Here, we use sea surface height (SSH) data from satellites to estimate the interannual variability of transbasin ocean transports at 26?N. From the in situ observations at 26?N, we find that the variations at the western boundary dominate interannual variability of the MOC. Using a simple regression between SSH and transport, SSH near the western boundary covaries with the transbasin transports on interannual timescales and additionally shows the broad pattern of SSH anomalies associated with changes in transports.

Combining SSH-derived estimates for transbasin transport with surface Ekman transport and cable measurements of the Florida Current, we construct a proxy time series of the MOC from 1993-2014. This satellite-based estimate recovers over 90% of the interannual variability of the MOC at 26?N as measured by the RAPID array. These results complement in situ observational efforts to measure transports at multiple latitudes, and open the door to a broader spatial understanding of the Atlantic circulation variability.

IAPSO (Physical Oceanography)

P08c - P08 MOC and Deep Currents

IUGG-0411

Evolution of Atlantic water masses since the Last Glacial Maximum based on a transient run of a global climate model

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During the last deglaciation, the high latitudes of the Atlantic Ocean underwent major changes. Besides the continuous warming, the polar and subpolar ocean surface received a large amount of meltwater from the retractring ice sheets. These changes in temperature and salinity affected deep waters, such as the Antarctic Bottom Water (AABW) and the North Atlantic Deep water (NADW), which formed in the Southern Ocean and in the northern North Atlantic, respectively. In this paper, we present the evolution of the physical properties and the distribution of the AABW and NADW since the Last Glacial Maximum using the results of a transient simulation with the NCAR-CCSM3. Our results show that NADW was absent in the beginning of the deglaciation, while its intermediate version -- Glacial North Atlantic Intermediate Water (GNAIW) -- was being formed. GNAIW was a fresh and cold water mass, very similar to AAIW in the thermohaline domain. The deep and abyssal Atlantic basin was dominated by AABW in the first half of the simulation. The transition from GNAIW to NADW occurred after the Heinrich Stadial 1. When the NADW appears, at nearly 12 thousand years ago, AABW retracts and is constrained to lie near the bottom.

IAPSO (Physical Oceanography)

P08c - P08 MOC and Deep Currents

IUGG-2577

The Meridional Overturning Circulation in global coupled models: current understanding of its variability and predictability and remaining challenges.

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Through its associated heat and salt transports, the Atlantic meridional overturning circulation (MOC) has been shown to have a significant influence on global climate through interactions with the atmosphere on interannual and decadal time scales. Because of the rather short record of continuous observational estimates of MOC transports, support for such a prominent role for the MOC primarily comes from coupled general circulation model simulations, many of which show rich variability of the MOC particularly on decadal and longer time scales. It is important to identify the uncertainties of current generation climate models in simulating MOC-related changes that result from both internal variations and external forcing. We review in this talk the mechanisms of variability of the MOC in global coupled models. We present the robustness and discrepancies between selected models in terms of MOC magnitude, time scales of variability, response to atmospheric forcing, and sensitivity to freshwater forcing. The surface temperature anomalies associated with the MOC fluctuations on decadal time scales resemble the observed Atlantic Multidecadal Variability (AMV) pattern, which has been shown to be an important driver of climate in the North Atlantic and surrounding areas as well as in many regions beyond the Atlantic. We present the ability of the GFDL climate models to simulate these impacts when the AMV is prescribed and we assess the extent to which these impacts can be predicted in advance when the ocean is initialized from observational estimates. Finally, we explore the influence of oceanic resolution in simulating MOC variability and discuss the influence of oceanic mesoscale processes in representing MOC pathways in the South Atlantic.

IAPSO (Physical Oceanography)

P08c - P08 MOC and Deep Currents

IUGG-3010

Energy transfer of surface wind induced currents to the deep ocean via resonance with the Coriolis force

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There are two main comparable sources of the energy of the deep ocean--winds and tides. There are various mechanisms for the indirect transformation of surface winds into the deep ocean. Here we show, using oceanic GCM, that the wind directly supply energy down to the bottom of the ocean when it is stochastic or when it is periodic with a frequency that is equal to the Coriolis frequency. Basically, under such conditions one of the wind components resonates with the Coriolis frequency. Using the finite depth Ekman layer model we show that when the wind stress is purely periodic with a frequency that is equal to the Coriolis frequency, the surface current speed is proportional to the depth of the ocean, the current speed decreases linearly with depth, and the total kinetic energy is proportional to the cube of the depth of the ocean. When the wind stress is stochastic the second moment of the surface current speed increases logarithmically as a function of depth, the current speed decreases linearly with depth in the deep ocean, and the total kinetic energy is proportional to the depth of the ocean. Our results suggest that (i) the wind contribution to the energy of the deep ocean may be significantly larger than that of tides and that (ii) the seminal, infinitely deep, depth depended Ekman layer model is ill defined when forced by stochastic wind (or periodic wind with a frequency that is equal to the Coriolis frequency) unless a friction term is added.

IAPSO (Physical Oceanography)

P08c - P08 MOC and Deep Currents

IUGG-4661

Millenium timescale variability of the meridional overturning circulation: The Dansgaard-Oeschger oscillation

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Under cold glacial conditions it has been well established on the basis of ice-core derived inferences of polar atmospheric temperatures that the global ocean circulation has exhibited intense oscillations on a millenium timescale. Although their existence was inferred more than 30 years ago, it is only recently that they have been recovered in a comprehensive model of coupled climate evolution (Peltier and Vettoretti, GRL 41(20), 7306-7313, 2014). Because the coupled model of them is complete, it has been possible to connect the phenomenon unambiguously to a nonlinear oscillation of the Meridional Overturning Circulation (MOC). As we have shown, the physics underlying the process involves what we have referred to as a 'kicked' salt oscillator in the Atlantic Basin. During a single period of the oscillation salinity in the sub-tropical gyre increases and decreases as does the salinity beneath the ephemerally sea ice covered region of the North Atlantic. In the 'stadial state' of low overturning strength, the salinity steadily increases in the sub-tropical gyre and diminishes in a polar halocline beneath the region of North Atlantic sea ice cover. When a critical latitudinal gradient of surface salinity is exceeded, the overturning strength re-invigorates and interstadial conditions of strong overturning are re-established. The model explains not only the existence of the oscillation and its timescale but also the bipolar 'seesaw' nature of its connection to the southern hemisphere. As we demonstrate a primary additional determinant of its properties concerns the representation of the turbulent diapycnal difusivity that is employed to represent the vertical flux of mass that is needed to enable the upwelling of abyssal waters back to the surface in the southern ocean.

IAPSO (Physical Oceanography)

P08c - P08 MOC and Deep Currents

IUGG-5676

Changes in ocean vertical heat transport with global warming

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Heat transport between the surface and deep-ocean strongly influences transient climate change. It has been proposed that the nature of the mean deep overturning circulation could set the rate of ocean heat uptake under anthropogenic warming. This is investigated using coupled climate models and by projecting ocean circulation into the temperature-depth diagram. In the pre-industrial climate, a 'cold cell', coincident with Antarctic Bottom Water, cools the deep ocean. This cooling is balanced by warming due to a `warm cell', coincident with the inter-hemispheric overturning and previously linked to wind and haline forcing. With anthropogenic warming, the cold cell collapses -- consistent with the capping of a thermally driven circulation -- while the warm cell continues to warm the deep ocean. Simulations with increasingly strong warm cells, set by their mean Southern Hemisphere winds, exhibit increasing deep-ocean warming in response to the same anthropogenic forcing. It is argued that the partition between components of the circulation which cool and warm the deep ocean in the pre-industrial climate, is a key determinant of ocean vertical heat transport with global warming.

IAPSO (Physical Oceanography)

P08d - P08 MOC and Deep Currents

IUGG-1465

Observations of the meridional overturning circulation in the Southern Ocean

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The Antarctic Circumpolar Current (ACC) is the planet's largest current, comprising multiple deep-reaching fronts that encircle the globe, distributing heat, salt and freshwater between the major oceans. Strong westerly winds of the Southern Hemisphere drive upwelling and ventilate water masses along the steeply shoaling isopycnals associated with the ACC fronts. In a zonally-averaged framework, meridional exchange across the ACC has been idealized as a vertical meridional overturning circulation (MOC). In the upper MOC cell, upwelled water is transported northward in the Ekman layer and eventually subducts into the ocean interior as Antarctic Intermediate Water; this northward Ekman transport is countered by southward eddy transports. In the lower MOC cell, water upwelled close to the continent is transformed into Antarctic Bottom Water and returns north as a deep abyssal flow. The rate of Southern Ocean upwelling and meridional transport provides a control on the exchange of heat and carbon between the subthermocline reservoirs of the subtropical oceans and the atmosphere and is thus an important regulator of global climate. Despite the significance of the Southern Ocean MOC, many outstanding questions remain regarding the mechanisms, magnitude and locations of meridional exchange along the ACC, in part due to a deficiency of historical observations in this remote region. Southern Ocean observations are increasing rapidly, however, from modern platforms such as satellite altimeters and autonomous floats and also from recent intensive field programs. This talk provides a review of both recent and historical observations that give insight into the 3-D Southern Ocean meridional overturning circulation.

IAPSO (Physical Oceanography)

P08d - P08 MOC and Deep Currents

IUGG-1810

Structure and Variability of the Indonesian Throughflow across 114ºE in an Global, Eddy-Resolving Numerical Simulation

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Outputs from a numerical experiment are analyzed to investigate the vertical structure and time variability of the zonal transports of volume, heat and salt across 114ºE. The model is a 1/12-degree, global implementation of the Hybrid Coordinate Ocean Model (HYCOM) and the experiment is forced with products of the NCEP Reanalysis, for the period 1949 to 2014. Time series of the 10 days-averaged model results show that the zonal fluxes are predominantly westward and concentrated in a shallow jet between 13ºS and 9ºS, from the surface to depth of approximately 500m. The total volume transport across 114ºE, integrated from 22ºS to 8ºS, shows variability from annual to interannual scales, with a mean value of about 1 Sverdrup to the west. Further analyses are being conducted and the results will be compared with observations and results of other numerical models.

IAPSO (Physical Oceanography)

P08d - P08 MOC and Deep Currents

IUGG-2550

Mechanisms of Meridional Overturning Circulation hysteresis in a Global Climate Model and the importance of hosing scenarios

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A previous paper (Hawkins et al, 2011) described the first time in which a hysteresis of the Meridional Overturning Circulation has been found in a general circulation model. They showed that, for a given input of fresh water into the north Atlantic, there existed two possible states: one with a strong overturning in the north Atlantic and the other with a reverse Atlantic cell.

In this study we investigate the mechanisms behind the hysteresis. We assess the changes in surface fluxes and advection that lead to nonlinear Meridional Overturning Circulation changes and the connection between the Atlantic and Pacific overturning circulations. The formulation of the hosing scenario, and in particular how the input of fresh water into the Atlantic is compensated, is found to be very important.

Hawkins et al (2011), Bistability of the Atlantic overturning circulation in a global climate model and links to ocean freshwater transport, GRL, 38, L10605, doi:10.1029/2011GL047208.

IAPSO (Physical Oceanography)

P08d - P08 MOC and Deep Currents

IUGG-4950

Abyssal volume and heat transport through the Samoan Passage: A 16-month timeseries based on recent observations

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The flow of dense water through the Samoan Passage accounts for the majority of the bottom water renewal in the North Pacific, thereby making it an important element of the Meridional Overturning Circulation. Here we report recent measurements of the flow of dense waters of Antarctic and North Atlantic origin through the Passage. A sixteen month long moored time series of velocity, temperature and salinity of the abyssal flow was recorded between 2012 and 2013. This allows for an update of the only prior volume transport time series from the Samoan Passage from 1992/1993. While highly variable on various time scales, the overall pattern of the abyssal flow through Samoan Passage was remarkably steady. The time-mean northward volume transport of about 5.5 Sv in 2012/2013 stayed within the uncertainty of +/- 1 Sv of the earlier measurements. However, the abyssal current significantly warmed on average by 1 mdeg/year over the past two decades. This implies increased heat transports into the deep North Pacific.

IAPSO (Physical Oceanography)

P08d - P08 MOC and Deep Currents

IUGG-5480

The importance of wind and buoyancy forcing for the boundary density variations and the AMOC at 26°N

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It is widely thought that changes in both the surface buoyancy fluxes and wind stress drive variability in the Atlantic meridional overturning circulation (AMOC), but that they drive variability on different time scales. For example, wind forcing dominates short-term variability through its effects on Ekman currents and coastal upwelling, whereas buoyancy forcing is important for longer time scales (multiannual and decadal). However, the role of the wind forcing on multiannual to decadal time scales is less clear.

Here we present an analysis of simulations with the 1 degree Nucleus for European Modelling of the Ocean (NEMO) ocean model with the aim of explaining the important drivers of the zonal density gradient at 26°N, which is directly related to the AMOC. In the experiments, only one of either the wind stress or the buoyancy forcing is allowed to vary in time, whereas the other remains at its seasonally varying climatology. On subannual time scales, variations in the density gradient, and in the AMOC minus Ekman, are driven largely by local wind-forced coastal upwelling at both the western and eastern boundaries. On decadal time scales, buoyancy forcing related to the North Atlantic Oscillation dominates variability in the AMOC. Interestingly, however, it is found that wind forcing also plays a role at longer time scales, primarily impacting the interannual variability through the excitation of Rossby waves in the central Atlantic, which propagate westward to interact with the western boundary, but also by modulating the decadal time-scale response to buoyancy forcing. An assessment of the robustness of these results to model resolution and a comparison to the RAPID observations will also be presented.

IAPSO (Physical Oceanography)

P08e - P08 MOC and Deep Currents

IUGG-0717

Flow of Antarctic bottom water into the Romanche fracture zone

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We analyze the flow of Antarctic Bottom Water through a narrow gap in the western part of the Romanche Fracture Zone that allows the bottom water propagate into the fracture. Before, there were no studies of the flow in this region reported in the literature and databases. We found a deep-water cataract in the region where AABW flow enters the Romanche Fracture Zone approximately at 01°05' S, 22°27' W. Measurements with CTD and LADCP were repeated four times in 2011-2014. A mooring with current meters was deployed in the cataract for six months. The mean horizontal velocities of the flow near the bottom are 0.40 m/s, but they reach 0.65 m/s, and the mean vertical velocities are as high as 0.05 m/s. The slope of the flow in the cataract is 1/10. The transport of bottom water with θ < 1.00°C in the cataract based on the LADCP measurements is estimated at 0.23–0.27 Sv, which is approximately 40% of the known transport estimates through the fracture in its middle part. The cataract is a cascade of the flow initially over two sills with depths of 4570 and 4430 m, and then they merge in a flow over a sill of 4870 m deep. The flow over the first sill is directed to the east, the flow over the second sill (the maximum transport) is in the northern direction and the merged flow continues to the east. We recorded a minimum temperature of 0.501°C at the entrance to the fracture.

IAPSO (Physical Oceanography)

P08e - P08 MOC and Deep Currents

IUGG-1312

Relationship between decadal variability of European and North American heat waves and South Atlantic Meridional heat transport.

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This study tested the hypothesis whether low frequency decadal variability of the South Atlantic meridional heat transport (SAMHT) and meridional overturning circulation (MOC) influences decadal variability of extreme events of the form of heat waves. A multi-century run from a state-of-the-art coupled general circulation model is used as basis for the analysis. Results suggest that weaker SAMHT leads to increase occurrence and severity of heat waves over Eastern Europe and Western North America as measured by their duration and amplitude. For the Eastern Europe case, weaker SAMHT is associated with stationary atmospheric wave flux from the subtropical Atlantic Ocean towards Europe along with SST anomaly gradient, interacting with enhanced monsoonal circulation over the Indian Ocean during boreal summer. This produces subsidence and heat wave condition over Eastern Europe.

An increased in the number and severity of heat waves over western North America is also linked to SAMHT. Weaker SAMHT is associated with enhanced diabatic heating source from the East Asia summer monsoon. This excites atmospheric Rossby waves in conjunction with enhance North American monsoon circulation, producing blocked flow over the Western United States. We conclude that the link between weaker SAMHT, stronger monsoons, and increased heat waves conditions over Europe and North America is through a strengthening of the southern hemisphere Hadley Circulation. This anomalous circulation transports more moisture towards the northern hemisphere, enhancing convection and monsoonal circulation. There is an anomalous southward heat transport associated with weaker SAMHT and stronger southern hemisphere Hadley Circulation, suggesting complex ocean-atmosphere interaction on decadal timescales.

IAPSO (Physical Oceanography)

P08e - P08 MOC and Deep Currents

IUGG-1447

Variability of Deep Currents in the Western South Atlantic: Observations and modeling

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Observations and outputs from a numerical experiment are analyzed to investigate the structure and variability of deep currents in the Southwestern Atlantic. The model is a 1/12-degree, 32 sigma2 layers, global implementation of the Hybrid Coordinate Ocean Model (HYCOM). The data were measured continuously, from Dec/2012 to Oct/2014, with two current-and-pressure-equipped inverted echo sounders (CPIES), deployed at 50.5ºW, 34.5ºS (site AA, 2885m) and 48.5ºS, 34.5ºS (and site BB, 4140m). The time series of the daily-averaged current meter data, measured 50m above the sea floor, show intense variability in a wide range of frequencies. At both sites, the meridional (N-S) component of the flow is less energetic than the zonal (E-W) component; particularly at Site BB. Preliminary calculations show values of mean and standard deviation as follows. Site AA: 1.7±4.8 cm s^{-1} for the zonal flow and 1.2±3.2cm $s^{-1}$for the meridional flow; Site BB: 7.1±14.0 cm s^{-1} and 0.4±3.2 cm s^{-1}, respectively. Despite having lower mean values, the model shows standard deviations in good agreement with the observations at the two sites. Horizontal maps of the model's results suggest that the deep flow in the region is dominated by intense mesoscale eddy-activity and is oriented alongshore.

IAPSO (Physical Oceanography)

P08e - P08 MOC and Deep Currents

IUGG-1784

South Atlantic MOC observations: past, present, future

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The South Atlantic Ocean is unique in its role as a nexus for water masses formed elsewhere and en-route to remote regions of the global ocean. In particular, within the MOC, it links the extreme-climate regions of the Southern Ocean with the North Atlantic. Cold/salty North Atlantic Deep Water flows southward along the eastern coast of South America and through the basin interior, compensated by a northward flow that is a mixture of warm/salty upper thermocline waters and cooler/fresher Antarctic Intermediate Waters as well as veins of bottom water formed around the Antarctic continent. In this way, the South Atlantic Ocean is the only major ocean basin that transports heat from the pole towards the equator. The Drake Passage and the Agulhas Retroflection Region are the main gateways for the entrainment of surface and intermediate waters from the Indian and Pacific basins into the South Atlantic. However, the South Atlantic is not merely a passive conduit for remotely formed water masses. Indeed, within this basin water masses are significantly altered by local air-sea interactions and diapycnal/isopycnal fluxes, particularly in regions of intense mesoscale activity. These contributions have been shown to have a crucial role in the strength of the MOC in paleoceanographic and modeling studies.

The monitoring of the North Atlantic portion of the MOC has been ongoing for a decade now through the RAPID/MOCHA/WBTS program as well as other national and international initiatives. They all provide a scope for understanding the MOC variability in that region.This talk will discuss the considerable observing effort beginning in the South Atlantic Ocean in relation to the monitoring of the MOC and large-scale interbasin fluxes of climate-relevant quantities.

IAPSO (Physical Oceanography)

P08e - P08 MOC and Deep Currents

IUGG-4526

The pathway of the deep circulation in the South Atlantic Ocean

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We compare the pathways of AAIW and NADW in the South Atlantic using the results of eddy- and non-eddy resolving models. The non-eddy resolving model shows water masses pathways that are identical to those portrayed in early observational studies, which posits that surface and AAIWs are entirely drawn from the Indian Ocean (the warm path) and that the DWBC spreads continuously along the continental slope of South America. The eddy-permitting model, however, produces substantially different pathways. Surface and intermediate waters, for example, are not only entrained from the Indian Ocean (the warm path) but also from the Southern Ocean (the cold path). The difference between eddy- and non-eddy permitting models increases with depth. At the NADW level, for example, the eddy-permitting model shows a circuitous pathway that contrasts sharply with the corresponding pathway of the non-eddy permitting model, but is in good agreement with observations.

IAPSO (Physical Oceanography)

P08p - P08 MOC and Deep Currents

P08p-456

Deep Western Boundary Current measurements at 34.5°S in the South Atlantic: Observed variability and structure during 2009-2014

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The Deep Western Boundary Current (DWBC) at 34.5°S in the South Atlantic has been observed continuously for just over five years from 2009 to 2014 using a line of four pressure-equipped inverted echo sounders (PIES). The array was further augmented in late 2012 with an additional two current-and-pressure-equipped inverted echo sounders (CPIES). The data from these PIES and CPIES instruments can, when combined with hydrographic information from the region, provide daily estimates of the full-water-column profiles of temperature, salinity, density and the meridional component of the absolute geostrophic velocity. Variations in the DWBC, which carries a significant fraction of the cold deep limb of the Meridional Overturning Circulation, have previously been shown (using data from 2009-2010) to equal or exceed those found in a longer-term observing array at 26.5°N in the North Atlantic. This presentation will include an additional three years of data at 34.5°S to evaluate the magnitude and time scales of the observed DWBC variations to do a more complete comparison with other latitudes. The CPIES instruments deployed in 2012 also greatly improved the horizontal resolution of the overall array, and as such new insights on the horizontal structure of the DWBC will also be presented.

IAPSO (Physical Oceanography)

P08p - P08 MOC and Deep Currents

P08p-457

Abyssal Flows through the Gaps in the Azores Ridge (37° N) in the East Atlantic

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The East Azores Ridge is considered as the northern limit of the propagation of Antarctic Bottom Water in its classical definition as the water with potential temperature less than 2.0°C. However, abyssal waters north of the Ridge are also considered as the waters of Antarctic origin. Two hydrographic sections consisting of 3 stations with CTD-measurements were carried out across two deepest gaps in the Ridge in October 2011 and in September 2013 to investigate the flow of abyssal Antarctic waters across the Ridge. The section in 2011 across the east gap (Discovery Gap, 16° W) was repeating the line of the British sections in 1982. Our measurements revealed the lowering of near-bottom potential temperature approximately by 0.01°C (from 2.011°C to 2.002°C), which is a significant value in view of very weak abyssal temperature (and density) stratification in the region around the Ridge. Analysis of the historical CTD-database (WOD09) showed that this decrease is likely due to the general cooling of abyssal waters around the East Azores Ridge. The section in 2013 was the first set of hydrographic measurements across the West Gap (19°30′ W). These measurements showed that the West Gap is deeper than the Discovery Gap (4790 m vs. 4680 m); the bottom water in the West Gap was colder (1.995°C). The transport estimate of water colder than 2.025°C based on the LADCP-measurements was 0.15 Sv. This potential temperature of the upper boundary of the flow (taking into account the cooling o abyssal waters) is almost equivalent to a temperature of 2.05°C in the Discovery Gap in 1982. The transport of water colder than 2.05°C in this gap was estimated as 0.21 Sv in 1982. Thus, the transport of abyssal waters through the West Gap is almost the same as through the Discovery Gap.

IAPSO (Physical Oceanography)

P08p - P08 MOC and Deep Currents

P08p-458

Freshwater advection into the Labrador Sea

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Deep convection in the Labrador Sea forms the sinking limb of the Atlantic MOC. While the amount of heat lost to the atmosphere is an important factor to the strength of convection, changes in surface buoyancy, such as additional freshwater, are also critical and can lead to a suppression of deep mixing. With increasing melt rates from Arctic and Greenland ice, freshwater could therefore impact the formation of deep water. Whether the freshwater reaches regions of deep convection is still debated. Using a Lagrangian approach with particles in a NEMO 1/12 degree ocean model, we investigate how and where freshwater from the Greenland boundary currents reaches the central Labrador Sea or if it is simply advected south via the boundary currents. At the surface, particles are advected into the central basin along the entire boundary of the Labrador Sea, while only certain key regions are important in deeper layers. This suggests that Ekman transport as well as eddies are an important factor in transporting freshwater to the basin. Furthermore the key regions in the exchange between the boundary and basin and therefore the freshwater flux show variability over the last decade

IAPSO (Physical Oceanography)

P09a - P09 The North Atlantic and Climate Change

IUGG-1018

Circulation and water mass transport in the subpolar North Atlantic

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The subpolar North Atlantic is characterized by an inflow of the deep reaching warm and saline subtropical water, its transformation in colder and denser water, and a southward export of deep water. We study circulation and water mass transformation with shipboard measurements (hydrography, tracer, velocity), Argo profiles and satellite data. Moored instruments are positioned in the Newfoundland basin and parallel to the Mid Atlantic Ridge. We combine observations with the results of a high resolution ocean model, and present recent results about the circulation and transports of deep-water masses.

IAPSO (Physical Oceanography)

P09a - P09 The North Atlantic and Climate Change

IUGG-1202

Impact of Arctic climate change on the North Atlantic ocean circulation: a model study

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Remote oceanic impacts of Arctic climate change are studied using a surface forced ocean general circulation model. Surface atmospheric fields observed during the Arctic sea ice minimum year 2007 are specified over the Arctic, whilst outside the Arctic observed forcing from 1985 is specified. Relative to a control simulation with 1985 forcing everywhere, modified Arctic forcing causes major changes to the Atlantic Meridional Overturning Circulation (AMOC) and to the temperature, salinity and gyre circulation of the subpolar North Atlantic on timescales of one year to several decades, including modification of the seasonal cycle. A net weakening of the AMOC of ~25% results from a combination of reduced deep convection in the ice free region of the Greenland Sea due to modified surface wind patterns, increased convection in the marginal ice zone of the Greenland Sea due to retreat of sea ice; and modification of Labrador Sea circulation forced remotely from the Greenland Sea and the High Arctic. Transmission to the Atlantic occurs via propagation of barotropic and baroclinic Kelvin waves along the northern and western boundary of the Atlantic, and resulting pressure changes modify the AMOC. The strong response in the North Atlantic subpolar gyre is a consequence of Rossby wave propagation advected by the mean flow associated with the Gulf Stream and the North Atlantic Current. The wave response is strongly modified compared to previous studies because of the inclusion of sea ice, realistic coastlines, ocean bottom topography and mean flow effects.

IAPSO (Physical Oceanography)

P09a - P09 The North Atlantic and Climate Change

IUGG-1220

Pathways of oceanic heat transport from the subtropical to the subpolar gyres in the North Atlantic

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We explore both pathways and variability of the upper-layer throughput from the subtropical to the subpolar gyres of the North Atlantic to understand how, to what extent, and on what time scales oceanic thermal anomalies travel from one gyre to the other. Past studies with both modeled and observed Lagrangian floats have indicated that surface throughput between the two gyres is limited and that sub-surface pathways dominate. We translate these results to the oceanic heat transport by first using the modern satellite SST record (1981-2013) to reconcile the lack of inter-gyre connectivity at the surface with previous findings that showed an advection of SST anomalies from the subtropics to the subpolar gyre. We then launch synthetic trajectories in the FLAME model from the Florida Straits to trace the pathways of water particles along the Gulf Stream/North Atlantic Current. Along these time-varying pathways, we compare the Lagrangian integral time scales of the floats' temperature anomalies to their travel time from the Florida Straits to the subpolar gyre in order to understand whether particles advect any memory of their anomalous temperature into the subpolar region. We then use the synthetic trajectories from FLAME to determine whether the trajectories that reach the subpolar gyre at a given time period collectively influence the upper ocean temperature of the region. Our results cast doubt on the idea that coherent water masses advect temperature anomalies from the subtropical to the subpolar gyres as well as demonstrate the importance of mixing to oceanic heat transport.

IAPSO (Physical Oceanography)

P09a - P09 The North Atlantic and Climate Change

IUGG-1254

Mechanisms of heat content change in the subtropical and subpolar North Atlantic

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North Atlantic climate variability on decadal time scales is often characterised by basin-scale changes in sea surface temperature, which are generally attributed to coherent changes in the meridional overturning circulation. However, this view is inconsistent with striking gyre-scale contrasts in ocean heat content and thermocline depth over the basin: the subtropics are often warm and thermocline thick when the subpolar gyre is cool, and vice versa. The mechanisms controlling the gyre-scale changes in heat content and thermocline depth are examined using dynamical assimilations of historical temperature and salinity data from 1965 to 2011. The tendency of the subtropical heat content is primarily controlled by heat convergence, stronger Trade winds enhancing the influx of heat from the tropics, augmented by the poorly-known air-sea heat fluxes. The tendency of the subpolar heat content is not directly connected to the air-sea heat input integrated over the gyre, but instead is controlled by the convergence in heat transport. The heat transport into the subpolar gyre is though affected by boundary density changes induced by atmospheric forcing: density increases along the Labrador Sea are associated with enhanced overturning at the subtropical/subpolar interface, which then drives a warming of the subpolar gyre. Hence, the heat content anomalies for each gyre are formed via different mechanisms, either directly via the winds and air-sea heat fluxes over the subtropical gyre or indirectly via atmospheric-induced changes in boundary density over the subpolar gyre.

IAPSO (Physical Oceanography)

P09a - P09 The North Atlantic and Climate Change

IUGG-4022

Heat and salt transport in the North Atlantic: New insights from eddy resolving ocean models for climate.

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In the subpolar North Atlantic, warm and saline waters flow towards the Nordic seas; cold and relatively fresh waters sink and flow southward as a boundary current to form the lower limb of the Meridional Overturning Circulation (MOC). These flows and the associated transports of heat and salt contribute to shape the Earth's climate. Coupled climate models usually represent the MOC as a sluggish and viscous flow, because of the coarse resolution of the model grids. The DRAKKAR global models at 1/12°, based on the NEMO modelling framework, represent explicitly boundary currents and eddies at the subtropical fronts, at the entrance of the subpolar gyre. This has made possible in-depth investigations of the mechanims underlying the meridional transports of heat and salt, taking into account the eddy contributions. However we point out deficiencies in the polar regions, where this class of model grids is yet too coarse to reach the eddy resolving regime. Grid refinement strategies allow considerable improvement in the representation of boundary currents and the associated mesoscale and submesoscale instabilities. We review these techniques, developed in the context of the European EMBRACE project, and present preliminary results of subpolar gyre simulations with grids finer than 1/30°. We particularly highlight the role of mesoscale processes in the subpolar gyre in setting the horizontal and vertical structure of the boundary currents.

IAPSO (Physical Oceanography)

P09b - P09 The North Atlantic and Climate Change

IUGG-0791

Association of synoptic variability in surface turbulent fluxes with cyclone characteristics in the North Atlantic

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Surface turbulent heat fluxes are responsible for variability of surface ocean heat budget on synoptic and interannual scales. This variability is driven by variations of near surface atmospheric characteristics controlled in midlatitudes by atmospheric cyclones. We focus on understanding the mechanisms of synoptic variability of surface turbulent fluxes and on the origins of extreme turbulent fluxes and their impact on the atmospheric dynamics. The main questions addressed in this study are (i) what are the large scale atmospheric conditions associated with extreme ocean surface fluxes and are they related to cyclones, (ii) what is the role of extreme surface fluxes in the variability of oceanic heat content, and (iii) which characteristics of atmospheric cyclones are sensitive to the surface ocean flux signals? To answer these questions, we derived characteristics of the extreme surface fluxes from their empirical probability distributions from the NCEP-CFSR reanalysis, 1979-onwards and analyse them together with cyclone characteristics over the midlatitudinal North Atlantic. Cyclone tracking has been performed using state of the art numerical tracking algorithm applied to the reanalysis SLP at 6-hourly resolution. We argue that the presence of the high pressure system following to the rare part of propagating cyclone is a critical condition for the formation of extreme surface ocean fluxes which are associated with the cyclone-anticyclone interaction zone rather than with cyclone per se. We also demonstrate that the fraction of oceanic heat loss due to extremes linked to the atmospheric circulation. Locally this fraction can be as large as 50%. We also show that over the Gulf Stream more than 60% of cyclogenesis were associated with extreme surface fluxes.

IAPSO (Physical Oceanography)

P09b - P09 The North Atlantic and Climate Change

IUGG-1737

Extreme air-sea interaction over the North Atlantic subpolar gyre during the winter of 2013-14 and its sub-surface legacy

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Exceptionally low North American temperatures and record-breaking precipitation over the British Isles during winter 2013-14 were interconnected by anomalous ocean evaporation over the North Atlantic Subpolar Gyre region. This evaporation (or oceanic latent heat release) was accompanied by strong sensible heat loss to the atmosphere. The enhanced heat loss over the Subpolar Gyre was caused by a combination of surface westerly winds from the North American continent and northerly winds from the Nordic Seas region that were colder, drier and stronger than normal. A distinctive feature of the air-sea exchange was that the enhanced heat loss spanned the entire width of the Subpolar Gyre, with evaporation anomalies intensifying in the east while sensible heat flux anomalies were stronger upstream in the west. The immediate impact of the strong air-sea fluxes on the ocean-atmosphere system included a reduction in ocean heat content of the Subploar Gyre and a shift in basin-scale pathways of ocean heat and atmospheric freshwater transport. Atmospheric reanalysis data and the EN4 ocean data set indicate that a longer-term legacy of the winter has been the enhanced formation of a particularly dense mode of Subpolar Mode Water - one of the precursors of North Atlantic Deep Water and thus an important component of the Atlantic Meridional Overturning Circulation. Using particle trajectory analysis, the likely dispersal of newly formed Subpolar Mode Water is evaluated, providing evidence for the re-emergence of anomalously cold Subpolar Mode Water in early winter 2014/15.

IAPSO (Physical Oceanography)

P09b - P09 The North Atlantic and Climate Change

IUGG-2034

Long-term changes in cloud cover and short wave radiation over the North Atlantic

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We analyze cloud cover characteristics along with computed short wave radiative fluxes over the North Atlantic for the last several decades. Characteristics of cloud cover were derived from the Voluntary Observing Ship reports available from International Comprehensive Ocean-Atmosphere Data Set. Frequency distribution of fractional cloud cover was approximated by 3-paramter probability density function, accurately capturing most of variants of cloud cover probability density distribution. Interannual to decadal changes in characteristics of cloud cover (linear trends and shorter term variations) are analyzed in terms of the parameters of this distribution. Next, changes in the cloud cove characteristics over the North Atlantic were associated with variability of short-wave radiation fluxes derived from Voluntary Observing Ship reports for the last 6 decades using a new parameterization, which accounts not only for cloud amount but also for cloud types. The latter is critically important for the conditions close to overcast and may strongly affect short-wave radiation fluxes. Computations demonstrate generally slightly decreasing over the last decades shortwave radiation flux in mid latitudes and also evident interdecadal variability in the tropics of the North Atlantic. These changes are discussed in the context of variability of cloud cove characteristics and in conjunction with changes in turbulent heat fluxes.

IAPSO (Physical Oceanography)

P09b - P09 The North Atlantic and Climate Change

IUGG-2436

Comparative assessment of turbulent air-sea heat fluxes from reanalyses and satellite based products using flux probability density function concept

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North Atlantic surface turbulent sensible and latent heat fluxes from modern era reanalyses (NCEP-DOE, ERA-Interim, MERRA NCEP-CFSR, JRA-25) and satellite products (IFREMER, J-OFURO, HOAPS, SEAFLUX) were intercompared with each other for the last several decades. Overall comparison covered the period of overlap of different products (2000-2007), while comparison for reanalyses was performed for a longer period starting from 1979. The concept of intercomparison besides conventional comparisons of mean values included also analysis of probability density functions derived from high resolution surface flux time series from different products. Surface turbulent flux PDFs were approximated by Modified Fisher-Tippett (MFT) distribution whose parameters put more light on the nature of differences between different surface flux products, Furthermore, this concept allows for robust estimation of extreme flux values which can amount to several thousands W/m^2. Finally, using this concept we can account for the fractional contribution of fluxes exceeding a given percentile to the total flux integrated over long time (e.g. month, year). Comparison performed demonstrated that the highest extreme turbulent latent heat fluxes are diagnosed in NCEP-DOE, ERA-Interim and NCEP-CFSR reanalyses with the smallest being in MERRA. These differences may not necessarily reflect the differences in mean values. Satellite products (e.g. SEAFLUX) may demonstrate even stronger relative extremeness of surface turbulent fluxes than reanalyses, thus capturing better fluxes associated with extreme synoptic conditions.

IAPSO (Physical Oceanography)

P09b - P09 The North Atlantic and Climate Change

IUGG-2875

Surface warming hiatus caused by increased heat uptake across multiple ocean basins; the role of the North Atlantic

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The first decade of the 21st century was characterized by a hiatus in global surface warming. Apart from changes in radiative forcing, increased ocean heat uptake might explain the warming hiatus. Direct estimates from observations are inconclusive in this respect, although increases in estimated heat content and ocean reanalyses do suggest increased ocean heat uptake. The increased heat uptake has been linked to surface cooling in the Tropical Pacific evident over this period, associated with persistent easterlies and greater prevalence of La Niña relative to El Niño. An alternative way to estimate ocean heat uptake is to diagnose changes in heat uptake from ocean hindcast simulations forced by atmospheric fields from meteorological reanalyses, but with SSTs that are free to evolve though partly constrained by surface air temperature and winds. Ocean model hindcasts and reanalyses show that heat uptake between the 1990s and 2000s increased by 0.7 ± 0.3Wm-2. Approximately 30% of the increase is associated with colder sea surface temperatures in the eastern Pacific. The major part, however, comes from reduced heat loss to the atmosphere in subpolar areas, in particular, the Southern Ocean and North Atlantic. A different mechanism is important at longer timescales (1960s–present) over which the Southern Annular Mode trended upward. Over multidecadal timescales increased ocean heat uptake largely arises from reduced heat loss associated the upward trend in the Southern Annual Mode and southward displacement of the Southern Ocean westerlies.

IAPSO (Physical Oceanography)

P09b - P09 The North Atlantic and Climate Change

IUGG-4376

North Atlantic freshwater and heat fluxes: An overview

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Air-sea exchanges of freshwater and heat in the North Atlantic will be reviewed with a focus on the processes controlling these exchanges, methods by which they may be estimated and their impacts on the ocean. The main characteristics of the long term mean exchange fields will be presented with reference to reanalysis, remote sensing, ship observation and blended/hybrid datasets. The diverse range of currently available flux datasets will be assessed in terms of the implied ocean freshwater and heat transports, and the degree of consistency with hydrographic estimates. Variability in the exchanges will also be explored with particular consideration of changes associated with large-scale modes of atmospheric variability and potential changes in E-P linked to the changing hydrological cycle. The ocean impacts of changes in the surface fluxes will examined with a focus on modification of near-surface properties including sea surface salinity.

IAPSO (Physical Oceanography)

P09c - P09 The North Atlantic and Climate Change

IUGG-0242

How the North Atlantic Ocean affects upon the climate of Eurasia

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In the mid-1970s a heat content in the North Atlantic Ocean has substantially changed. Because of its high energy value the event appears to have a significant impact on the regional environment. To verify this suggestion we analyzed the global ocean-atmosphere data related to the negative (1950-1970) and positive (1980-1999) phases of the North Atlantic Oscillation (NAO). The analysis of these data have shown the existence of a thermal dipole in the North Atlantic upper layer which can be interpreted in a sense as an oceanic counterpart of atmospheric NAO. To identify a dynamic of this North Atlantic Dipole (NAD) its index was considered as the ocean 0-100-m layer temperature difference between regions (20-40N; 80-30W) and (50-70N; 60-10W). Then the NAD index was suggested as a factor of the regional ocean-atmosphere system variability possible physical mechanism which in turn could produce a draw effect on the recent climate of Eurasia. To assess the variability of ocean heat content it was used a General Ocean Circulation model developed at the Institute of numerical mathematics RAS. This model belongs to the class of σ-models, and its distinguishing feature is the splitting of the physical processes and spatial coordinates. By using the model there were performed numerical experiments to reproduce an evolution of hydrophysical regime of the North Atlantic Ocean for the period of 1958-2006. As a result there have been revealed quasi-antiphase of 700-m layer heat content variability within two areas under consideration. In respect to prognostic targets it was supposed that the result could be essential for disclosure of relationships between climatic parameters of the Eurasian continent and the thermodynamic processes in the specific areas of the North Atlantic Ocean.

IAPSO (Physical Oceanography)

P09c - P09 The North Atlantic and Climate Change

IUGG-1044

A simple model of the response of the Atlantic to the North Atlantic Oscillation

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The response of an idealised Atlantic ocean to wind and thermohaline forcing associated with the North Atlantic Oscillation (NAO) is investigated both analytically and numerically in the framework of a reduced-gravity model. The NAO-related wind forcing is found to drive a time-dependent ``leaky'' gyre circulation that integrates basin-wide stochastic wind Ekman pumping and initiates low-frequency variability along the western boundary. This is subsequently communicated, together with the stochastic variability induced by thermohaline forcing at high latitudes, to the remainder of the Atlantic via boundary and Rossby waves. At low frequencies, the basin-wide ocean heat content changes owing to NAO wind forcing and thermohaline forcing are found to oppose each other. The model further suggests that the recently reported opposing changes of the meridional overturning circulation in the Atlantic subtropical and subpolar gyres between 1950-1970 and 1980-2000 may be a generic feature caused by an interplay between the NAO wind and thermohaline forcing.

IAPSO (Physical Oceanography)

P09c - P09 The North Atlantic and Climate Change

IUGG-2781

Can the big drop of winter NAO index of 2000/2001 be related to a shift of the Labrador Current?

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The changes of the Labrador Current from 1990 to 2007 are investigated using a high resolution North Atlantic model. Our study suggests that the strength of the western part of the Labrador Current, which is defined as between 300 to 2500 m isobath, jumped by 4.8 Sv from 2000 to 2002. The strength of the eastern part of the Labrador Current (from 2500 to 3400 m isobath) was strong in high NAO years (from 1990 to 1995), and it shows a declining trend from 1995 to 2007. The declining trend of the AMOC is consistent with the declining trend of the eastern part of the Labrador Current, but the declining trend of the AMOC is not shown in the western part of the Labrador Current. Our study suggests that the shift in the western part of the Labrador Current is from a westward shift of the atmospheric system in 2001, which is reflected in the winter NAO index of 2000/2001.

IAPSO (Physical Oceanography)

P09c - P09 The North Atlantic and Climate Change

IUGG-3251

Impact of climate change on European weather extremes

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An emerging scientific consensus is that global climate change will result in more extreme weather events with associated financial losses. Key questions that arise are: Can an upward trend in the frequency/intensity of extreme events be recognised and predicted at the European scale? What are the key drivers within the climate system that are changing and making extreme weather events more frequent, more intense, or both?

Using several state-of-the-art high-resolution coupled climate simulations (HadGEM3-GC2, historical and future scenario runs) as well as real observations (SST and RAPID-AMOC observations), we highlight the potential of the most advanced forecasting systems to progress understanding of the drivers of European weather extremes, and assess future frequency and intensity of extreme weather under various climate change scenarios.

Particular emphasis is given to the link between the Atlantic meridional overturning circulation (AMOC) and European extreme events. Recent research has shown that Atlantic Ocean conditions can increase the likelihood of extreme winters such as occurred in 2009/10 and 1969/70. Using the 26ºN RAPID observations of the Atlantic overturning circulation and the Atlantic Multidecadal Oscillation index timeseries, we analyse extremes in these datasets and investigate whether they are conducive to the occurrence of extreme precipitation and temperature events over Europe.

IAPSO (Physical Oceanography)

P09c - P09 The North Atlantic and Climate Change

IUGG-4473

Seasonal cycle and annual destruction of Eighteen Degree Water

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Eighteen Degree Water (EDW), the subtropical mode water of the western North Atlantic, is a voluminous, weakly-stratified upper ocean water mass. This thick layer acts as a subsurface reservoir of heat, nutrients, and CO2 as it persists throughout the year, but nearly half of its volume is dispersed or mixed away from the time of its formation until it is renewed the following winter, diffusing its properties into the thermocline. The relevant processes responsible for this large annual cycle of EDW destruction are being investigated as part of CLIMODE. CTD observations from Argo and CLIMODE profiling floats are used to observe the cycle of the seasonal pycnocline, which isolates EDW from the surface mixed layer during spring, summer, and fall, and to quantify EDW destruction rates. The highest EDW destruction rates occur during summer when the stratification of the seasonal pycnocline is increasing, while slower, steady EDW destruction is observed in early winter, as stratification weakens. Profiling float observations suggest that EDW is mixed away via three-dimensional processes near the Gulf Stream in the northern part of the subtropical gyre, whereas EDW destruction via 1-D vertical diffusion likely prevails in the southern part of the gyre. Lateral dispersion of EDW is assessed using CLIMODE temperature and velocity data from 40 acoustically-tracked, bobbing profiling floats. The relative contributions of vertical vs. lateral mixing are compared directly within the framework of the EDW potential vorticity budget.

IAPSO (Physical Oceanography)

P09c - P09 The North Atlantic and Climate Change

IUGG-5052

Variability of North Atlantic ocean ventilation

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In the subtropical gyres, only water subducted in late winter will remain in the ocean interior for longer than a seasonal cycle. The fast seasonal migration of outcropping density surfaces relative to the slow southward advection of water in the ocean interior means that water subducted before late winter has insufficient time to escape entrainment back into the mixed layer as the outcrop advances southward, a phenomenon denoted Stommel's demon. We investigate whether a similar process operates on inter-annual timescales. Lagrangian analysis of a 1/4 degree ocean model reveals the ventilation age on interior density surfaces. We find that significant inter-annual variability exists and that it is related to changes in the location of the late winter outcrop from year to year. Our results suggest that Stommel's demon is a multi-year process that impacts ventilation on timescales longer than a seasonal cycle. This carries implications for the properties of the main thermocline, nutrient cycling and the transport of atmospheric tracers into the ocean interior.

IAPSO (Physical Oceanography)

P09d - P09 The North Atlantic and Climate Change

IUGG-0550

Changes in Fresh Water Content in the Arctic Basin and their relationship with increased water inflow from the North Atlantic

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Calculations of freshwater content (FWC) in the upper layer above the 34.80 psu isohaline depth and properties of Atlantic Water (AW) layer in the Arctic Basin (AB) for the 1950-2014 period are presented. Oceanographic observations collected at drifting stations 'North Pole', ship-based expeditions and drifting buoys with autonomous profilers were used in this study. These data were obtained by researchers from many Arctic countries and became available through international cooperation for Arctic Ocean study. We used the data collected in the oceanographic database of the Ocean-Air Interaction department of Arctic and Antarctic Research Institute (AARI). FWC and AW layer properties were obtained for individual stations, which are then interpolated to the nodes of regular grid, averaged over the decade and mapped. In addition, time series of FWC and AW properties were derived for certain areas where the observations span almost entire period under review (i.e. 1950-2014). For the 1990s, 2000s and 2010s decades, anomalies of FWC and AW layer properties were calculated relative to 1970s. The results show the rise of FWC in the AB since the mid-1990s with modern FWC values found close to those observed in the 1970s, during the Great Salinity Anomaly. The distribution of FWC in the AB is connected with position of upper boundary of the AW layer – decreasing over the areas where this boundary domes. In the 2000s, the thickness of fresh water layer in the Canada Basin is more than in the 1970s, but the lens of fresh water is less than was observed in the 1970s, and it was shifted to the Canadian Arctic Archipelago.

IAPSO (Physical Oceanography)

P09d - P09 The North Atlantic and Climate Change

IUGG-2957

Response of the subpolar North Atlantic to increasing Greenland Ice Sheet melting in a very high resolution ocean model.

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The Greenland Ice sheet (GrIS) has experienced an increasing mass loss since the 1990s, consistent with the warming of the Arctic atmosphere in response to global warming. The enhanced freshwater (FW) flux due to both surface melt and outlet glacier discharge has contributed to the acceleration in global sea level rise in the recent decades, and has become an important influence on the changing FW budget of the subarctic Atlantic. There is a concern that increasing FW fluxes from Greenland may strengthen the decline of the Atlantic meridional overturning circulation (AMOC) expected from the projected increases in high latitude temperature and precipitation. However, our understanding of the oceanic response to the actual acceleration in Greenland melting is limited due to idealizations in the FW forcing scenarios and lack of spatial resolution used in previous ocean climate model studies. Here we present an assessment of the impact of the spatially distributed increases in FW fluxes obtained from a recent reconstruction, using a global ocean circulation model with a refined grid spacing (of about 3 km) to capture the small-scale, eddying transport processes in the subpolar North Atlantic. Our model simulation suggests that the gradual increase of meltwater invading the Labrador Sea by mesoscale eddies will begin to have a dampening effect on the deep winter convection in the next years. On the other hand, an impact on the AMOC may not be discernible for several decades.

IAPSO (Physical Oceanography)

P09d - P09 The North Atlantic and Climate Change

IUGG-3710

The arctic-subarctic sea ice system has entered the seasonal regime

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We define a non-dimensional seasonality number to quantify the degree of seasonal change compared to the average of an annually-periodic variable. Application to sea ice extent and volume estimates from satellite data and models, suggests that the Arctic-Subarctic sea ice system has already entered the seasonal regime. For sea ice extent, it now approaches the same level of seasonality as seen in the Antarctic. For sea ice volume, the Arctic-Subarctic system appears to have exceeded the Antarctic seasonality. Three coupled climate models exhibit realistic variability in their degree of seasonality, but fail to match the speed of change, or change too late. Taken as a whole, the northern hemisphere sea ice system now exhibits similar levels of seasonality to the Canadian Arctic Archipelago, Baffin Bay, Nordic Seas, and subpolar North Atlantic Ocean of the 1980s and 1990s. There is no evidence that the Arctic-Subarctic sea ice system will move from the seasonal to the seasonally-episodic regime---where the seasonal change exceeds five times the average---in the 21st century. The impacts of this transition to the seasonal ice regime on the Arctic-Subarctic freshwater system, and downstream, is discussed.

IAPSO (Physical Oceanography)

P09d - P09 The North Atlantic and Climate Change

IUGG-4619

Greenland Ice Sheet changes and North Atlantic variability: Whatare the connections?

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Ice loss from the Greenland Ice Sheet quadrupled over the past two decades, contributing to a quarter of the observed global sea-level rise and to increased freshwater discharge into North Atlantic. Increasing evidence suggests that the acceleration of glaciers in western and southeastern Greenland, that is responsible for part of the mass loss, was triggered by the warming of the subpolar North Atlantic. The mechanism invoked is increased submarine melting at the glaciers' margins. Yet linking changes in submarine melting of glaciers to subpolar gyre variability is far from trivial given the wide range of processes and scales involved: cross-shelf exchange, fjord circulation and meltwater plume dynamics. Here, I use a combination of synoptic and moored data collected in two major fjords in southeast Greenland, and nearby shelf region, along with Argo data from the subpolar gyre, to present evidence that changes in the subpolar North Atlantic affect the waters reaching the glaciers' margins. The implication of these findings in the context of both the impact of North Atlantic variability on the ice sheet, and vice versa, will be discussed.

IAPSO (Physical Oceanography)

P09d - P09 The North Atlantic and Climate Change

IUGG-5509

Ocean circulation and marine terminating glaciers of the Canadian arctic archipelago and the Greenland ice sheet

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Higher latitudes have experienced a significant change in climate and physical processes within recent years. This study focuses on two regions that have experienced rapid change, the Canadian Arctic Archipelago and the Greenland Ice Sheet. It has been shown that relatively warm ocean waters may accelerate melt production of marine terminating glaciers. We explore and classify the pathways for the warmer Atlantic waters that reach the fjords along the coasts of Greenland as well as in the Canadian Arctic Archipelago. Additionally, given that the melt of these glaciers is accelerating, we look at the pathways of the low salinity melt waters from these coastal glaciers and where it is taken up in the surrounding basins. This analysis is carried out using an Arctic and North Atlantic configuration of the NEMO ocean/sea-ice general circulation model run at both 1/4 and 1/12 degree resolution. Pathways are determined using the Ariane Lagrangian float package using both forward and reverse trajectory analysis.

IAPSO (Physical Oceanography)

P09e - P09 The North Atlantic and Climate Change

IUGG-2137

Insights from Sustained Monitoring of the Atlantic circulation

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A decade of measurements has revealed surprising aspects of the Atlantic meridional overturning circulation. Observations of the Atlantic meridional overturning circulation by the Rapid system have been made over the last decade (2004-14) along 26.5 °N in the Atlantic from Florida to Africa. These are unique, being the first attempt to continuously measure the strength and vertical structure of the Atlantic meridional overturning circulation. The importance of Atlantic meridional overturning circulation heat transport for climate is widely acknowledged and most coupled climate models predict a slowdown in the Atlantic overturning under global warming, with significant impacts. Over 10 years, these Rapid observations have produced a succession of surprises that include: the unforeseen range of variability within a year; the amplitude and phase of the seasonal cycle and the mechanisms that drive this seasonal variability; the year-to- year variability in the size of the overturning and its effects on ocean heat and salt content north and south of 26.5°N; and the decline of the overturning circulation over the decade. Both the latter two exceed climate model projections. The decline in the Atlantic meridional overturning circulation over 10 years is associated with a weaker southward flow of North Atlantic Deep Water in the deep western boundary current and an increased southward thermocline recirculation in mid ocean. Such observations provide insights into the mechanisms of ocean circulation adjustment under climate change forcing. Such surprises demonstrate the value of sustained, basin-scale observations for understanding the role of the ocean in the climate system.

IAPSO (Physical Oceanography)

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IUGG-2644

Structural coherence and variation of North Atlantic sea level over the last two decades

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Although global mean sea level has been increasing, the regional manifestation, for example in the North Atlantic and its sub-basins, is complicated. Identification of coherent patterns of sea level and its adjustment due to ocean dynamics or thermodynamics is often obscured by transient processes and the large degrees-of-freedom of the system. These qualities impair the ability of empirical orthogonal functional analysis of sea level.

Here we examine AVISO dynamic topography from 1993 onwards using an area-based coordinate system in order to simplify the interpretation. We find both intermittent, abrupt regional changes over months to years and strikingly coherent regional variability that persists throughout the observational record. We discuss the possible dynamical processes governing these types of behaviour.

IAPSO (Physical Oceanography)

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IUGG-3326

"Intradecadal modulation of ENSO by the Atlantic Multidecadal Variability"

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The North Atlantic sea surface temperature (SST) anomalies are characterized by a marked low-frequency variability known as the Atlantic Multidecadal Variability (AMV). The AMV has been shown to modulate climate over many areas of the globe including Europe, North America, Africa, South East Asia or South America, but the physical processes behind several of these teleconnections are not well understood. In this study, we focus on the link between the AMV and the tropical Pacific variability. We present experiments based on the GFDL CM2.1 model in which SSTs in the North Atlantic sector are restored to the observed AMV pattern, while the other basins are left fully coupled. In order to explore and isolate the potential AMV impacts and maximize the signal-to-noise ratio, we use an ensemble simulation of 100 members run for 10 years. We show that a positive AMV phase leads to the set up of a negative Pacific Decadal Variability pattern characterized by cold anomalies in the tropical Pacific and warm anomalies in the western Pacific mid-latitudes. The response of the tropical Pacific ocean to a positive phase of the AMV is similar to that observed during a development of a La Niña event. However the AMV-induced anomalies are not stationary and our results suggest that the AMV can modulate ENSO on intradecadal timescale. We investigate the frequency of occurrence of El Niño and La Niña events and find that the probability of La Niña events increases by about 15% during the first 4 years of the simulation and is followed by an increase of about 15% of El Niño events for the following 2 years. We propose a physical mechanism to explain this modulation of ENSO by the North Atlantic variability and we show hints of it in observational estimates.

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IUGG-4889

Is an abrupt cooling over the North Atlantic a real eventuality or a sporadic model propensity?

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In opposition to the sea surface temperature (SST) global increase experienced throughout the 20th century, observations and reanalysis data show a cooling trend in the subpolar North Atlantic (NA). Such a long-term tendency mostly sharpened around 1970s with an abrupt SST drop, thus spotlighting the eventuality of a regional abrupt cooling under global warming conditions. Here, we search for such a possibility in forty state-of-the-art General Circulation Models (GCMs) involved in the CMIP5 project, in response to different scenarios of increasing radiative forcing. In more than a half of the experiments, the SST in the subpolar NA grows, although, in most cases, at a slower rate than the global trend. Nevertheless, a sizeable number of experiments predicts a net decrease in SST over the same region. Among a few of them, the cooling emerges as an abrupt event, with the mean oceanic state changing in less than a decade. Our analysis shows that the source for such a model uncertainty possibly lies behind different model representations of the background stratification for present-day conditions over the Labrador/Irminger Sea. Indeed, a local collapse of the deep-water convection in this region is shown to be the main mechanism triggering the rapid cooling. Comparisons with observations and reanalysis data reveal that those models not showing a rapid cooling are, on average, already too stratified in the Labrador/Irminger Sea in present-day conditions to permit the external forcing to establish a new state for the deep convection. This suggests that the subpolar NA may be more sensitive to radiative forcing than what most of the state-of-the-art GCMs have shown so far. Such a possibility would have strong implications in the evaluation of future climate change impacts.

IAPSO (Physical Oceanography)

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IUGG-5054

Overturning in the North Atlantic: The Lagrangian view

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Our understanding of the meridional overturning in the North Atlantic has been developed over the past many decades from modeling, theoretical and observational studies largely conducted in an Eulerian framework. From such studies, the meridional overturning circulation is described as a conduit that carries warm, near-surface waters poleward and cold, deep waters equatorward. Anomalies in temperature or salinity from high-latitude sources waters are assumed to be carried along the deep limb of the overturning circulation and, similarly, surface temperature anomalies from the subtropical region are expected to be throughput to the subpolar region via the upper limb. Starting in the 1990s when drifter and float data became more plentiful, a Lagrangian view of the overturning began to emerge. Twenty years later, this Lagrangian view challenges our conventional understanding of the overturning on a number of fronts, including the temporal and spatial description of the throughput of upper waters from the subtropical to the subpolar gyre and of deep waters from the subpolar to the subtropical gyre. Additionally, this Lagrangian view has reinforced a growing appreciation for the contribution of eddies to the pattern of the deep velocity and property fields in the North Atlantic, patterns that also impact overturning pathways. This talk will draw from studies over the past decade to provide an overview of the overturning circulation in a Lagrangian framework.

IAPSO (Physical Oceanography)

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IUGG-0828

Transports and storages of anthropogenic CO2 in the tropical North Atlantic

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The meridional transport of anthropogenic CO_2 (C_{ant}) in the tropical North Atlantic (TNA) is investigated using data from transoceanic sections along 7.5ºN and 24.5 ºN, carried out in the early 1990s and 2010s. The transport across 7.5ºN increases from 315 ± 31 kmol s^{-1} in 1993 to 493 ± 43 kmol s^{-1} in 2010; similary, a gain from 530 ± 41 kmol s^{-1} in 1992 to 662 ± 45 kmol s^{-1} in 2011 is detected across 24.5°N. These changes are the result of modification in the circulation patterns of the deep and intermediate waters and an increase in C_{ant} within the thermocline waters. In deep waters, lateral advection causes a C_{ant} convergence of 112 ± 57 kmol s^{-1} (234 ± 65 kmol s^{-1}) in 1992-93 (2010-11). Within deep waters, the storage rate of C_{ant} is not statistically different from C_{ant} convergence, 139 ± 21 kmol s^{-1} (188 ± 21 kmol s^{-1}) in 1992-93 (2010-11) – the C_{ant} increase detected in the TNA deep water is due to the large injection of C_{ant} across 24.5ºN by the Deep Western Boundary Current (DWBC) and the northward recirculation of North Atlantic Deep Water (NADW) along 7.5ºN. In contrast, a large C_{ant} divergence is found in the upper layer owned to the Florida Current. Despite this divergence, the C_{ant} accumulates at a rate of 215 ± 24 kmol s^{-1} (291 ± 24 kmol s^{-1}) referenced to year 1993 (2010). From the two C_{ant} budgets, we infer a C_{ant} air-sea flux of 0.25 ± 0.05 Pg yr-1 in the TNA, much larger than previously estimates.

IAPSO (Physical Oceanography)

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IUGG-0844

Changes in Arctic fresh water export: a new proxy from 30 years of hydrographic surveys in the Labrador Sea

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The Arctic Ocean is the most rapidly changing environment in the globe. One of the observed changes is a significant increase in the freshwater storage at the region. It is believed that a large and rapid export of this freshwater into the North Atlantic could potentially affect high-latitude dense water formation, the overturning circulation and climate. However, Arctic freshwater fluxes to the Labrador Sea are poorly known and observational time series are not available beyond the last decade. We present a new insight in Labrador shelf dynamics, which allows us to connect locally-observed property variability to net Arctic freshwater exports west of Greenland. By combining the high-resolution (1/12 degree) NEMO model and hydrographic observations at the Labrador Shelf, we describe two major components of the shelf circulation. On the one hand the Labrador Current fills the shelf with Arctic originated waters. On the other hand, the Hudson Strait Outflow generates a very distinctive inshore buoyancy-driven flow. This newly described current is geographically and dynamically independent of the Labrador Current, and we are able to separate it from the waters of Arctic origin which flow further offshore. We apply this methodology to a Labrador hydrographic time series of over 30 years in length, allowing us to generate a proxy that we can use to assess the variability of Arctic freshwater export west of Greenland for over 30 years. We show that on decadal timescales, periods of decreased freshwater export on the Labrador Shelf coincide with periods of increased Arctic freshwater content.

IAPSO (Physical Oceanography)

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IUGG-1466

Structure and dynamics of the Lofoten eddy in the Nordic Seas from joint satellite and deep sea measurements

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The anticyclonic Lofonten Eddy (LE) is a prominent mesoscale structure in the Nordic Seas regularly documented in hydrographic observations for about a century. Permanent nature of LE makes it a reliable indicator of long-term variations of the state of Atlantic Water entering the Nordic Seas from the North Atlantic Ocean. The eddy has typical horizontal scale of few tens of kilometers and anomalously warm and saline core at intermediate depth, with maximum anomaly at 600-800 m. Depending on the season, LE is manifested either as classical anticyclone (in winter and spring), or as an intrapycnoclinic lens (in summer and fall). Location of the LE is quite stable within the deepest part of the Lofoten Basin. Key features of the LE were studied in 1980s on the basis of traditional hydrographic surveys. Application of new methods of measurements in 2000s, including remote sensing, confirmed some earlier suggested concepts, but also highlighted new features, which could not be revealed from low resolution observations back in 1980s. In this presentation we focus on the advantages, which are provided by joint analysis of satellite observations and deep sea measurements by Argo floats. Our analysis shows that the LE is reasonably identifiable from satellite data. Vertical profiles of temperature and salinity in the center of LE, as detected from satellite, corroborate with vertical profiles of temperature and salinity to be expected in the LE center in the corresponding season. Seasonal variation of LE structure - anomaly strengthening in winter and summer relaxation, are also supported by these new data. Long term (50 years) time series of temperature and salinity in the LE demonstrate consistent warming and salinity increase in the upper 600 m in 2000s.

IAPSO (Physical Oceanography)

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IUGG-3111

Recent hydrographic variability in the Labrador, Nordic and Barents Seas and possible linkages

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Using a combination of vessel, Argo float and moored measurements in the Labrador Sea and hydrographic data from the Nordic and Barents Seas, we construct a set of regional climate indices and time-distance diagrams for various layers in their shelf, slope and deep-sea sectors.

Upper-layer freshening events spread across the two regions in 2008-2010 and 2011-2014 with the strongest signals observed in the coastal and slope waters. We investigate whether either or both of these events were connected to the high melt rates of the Arctic and Greenland ice covers observed in the last decade. The effects of the observed freshening on the upper layer's density and stratification and on its mixing with deeper waters are also discussed.

Over the past two decades the lower intermediate layer of the Labrador Sea (1000-2000 m) has steadily become warmer and saltier, although these trends were interrupted on several occasions. The most remarkable disruptions were associated with enhanced wintertime convection during the winters of 2008-2009 and 2013-2014, which mixed the accumulated fresher upper-layer water into the lower intermediate layer, leading to the formation of two new relatively cold and fresh classes of the Labrador Sea Water.

In the Labrador Sea's abyssal layer which is mostly occupied by the Denmark Strait Overflow Water transported through the region by the Deep Western Boundary Current, there was an unprecedented increase in salinity, temperature and density between 2000 and 2010. Its causes and possible effects on the dynamics of the deep waters are discussed together with its upstream and downstream linkages.

IAPSO (Physical Oceanography)

P09f - P09 The North Atlantic and Climate Change

IUGG-4726

Regional scale climatology of global change carbon dioxide flux on the ocean surfacefor North Atlantic and the Arctic

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Calculating climatology of the air-sea flux of CO2 and ocean sinks of the anthropogenic CO2 budget is important because there is still a lot of open question on carbon sinks, especially for the northern hemisphere. The CO2 partial pressure data are used in the monitoring of direction and magnitude of the net carbon air-sea flux. We used calculated averaged measurements of this pressure. However the regional and temporal means depend on parametrization of gas transfer velocity as well as on the wind/waves fields used for calculations.

Our study is part of the new ESA funded OceanFlux Evolution project as well as the PhD thesis of one of us (IW) funded by Centre of Polar Studies "POLAR-KNOW" (a project of the Polish Ministry of Science). The aim of this is to provide ensemble of regional monthly averages of the CO2 flux climatology for the North Atlantic and Artic waters using multiple combinations of forcing fields and gas transfer velocity parametrizations. The results of the study are intended in the future to grown from regional to global scale and cover the whole of North Atlantic and Artic waters. The study is possible thanks to a recently developed tool, FluxEngine created within ESA funded (SOLAS related) OceanFlux Greenhouse Gases project.

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P09p-115

Application of the d18? as tracer of fresh water masses in the Fram Strait

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Introduction
Water masses in the Fram Strait and on the self of the Barents Sea have similar temperature and salinity characteristics but different isotope content due to different reasons of salinity decrease. It could be explained by fresh water input as result of the Greenland glaciers melting in the Independence fjord and Denmark fjord, on the other hand surface salinity decrease could happened during the processes of the sea-ice melting. The isotope-tracer method allows to distinguish water masses with similar salinity characteristics and different origin.
Data and Method
The data used in this study where downloaded from the open access data base [http://data.giss.nasa.gov/o18data/].It is assumed that each sample is a mixture between marine water (fmar), river runoff (fr), and sea ice meltwater (fi) [Bauch D. et al., 1995].
Results and Conclusions
On the base of detailed description of the δ18?-S diagram and TS-diagram and calculated fractions for Atlantic water masses, water modified during processes of sea ice melting/formation and fresh water formed due to influence of river runoff or glacier melting following conclusions were done: The reason of the surface water freshening in the Fram Strait (east of Greenland) during 1972 – 1989 and 1990 – 1999 years could be melting of glaciers in the Independence fjord and Denmark fjord and partly melting of sea-ice in 1990 – 1999;Salinity decrease of the surface water in the Stor fjord in 2000 – 2008 years happened due to melting of the sea-ice;Summary Oxygen isotope-tracer method is unique oceanographic instrument to make quantity description of the main fresh water members of water balance for the region plying key role in formation of the Arctic ?cean thermohaline structure.

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P09p-116

Sources, variability and pathways of the Denmark Strait Overflow Water (DSOW) in an eddy-resolving resolution model

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In this study we focus on the densest part of the DSOW, which is feeding the lower limb of the Atlantic Meridional Overturning Circulation (AMOC). Output of a high resolution model (VIKING20) hindcast, forced with CORE 2 interannually varying atmospheric forcing fields (1948-2009), has been used to investigate local sources and pathways of the DSOW north of Iceland. The fine model mesh allows to simulate the local conditions and circulation quite realistically, and the results suggest a complex mixture of different sources contributing to the DSOW at the sill. Based on the model results evaluated along a northward shifted Kögur section, the East Greenland Current (EGC) is the main contributor (1.5 Sv) for the DSOW, while both the separated EGC (0.9 Sv) and North Icelandic Jet (NIJ, 0.6 Sv) are contributing the second half of the DSOW. All different branches merge south of the original Kögur section and flow along the Iceland coast towards the Denmark Strait. The EGC shows a strong seasonal cycle (strong during winter season) which is partly compensated by an enhanced northward local recirculation in the Blossville Basin and causing possibly the existing anti-correlation between EGC and separated EGC on seasonal time scales. The NIJ contribution seems rather stable over the simulation period, while the EGC and separate EGC also show clear variability on interannual timescales. These eulerian analyses are further complemented by back- and forward lagrangian trajectories, seeded in the DSOW core in the Denmark Strait and provide more insights about pathways and the origin and fate of the DSOW in the Nordic Seas and Subpolar North Atlantic.

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P09p-117

Solar wind: A possible trigger to result in the tripolar SSTA mode over the North Atlantic

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Abstract:*The effect of solar wind (SW) on the North Atlantic sea surface temperature (SST) in boreal winter is examined in the paper. The results are obtained through the analysis of observational solar wind speed (SWS) data from the OMNI database of Goddard Space Flight Center, sea surface temperature (SST) from NOAA and NCEP/NCAR atmospheric reanalysis data from 1964 to 2013. The results suggest that a pronounced meridional tripolar pattern of SST anomalies response to solar wind speed (SWS) variations. The tripolar pattern of SSTA is broadly similar to the first leading mode of wintertime interannual SST variability EOF over the North Atlantic sector. The positive SSTA appears in North Atlantic middle latitudes with negative SSTA to north and south during strong SWS years. It demonstrates opposite feature in weak SWS years. Regression winter (DJF) SST also resulted in similar sandwich SSTA pattern accounting for 26.7% of the total deviation variance. The closely relationship is remained when the ENSO signal is removed. Further analysis revealed that SWS is closely related not only with SST mode but also the atmospheric general circulation mode. The close relationship between SWS and North Atlantic Oscillation (NAO) was noticed early. And it was shown that SWS have distinct impact on atmospheric circulation for synoptic time scale. The North Atlantic tripolar SSTA mode presents the climate effect of solar wind. Solar wind is likely a possible trigger to form the tripolar SSTA mode over the North Atlantic.*

IAPSO (Physical Oceanography)

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P09p-118

Influence of Arctic freshwater inflow on thermohaline anomalies in Northwest Atlantic and Nordic Seas

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Arctic impact on global climate reflects in fresh water and sea ice export to North Atlantic. There are two fresh water flows from Arctic: through Fram Strait, then with West-Greenland current and through Canadian Arctic Archipelago to Labrador Sea.

Oceanographic data from Northwest Atlantic and Nordic Seas was collected for the following investigation. Contents of fresh water in upper layer, time series of representative parameters of thermohaline anomalies, climatological fields and sections of salinity and temperature were used to consider the influence of fresh cold flows from the Arctic on vertical mixing in North Atlantic.

In North European basin and North-West Atlantic there are periods of freshening in the upper layer in the beginning of 1960s, middle 1970s and 2000s. These freshening periods are connected with summer melting (early 1960s and 2000s). Influence of summer warming in Arctic is observed in freshwater content and freshwater advection to North Atlantic through Fram Strait and straits of Canadian Arctic Archipelago.

Sea ice arriving through Fram Strait leads to steady formation of convection in Greenland Sea and increased freshwater flux with East-Greenland current in the upper layer of Labrador Sea makes convection weak. Flux of fresh water and sea ice weaken convection in the years of significant export from Arctic with later cooling and freshening almost in all layers (from 1960s to 1980s in Greenland Sea, from 1970s to 2000 in Labrador Sea). Nowadays flows of fresh water weaken convection in Labrador Sea, in Greenland Sea vertical mixing is not observed because of strong warming of upper layers.

IAPSO (Physical Oceanography)

P09p - P09 The North Atlantic and Climate Change

P09p-119

North Atlantic wave climate and storms: the SW Spanish and Wales coasts examples

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The North Atlantic plays an important role in ongoing climate change and is likely to do so in the future as climate models predict a weakening of the overturning circulation that may affect regional and global climate, sea level and extreme waves. In this sense, the occurrence and distribution of storms are important issues in the incidence of coastal erosion, deterioration and/or complete disappearance of ecosystems in this region. This work presents the characterization of wave climate, wave energy, coastal storms and the determination of their recurrence intervals and relationships with several regional cycles in Cadiz (SW Spanish Atlantic coast) and Tenby (S Wales, UK). At the former site, wave records include 22 years of data covering the period between 1987 and 2012. Storms characterization was carried out using the Storm Power Index and five classes were obtained, from class I (weak events) to V (extreme events). Storm occurrence probability was 96% for class I (i.e. almost one event per year) to 3% for class V. The return period for class V was 25 years and ranged from 6 to 8 years for classes III and IV storms, e.g. significant and severe events. Classes I and II showed a period of recurrence ranging from 1 to 3 years. Approximately 40% of the change in monthly wave data and storminess indices was related to several teleconnection patterns, being the Arctic Oscillation (AO), with 21.45%, and the North Atlantic Oscillation (NAO), with 19.65%, the most important drivers of change.

IAPSO (Physical Oceanography)

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P09p-120

Multiple steady solutions of a model subpolar ocean forced by localized wind

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A simple model of the subpolar North Atlantic can produce closed, recirculating cells in the Irminger and Labrador Seas, consistent with float data. But it can also produce an inertial solution with swift, open currents that do no recirculate. We explore this transition in a periodic channel to isolate the dynamics at work. Weak forcing leads to the classic beta plume, while strong forcing causes the circulation to strengthen and elongate.

IAPSO (Physical Oceanography)

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P09p-121

A simple model of ocean dynamics in Nares Strait

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The Canadian Arctic Archipelago is one of the two major oceanic gateways between the Arctic and the Atlantic Ocean. It has been estimated that the flow through this region currently accounts for about half of the freshwater transport between these two oceanic basins, its importance potentially increasing with increased melting of sea ice. However, factors such as its complex morphology, harsh meteorological conditions, the remote location and an almost continuous presence of sea ice form a hindrance to understanding the dynamics that force the flow through this region. In contrast to previous efforts which all used realistic model configurations, the approach in this study is one of a simple straight channel representing Nares Strait in a 3D primitive equation model. This enables us to disentangle and quantify the effects of barotropic forcing, baroclinic forcing, wind stress, ice cover and tides acting to drive or reduce the throughflow or alter its cross-strait structure.

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P09p-122

Impact of Barents Sea air-sea exchanges on Fram Strait dense water transport

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Impacts of extreme Barents Sea air-sea exchanges are examined using the HadCM3 coupled ocean-atmosphere model. Variability in the Barents Sea winter air-sea density flux is found to be a potentially significant factor in determining changes in the southward transport of dense water through Fram Strait. The density flux variability is primarily driven by the thermal term, F_T, due to heat loss to the atmosphere. The other two terms (haline flux and ice formation) play a relatively minor role. The difference in ocean circulation between winters with extreme strong and weak Barents Sea surface density flux anomalies is analyzed. This reveals an increase in strong winters of both the north-westward intermediate depth flow out of the basin and the east-west deep flows north of Spitsbergen and south through the Fram Strait. A linear fit yields a Fram Strait southward transport increase of 1.22 Sv for an increase in F_T of 1×10^{-6} kg m^{-2} s^{-1}. For the 10 strongest Barents Sea surface density flux winters, the Fram Strait winter southward transport increases by 2.4 Sv. This compares with a reduction of 1.0 Sv for the corresponding weakest winters. Furthermore, the properties of the southward flowing water are modified in strong density flux winters. In such winters, the Fram Strait water below 250 m is colder by up to 0.5°C and fresher by 0.05 than the climatological winter mean.

IAPSO (Physical Oceanography)

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P09p-123

A modeling study on the inflow of the Atlantic Water to the Arctic Ocean

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Recent decline of sea ice in the Arctic Ocean influences the climate system around the Northern polar region. The Atlantic Water is the warmest water and has a significant role on the melting of sea ice in the Arctic Ocean. The Atlantic Water enters the Arctic Ocean through the Fram Strait and Barents Sea. We focus on the influx of the Atlantic Water to the Arctic Ocean by using an ice-ocean general circulation model. In order to explicitly calculate the West Spitzbergen Current (WSC), which transports the Atlantic Water at the Fram Strait, and eddy activities (deformation radius is ~ 10 km), the horizontal size of grid is set to 2-4 km around the Fram Strait and Barents Sea. The WSC, which is not reproduced by low resolution ocean models, is well simulated in our model. The routes of the Atlantic Water through the Barents Sea are consistent with many observations. The observed eddy activity and meandering of sea-ice edge are also well reproduced around the Fram Strait. The westward bifurcations of the WSC, which have been inferred by hydrographic observations, are also simulated. The eddy activities and bifurcations decrease the heat flux to the Arctic Ocean through the Fram Strait. The observed increase of heat flux through the Fram Strait from 1990s to 2000s is simulated. The causes of the interannual variability of the heat flux are under investigation.

IAPSO (Physical Oceanography)

P09p - P09 The North Atlantic and Climate Change

P09p-124

Sea-level fluctuations show ocean circulation controls Atlantic multi-decadal variability

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We present observational evidence that ocean circulation controls the decadal evolution of heat content and consequently sea-surface temperatures (SST) in the North Atlantic. Positive (negative) phases of the Atlantic multidecadal oscillation (AMO) are associated with warmer (cooler) SSTs. Positive phases of the AMO have been linked with decadal climate fluctuations including increased summer precipitation in Europe; increased northern hemisphere land temperatures, fewer droughts in the Sahel region of Africa and increased Atlantic hurricane activity. It is widely believed that the Atlantic circulation controls the phases of the AMO by controlling the decadal changes in heat content in the North Atlantic. However, due to the lack of ocean circulation observations, this link has not been previously proven.
We present a new interpretation of the sea-level gradient along to the east coast of the United States to derive a measure of ocean circulation spanning decadal timescales. We use this to estimate heat content changes that we validate against direct estimates of heat content. We use the longevity of the tide gauge record to show that circulation, as interpreted in sea-level gradient changes, drives the major transitions in the AMO since the 1920's.
We show that the North Atlantic Oscillation is highly correlated with this sea-level gradient, indicating that the atmosphere drives the circulation changes. The circulation changes are essentially integrated by the ocean in the form of ocean heat content and returned to the atmosphere as the AMO.
An additional consequence of our interpretation is that recently reported accelerations in sea-level rise along the US east coast are consistent with a declining AMO that has been predicted by a number of authors.

IAPSO (Physical Oceanography)

P09p - P09 The North Atlantic and Climate Change

P09p-125

Dissolved Inorganic Carbon budget in the eastern Subpolar North Atlantic in the 2000s: Anthropogenic perturbation versus biological activity

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Dissolved inorganic carbon (DIC) budget between the OVIDE section and the Greenland-Iceland-Scotland sills (the eastern subpolar North Atlantic) is analysed using in situ data of the first decade of the 21st century. The increase in DIC inventory during the 2000s is explained by the anthropogenic perturbation and has the same magnitude as the biological consumption of DIC which is essential to close the DIC budget. The lateral advection of DIC is convergent. The CO_2 air-sea flux deduced from the DIC budget is consistent with independent estimates from SOCAT database.

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P09p-126

Arctic oscillation or atlantic multidecadal oscillation: Oceanic or atmospheric influences on the arctic temperatures?

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The sources of Arctic amplification are a subject of lively scientific debate. The local greenhouse effect and resultant albedo changes are doubtless drivers of Arctic changes. However it is not clear how changes of AO/NAO indices influence advection of warmer air masses and at the same time export of sea ice through Fram Strait. On the other hand, increased inflow of warm Atlantic waters were observed by research ships and moorings in recent decades. There are incompatible views in the published literature on the relative importance of those atmospheric and oceanic heat fluxes.

We perform a simple statistical analysis of the correlation of AO/NAO and AMO oscillations on temperature variability in the Arctic. To distinguish their effects from global warming we use detrended temperature series in the period of relatively linear increase of global temperatures since 1975. This allows enough length of the time series with enough variability to notice possible effects of the time series. We expect almost instantaneous effects of the atmospheric oscillations (AO/NAO) and lagged effects of North Atlantic surface temperature due to the observed speed of ocean water advection into the Arctic. The study aims at constraining the effects of both kinds of oscillations on the surface temperature in different regions of the Arctic Ocean and neighboring land masses.

IAPSO (Physical Oceanography)

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P09p-127

The Mediterranean overflow water and its effect on the north Atlantic

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The Mediterranean Overflow Water is created due to an excess of evaporation over precipitation and river runoffs in the Mediterranean sea. As a result, the incoming surface waters from the Atlantic become denser and saltier. These waters return to the Atlantic trough Gibraltar Strait and start mixing with the surrounding waters forming a warm and saline tongue of water, which spread westward. In this exchange of waters between the Atlantic and the Mediterranean, other magnitudes such as heat and salt are transported. In the last case, the salt transport between the two basins shows a decadal variability. These oscillations produce two different states, one where the Mediterranean exports salt to the Atlantic and another where the Mediterranean imports salt from it. The Mediterranean-Atlantic system alternates these two states. The aim of this study is to analyze the effects of these multi-decadal oscillations on the North Atlantic.
This study is performed using data from the climate model EC-EARTH run under pre-industrial conditions, where the greenhouse gas forcing is constant. The analysis of the total salt transport through Gibraltar Strait show periods where salt is imported from the Atlantic and vice-versa. The results show a larger impact of the outgoing salt transport on the total Atlantic salt transport north of Gibraltar strait (in a region between 40N-50N). These results oppose to the ones obtained when the impact of the outgoing salt transport and the salinity at depth of 1000 m were compared. In this case, the impact was distributed more uniformly around the strait. The impact of the variability of the salt transport in the Atlantic Meridional Overturning Circulation is also discussed. The same analysis for a historical run is currently carried through.

IAPSO (Physical Oceanography)

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P09p-128

Recent hydrographic variability along the outer continental margin off Atlantic Canada

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Temperature, salinity and density variability over the NW Atlantic's continental slope and rise between Labrador and Nova Scotia are described using historical datasets, ongoing vessel observations, Argo profiles, and moored measurements. The latter includes near-bottom temperature on the Labrador Slope (AR7W line) since 1980, temperature and salinity across Orphan Basin during 2004-2010, and near-bottom observations on the eXtended Halifax Line (XHL) across the Scotian Slope and Rise since 2000. Attention is focussed on the along-margin connectivity of hydrographic changes and events, and of particular water masses such as the Labrador Sea Water (LSW) and the Denmark Strait Overflow Water, associated with the Labrador Current and the Deep Western Boundary Current (DWBC) navigating complex topography and encountering the Gulf Stream and the Antarctic Bottom Water. For example, there has been a notable warming of the mid-slope near-bottom (~1000m) waters on the Labrador Slope since the early 1990s and on the Scotian Slope since the late 1990s which may include a contribution from anthropogenic climate change. However, examination of earlier data indicates higher temperatures in the preceding decades, and that this change is at least in part a recovery from cooling associated with enhanced LSW production in the late 1980s and early 1990s. There are also indications of decadal-scale variations in the properties of deeper waters in the DWBC and above that can reach the Scotian Rise, resulting from anomalous events in their upstream formation regions.

IAPSO (Physical Oceanography)

P09p - P09 The North Atlantic and Climate Change

P09p-608

Seasonal variation in ocean mixing and circulation diagnosed using the Tracer Contour Inverse Method and an Argo climatology

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The meridional overturning circulation of the oceans is a key component of the global climate system, and dominates poleward ocean heat transport over the extratropical North Atlantic. Ocean mixing plays an important role in the circulation as it allows cold dense waters created at the poles eventually to return to the surface, closing the circulation. The Tracer Contour Inverse Method (TCIM) outputs estimates of average isopycnal and diapycnal mixing rates on isopycnals based on an enclosed box of temperature and salinity observations. Here we use the Argo-only data subset of the CSIRO Atlas of Regional Seas (CARS) climatology along with the Tracer Contour Inverse Method to investigate seasonal variations in mixing in the North Atlantic, and present some preliminary results. This work represents a contribution to the Overturning in the Subpolar North Atlantic Program (OSNAP), which is an international collaborative project combining in-situ measurements with numerical modelling efforts to improve our understanding of the role of the North Atlantic subpolar gyre in the overturning circulation and climate.

IAPSO (Physical Oceanography)

P09p - P09 The North Atlantic and Climate Change

P09p-614

Distal and proximal controls on the silicon stable isotope composition of north atlantic deep water

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Diatom uptake of silicic acid fractionates the stable isotopes of silicon (Si), producing variations in the stable isotope composition of Si (expressed as $d^{30}Si$) in seawater that can be used to study the marine Si cycle. Recent observational studies have shown coherent structure in the $d^{30}Si$ distribution, indicating that $d^{30}Si$ traces large-scale Si transport and may bear information on the pathways of nutrient transport to the ocean's surface: the high $d^{30}Si$ signature of North Atlantic Deep Water (NADW) has been postulated to result from the injection of a high $d^{30}Si$ value into the thermocline by Southern Ocean mode/intermediate waters, and its transport to the North Atlantic by the meridional overturning circulation. This in turn suggests that most deep- to light-water conversion, and associated nutrient supply, takes place in the Southern Ocean. Here, we test this hypothesis in a suite of coarse-resolution ocean general circulation models (OGCMs) that simulate the marine cycle of Si and its isotopes, whilst also tracing Si supplied to the NADW formation region from Southern Ocean mode/intermediate waters, the deep Southern Ocean, and the North Pacific. All members of the model suite reproduce the observation of a high NADW $d^{30}Si$ signature, as well as a major or dominant contribution from Southern Ocean mode/intermediate waters to its Si inventory. By deconvolving the transport of distal isotope signals created in the high latitudes from the proximal signal of low-latitude isotope fractionation, we show that the OGCM suite supports the hypothesis that NADW's $d^{30}Si$ signature derives from cross-equatorial transport of a fractionation signal created by diatom Si uptake in the Southern Ocean.

IAPSO (Physical Oceanography)

P10a - P10 Sub-Mesoscale Eddies

IUGG-0233

Point vortex dynamics of a fluid near a boundary with a buy

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The motion of a point vortex along a rectilinear boundary with a circle cavity, which models the coastline of a bay, and associated fluid particle advection are studied within a model of barotropic inviscid fluid. Using an analytical expression for the complex potential through which the velocity field is determined, we show that fluid particles start moving irregularly when the vortex is passing the cavity due to the non-stationary of the velocity field generated by the vortex. Some of the fluid particles, which were initially inside the vortex atmosphere, leave it due to the irregularity and remain within the cavity vicinity. Depending on the initial position of the vortex and a parameter that determines the cavity size, the fraction of these fluid particles can differ significantly from fluid particles initially uniformly distributed within the vortex atmosphere. The escape of fluid particles from the vortex atmosphere is shown to be most efficient in the case of a relatively closed cavity under the condition that the initial vortex atmosphere area should be significantly smaller than the cavity area.

IAPSO (Physical Oceanography)

P10a - P10 Sub-Mesoscale Eddies

IUGG-0251

Lagrangian reconstructions of temperature and velocity in surface ocean turbulence

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The characterization of submesoscale dynamics is crucial to understand the impact of these motions on the global ocean properties. Direct measurements of fine structures over the world oceans, nevertheless, are at present severely limited by the spatial resolution of satellite products. We numerically investigate the possibility to reconstruct tracer fields, like surface temperature, at small scales, from low-resolution data using a Lagrangian technique. The capabilities of the method are explored in the context of a forced surface-quasigeostrophic turbulent flow representing a large-scale meandering jet and smaller-scale eddies. Both qualitative and quantitative comparisons are performed between the original (high-resolution) fields and their reconstructions that use only low-resolution data. Good agreement is found for filamentary structures, even in the presence of a large-scale forcing on the tracer dynamics. The statistics of tracer gradients, which are relevant for assessing the possibility to detect fronts, are found to be accurately reproduced. Using surface-quasigeostrophic theory, the reconstruction technique is then extended to obtain the velocity field in three dimensions when temperature is the tracer. The results indicate that relevant features of dynamical quantities at small scales may be adequately deduced from only low-resolution temperature data. However, the ability to reconstruct the flow is critically limited by the energetic level of submesoscales. Indeed, only structures generated by non-local mesoscale features can be well retrieved, while those associated to the local dynamics of submesoscale eddies cannot be recovered.

IAPSO (Physical Oceanography)

P10a - P10 Sub-Mesoscale Eddies

IUGG-1897

Interaction of a surface quasi-geostrophic buoyancy anomaly strip and an internal vortex

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We propose a study of the nonlinear evolution of a strip of buoyancy anomaly at the surface of an idealised ocean. A finite core quasi-geostrophic spherical vortex is initially placed in the interiorof the fluid domain and interacts with the surface anomaly. The investigation is primarily performed from the analysis of nonlinearsimulations of the flow using a hybrid Eulerian/Lagrangian algorithm (based on the Contour-Advective-Semi-Lagrangian algorithm) of a coupled model QG/SQG introduced in Perrot et al. (2010). The behaviour of the flow depends on the relative position of the vortex with respect to the strip as well as their relative intensities (and more importantly their relative sign). In the case of like-signed interactions, a large fraction of the buoyancy anomaly tends to converge directly above the vortex whereas this region is depleted of buoyancy in the opposite-signed case. Nonetheless, in both cases, the surface buoyancy is stretched and spirals due to the rotation induced by the interior vortex. The strip may destabilise and break into fine structures, providing a rapid route for a cascade to small scales. The rolling-up of the structures stretches parts of the original strip into narrow filaments of increasing length. The non-diffusive nature of the Lagrangian method which tracks the buoyancy gradients allows to follow their stretching and deformation as a function of time. Both of generation of the secondary structures and the filamentation associated with their development play an important role in the scaletransfer at the surface. We first analyse the effect of vortex placed at the vertical of the strip of buoyancy for various intensity ratios, and then we investigate to the effect of a horizontal offset between the two structures.

IAPSO (Physical Oceanography)

P10a - P10 Sub-Mesoscale Eddies

IUGG-3518

Surface semi-geostrophic turbulence: Freely-evolving dynamics

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Observations and high-resolution numerical simulations show the importance of submesoscale dynamics in the oceanic mixed layer that are out of geostrophic balance, as they are locally characterized by Rossby and Richardson numbers of O(1). Models based on a quasi-geostrophic approximation as the surface quasi-geostrophic model (SQG) tend to fail in representing the statistics of these processes. A possible way for the study of ageostrophic instabilities is given by the semi-geostrophic approximation, originally introduced to study frontogenesis in the atmosphere. The surface semi-geostrophic model (SSG) differs from SQG in being formulated in geostrophic coordinates and in the presence of a nonlinear Monge-Ampere inversion equation for the streamfunction. In this work we perform model studies of turbulent SSG flows in a double-periodic domain in the horizontal and we compare them with the SQG case. Results show that while SQG dynamics is dominated by a symmetric population of cyclones-anticyclones, SSG dynamics feature a prominent role of fronts and filaments. The resulting distribution of buoyancy anomalies and vorticity are strongly asymmetric, confirming previous works on the role of ageostrophic processes in determining cyclones-anticyclones asymmetries in geophysical turbulence. In SSG energy spectra tend to be less steep than in SQG, with more energy concentrated at small scales. Overall the the statistics of SSG turbulence qualitatively agrees with observations and numerical simulations of submesoscale processes in the oceanic mixed-layer.

IAPSO (Physical Oceanography)

P10b - P10 Sub-Mesoscale Eddies

IUGG-0929

Interaction between mesoscale barotropic eddy and sub-mesoscale intrathermocline lenses

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INTERACTION BETWEEN MESOSCALE BAROTROPIC EDDY AND SUB-MESOSCALE INTRATHERMOCLINE LENSES

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Intrathermocline, anticyclonic and cyclonic vortices are localized at intermediate depths (600–1600 m). Usually, they are elliptically shaped. These lenses are mostly observed in the North Atlantic, but they can appear in numerous areas of the World Ocean. These vortices are surprisingly long-lived (the mean period of their life consists of 3-5 years), and they play an important role in the turbulent exchange and in the processes of heat, salt and admixture transport at intermediate depths.In the course of lens self-motion or their advection by a current, they experience the influence of the bottom relief, irregularities of the coast and effect of vortices of other nature. Numerous studies of these processes are widely reported in literature. However, only the effect of external factors, such as stationary external current, continents' borders, islands and submersed mountains, on the lenses' behavior have been observed and studied, and no proper attention has been paid to the process of joint interaction where the influence of the lenses on the external dynamic structures is taken into account.This work, in the frame of a simple model, is aimed to investigate the interaction between intrathermocline vortices and the mesoscale gyres, occupying the ocean body. We show that lenses can affect a larger vortex and both change its shape and motion as a whole, and cause its decay into separate parts of smaller scales.

IAPSO (Physical Oceanography)

P10b - P10 Sub-Mesoscale Eddies

IUGG-3039

Generation of submesoscale filaments in the mixed layer of mesoscale vortices

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Submesoscale-permitting simulations show the development of submesoscale filaments in the mixed layer of mesoscale anti-cyclonic eddies. These submesoscale filaments are ageostrophic and are associated with the upwelling of cold water from the thermocline. The filaments are generated in the mixed layer of mesoscale vortices where down-front winds lead to negative potential vorticity. The dynamical conditions that give rise to the filaments are investigated and symmetric instability is found to be the most likely mechanism. The intense upwelling associated with the filaments is not accounted for by traditional estimates of vertical velocity by methods such as the omega equation. The symmetric instability mechanism may explain the elevated levels of biological production observed inside mesoscale anticyclonic eddies in the oligotrophic mid-latitude ocean.

IAPSO (Physical Oceanography)

P10b - P10 Sub-Mesoscale Eddies

IUGG-3197

Intense sub-mesoscale variability revealed by multi-platform sampling in the offshore waters west of Sardinia (Mediterranean Sea)

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In the framework of the REP14-MED sea trial conducted 8-23 June 2014 in the offshore area west of Sardinia Island (Western Mediterranean Sea), ship-borne CTD casts, eleven underwater gliders, and towed instruments provided a huge dataset of various physical parameters at very high horizontal resolution (up to < 10 metres). Hydrographic sections were oriented orthogonal to the coastline of Sardinia and extended from the wide continental shelf into the deep ocean. Preliminary analyses show a significant and unexpected spatial variability, which to date could not be resolved using CTD casts alone. At several locations, temperature and salinity change abruptly, suggesting the presence of isolated upwelling or downwelling events which are expected to have important implications on mixing, and thus also on biogeochemistry. Multiple interleaving features and vertical structures that were only a few tens of meters wide, extended from the surface to approximately 100-m depth into the thermocline. The oceanographic observations constitute an unprecedented high-resolution data set which provides a relevant contribution to the current knowledge of the hydrography in the area west of Sardinia Island. Exploitation of this dataset offers us the opportunity to improve our understanding of the sub-mesoscale processes occurring in the thermocline layer, and that could be hardly observed by means of traditional sampling techniques.

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P10b - P10 Sub-Mesoscale Eddies

IUGG-3469

An annual cycle of submesoscale and mesoscale vertical flows in the upper ocean

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The upper ocean at the Porcupine Abyssal Plain site in the Northeast Atlantic has been observed using two nested clusters of mesoscale- and submesocale-resolving moorings deployed for one year (Sep 2012 - Sep 2013). Vertical velocity is estimated from each of the mooring clusters to assess the relative roles of mesoscale and submesoscale dynamics in inducing vertical flow, and the relation between the two.Results show that differences between submesoscale and mesoscale vertical velocities are modest at times of weak mesoscale eddy activity, but are often large(over 100 m/day) when energetic mesoscale features propagate through the mooring array. Submesoscale vertical velocities are found to be more variable during the latter periods. The physical phenomena underpinning these findings will be discussed.

IAPSO (Physical Oceanography)

P10b - P10 Sub-Mesoscale Eddies

IUGG-5477

Meso and submesoscale structures from the Geostationary Ocean Color Imager and a model in the southwestern East Sea

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Using high resolution (~500 m) ocean color images taken by the Geostationary Ocean Color Imager we investigated the power spectral density (PSD) of meso and submesoscale flow features in summer and winter separately over the southwestern part of the East Sea. Over the mesoscale range the power dependence of PSD to wavelength k was about -1.7 in both seasons. Over the submesoscale range the power dependence was smaller but showed seasonal difference. The power dependence was smaller in winter suggesting stronger submesoscale activities. We confirmed these findings using a high resolution ocean circulation model. The strength of mixing estimated using the Finite-Size Lyapunov Exponents and vertical relative dispersion coefficients with the model outputs was highly correlated with the submesoscale features rather than the mesoscale ones although the energy level of the former is much smaller than that of latter. Thus mixing would be stronger during winter when submesosacle flows are more active.

IAPSO (Physical Oceanography)

P10c - P10 Sub-Mesoscale Eddies

IUGG-0335

Observations of submesoscale eddies using high-frequency radar-derived kinematic and dynamic quantities

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The spatio-temporal variability of submesoscale eddies off southern San Diego is investigated with two-year observations of subinertial surface currents [O(1) m depth] derived from shore-based high-frequency radars. The kinematic and dynamic quantities — velocity potential, stream function, divergence, vorticity, and deformation rates — are directly estimated from radial velocity maps using optimal interpolation. For eddy detection, the winding-angle approach based on flow geometry is applied to the calculated stream function. A cluster of nearly enclosed streamlines with persistent vorticity in time is identified as an eddy. About 700 eddies were detected for each rotation (clockwise and counter-clockwise). The two rotations show similar statistics with diameters in the range of 5–25 km and Rossby number of 0.2–2. They persist for 1–7 days with weak seasonality and migrate with a translation speed of 4–15 cm s^{-1} *advected by background currents. The horizontal structure of eddies exhibits nearly symmetric tangential velocity with a maximum at the defined radius of the eddy, non-zero radial velocity due to background flows, and Gaussian vorticity with the highest value at the center. In contrast divergence has no consistent spatial shape. Two episodic events are presented with other in situ data (subsurface current and temperature profiles, and local winds) as an example of frontal-scale secondary circulation associated with drifting submesoscale eddies.*

IAPSO (Physical Oceanography)

P10c - P10 Sub-Mesoscale Eddies

IUGG-4868

Quantifying the kinetic and potential energy of a submesoscale eddy from in situ and aerial observations

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Submesoscale features are thought to play an important role in a variety of oceanic processes, including local energy cascades, the stratification and mixing of the upper-ocean, the vertical transport of nutrients and gases, and phytoplankton productivity. However, due to their short temporal scales and small spatial scales, in situ measurements of these features are rare. We present results of very high-resolution measurements of a submesoscale eddy with a 1 km diameter in the Southern California Bight. A combination of in situ measurements and aerial images allowed us to track the cyclonic eddy over a period of several hours. Measured changes in the eddy's shape (remote and in situ data), rotational speed (ADCP), and water density distribution (towed CTD chain) allowed us to analyze changes in the eddy's potential and kinetic energy, and find evidence of energy dissipation through mixing.

IAPSO (Physical Oceanography)

P10c - P10 Sub-Mesoscale Eddies

IUGG-5193

Physical-biogeochemical observations of a submesoscale coherent vortex formed by deep vertical mixing in the north-western Mediterranean Sea

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In this study, we analyze in-situ data collected by R/V and a glider in June 2013 during which a Submesoscale Coherent Vortex (SCV) was extensively sampled (~60 glider profiles down to 1000m + 1 full-depth CTD cast from R/V within the core of the eddy). The hydrological characteristics of the core suggests the SCV is formed during the previous winter in the Ligurian Sea. It has a strongly baroclinic signature with peak velocities (~15cm/s) located at intermediate depths (~800m) and a small radius of ~5km.

Thanks to the depth-average currents estimated by the glider, we reconstruct a high-resolution radial description of the SCV in terms of T/S characteristics and biogeochemical properties (Oxygen and Chl-a fluorescence) and estimate orbital velocities and Potential Vorticity. Such SCVs are long lived vortices characterized by high Rossby (~0.5) and Burger (~1) numbers.

A CTD cast collected within the SCV core enables its description over the whole water column. Nutrients concentrations (NO3, PO4 and SiOH4) were found to be lower by about 20% compared to their background level, probably due to the dilution of these tracers during the SCV formation process. This persistence of this nutrients depletion confirms that vertical and horizontal exchanges within the SCV are particularly small.

We eventually discuss the origin of such circulation features, their formation process, their impacts on the open-ocean deep convection processes and on phytoplankton growth.

IAPSO (Physical Oceanography)

P10c - P10 Sub-Mesoscale Eddies

IUGG-5196

The seasonal signature of submesoscale turbulence from moorings in the North Atlantic

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An array of closely-spaced moorings were deployed in the North Atlantic (48.69°N, 16.19°W) during September 2012-September 2013 in order to monitor dynamics within the upper ocean. Measurements made include temperature, salinity and horizontal velocity from moored instruments (50-500 m) and ocean gliders (0-1000 m). This study focuses on mooring measurements and the seasonality of submesoscale turbulence. We use mixed layer depth as a proxy for the season and divide the record into winter and non-winter periods.

*Lateral gradients in velocity depict a richness of structure characteristic of the submesoscale. Relative vorticity normalised by the Coriolis parameter, **Ro**, displays positive skewness during winter and zero skewness during non-winter; typical wintertime magnitudes of **Ro** are 0.4-0.5. Vorticity, divergence and strain rate reveal increased variance in winter, with statistically significant values within the mixed layer. In all cases, variances of the three quantities decrease with increasing depth, supporting the concept of a surface-trapped or surface-intensified signal. In addition, the wintertime ratio of vertical stratification to vertical shear (Richardson number, **Ri**) is order one. Observed statistics are supported with calculations from a seasonally-varying, high-resolution numerical model [Brannigan et al. 2015, submitted]. Our study represents one of the first observational studies of seasonally-varying submesoscale turbulence.*

IAPSO (Physical Oceanography)

P10c - P10 Sub-Mesoscale Eddies

IUGG-5317

A seasonal cycle of open-ocean submesoscale motions from ocean gliders

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The impact of submesoscale instabilities, particularly symmetric instability, on upper ocean mixing has been well documented in strong, persistent fronts such as the Kuroshio and Gulf Stream western boundary currents. The prevalence and importance of these dynamics on near-surface stratification in the open ocean, where submesoscale fronts are typically associated with coherent mesoscale eddies, has received limited attention and observations of these processes are sparse. Between September 2012 and September 2013 a unique time series of near-surface lateral buoyancy distributions, potential vorticity and submesoscale instability characteristics was obtained using pairs of ocean gliders. The ocean gliders continuously sampled a 400 square kilometer region of the northeast Atlantic ocean, resulting in roughly 4000 upper ocean profiles of temperature, salinity, dissolved oxygen, fluorescence and optical backscatter.

The glider observations show distinct seasonal characteristics in near-surface mixing. Throughout the fall, the mixed layer gradually deepens predominantly through gravitational instability, suggesting that surface cooling dominates submesoscale re-stratification processes. During winter months, mixed layer depths are more intermittent. During this period, estimations of the Richardson angle (a measure of the ratio of lateral and vertical buoyancy gradients) show persistent occurrences of symmetric instability. These events coincide with observed injections of near surface properties, such as salinity and fluorescence, into the interior, consistent with strong mixing along isopycnal surfaces. A parameterization for the rate of kinetic energy extracted by SI is used to estimate a turbulent dissipation contribution during different seasons.

IAPSO (Physical Oceanography)

P10p - P10 Sub-Mesoscale Eddies

P10p-512

Vertical diffusion enhancing the particle flux from the vortex into the sheared environment

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We study the impact of diffusion on particle advection occurring in an analytical model for a constant-vorticity distributed vortex, namely the ellipsoidal vortex embedded in a constant-buoyancy frequency shear flow. Without the diffusive feature, the model is well-studied, and it has been already established that the model allows Lagrangian chaotic mixing of fluid particles outside the ellipsoid vortex to occur. However, the fluid particles within the vortex always move regular since no non-stationary perturbations affect them. As the particles move regular, they cannot cross the vortex's boundary implying that the volume of the vortex is always constant, so, the vortex cannot disappear, which never chances in nature as all the vortices tend to break down. Thus, we improve the model letting fluid particles transit through the vortex's boundary due to diffusion. Emphasis of this paper is on the vertical component of diffusion that significantly increases the particle flux from the vortex core into the exterior flow. Although the vertical component of diffusion is smaller than the horizontal one, it still causes comparable to the horizontal one flux from the vortex since vertical scale of the vortex is proportionally smaller than the horizontal one. We estimate this flux, and assess the characteristic time scales of vortices to survive in the presence of active vertical and horizontal diffusion.

IAPSO (Physical Oceanography)

P10p - P10 Sub-Mesoscale Eddies

P10p-513

QG dynamics of two surface vortex patches

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QG DYNAMICS OF TWO SURFACE VORTEX PATCHES

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Mesoscale and sub-mesoscale processes in the surface ocean have received an increasing interest in the recent years due in particular to theoretical research on the nature and the role of the submesoscales and to observational programs such as altimetric or ocean color satellite missions that emphasize a strong submesoscale activity of relevance both for physics and biochemistry. The NASA-CNES SWOT satellite mission, which will soon observe the ocean with an unprecedented resolution, provides a strong incentive for this research. In this work, we study the interaction of two initially circular vortex patches located in the upper ocean, basing on a two-layer quasi-geostrophic model. Contour dynamics method allows obtaining numerically diagrams of various states of vortex structures, depending on the upper layer thickness and the Froude number. In particular, in the space of external parameters, the evidence of a new quasi-stationary state is shown and its domain of existence characterized. Its formation scenario is as follows: after a brief merging stage of two vortex patches, a structure of three vortices is formed; further these vortices re-merge, and split again in a cascade way. The final tripolar structure behaves as a stable structure.We suggest that this kind of vortex tripoles might be one essential attribute of surface QG-dynamics of the open ocean.

IAPSO (Physical Oceanography)

P10p - P10 Sub-Mesoscale Eddies

P10p-514

Submesoscale eddies in the North Sea: observational evidence provided by satellite imagery

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The present work proposes a method for studying eddy activity in a given basin from satellite imagery. Special focus is given to submesoscale eddies and their role in the available potential energy and kinetic energy budget. As a region of interest the North Sea was chosen.

As a research material a comprehensive dataset of Advanced Synthetic Aperture Radar (ASAR, 2006-2007), Medium Resolution Imaging Spectrometer (MERIS, 2008-2011), and Advanced Very High Resolution Radiometer (AVHRR, 2006-2011) imagery was used. On analysis of the images, location and length scale of almost 9.500 eddies, with diameters between 1 km and 190 km, were defined. Based on these measurements the spatial and seasonal distribution of eddies of different sizes were obtained considering the observational biases due to inhomogeneous images' coverage density and tracers' distribution.

As a result, the main zones with different eddy activity were defined with an area along the Norwegian coast being the most eddy active zone. This area corresponds to the strongest currents of the North Sea and demonstrates the sharpest thermal gradients as shown with a frontal analysis of the infrared imagery and its structure function. Then follows the south-eastern part of the central North Sea where most of submesoscale eddies were detected. The least eddy activity was noticed in the well-mixed southernmost part of the North Sea.

An analysis of the temporal distribution of the eddies revealed a sharp seasonality in appearance of submesoscale eddies with June being the most eddy-active period.

Based on the statistics obtained the contribution of submesoscale eddies in energy budgets was assessed.

IAPSO (Physical Oceanography)

P10p - P10 Sub-Mesoscale Eddies

P10p-515

Modeling of eddy structures and their role in the restratification of Baltic Sea

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In this work we consider the dynamic effects of mesoscale and submesoscale eddies of different physical natures and different spatial resolutions. For the numerical experiments we use NEMO ocean model realization for Baltic Sea including free surface, time split surface pressure gradient, variable volume, GLS mixing, iso-neitral lateral diffusion.

The mesoscale eddies appear due to the baroclinic instability of the main currents. Diameters of such eddies are between 2 and 7 of Rd, where Rd is the local Rossby radius of baroclinic deformation [Zatsepin et al. 2011]. At the next level of the cascade of energy dissipation are the smaller sub-mesoscale eddies (radius <= Rd). In the Baltic sea the Rossby radius varies from 1 to 7 km [Fennel W. et al. 1991]. With horizontal resolution 1 nm the model can explicitly resolve mesoscale eddies while submesoscale dynamic remains only partly resolved and was parametrized as it proposed in [Gent et al. 1995].

Modeled mesoscale eddies generated by baroclinic instability of density front formed by North Sea inflow lead to rapid restratification of entire water column. The net influence of eddy motion characterized by upward Ekman pumping velocity changing the slope of the isopycnic surfaces. Due to isoneutral lateral diffusion used eddy induced variations in stratification also affect the distribution of salty plume propagating along the density iso-surface. We had found a considerable impact of short term mixed layer depth variations on near bottom salinity concentration during North Sea salty water inflow event. It appears to be highly sensible to the empirical parameter of submesoscale parametrization estimated fom comparison of the magnitude of SSH variations associated with Ekman pump against satellite altimetry observations.

IAPSO (Physical Oceanography)

P10p - P10 Sub-Mesoscale Eddies

P10p-516

Chaotic advection above the ocean submerged obstacle of Gaussian shape

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In the framework of background currents, we examine a dynamically consistent model of a periodic flow over an isolated submerged obstacle of Gaussian shape. We found two topographic vortices revolving about a rotation center. That vortex system forms a circular external flow. Under the periodic perturbations of background flow, the motion of fluid particles near the vortex system is chaotic in some area and regular in another one. Vortex-type quasi-periodic structures, identified with nonlinear resonances, can arise near the obstacle. It became possible to obtain asymptotic expansion for action-angle coordinates in the case of lager action, i.e. small background velocity. This method allowed obtaining the distance between domains of nonlinear resonances, their width and accurate estimation of chaotic region. Transport fluxes determined by chaotic advection, regular barriers for transport and the conditions of their existence are studied. Because of nonlinear effects, the domains involved in quasi-periodic and chaotic motions can be much larger than the domain occupied by steady topographic vortices.

IAPSO (Physical Oceanography)

P10p - P10 Sub-Mesoscale Eddies

P10p-517

Submesoscale disturbances associated with mesoscale phenomena: A case study in the Kuroshio-Oyashio mixed water region

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Submesoscale disturbances have been shown to be ubiquitous in the ocean based on high resolution Ocean General Circulation Model simulations, suggesting that they play an important role in the vertical transport of dynamical and biogeochemical properties over a wide area of the ocean. However, regional/basin-scale characteristics of the submesoscale disturbances have not been examined based on observations because observations resolving these disturbances are very limited. On the other hand, since submesoscale disturbances often result in intrusion structures of water mass, these structures can be used to find a trace of the disturbances. If this is the case, regional/basin-scale statistical characteristics of submesoscale disturbances are possibly examined by using Argo profile data distributed over the world oceans homogeneously in time and space. To test this idea, we focus on the intrusion structures possibly resulted from submesoscale disturbances and detect these structures associated with mesoscale phenomena by using intensive observation data of a mesoscale eddy in the Kuroshio-Oyashio mixed water region along with output of high resolution realistic Ocean General Circulation Model simulation in the same region. Intrusion structures are detected as vertical extrema of second derivative of spiciness with respect to potential density from large number of temperature/salinity profiles obtained by profiling floats and research vessels. We show spatial/temporal distribution of intrusion structures in and around the eddy and argue that these intrusions are associated with submesoscale disturbances.

IAPSO (Physical Oceanography)

P11a - P11 Wind Waves, Including Extreme Waves

IUGG-3975

Foam input into air-sea interaction in hurricane conditions

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The air – sea system has been modeled by a three-fluid system of the foam layer sandwiched between the atmosphere and the ocean, by distributing the foam spots homogeneously over the ocean surface. In the present study, the problem is reduced to modeling of the wind waves over the foam-free portion of the ocean surface under the effect of the log-wind profile averaged over alternating foam-free and foam-covered portions of the ocean surface.
The Kelvin–Helmholtz instability (KHI) of a three-fluid system of air, foam and water is examined within the range of intermediately short surface waves. The foam-layer thickness necessary for effective separation of the atmosphere and the ocean is estimated. Due to high density contrasts in the three-fluid system, even a relatively thin foam layer between the atmosphere and the ocean can provide a significant stabilization of the water surface by the wavelength shift of the instability towards smaller scales. It is conjectured that such stabilization qualitatively explains the observed reduction of roughness and drag. The central point of the study is the calculation of the wave growth rate, which is proportional to the fractional input energy from the weakly sheared logarithmic wind to the wave exponentially varying with time. Model the sea surface stability based on the effective aerodynamic roughness in the logarithmic wind profile instead of the effective aerodynamic roughness based on Charnock's formula.

It is shown for hurricane conditions that the Miles-type stability model based on the Charnock's formula with the standard constant coefficient underestimates the growth rate ~5–50 times as compared with the model that employs the roughness adopted from the experimental data for hurricane winds.

IAPSO (Physical Oceanography)

P11a - P11 Wind Waves, Including Extreme Waves

IUGG-4996

Towards modelling transient sea states

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At present the modelling of random oceanic wind waves is based upon the Hasselmann equation and/or its reductions. The derivation of the Hasselmann equation assumes quasi-stationarity of the random wave fields under consideration. Rapid changes of wind are not uncommon in nature, however, how they might affect wave evolution is practically unknown. It is extremely difficult to study such transient processes in nature, while so far the modelling lacked the suitable tools since, the Hasselmann equation is invalid for such processes. Here we examine short-lived transient sea states caused by rapid changes of wind using the Generalized Kinetic Equation (GKE) which does not require the quasi-stationarity assumption and direct numerical simulation (DNS) within the framework of the Zakharov equation. The focus of the work is a detailed analysis of the fast evolution after an instant change of forcing, and of the subsequent transition to the new quasi-stationary state of a wave field. The DNS is used to verify validity of the simulations based on the GKE and to find phenomena the GKE does not capture. The generalised theory allows us to trace the evolution of higher statistical moments of the field, notably the kurtosis and skewness, and, hence the wave height probability density function, which enables us to identify the transient sea states with higher risk of freak waves. A special consideration is given to the case of the squall, i.e. an instant and large increase of wind, which lasts for about a hundred characteristic wave periods.

IAPSO (Physical Oceanography)

P11a - P11 Wind Waves, Including Extreme Waves

IUGG-5542

Wave stirring and spatially coherent organized motion in the near-surface layer of the ocean

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In addition to turbulent mixing due to wave breaking and shear and convective instability, spatially coherent organized motions (Langmuir circulation, ramp-like structures, etc.) have been recognized as an important part of turbulent boundary layer processes. Models of Langmuir circulation are now very sophisticated, but still pose some questions. In particular, from the basic principles of nonlinear dissipative systems, the process of self-organization reduces chaos and dissipation in the system and increases the effectiveness of property transport (Soloviev and Lukas 2014). Nevertheless, the traditional LES models of Langmuir circulation demonstrate significant increase of turbulence and dissipation. Traditional models also do not account for the so-called ramp like structures, which are widespread features in the upper ocean turbulent boundary layer, with axes perpendicular to the axes of Langmuir circulation. In order to resolve these remaining issues, we have developed a new concept, which links the Langmuir circulation and ramp-like structures to wave stirring and Tollmien-Schlichting instability. Using computational fluid dynamics tools, we have been able to reproduce both Langmuir cells and ramp-like structures coexisting in space but intermittent in time. Finally, we discuss observational data that can help with verification of models of spatially coherent structures in the upper ocean turbulent boundary layer, including TOGA Coupled Ocean-Atmosphere Response Experiment data.

IAPSO (Physical Oceanography)

P11a - P11 Wind Waves, Including Extreme Waves

IUGG-5636

Ocean surface waves in hurricane Ike (2008) and superstorm Sandy (2012):Coupled modeling and observations

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Hurricane-induced ocean surface waves are complex, especially near landfall when the hurricane winds and water depth varies significantly and the surface waves refract, shoal and dissipate. In this study, we examine the spatial structure, magnitude, and directional spectrum of hurricane-induced ocean waves using a high resolution, fully coupled atmosphere-wave-ocean model and observations. The coupled model predictions of ocean surface waves in Hurricane Ike (2008) over the Gulf of Mexico and Superstorm Sandy (2012) in the northeastern Atlantic and coastal region are first evaluated with the NDBC buoy observations. Although there are characteristics that are general to ocean waves in both hurricanes as documented in previous studies, wave fields in Ike and Sandy possess unique properties due mostly to the distinct wind fields and coastal bathymetry in the two storms. Several processes are found to significantly modulate hurricane surface waves near landfall. First, the phase and group velocity decrease as the waves become shorter and steeper in shallow water, effectively increasing surface roughness and wind stress. Second, the bottom-induced refraction acts to turn the waves toward the coast, increasing the misalignment between the wind and waves. Third, as the hurricane translates over land, the left side of the storm center is characterized by offshore winds over very short fetch, which opposes incoming swell. Comparisons of directional wave spectrum between the deep and shallow waters reveal that all four quadrants of a landfalling hurricane contain overall weaker and broader wave spectrum than that of the open ocean. The front-left quadrant is most complex, where the combination of windsea and swell propagating against the wind as shown in the coupled model.

IAPSO (Physical Oceanography)

P11b - P11 Wind Waves, Including Extreme Waves

IUGG-0457

Rogue wave run-ups on the beach: observations, measurements and theoretical predictions

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For several decades rogue waves have been the topic of active scientific discussions and investigations. Waves of extreme height appearing randomly at the sea surface have been measured in both deep and shallow waters and have been involved in a number of ship accidents. Nowadays rogue waves are frequently recorded all over the world with several different instruments (range finders installed on offshore platforms, deployed buoys, radars including SAR, etc.).
Rogue wave also occur at the coast, where they appear as either sudden flooding of coastal areas or high splashes over steep banks or sea walls. Here we will call them rogue wave run-ups. These waves are especially dangerous for beach users and lead regularly to human injuries and fatalities. Here we will present numerous observations of rogue run-ups on beaches all over the World. Despite numerous reports of human accidents, coastal rogue waves have not yet been recorded experimentally. In this paper we discuss the recording of rogue wave events at German North Sea coasts by using high-resolution beach cameras. The recorded rogue waves are observed during different tide levels and different weather conditions. Possible physical mechanisms responsible for generation of these rogue run-ups are discussed.

IAPSO (Physical Oceanography)

P11b - P11 Wind Waves, Including Extreme Waves

IUGG-2115

Ocean wave directional spectra estimated from high-frequency radar

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It is possible to estimate ocean surface currents and waves using high-frequency radars. We have developed a method to estimate ocean wave directional spectra from Doppler spectra of backscattered signals from the sea surface . A wave spectrum is estimated from the inversion of the integral equation which relates the wave spectrum with the Doppler spectrum. The constraints of the wave spectrum are the integral equation, energy balance equation and regularization constraints. The wave spectra are estimated at the regular cells in the radar coverage area. However, it is possible to estimate spectra in the non-overlapping radar coverage area, while other methods are limited to the overlapping coverage between two radar systems. The signal to noise ratio in the Doppler spectrum is critical for wave estimation. The method to select the Doppler spectrum for wave estimation is also developed. The selection method is a combination of the identification of the first-order scattering, SOM (Self organization map) analysis method and the estimate of ratio of the second-order scattering to the first-order scattering. The method to estimate wave spectra can be applied to both the single radar case and dual radar array case. Examples of radar-estimated directional spectra are reasonable. The radar-estimated wave height are compared with in-situ observed wave heights, in which only the Doppler spectrum from the single radar can be available. The agreement for the dual radar case is good. The agreement of wave heights for the single radar case is not so good as the dual radar case.

IAPSO (Physical Oceanography)

P11b - P11 Wind Waves, Including Extreme Waves

IUGG-4207

Developing the Indo-Pacific GPS-Aided Tsunami Early Detection (DATED) System

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This talk reviews how tsunamis form from earthquakes and how GPS technologies can be used to detect tsunami energy scales in real time. Most tsunami fatalities occur in near-field communities of earthquakes at offshore faults. Tsunami early warning is key for reducing the number of fatalities. Unfortunately, an earthquake's magnitude often does not gauge the resulting tsunami power. Here we show that real-time GPS stations along coastlines are able to detect seafloor motions due to big earthquakes, and that the detected seafloor displacements are able to determine tsunami energy and scales instantaneously for early warnings. Our method focuses on estimating tsunami energy directly from seafloor motions because a tsunami's potential or scale, no matter how it is defined, has to be proportional to the tsunami energy. Since seafloor motions are the only source of a tsunami, their estimation directly relates to the mechanism that generates tsunamis; therefore, it is a proper way of identifying earthquakes that are capable of triggering tsunamis, while being able to discriminate those particular earthquakes from false alarms. Examples of detecting the tsunami energy scales for the 2004 Sumatra M9.1 earthquake, the 2005 Nias M8.7 earthquake, the 2010 M8.8 Chilean earthquake, and the 2011 M9.0 Tohoku-Oki earthquake will be presented. The development of the Indo-Pacific GPS-Aided Tsunami Early Detection (GATED) system will be reported.

IAPSO (Physical Oceanography)

P11b - P11 Wind Waves, Including Extreme Waves

IUGG-4708

Swell-dominant surface waves observed by a moored buoy with a GPS wave sensor in Otsuchi Bay, a ria in Japan

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Real-time monitoring of wind and surface waves in Otsuchi Bay, a ria in the Pacific coast of Tohoku, Japan, has been continued since October 2012, using a mooring buoy with an ultrasonic anemometer and a single-mode GPS wave sensor. Horizontal wind velocity was recorded hourly for 600 s with 0.5 s intervals, and height, period, and direction of surface waves were estimated hourly from the three-dimensional displacement of the buoy for 1200 s with 0.4 s intervals. Statistical data such as mean wind speed and direction, and significant wave height, period and direction, are distributed hourly in real time via the Internet along with a chart of their time series. We analyzed data monitored from October 2012 to December 2014 in order to assess the variability and occurrence of wind and waves and to elucidate the main reasons for wave variation in Otsuchi Bay. The monitoring data revealed that surface waves in the bay were predominantly affected by swells propagated from the northeastern offshore region and that the wave height was significantly correlated with the component of wind velocity toward Otsuchi Bay in the northeastern offshore region that faces the bay mouth. The offshore wind field was expected to provide information useful for predicting coastal waves in a ria bay in Sanriku such as Otsuchi Bay. However, it should be emphasized that the horizontal distribution of the offshore wind field, which has a significant effect on the surface waves in a ria bay, depends heavily on the topographic shape of the bay.

IAPSO (Physical Oceanography)

P11b - P11 Wind Waves, Including Extreme Waves

IUGG-5547

Nonlinear infragravity waves

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A general dynamical equation for the full mixed edge-leaky spectrum over a laterally uniform beach was derived based on Hamiltonian formalism [Zakharov, 1968, 1999b]. The introduction of canonical variables in this formalism significantly simplifies the complicated derivation of the nonlinear interaction coefficient in the previous work. The subharmonic resonance mechanism for edge-wave excitation [Guza and Davis, 1974] is retrieved from the model equation as a special case. The effects of dissipation induced by bottom friction are included using a perturbation approach. A kinetic equation for Zakharov's canonical variables can also be derived. The process of determining exact and near resonant triads has been automated by transforming the resonance condition into an algebraic system of equations. The resonance conditions are investigated for plane and exponential beaches. A numerical adaption of the dynamical equation was developed and tested for isolated edge-wave triads in the absence of leaky waves.

IAPSO (Physical Oceanography)

P11p - P11 Wind Waves, Including Extreme Waves

P11p-058

The analysis of the cyclone movement by continental seismological observation

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The ocean wave and low pressure cyclonic coming from the seas around Eurasia can trigger strong continuous seismic signals in continental seismological observation. Changes of the signals are consistent with cyclone motion process. In this paper, according to analysis and comparison the changes of seismic signal associated with the Western Pacific typhoon observed in mainland, signal source location, then to analyse the correlation between various characteristics of signal and cyclone motion pass the shallow , the coast and land. The results show that: the changes of signals in different frequency domain are associated with cyclone type and movement path, this can reflect changes of the geographical terrain in cyclonic tracks. These features and the results of the analysis will help explore cyclone status, the changes of interaction between cyclone and the surface, and the generation mechanism of continuous seismic signal.

IAPSO (Physical Oceanography)

P11p - P11 Wind Waves, Including Extreme Waves

P11p-059

Freak waves in soliton gas in the framework of modified Korteweg – de Vries equation

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The dynamics of heteropolar soliton field in the framework of modified Korteweg – de Vries equation is considered. Interaction of two solitons with different polarity leads to amplitude increasing of final impuls in the moment of nonlinear interaction. That makes the appearence of abnormal waves in such soliton fields possible. The main attention is present work is paid to study of freak waves appearence in heteropolar soliton fields. Distribution functions of amplitude characteristics are analized. Statistical moments are found as well. Probability and intencity of freak waves appearence in soliton fields with different soliton dencity are analized.

IAPSO (Physical Oceanography)

P11p - P11 Wind Waves, Including Extreme Waves

P11p-060

Significant wave height of extreme marine environment in the east China sea

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The East China Sea is located in the subtropical climate belt. Affected by continental high atmospheric pressure in winter, When the cold wave moves to the south, it often generates northerly winds 6-8 level and accompanies with obvious cooling after a cold front.. Because of the frequent influence of tropical cyclone, there are 5-6 typhoon passing the East China Sea in summer. The East China Sea has conditions to generate the extreme marine environment. The coast of east China sea has a lot of economic developed city with densely populated, each year the marine disaster caused by extreme marine environment extreme bring huge loss. So researching the waves of wave height in extreme marine environment in the east China sea has important implications for marine disaster forecasting. This article take the typhoon which passed through the East China Sea from 1949 to 2010 ,comping the ECOMSED hydrodynamic module and SWAN wave model, simulated the current waves during typhoons, and validate the measured current and wave data, proving the rationality of the model. Based on the simulated results, it is concluded the significant wave height distribution in the east China sea during the typhoon transit, it has certain reference value for future wave forecasting and accurate simulation in extreme marine environment in the east China sea.

IAPSO (Physical Oceanography)

P11p - P11 Wind Waves, Including Extreme Waves

P11p-061

Linear Hydrodynamic Dissipative Instability of Hagen-Poiseuille, Plane Poiseuille and Couette Flows, and Possible Mechanism of Freak Waves Arising

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It has been shown (S.G. Chefranov, A.G. Chefranov, JETP, vol.119(2), 331-340 (2014)) that the conclusion of the linear instability of the Hagen- Poiseuille flow at finite Reynolds numbers requires the refusal of the use of the traditional 'normal' form of the representation of disturbances, which implies the possibility of separation of variables describing disturbances as functions of the radial and longitudinal (along the axis of the tube) coordinates. In the absence of such separation of variables it has been shown that consideration of even two (N=2)linearly interacting radial modes (which have difference between their periods of longitudinal variability) can provide linear instability of the Hagen- Poiseuille flow at finite Reynolds number. Near the same result obtained by the energetic method for N=600 radials modes. Similar approach was applied also to the Plane Poiseuille and Plane Couette flows. The Plane Couette flow linear instability conditions, we note, provide an additional opportunity of modeling the mechanism of freak wave arising in the presence of wind - induced current for the finite depth water regions.

IAPSO (Physical Oceanography)

P12a - P12 IIOE to IIOE-2 - Five Decades of Indian Ocean Oceanography: Challenges in Physics and Biogeochemistry of Indian Ocean

IUGG-0705

Strong internal tides near the Mascarene Ridge and Subsurface equatorial current in the Indian Ocean

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The Mascarene Ridge is likely to be the place where the strongest internal tides in the world are generated. Six moorings with temperature and velocity meters were deployed near the ridge in the region of the Saya de Maya and Nazareth banks. We measured extremely strong internal tides east of the Mascarene Ridge. The vertical displacements associated with internal tides were as high as 160 m. The wavelength was estimated at 140 km. The wave propagated to the southeast from the ridge. Very high coherences were measured between the temperature sensors over the vertical and between the sensors at different moorings. The vertical structure of internal tide provides evidence that the first vertical mode is dominating.

Moored measurements of currents were performed at four sites near the equator of the Indian Ocean in December-February 1974 (55°, 65°, 75°, and 85° E). The measurements revealed the existence of Subsurface equatorial countercurrent of the Cromwell type in the Indian Ocean.

IAPSO (Physical Oceanography)

P12a - P12 IIOE to IIOE-2 - Five Decades of Indian Ocean Oceanography: Challenges in Physics and Biogeochemistry of Indian Ocean

IUGG-1944

Role of mixed layer depth in surface frontogensis: the Agulhas Return Current front

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The sea surface temperature (SST) front in the Agulhas Return Current region plays an important role in the air-sea interaction over the southern Indian Ocean. In this study, we examine how meridional variations in the mixed layer depth (MLD) across the SST front in the Agulhas Return Current region contribute to relaxation of the SST front. While the air-sea heat flux frontal variations tend to relax the SST front, the frontolysis is amplified (damped) in summer (winter) when frontal variations in the MLD are incorporated. The stronger (weaker) frontolysis associated with the MLD variations is due to the fact that the warming (cooling) by the surface heat flux is amplified south of the front where the MLD is shallower, and is reduced north of the front where the MLD is deeper.

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P12a - P12 IIOE to IIOE-2 - Five Decades of Indian Ocean Oceanography: Challenges in Physics and Biogeochemistry of Indian Ocean

IUGG-1978

Recent advances in the understanding of the Northern Indian Ocean variability

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[2]*IRD & NIO, LOCEAN & POD, Paris, India*

Authors: Vialard, J., M. Lengaigne, V.P. Akhil, A.V.S. Chaitanya, S. Neetu, I. Suresh, B.P.S.P. Krishna Mohan, M. Teesha, F. Durand, G. Samson, F. Papa

An active collaboration in the field of Indian Ocean oceanography and climate variability has been developed between several institutes in France and India since 2003. Some of the scientific advances resulting from this collaboration will be presented in this talk, focussing on the Northern Indian Ocean. For instance, recent progresses in observing the Bay of Bengal salinity structure now allow a much-improved description of processes responsible for its seasonal cycle and interannual variability. I will also review the possible impacts of the Bay of Bengal very strong haline stratification on air-sea interactions in the region, including its effect on tropical cyclones. I will finally also review recent advances in understanding the west coast of India sea level variability, its various driving processes, and its consequences on the occurrence of anoxic events there.

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P12a - P12 IIOE to IIOE-2 - Five Decades of Indian Ocean Oceanography: Challenges in Physics and Biogeochemistry of Indian Ocean

IUGG-2218

The Surface Diurnal Warm Layer in the Indian Ocean during CINDY/DYNAMO

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A surface diurnal warm layer is diagnosed from Seaglider observations and develops on half of the days in the Cooperative Indian Ocean Experiment on Intraseasonal Variability/Dynamics of the Madden–Julian Oscillation (CINDY/DYNAMO) Indian Ocean experiment. The diurnal warm layer occurs on days of high solar radiation flux (>80 W m^{-2}) and low wind speed (<6 m s^{-1}) and preferentially in the inactive stage of the Madden–Julian oscillation. Its diurnal harmonic has an exponential vertical structure with a depth scale of 4–5 m (dependent on chlorophyll concentration), consistent with forcing by absorption of solar radiation. The effective sea surface temperature (SST) anomaly due to the diurnal warm layer often reaches 0.8°C in the afternoon, with a daily mean of 0.2°C, rectifying the diurnal cycle onto longer time scales. This SST anomaly drives an anomalous flux of 4 W m^{-2} that cools the ocean. Alternatively, in a climate model where this process is unresolved, this represents an erroneous flux that warms the ocean. A simple model predicts a diurnal warm layer to occur on 30%–50% of days across the tropical warm pool. On the remaining days, with low solar radiation and high wind speeds, a residual diurnal cycle is observed by the Seaglider, with a diurnal harmonic of temperature that decreases linearly with depth. As wind speed increases, this already weak temperature gradient decreases further, tending toward isothermal conditions.
We conclude with a summary of upcoming fieldwork in the southern Bay of Bengal in summer 2016 to investigate the effect of these processes on monsoon rainfall.

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IUGG-5041

Immediate response of the ocean to MJO wind bursts and potentials for long-lasting feedbacks

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An extended series of measurements in the equatorial Indian Ocean as part of the DYNAMO experiment in 2011 included 2+ months from ship at 0, 80E. Moorings at 0, 80E and 0, 90E with chipods to measure mixing extended detailed measurements to almost a full year. This time period encompassed four MJO events, each lasting a few days. The immediate oceanic response to the accompanying westerly wind bursts was an eastward surface current (the Yoshida-Wyrtki Jet) and intense surface-forced mixing. Yet long after the passage of the MJO, the Jets persisted. Enhanced shear at the Jet's base continued to drive subsurface mixing, thereby continuing to modify sea surface temperature changes. The relative importance of MJO-initialized mixing to continued sea surface temperature modification is discussed within the framework of the DYNAMO observations.

Atmosphere as hare, ocean as tortoise?

Atmosphere as sieve, ocean as elephant?

IAPSO (Physical Oceanography)

P12b - P12 IIOE to IIOE-2 - Five Decades of Indian Ocean Oceanography: Challenges in Physics and Biogeochemistry of Indian Ocean

IUGG-1262

Volume transports of the Wyrtki Jets

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The equatorial Indian Ocean is characterized by strong eastward surface flows in boreal spring and fall referred to as the Wyrtki jets. These jets are driven by westerly winds during the transition seasons between the Southwest and Northeast Monsoons and represent a major conduit for mass, heat, and salt transfer between the eastern and western sides of the basin. Since their discovery over 40 years ago, there have been very few estimates from direct observations of the volume transports associated with these currents. In this presentation we will describe seasonal to interannual time scale variations in volume transport based on four years of unique measurements from a meridional array of acoustic Doppler current profilers along 80°5E in the center of the basin. The relation of these transports to zonal wind stress forcing, sea surface height variations and sea surface temperature variations in association with the Indian Ocean Dipole will be highlighted. We will also illustrate the role of wind-forced equatorial waves in affecting transport variations.

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P12b - P12 IIOE to IIOE-2 - Five Decades of Indian Ocean Oceanography: Challenges in Physics and Biogeochemistry of Indian Ocean

IUGG-2843

The interesting evolution of Indian Ocean climate research on the backdrop of IIOE-2

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The Indian Ocean was one of the last to be scientifically explored among the world oceans though it was one of the first to be used in maritime trades. Though there are evidences of sporadic ocean observations in the basin, no major studies were undertaken in the basin until the International Indian Ocean Expedition (IIOE) initiated in 1961. Recent discovery of the Indian Ocean Dipole (IOD) mode has generated a lot of research interests in the basin owing to its large socioeconomic impacts. JAMSTEC deployed TRITON buoys soon after the discovery of the IOD. Additional deployments from USA and India have strengthened the observational network. The JAMSTEC group also developed a state of the art climate prediction model called SINTEX-F to predict IOD besides El Niño/Southern Oscillation (ENSO). The model has consistently predicted recent El Niño/La Niña and IOD events at least several seasons ahead. It is shown that the predictability of ENSO is aided the predictions of IODs. However, predictability of the IOD is limited by the occurrences of chaotic and unpredictable intraseasonal oscillations (ISO) in the Indian Ocean. Hence, field observations and process studies will be of paramount interests to improve ISO and IOD predictabilities. In addition to tropical variations, a subtropical dipole mode is also observed in the southern Indian Ocean. It is shown to have strong influences on the climate variations of Southeastern Africa. Furthermore, a coastal phenomenon known as the Ningaloo Nino is also discovered off Western Australia that has huge impacts on the coastal and continental ecosystems. Therefore, the second version of the international campaign, the IIOE-2, will have a lot more to take into account and explore.

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P12b - P12 IIOE to IIOE-2 - Five Decades of Indian Ocean Oceanography: Challenges in Physics and Biogeochemistry of Indian Ocean

IUGG-3094

Surface circulation and upwelling around Sri Lanka and formation of the Sri Lanka dome

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Sri Lanka occupies a unique location within the equatorial belt in the northern Indian Ocean and experiences bi-annually reversing monsoon winds. This allows for the island to interact with the reversing monsoon currents, leading to the island mass effect and enhanced primary production. This study explored elements of the dynamics of the surface circulation and coastal upwelling in the waters around Sri Lanka using satellite imagery and numerical simulations using the Regional Ocean Modelling System (ROMS). The results confirmed the presence of the reversing current system, between the equator and Sri Lanka, in response to the changing wind field: the eastward flowing Southwest Monsoon Current (SMC) during the Southwest (SW) monsoon transporting 11.5 Sv and the westward flowing Northeast Monsoon Current (NMC) transporting 9.5 Sv during the Northeast (NE) monsoon, respectively. A recirculation feature located to the east of Sri Lanka during the SW monsoon, the Sri Lanka Dome, is shown to result from the interaction between the SMC and the Island of Sri Lanka. Along the eastern and western coasts, during both monsoon periods, flow is southward converging along the south coast and the major upwelling region, during both monsoon periods, is located along the south coast. The location of the upwelling centre (flow convergence) was dependent on the relative strengths of wind driven flow along the east and west coasts: during the SW (NE) monsoon the flow along the western (eastern) coast was stronger migrating the upwelling centre to the east (west).

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P12b - P12 IIOE to IIOE-2 - Five Decades of Indian Ocean Oceanography: Challenges in Physics and Biogeochemistry of Indian Ocean

IUGG-3495

Freshening of the southeast Indian ocean during the argo period: Observations, causes, and impact on regional sea level change

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Argo measurements during 2005-2013 revealed a near-decadal freshening in the top few hundred meters of the southeast Indian Ocean. The freshening has contributed to two-third of the regional sea level rise during this period. This is the strongest halosteric contribution to large-scale, regional sea level change on near-decadal time scales in the world ocean observed during the Argo period. Neither local atmospheric forcing nor halosteric signal transmitted from the Pacific can explain this freshening. An observed strengthening of the Indonesian throughflow since early 2007, the enhanced precipitation in the Indonesian Seas inferred from various precipitation products, and strong tidal mixing in the Indonesian Seas are the likely causes of the observed freshening in the southeast Indian Ocean. The findings have implications to the potential influence of regional water cycle and ocean currents in the Maritime Continent region to sea level changes in the South Indian Ocean prior to the Argo era and to sea level projection in the future in response to climate change. The implications of the related processes to biogeochemistry of the Indian Ocean need to be investigated.

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IUGG-4565

Circulation of the south Indian Ocean.

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We recently encountered the eastward 'South Indian Ocean Counter Current (SICC)' between Madagascar and Australia. It flows in the upper layer against the direction of the wind-driven circulation that moves underneath it. Large vertical shear between these counterflowing currents leads to (baroclinic) instability and an abundance of (intra thermocline) eddies that propagate westward. The wind-driven flow is embedded in the subtropical super gyre that connects all three Oceans via the Agulhas and Tasman Gateways. Hypotheses on the nature and large-scale coherence of the SICC range from a local frontal jet to a system that involves the Indonesian Throughflow, the Mozambique Channel and Agulhas Current, the SICC and the Leeuwin Current System.
Interestingly the SICC was already measured during IIOE1 and incorporated in the 1971 Atlas of the International Indian Ocean Expedition but it stayed unnoticed for several decades. A series of programs has been carried out in the last decade focussing on the inter ocean exchanges and their controls with observational, satellite and modelling programs around all gateways. We will present relevant results from these post IIOE 1 programs to derive a new coherent large-scale picture of the south Indian Ocean circulation.

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P12c - P12 IIOE to IIOE-2 - Five Decades of Indian Ocean Oceanography: Challenges in Physics and Biogeochemistry of Indian Ocean

IUGG-0582

Climate Change and Bio geographical distribution of living resources in seas surrounding Lakshadweep Islands, India

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Marine fauna in ecological niches of Lakshadweep sea are reported to be eurytopic in nature and have wide geographical distribution from tropical Indo- Pacific origin. Environmental parameters and productivity from three locations near Minicoy, Agatti and Chetlat Islands, in Lakshadweep sea procured from Atlas of National institute of Oceanography ,India, based on data collected during February 1999- December 2006, were analysed in the present study. Temperature, salinity, dissolved oxygen, nutrients such as nitrate, nitrite, phosphate and silicate , chlorophyll, primary production, zooplankton biomass, copepods, chaetognaths, ostracods, amphipods, medusa, salps & doliolids, decapods, fish eggs, fish larvae were estimated from Atlas. Seasonal data is available from surface, 10 M, 50 M, 100 M, 150 M, and 200 M for Summer monsoon (June- September), Inter Monsoon fall (October), Winter Monsoon (November-February) and Inter Monsoon Spring. Distribution of above parameters was examined to identify productivity and abundance of fishery resources in Lakshadweep sea. Fishery resources captured from Lakshadweep sea and landed at Minicoy, Agatti and Chetlat during period (1997- 2006) were examined along with environmental parameters. There are evidences of biogeographical movements of fish, benthic, plankton especially copepods from tropical waters to polar regions due to climate change. In the present study above bio geographical migration is discussed for Lakshadweep sea.

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P12c - P12 IIOE to IIOE-2 - Five Decades of Indian Ocean Oceanography: Challenges in Physics and Biogeochemistry of Indian Ocean

IUGG-1143

Interannual chlorophyll variations in the Northern Arabian Sea

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The Arabian Sea (AS) provides an excellent test bed for studying the biophysical interactions, because the large fluctuations of entrainment, mixed layer thickness, and biological activity in response to the strong annually reversing monsoon forcing. At seasonal timescales, mixed layer depth (MLD) variations are shown to largely control the chlorophyll evolution. Although there have been significant advances in our ability to describe and model the oceanic environment, the chlorophyll variations at other timescales in this region remain largely unknown. In this study, we describe the winter interannual chlorophyll variations in the AS from various satellite products and relate them to the fluctuations of their physical environment derived from Argo data. Our results reveal that chlorophyll anomalies from the various satellite products exhibit a very good phase agreement, although with large amplitude discrepancies. We further show that these interannual fluctuations of the winter bloom amplitude are largely related to interannual fluctuations of the MLD rather than thermocline depth variations. Anomalously high chlorophyll signals in the AS results from deeper than usual MLDs, which are driven by anomalously cold air temperature and related buoyancy fluxes anomalies. Our study therefore demonstrates that the mechanisms controlling chlorophyll variations at seasonal timescales also operates at the interannual one.

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P12c - P12 IIOE to IIOE-2 - Five Decades of Indian Ocean Oceanography: Challenges in Physics and Biogeochemistry of Indian Ocean

IUGG-4005

The dynamics of Ganga-Brahmaputra river plume: Seasonal variations

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Ganga-Brahmaputra river system is the fourth largest in the world by outflow and it empties into the freshest bay in the world. In this study, we present numerical simulations of movement of Ganga-Brahmaputra river plume and its dynamics, using Regional Ocean Modelling System. Two experiments were carried out to study the fate of seasonal discharge after it enters the Bay of Bengal; one in which the Ganga-Brahmaputra river forcing was excluded and the other in which it was included. The plume remains confined to north of 16^0 N during the summer monsoon (June-September). A predominantly southward spread of the plume along the east coast of the bay is also found during the summer monsoon. During winter monsoon, the plume separates into two distinct branches, one along the east coast of the bay and the other along the west. Along the east coast of India, trapped to the coast, the plume spreads a great distance southward consistent with existing observations. During spring (March-April), plume water circulates in the northern and central bay. Freshwater thickness, defined as the fraction of the total freshwater in the water column, is about 1 meter for Ganga-Brahmaputra discharge and its spatial distribution confirms the seasonal orientation of the plume. The movement of the plume is dictated by two important forcing mechanisms of the Bay of Bengal circulation; monsoon winds and remote forcing.

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P12c - P12 IIOE to IIOE-2 - Five Decades of Indian Ocean Oceanography: Challenges in Physics and Biogeochemistry of Indian Ocean

IUGG-5340

Biogeochemistry of the Leeuwin Current and its Mesoscale Eddies in the South Eastern Indian Ocean

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The Leeuwin Current in the eastern Indian Ocean becomes unstable in the austral autumn triggering the formation of eddies at the Western Australian shelf break. We hypothesized that eddy formation represented the major driver of cross-shelf transport during the autumn. ADCP profiles confirmed periodic offshore movement of ~2 Sv of shelf waters into the forming eddy from the shelf, carrying a load of coastally-sourced organic particles. This was followed by closing of the gap between inflow and outflow, such that the forming eddy became isolated from further direct input of coastal waters over 2 weeks. Drifter tracks supported an anticyclonic surface flow peaking at the eddy perimeter and decreasing in velocity at the eddy centre.

Oxygen and nutrient profiles suggested rapid remineralization of nitrate mid-depth in the isolated water mass as it rotated, with a total drawdown of oxygen of 3.6 mol m^{-2} *to 350 m (~0.5 mol* O_2 m^{-2} d^{-1}*). We traced depletion of oxygen, and release of nitrate, within the rotating water mass on the timescale of ~1 week. This suggests a more local source of nitrogen (N) that has recently been proposed (Thompson et al., 2011; Waite et al 2013), essentially a source of organic carbon within several 100 km. In addition, N supply and N turnover are extremely rapid in this system, such that nitrate is acting primarily as a regenerated nutrient rather than as a source of new nitrogen. We track the coastal particle injection as particle accumulations along density interfaces. We speculate that coastal particle sources include macrophytes and seagrasses, known to produce copious detritus which is prone to resuspension and offshore transport.*

IAPSO (Physical Oceanography)

P12c - P12 IIOE to IIOE-2 - Five Decades of Indian Ocean Oceanography: Challenges in Physics and Biogeochemistry of Indian Ocean

IUGG-5523

GEOTRACES highlights in the Indian Ocean and plans for the future

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GEOTRACES will present its past work in the Indian Ocean and the plans for future. GEOTRACES (www.geotraces.org) is an international programme which aims to study the marine biogeochemical cycles of trace elements and their isotopes. Scientists from 35 nations have been involved in the programme, designed to study all major ocean basins over the next decade. So far, 732 stations have been already sampled during 51 cruises resulting in more than 1000 data sets of hydrographical and geochemical data. To facilitate access to these data, four years after the launch of the programme, the first GEOTRACES Intermediate Data Product is already freely available on-line from the GEOTRACES site. Digital data is accompanied by an electronic atlas (www.egeotraces.org) that provides 2D and 3D images of the ocean distribution of many of the parameters. As part of this talk, selected original data will be shown, illustrating the power of geochemical tracers to reveal oceanographic features: hydrothermal inputs more important than what was ever observed for Fe, water mass sources and transports traced by Pb and Ra isotopes, trace element budgets and particle fates on the Kerguelen Plateau. Japan, India and France have completed GEOTRACES cruises in the Indian Ocean and Australia, Germany, France and UK have plans for future cruises.

IAPSO (Physical Oceanography)

P12d - P12 IIOE to IIOE-2 - Five Decades of Indian Ocean Oceanography: Challenges in Physics and Biogeochemistry of Indian Ocean

IUGG-2052

Contribution of Observations from Space 50 years after International Indian Ocean Expedition (IIOE)

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University of Washington contributed a floating platform to measure ocean-atmosphere turbulent fluxes that also included moving sensors measuring the vertical profiles or wind, temperature and humidity in the first IIOE. We have used the advanced techniques for research and education in the decades that followed, and the flux-profile relations validated during the IIOE formed the basis of our flux parameterization that is used by the community today. We will provide an overview of spacebased measurements that will help the design and complement the next expedition with spatial and temporal coverage. Decades of ocean surface wind and stress vectors are available from scatterometers. Sensible and latent heat fluxes have been operationally computed from microwave radiometers. Vertically integrated moisture transport, the divergence of which may give the surface water flux, has also been derived. There are rain products from merging satellite and in situ measurements. Surface radiative fluxes, including the effects of aerosols and diurnal variation, are being produced. Several international efforts are producing high-resolution sea surface temperatures (SST) from both infrared and microwave radiometers. Ocean surface dynamic height, chlorophyll, and salinity are continuously measured. Ocean is studies as source and sink of carbon dioxide (CO2) by missions that measured column-integrated CO2. We have trained a statistical model with coincident in situ and spacebased measurements we collected over the past decades to estimate ocean surface CO2 partial pressure using spacebased SST, chlorophyll, and salinity and produced a decade-long data set. The deficiency of training and validation data in the Indian Ocean will be discussed.

IAPSO (Physical Oceanography)

P12d - P12 IIOE to IIOE-2 - Five Decades of Indian Ocean Oceanography: Challenges in Physics and Biogeochemistry of Indian Ocean

IUGG-3275

Planning for the Second International Indian Ocean Expedition (IIOE-2)

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The International Indian Ocean Expedition (IIOE) of 1959-65 left an important societal legacy. Five decades on, IOC and SCOR again, along now with the Indian Ocean Global Ocean Observing System Regional Alliance (IOGOOS), are working to stimulate a contemporary phase of coordinated international research and associated applications/knowledge transfer through capacity building (ie IIOE-2: 2015-20). This will encompass research on the Indian Ocean's oceanic and climatic phenomena of regional and global significance, guided by science priorities as per an IIOE-2 Science Plan developed under the auspices of SCOR. IIOE-2 will forge new international scientific research programs with far-reaching benefits for and beyond the Indian Ocean. IIOE-2 will provide a rich framework of data, process understanding and input to oceanographic and climate modelling, focusing on open ocean science but with oceanographic links to continental shelf and coastal systems and coupled climatic phenomena affecting societies regionally and globally. The transfer of knowledge and tangible outputs for societal application and benefit is a key pursuit.

To plan for IIOE-2, there have been a number of internationally supported workshops and national efforts since 2011. The IOC Assembly of 147 Member States has been formally considering science and complementary plans for IIOE-2, along with the required governance and timeframes for implementation through an IOC constituted IIOE-2 Interim Planning Committee (Group of Experts). This presentation will outline and report on the status of planning for IIOE-2, including the evolving frameworks for key themes such as the science, capacity building and data/information management and also the developing governance framework .

IAPSO (Physical Oceanography)

P12d - P12 IIOE to IIOE-2 - Five Decades of Indian Ocean Oceanography: Challenges in Physics and Biogeochemistry of Indian Ocean

IUGG-4801

Role of the Indian Ocean Dipole dynamics in the evolution of mega El Ninos

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The heightened expectations for a mega El Nino occurring in 2014, and its subsequent non-appearance brings to question conventional hypotheses for these extreme events. In this paper we present evidence from observations and modeling studies that points to equatorial teleconnections associated with the Indian Ocean Dipole as a plausible factor driving the evolution of mega El Ninos. In the early part of the talk, we focus on coupled ocean-atmospheric variations in the Indo Pacific sector during the year 2006. In particular we contrast the strong and robust development of a strong IOD with the intermittent and weak El Nino. Our analysis shows that strong and persistent westerly winds extending into the western Pacific warm pool were initiated and sustained by convective anomalies associated with the IOD through atmospheric Kelvin waves. In turn the initiation of the El Nino event was driven by these abnormal westerly winds which triggered the displacement of warm subsurface waters into the eastern Pacific through oceanic Kelvin waves. As coupled convective variability is weak over the tropical Pacific during the El Nino episode, we argue that the event was by and large controlled by the equatorial teleconnections generated and sustained by the IOD event. Numerical experiments using a dry linear baroclinic model are used to substantiate the role of Indian Ocean convection in driving zonal wind anomalies over the Indian Ocean, and idealized experiments are used to highlight the essential dynamics of these interactions. Finally we carry out a multi-event analysis spanning the last 60 years of observations to further substantiate our hypotheses.

IAPSO (Physical Oceanography)

P12d - P12 IIOE to IIOE-2 - Five Decades of Indian Ocean Oceanography: Challenges in Physics and Biogeochemistry of Indian Ocean

IUGG-4975

Seaglider observations of equatorial Indian Ocean Rossby waves associated with the Madden-Julian Oscillation

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During the CINDY-DYNAMO field campaign of September 2011-January 2012, a Seaglider was deployed at 80ºE and completed 10 north-south sections between 3 and 4ºS, measuring temperature, salinity, dissolved oxygen concentration and chlorophyll fluorescence. These high-resolution subsurface observations provide insight into equatorial ocean Rossby wave activity forced by three Madden-Julian Oscillation (MJO) events during this time period. These Rossby waves generate variability in temperature O(1ºC), salinity O(0.2 g kg^{-1}), density O(0.2 kg m^{-3}) and oxygen concentration O(10 μ mol kg^{-1}), associated with 10 m vertical displacements of the thermocline. The variability extends down to 1000 m, the greatest depth of the Seaglider observations, highlighting the importance of surface forcing for the deep equatorial ocean. The temperature variability observed by the Seaglider is greater than that simulated in the ECCO-JPL reanalysis, especially at depth. There is also marked variability in chlorophyll fluorescence at the surface and at the depth of the chlorophyll maximum. Upwelling from Rossby waves and local wind stress curl leads to an enhanced shoaling of the chlorophyll maximum by 10-25 m in response to the increased availability of nutrients and light. This influence of the MJO on primary production via equatorial ocean Rossby waves has not previously been recognised.

IAPSO (Physical Oceanography)

P12d - P12 IIOE to IIOE-2 - Five Decades of Indian Ocean Oceanography: Challenges in Physics and Biogeochemistry of Indian Ocean

IUGG-5217

Indian Ocean sea surface salinity: from occasional sections to weekly high-resolution maps from Aquarius/SAC-D

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The Aquarius/SAC-D mission has produced nearly four years of sea surface salinity (SSS) data in the Indian Ocean allowing high-resolution quantification of its space/time variability. In the tropical region, the SSS variability results from precipitation/evaporation, river input, and, in large part, seasonal and intraseasonal wind forcing, which results in energetic changes to the velocity field. Prior to satellite-based observations of SSS, our knowledge of the salinity field and its variability was based primarily on infrequent shipboard sections, time-series moorings, occasional process experiments, modeling studies, and, recently, the Argo array. Aquarius data enable a more detailed analysis of space-time variability at weekly and order ~100 km scales. In this study, we provide an overview of this variability of SSS in the Indian Ocean focusing on intraseasonal, annual and interannual variability over the nearly 4-year observation period, and quantify existing Aquarius biases with respect to Argo data. The study uses level-2 along-track data to quantify frontal regions at high resolution, and a new high-resolution SSS analysis (Melnichenko et al., 2015), produced at the University of Hawaii, to study space-time variations. The product is a weekly SSS analysis on a nearly-global 0.5-degree grid. The analysis method is optimum interpolation that takes into account analyzed errors of the observations, specific to the Aquarius instrument, and also includes a large-scale correction for satellite biases with respect to Argo data to produce more accurate SSS maps, free from spurious structures. Regional focus in this study includes the near-equatorial band, 10 S to 10 N, and the Bay of Bengal SSS fronts. Summary comments include issues and opportunities for future work.

IAPSO (Physical Oceanography)

P12d - P12 IIOE to IIOE-2 - Five Decades of Indian Ocean Oceanography: Challenges in Physics and Biogeochemistry of Indian Ocean

IUGG-5548

Eastern Indian ocean upwelling research initiative (EIOURI)

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Upwelling systems and associated ocean variability in the eastern Indian Ocean are important for regional and basin scale climate variations and also play important role in biophysical interactions in marine ecosystems in the region. To understand further on physical and biogeochemical/ecosystem variability associated with the upwelling systems in the eastern Indian Ocean, an international research initiative, named Eastern Indian Ocean Upwelling Research Initiative (EIOURI), is proposed as a part of IIOE-2 during 2015-2020. EIOURI includes an intensive observation campaign together with modeling and analyses of data from various sources. This research initiative mainly focus on the coastal upwelling system off Sumatra-Java, but also includes open ocean and coastal upwelling systems in the Bay of Bengal, Equatorial region, and area off northwestern coast of Australia as its target areas. Main topics of the initiative include; local and remote influences of oceanic processes on the upwelling systems, coastal and off-shore interactions, biogeochemical variability and their interactions with physical conditions, ecosystem variability associated with the upwelling variations. This presentation introduces science plan of EIOURI and discuss several specific key issues to be investigated during the initiative.

IAPSO (Physical Oceanography)

P12p - P12 IIOE to IIOE-2 - Five Decades of Indian Ocean Oceanography: Challenges in Physics and Biogeochemistry of Indian Ocean

P12p-225

Quantification of gas-hydrates from seismic velocity-resistivity transformed data in Krishna-Godavari basin, eastern Indian margin

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Gas-hydrates, future major potential energy resource of the world, have been recovered in fracture shale at site 10 in Krishna-Godavari (KG) basin in eastern Indian offshore by Expedition-01of National Gas Hydrate Program. Higher values in resistivity and sonic logs indicate gas-hydrates between 30 to 150 m below the sea floor, whereas the shallower and deeper sediments are brine-saturated. Direct application of simple Archie's formula to resistivity log data results in overestimation of gas-hydrates compared to that measured by pressure cores at few depths of this site. This is because of its isotropic assumption of anisotropic media caused by fractures. Considering gas-hydrates as part of matrix and brine in pores, we have established a relationship between the resistivity and velocity for sediments with and without gas-hydrates using log data. We estimate gas-hydrates from resistivities by employing modified Archie's formula with the saturation exponent that has been established by calibration with pressure core results. This saturation exponent incorporates the effect of fractures automatically. We have processed the high-resolution multi-channel seismic data at 62.5 m interval with a view to build the best possible velocity models and improved seismic images along two lines passing through site 10. The velocity-depth function at each point has been transformed into pseudo resistivity log using the velocity-resistivity relationship. Application of modified Archie's formula to the pseudo logs results in laterally and vertically varying gas-hydrates up to 28% along the lines. The method is simple; does not require Archie’s constants and porosity of sediments; and can be used in estimating gas-hydrates without any fracture modeling.

IAPSO (Physical Oceanography)

P12p - P12 IIOE to IIOE-2 - Five Decades of Indian Ocean Oceanography: Challenges in Physics and Biogeochemistry of Indian Ocean

P12p-226

Multidisciplinary Seaglider surveys in the Gulf of Oman

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The upwelling system off the coast of Oman is crucially important for fisheries and regulates the occurrence of harmful algal blooms and anoxia on the shelf. This politically sensitive area has suffered from piracy leading to a dearth of oceanographic surveys in the region. We present a campaign of Seaglider deployments being undertaken as part of an ONR and NERC supported project. A glider carrying CTD, dissolved oxygen, chlorophyll fluorescence and irradiance sensors will be deployed in March 2015 with the intention of maintaining a glider occupation throughout 2015 observing the two opposite monsoonal regimes and the intermonsoon period. The glider survey is designed to encompass shelf, slope and open ocean environments of the Gulf of Oman with a repeat of about a week to observe the formation of a seasonal cyclonic eddy linked to the Ras Al Hadd jet and subsurface dynamics along the shelf and slope. These observations will serve to determine the dominant processes and their variability which lead to the occurrence of phytoplankton blooms along the northern coast of Oman. In this poster we present the early results of the glider deployment. This is expected to include nearly 4 months of repeat hydrographic sections and dive average currents.

IAPSO (Physical Oceanography)

P12p - P12 IIOE to IIOE-2 - Five Decades of Indian Ocean Oceanography: Challenges in Physics and Biogeochemistry of Indian Ocean

P12p-227

Effects of salinity on geostrophic transport of the Indonesia Throughflow

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The Indonesian throughflow (ITF) is important to global ocean circulation as well as climate variability and change. Systematic, direct measurements of the ITF transports through various straits in the Indonesian Seas are challenging. No such measurements exist except for those obtained during the INSTANT program (2004-2006). The temperature profile data from the frequently repeated XBT line IX1 (Fremantle, Australia – Sumatra and Java, Indonesia) near the entrance of the ITF to the Indian Ocean have enabled estimates of ITF geostrophic transport relative to 700 m since the 1980s. But the estimates were based on temperature measurements and a climatological temperature (T) and salinity (S) relation. Although Argo floats have been providing T and S measurements since the mid-2000s, the density of the floats near the IX1 region is limited. How salinity regulates the ITF transport remains to be investigated. Here we use two products to evaluate the influence of salinity on ITF geostrophic transport: (1) the monthly objective analysis of T and S from JAMSTEC based on measurements from Argo, XBT, and tropical moorings, and (2) T and S output from the OGCM for Earth Simulator (OFES) with a 0.1-deg horizontal resolution. For each product, we estimate the geostrophic transports relative to 700 m near the IX1 line based on (1) monthly T and S fields, (2) monthly T and seasonal climatology of S, and (3) monthly T and climatological time-mean S. We compared these estimates to illustrate the effects of S on ITF geostrophic transport for the time mean and variability on different time scales, both for the model- and observation-based products.

IAPSO (Physical Oceanography)

P13a - P13 Internal waves dynamics in world oceans: from remote sensing, insitu monitoring to numerical modelling

IUGG-0606

Propagation and dissipation of nonlinear internal waves around dongsha in the South China Sea

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We use 3-dimensional, non-hydrostatic numerical model MITgcm to simulate internal solitary waves (ISWs) in the South China Sea (SCS) with high resolution. Firstly, in order to validate the accuracy of our model, the model results are compared to tidal data sets (TPXO7.1) and temperature data observed from the WISE field experiment in late June 2005, which accords well with the predicted dates. Driven by 8 tidal components, our model could predict the evolution and dissipation of ISWs derived from Luzon Strait (LS). The gradient of sea surface height indicates that, single ISWs with long crest line divide into two after the collision with Dongsha Atoll. These two waves with short crest line gradually interact and combine, but not becoming a completed single one at last. After the atoll effects on ISWs, multiple dynamic processes related to ISWs can be presented and be discussed in the article, such as the ISW packets being diffracted by the atoll, a weak reflected ISW, and intricate wave-wave interaction. Through calculating baroclinic energy flux, we compared the incident energy and reflect energy at Dongsha Atoll and found that in spring tide and neap tide, the reflected to incident energy ratios are different. We also choose three mooring sites and a profile which is perpendicular to the crest line of ISWs, to discuss the characteristics of amplitude and wave speed.

IAPSO (Physical Oceanography)

P13a - P13 Internal waves dynamics in world oceans: from remote sensing, insitu monitoring to numerical modelling

IUGG-1573

Internal wave generation and propagation in a geostrophic front

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In general internal wave studies, it is usually assumed that stratification is horizontally uniform. However, in continental shelf, the thermocline is tilted due to the presence of geostrophic flows, for example the Kuroshio in the west boundary of the North Pacific Ocean. In this case, an additional cross-derivative term appears in the linear internal wave equation, resulting new features for the internal wave generation and propagation. The new equation is then solved numerically and compared with the flat thermocline cases. For internal wave propagation, high mode internal waves will be scattered due to the tilted thermocline even with flat bottom. For internal wave generation, the internal tide generation becomes asymmetric on each side of a single ridge. Mixing rate is estimated for both cases. The MITgcm is implemented to validate the above analysis. Application in the Kuroshio region is also discussed.

IAPSO (Physical Oceanography)

P13a - P13 Internal waves dynamics in world oceans: from remote sensing, insitu monitoring to numerical modelling

IUGG-5022

Effects of mesoscale circulation on nonlinear internal waves in the South China Sea from observation and simulation

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This study presents observations of nonlinear internal waves acquired from a 2-D array of pressure-recording inverted echo sounders (PIESs) in the deep basin of the northeastern South China Sea for about 4 months in 2011, with the goal of assessing their propagation features affected by mesoscale circulations. The 2-D array measurements reveal that the northern side of the northeastern South China Sea is dominated by semidiurnal fluctuations, while its southern side is dominated by diurnal ones. The outputs from SUNTANS, a nonhydrostatic and unstructured grid ocean model, agree well with the observed nonlinear internal waves overall with some amplitude and arrival time deviations. We obtain time series of the deviations between our observations and the SUNTANS model simulations at each PIES site. Since the model was run with a horizontally homogeneous temperature profile obtained from a mean of historical observations, the deviations are analyzed in terms of mesoscale variability based on the data-assimilated HYCOM simulation results. We find that the amplitude and arrival time of nonlinear internal waves observed at PIES sites modulate significantly depending on time, which is associated with mesoscale circulation changes during the observation period. Deviations of internal wave arrival time are quite well simulated when they are derived from integration of the first internal-mode phase speed along 2-D ray-traced paths using HYCOM simulation results.

IAPSO (Physical Oceanography)

P13a - P13 Internal waves dynamics in world oceans: from remote sensing, insitu monitoring to numerical modelling

IUGG-5657

Numerical internal tide scattering, diffraction, and dissipation on the tasman continental slope

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Internal tides generated at steep topography tend to propagate far from their source with little local mixing. Where does this energy dissipate? One candidate is via reflection on continental slopes. The upcoming Tasmanian Internal Tide Experiment aims to look at the reflection of internal tide generated near New Zealand and track its reflection from the Tasmanian Continental Slope. Here we consider numerical studies to track the propagation of the internal tide onto this slope and its dissipation. We find a strong interference patterns sets up, as expected from a reflecting tide. The pattern is complicated by the ``Tasman Rise'' positioned near the center of the incoming internal tide beam, causing a diffraction pattern to focus and defocus the tide along the slope. Dissipative mechanisms on the slope include turbulent lee waves from small cross-slope ridges, and along-slope lee-waves trapped and breaking in corrugations in the slope.

IAPSO (Physical Oceanography)

P13a - P13 Internal waves dynamics in world oceans: from remote sensing, insitu monitoring to numerical modelling

IUGG-5721

Internal waves

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INTERNAL WAVES

Gravity waves in the ocean interior are as common as waves at the sea surface - perhaps even more so, for no one has ever reported an interior calm. Originally considered an unwanted noise in a variety of oceanographic observations, they are now recognized as an important source of ocean mixing and other vital ocean processes.

Theory for a two-layer system (Stokes 1847) and extension to continuous stratification (Rayleigh 1883) preceded observations by a century. I will emphasize the early history with which I am personally familiar.

Variability in hydrocasts was properly attributed to internal tides. The invention of the bathythermograph in 1940 revealed a high-frequency continuum of eight octaves between the inertial frequency and the buoyancy frequency. At the time, oceanographers had not yet become familiar with the required techniques for dealing with continuous spectra, and this led to many difficulties.

By the end of the century, the detection of centimeter surface signatures of internal waves from satellite altimeters led to a host of discoveries, including the recognition that internal wave processes are a critical element of ocean dynamics.

IAPSO (Physical Oceanography)

P13b - P13 Internal waves dynamics in world oceans: from remote sensing, insitu monitoring to numerical modelling

IUGG-0603

Seasonal variation and spectrum analysis of internal tides in Northern South China Sea

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The temporal-spatial variation and energetics of internal tides in northern South China Sea are investigated by a fully nonlinear, three-dimensional hydrostatic model (MITgcm) driven by eight principal tidal constituents. Four model different in driven tides and initial temperature and salinity fields were Simulated. The model results show that, the energy flux of internal tides in model area on January is stronger than other months. In Luzon Strait, for 30 days average ,the internal tidal energy generated on January, April, July and October is 32.7, 30.8, 32.0 and 29.0(GW) separately, diurnal, third-diurnal and quarter-diurnal component are mainly periods. About 20.8, 19.0, 19.9 and 18.0(GW) of the internal tidal energy subsequently pass from Luzon Strait, which flows westward into the SCS is slightly larger than eastward one. Power spectrum analysis about the series of energy show that the westward one is dominated by semidiurnal component and the eastward one consists of mainly semidiurnal and diurnal component both. The internal tidal energy of local dissipation is 11.1, 11.2, 11.2 and 10.3(GW), nearly 35% of the internal tidal energy generated in the LS dissipates locally. But, during neap tides, the proportion of local dissipation may as low as 10%.

IAPSO (Physical Oceanography)

P13b - P13 Internal waves dynamics in world oceans: from remote sensing, insitu monitoring to numerical modelling

IUGG-0876

Mode 2 internal waves in the sea: evidences from observations

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Until recently it was believed that the higher modes of internal waves, whose existence is predicted by the theory, almost never occur in the real ocean environment. Indeed it was reported only on observations of internal waves of the first mode. In recent years, the situation has changed and several reports on mode 2 internal wave observations in the South China Sea were appeared. In this paper, based on our own long-term measurements in different regions of the World Ocean, we present experimental evidences for the existence of internal waves of the second mode in a real sea environment. Mode 2 internal waves were met in the Indian Ocean near the Mascarene Ridge, in the Luzon Strait in the South China Sea, in the Black Sea shelf off the coast of the Crimea. Near the Mascarene Ridge we observed mode 2 solitary internal wave in the form of hydraulic jump behind the sill which disintegrated into packets of solitons with strong second mode components. Mode 2 internal solitary wave in the Luzon Strait had 50- meter amplitude, propagated from underwater ridge and had form of a convex wave. In the Black Sea we made observations from oceanographic platform in shallow water at 30 m depth. Mode 2 internal inertial waves (17-hour period) were revealed together with mode 2 short-period waves (periods of 5-30 min). Origins of mode 2 internal waves in some cases are not completely clear. *The work was partially supported by RFBR grant 13-05-01106.*

IAPSO (Physical Oceanography)

P13b - P13 Internal waves dynamics in world oceans: from remote sensing, insitu monitoring to numerical modelling

IUGG-4138

Observing the generation, propagation and dissipation of internal waves in the ocean

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Internal waves in the ocean account for a sizable fraction of the ocean's kinetic energy, attaining heights up to several hundred meters near strong generation sites. Their breaking gives rise to turbulence, whose transports of mass and heat must be parameterized accurately in climate models. Because internal waves are largely generated by wind and tides, and often travel across ocean basins prior to breaking, one approach is to attempt to understand separately their generation, propagation and dissipation. In this talk I will describe attempts to fill in this framework and show observational examples of each of these stages of internal waves with an ultimate goal (not to be reached in the talk) of a full geography, energy flow and life cycle of internal waves.

IAPSO (Physical Oceanography)

P13b - P13 Internal waves dynamics in world oceans: from remote sensing, insitu monitoring to numerical modelling

IUGG-5082

Hot-spots of internal solitary waves in the eastern arctic observed from space

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Internal solitary waves (ISWs) are important dynamical features significantly impacting the hydrology of the upper ocean through transferring the energy from tides to turbulent mixing. In the Arctic Ocean they are particularly important for sub-marine navigation and construction, formation of the water structure and the maintenance of the life activity in marine ecosystems. However, the Arctic region still remains largely unexplored and internal solitary waves there are still poorly investigated.

In this work taking the advantage of high resolution space-borne synthetic aperture radar (SAR) data we present first results of short-period ISWs observations in the Barents, Kara and White seas based on analysis of ENVISAT ASAR data for summer-autumn months in 2007-2011. More than 2000 ISW packets were identified in about 1600 SAR images. Detailed maps of IWs observational frequency and their spatial and kinematic properties for the three Arctic seas helped to identify main sites of regular IW generation. We also point out the regions where large-scale nonlinear ISW packets with wavelengths of 2-5 km and crest lengths >200 km are observed. For the first time SAR observations compared with historical ship measurements and modeling results uniquely uncover the complex picture of IW field in the Eastern Arctic seas.

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IAPSO (Physical Oceanography)

P13c - P13 Internal waves dynamics in world oceans: from remote sensing, insitu monitoring to numerical modelling

IUGG-1240

Tidally-forced flow in a rotating, stratified, shoaling basin

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Baroclinic flow of a rotating, stratified fluid in a parabolic basin is computed in response to barotropic tidal forcing using the nonlinear, non-hydrostatic, Boussinesq equations of motion. The tidal forcing is derived from an imposed, boundary-enhanced free-surface deflection that advances cyclonically around a central amphidrome. The tidal forcing perturbs a shallow pycnocline, sloshing it up and down over the shoaling bottom. Nonlinearities in the near-shore internal tide produce an azimuthally independent `set-up' of the isopycnals that in turn drives an approximately geostrophically balanced, cyclonic, near-shore, sub-surface jet. The sub-surface cyclonic jet is an example of a slowly evolving, nearly balanced flow that is excited and maintained solely by forcing in the fast, super-inertial frequency band. Baroclinic instability of the nearly balanced jet and subsequent interactions between eddies produce a weak transfer of energy back into the inertia-gravity band as swirling motions with super-inertial vorticity stir the stratified fluid and spontaneously emit waves. The sub-surface cyclonic jet is similar in many ways to the poleward flows observed along eastern ocean boundaries, particularly the California Undercurrent.

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IUGG-1250

New look on the nonlinear internal waves

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Internal solitary-like waves are observed everywhere on the ocean shelves. They are studied and modelled well now mainly for the first mode cases. The second mode solitary like waves were observed recently and their appearance also is explained. The ocean internal breather is difficult to select in irregular wave field, and just now we have indirect confirmation of breather-like packets in the ocean. The existence of internal breathers have been predicted by the asymptotic theory of long internal waves and their propagation have been modeled numerically in the frames of the Gardner equation as well as in the frames of the nonlinear Euler equations for stratified water. They can be generated due to horizontally variable background and the modulation instability. The modulation instability leads to generation of internal wave breather of huge amplitude. The possible scenarios are done for some ocean regions. We demonstrate also the second possible mechanism of internal breather generation into stratified water using various numerical, when internal solitary wave propagates through the turning point, where the quadratic nonlinearity change the sign. The third mechanizm of the internal breather generation is possible when the internal solitary wave of the second mode interacts with the bottom step.

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IUGG-1264

Parametric subharmonic instability of internal modes

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Waves can become unstable through parametric subharmonic instability (PSI) by transferring energy irreversibly to a pair of waves with collectively resonant wavenumber and frequency. It is well established that two-dimensional internal plane waves and modes in uniformly stratified fluid efficiently transfer energy to smaller scale waves and ultimately turbulent mixing through PSI. Recently it has been shown that PSI acts not just upon plane internal waves but also upon internal wavepackets and internal wave beams. All of these studies considered internal waves in uniformly stratified fluid.The numerical simulations of MacKinnon & Winters (GRL 2005) predicted PSI should act efficiently to disrupt the internal tide. However, while in situ observations showed the presence of PSI, it was not found to be appreciable. One reason for the discrepancy between simulations and observations is that the former examined an internal mode in uniformly stratified fluid whereas, in reality, the internal tide is manifest as the sinusoidal oscillation of the thermocline; it more closely resembles an interfacial wave. The resonant condition of PSI for a one-dimensional interfacial wave in a two layer fluid is so restrictive that the instability is suppressed. However, at a thick interface like the thermocline, PSI may occur by exciting subharmonic waves with vertical as well as horizontal structure. Certainly in the limit of uniform stratification, the occurrence of PSI is robust. Through theory and numerical simulations, we examine the onset and growth of PSI and the long-time energy transfer rate from a low mode internal wave to small scale disturbances as it depends upon the thickness of the interface and the modal structure of the parent wave.

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P13c - P13 Internal waves dynamics in world oceans: from remote sensing, insitu monitoring to numerical modelling

IUGG-3370

Baroclinic tides in the Celtic Sea: A new look at a well know problem

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Internal waves generated by tides in the Celtic Sea were investigated on the basis of in-situ data collected at the continental slope in July 2012, and theoretically using a weakly nonlinear theory and the Massachusetts Institute of Technology general circulation model. It was found that internal solitary waves generated over the shelf break and propagated seaward did not survive in the course of their evolution. Due to the large bottom steepness they disintegrated locally over the continental slope radiating several wave systems seaward and transforming their energy to higher baroclinic modes. In the open part of the sea, i.e. 120km away from the shelf break, internal waves were generated by a baroclinic tidal beam which was radiated from the shelf break downward to the abyss. After reflection from the bottom it returned back to the surface where it hit the seasonal pycnocline and generated packets of high-mode internal solitary waves. Another effect that had strong implications for the wave dynamics was internal wave reflection from sharp changes of vertical fluid stratification in the main pycnocline. A large proportion of the tidal beam energy that propagated downward did not reach the bottom but reflected upward from the layered pycnocline and returned back to the surface seasonal pycnocline where it generated some extra higher mode internal wave systems, including internal wave breathers.

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IUGG-5391

Nature of near-Inertial motions in the upper ocean and a possible route towards high-frequency radar probing of subsurface stratification

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Inertial band response of the upper ocean to changing wind is studied both theoretically and by analysis of observations in the Gulf of Lyons. The theoretical examination is carried out within the framework of the linearized Euler equations on the non-traditional f-plane. Due to the horizontal component of the Earth rotation for near-inertial waves with frequencies slightly below the local inertial frequency there is a waveguide in the mixed layer confined from below by the pycnocline. When the stratification is shallow and strong these near-inertial motions are the ones most easily and strongly excited by the changing winds. The linear model predicts that in the presence of seasonal stratification the inertial band response of the upper ocean is dominated by these sub-inertial motions. These motions have been overlooked in the previous studies since they are absent under the traditional approximation. The in situ observations which employed buoys with thermistors, ADCPs, HF radars and SST data were carried out in the Gulf of Lyons in April-June 2006. The observations support the theoretical picture: a pronounced inertial band response occurs only in the presence of strong shallow stratification and is sharply localized near the surface.

This changes the established understanding of how inertial motions are generated, where to they transfer momentum and energy. The surface signatures of sub-inertial motions are easily captured by HF radars. The sensitivity of the inertial band response (as seen by HF radars) to the upper ocean stratification provides a foundation for developing HF radar probing of seasonal stratification in the future.

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P13p-459

Observation of internal wave polarity conversion generated by a rising tide

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The observations reported here are based on time series of in situ observation data in Laoshan Bay off the Qingdao coast. A chain of thermistors (T-chain) at a fixed location recorded a sequence of elevation internal waves followed by depression internal waves passing by over an elapsed time of about one hour. This observed polarity conversion at a fixed location is caused by the vertical stratification variation mainly induced by the rising tide, which is believed to be the first reported observation of this kind. The process of an elevation internal wavetrain converting to a depression wavetrain is simulated using the variable-coefficient extended Korteweg-de Vries (veKdV) equation, which also provides a further comparison between the theory and the reported observations.

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P13p - P13 Internal waves dynamics in world oceans: from remote sensing, insitu monitoring to numerical modelling

P13p-460

Observed upper ocean response to typhoon Megi (2010) in the Northern South China Sea

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Typhoon Megi passed between, and within 30 km of, two subsurface moorings in the northern South China Sea in October 2010. This typhoon path gave a rare opportunity to examine upper-ocean thermal and dynamical response to a typhoon, with strong internal tides present, based on continuous current and temperature profiles measured by the mooring array. The entire observed water column (60–360 m) was cooled by Megi's strong Ekman-pumped upwelling (up to 50 m in the thermocline), with maximum cooling of 4.2°C occurring in thermocline. Near-inertial oscillations (NIO) in the mixed layer were relatively weak (maximum amplitude of 0.4 m/s) and quickly damped (e-folding time scale of 2 inertial periods). Power spectrum and wavelet analyses both indicated an energy peak (with maximum amplitude up to 0.2 m/s) at the sum frequency fD1 of NIO (f) and diurnal tide (D1), indicating enhanced nonlinear wave-wave interaction between f and D1 during and after Megi. Numerical experiments suggested that energy transfer from NIO to fD1 via nonlinear interaction between f and D1 may have limited the growth and accelerated the damping of mixed layer NIO generated by Megi. The occurrence of fD1 had a strong correlation with NIO; the vertical nonlinear momentum term, associated with the vertical shear of NIO and vertical velocity of D1 or vertical shear of D1 and vertical velocity of NIO, was more than 10 times larger than the horizontal terms and was responsible for forcing fD1. After Megi, surface-layer diurnal energy was enhanced by up to 100%, attributed to the combined effect of the increased surface-layer stratification and additional Megi-forced diurnal current.

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P13p-461

"Satellite observations of the internal waves in the Skagerrak"

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Two types of surface manifestations of internal waves in the Scagerrak Strait revealed in ERS-1/2 SAR and Envisat ASAR images are discussed. Internal waves of the first type are "classical" soliton trains found over the Norwegian Trench. As a rule, they propagate to the west of Cape Grenen being induced by the interaction of tidal currents with bathymetry and seasonal upwelling. The main parameters of the internal waves of the first type are: the average number of waves in a single package is from 4-6 to 8-10; wave length varies from 300-400 m to 1500-1700 m. Average wave front revealed on the images is up to 50 km.

The second type of internal waves refers to the densely packed narrow bands of alternating low and high backscatter arranged perpendicular to the coastline in a belt running along the most part of the Norwegian coast of the Skegerrak Strait. Their radar patterns are identical to those of "classical" internal wave solitons. These banded structures, however, are characterized by larger number of bands and moderate scales. Such structures can stretch from 50 to 100 km mostly along the coastline. Different bands are usually densely packed; its length rarely exceeds 100 m and hardly discerned one from another. They are observed only in that region and only in winter months, obviously having no connection with periodical currents, such as tidal ones, a well-known source of internal wave generation. Possible mechanisms behind the emergence of these structures and conditions favorable for their manifestation in radar images are considered.

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P13p-462

Trains of internal waves on the Black Sea shelf: The first simultaneous observation by high resolution SAR and ADCP

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Satellite SAR images of high spatial resolution open up new opportunities in studying processes on the sea shelf. This is especially true for internal waves. Typical short-period internal waves occurring on seasonal thermocline in the Black Sea have lengths of a few tens of meters, therefore SAR image resolution of 2-3 meters appears quite sufficient for observation. September 16, 2012 we carried out subsatellite measurements in the southeastern part of the Black Sea shelf near the town of Gelendzhik. The measurements were made using "Rio Grande 600 kHz" ADCP on board a motor yacht. Trains of intense internal waves of average length of 100 m were encountered on a cross section over the shelf. The heights of the waves were in the range of 8-12 m. Such wave amplitudes are the largest for the Black Sea. Wave motion of the water column spread from the shelf edge to the middle of the shelf. A TerraSAR-X image showed surface manifestations of all groups of the internal waves. They all were oriented approximately parallel to the shoreline. A detailed joint analysis of remote sensing data and contact data was performed. The results suggest that the internal wave trains were generated by a mesoscale anticyclonic coastal eddy. *This work was partially supported by RFBR grants 13-05-01106 and 14-05 – 00520.*

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P13p-463

Global mapping of low-mode semi-diurnal and diurnal internal tides with a data-assimilative reduced gravity model

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We have developed data assimilation methods for mapping low-mode phase-locked internal tides from altimetry data, using a reduced gravity (RG) approach. Dynamical equations are derived following the approach of Griffiths and Grimshaw (2007), with the vertical dependence of pressure and velocities in the linear Boussinesq 3D equations expanded in basis functions derived from local 1D modes for a stratified ocean. This results in a system of coupled 2D PDEs for the coefficients of the modal expansion. Excluding coupling terms between modes (which arise in the presence of variable bottom topography) the resulting equations for each mode are analogous to the usual shallow water equations for the barotropic tide. With modest changes to the OSU tidal inversion software (OTIS) an assimilation scheme for this linear model is readily implemented. The coupling terms can be used to derive the forcing (by the barotropic tide), and also can be used to quantifythe component of model error associated with unmodeled topographic scattering. Because the inversion yields currents as well as elevations, mode energy fluxes can obtained with minimal further calcultion. Relatively high spatial resolution (at least 1/30 degree) is required for the RG dynamical model, so the inversion must be done in modest sized overlapping patches, which can then be merged to obtain global maps of phase-locked low-mode internal tides. To obtain reliable results some care with preliminary data processing has proven necessary, including correction for lower frequency SSH variations in areas of strong mesoscale activity, and filtering to reduce Long wavelength error, especially in ERS/Envisat data. We will present global maps of M2 and K1 constituents.