IACS (Cryosphere)

C01a - C01 GLIMS and the Randolph Glacier Inventory: where Do We Go from Here?

IUGG-0865

Derivation and analysis of a complete modern-date glacier inventory for Alaska and Northwest Canada

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We present a detailed, complete glacier inventory for Alaska and neighboring Canada using multi-sensor satellite data from 2000 to 2011. For each glacier, we derive outlines and > 50 variables, including centerline lengths, outline types, and debris cover. We find 86,723 km^2 of glacier area (27,109 glaciers > 0.025 km^2), roughly 12% of the global glacierized area outside ice sheets. 13.4% of the area is drained by 51 marine-terminating glaciers (96 km of tidewater margin) and 19.3% by 148 lake- and river-terminating glaciers (420 km of lake-/river margin). The overall debris cover is 11%, with considerable differences among regions, ranging from 1.4% in the Kenai Mountains to 28% in the Central Alaska Range. Comparison of outlines from different sources on > 2500 km^2 of glacierized area yields a total area difference of 10%, emphasizing the difficulties in accurately delineating debris-covered glaciers. Preliminary analysis of the glacier database yields a new set of well constrained area/length scaling parameters and shows good agreement between our area-altitude distributions and previously established synthetic hypsometries. The new glacier database will be valuable to further explore relations between glacier variables and glacier behavior.

IACS (Cryosphere)

C01a - C01 GLIMS and the Randolph Glacier Inventory: where Do We Go from Here?

IUGG-1217

Glacier shrinkage, GLIMS and the Randolph Glacier Inventory

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The Randolph Glacier Inventory (RGI) is a long-exposure snapshot, dominated by information from 2000–2010, of glacier extents. GLIMS, the Global Land Ice Measurements from Space initiative, is a multitemporal database of glacier extents. Plans for the convergence of the two collections are beginning to yield results, but it is important that the value of a snapshot – that is, a fixed reference – not be lost during the convergence. As the accessibility of GLIMS improves, the concept of a time series of extents, currently buried in the documentation, will emerge more clearly and large-scale analyses of glacier change will become easier, but the need for a fixed reference state of the glaciers will remain. For now, the key to exploiting GLIMS and the RGI synergistically lies in the literature, and I present recent work on measured shrinkage rates harvested from more than 400 published sources of worldwide scope. The resulting dataset contains more than 12,000 glacier areas organized into more than 4,000 time series. The RGI provides basic information on unchanging or slowly-varying glacier attributes, while the sources provide information on varying rates of change. The main methodological challenge is to place all of the information, from irregular survey dates and study areas, on a common footing with quantified uncertainties. The RGI grid, with 0.5-degree geographical resolution, is a powerful aid in rising to this challenge and distilling the contents of the RGI itself, the literature and, in due course, GLIMS. For example it can resolve large drainage basins for water-resources applications and can complement glacier-by-glacier simulations of responses to climatic forcing, typically known only from more coarsely-resolved databases.

IACS (Cryosphere)

C01a - C01 GLIMS and the Randolph Glacier Inventory: where Do We Go from Here?

IUGG-1989

The Randolph Glacier Inventory: applications and future needs

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The Randolph Glacier Inventory (RGI) is the first globally complete compilation of glacier outlines and has spawned numerous studies over the last few years. Glacier inventory data are an indispensable baseline for all glaciological applications with a regional to global scope such as, for example, studying glacier contribution to sea level rise or runoff. Here, we present three selected studies that were only possible due to the advent of the RGI and provide a synthesis of future needs to further increase its value to the glaciological community.

By intersecting outlines of all roughly 200'000 RGI glaciers with global terrain models, surface hypsometry can be extracted. This allows the determination of glacier length and the tracking of centerlines using automated procedures for each individual glacier. Furthermore, ice thickness distribution can be inferred based on simple considerations of ice flow mechanics. Such data sets represent a major step forward regarding the application of physically-based models for calculating future glacier evolution and for assessing the impacts of glacier change at a global scale. Centerlines for each glacier worldwide allow determining length changes for large samples based on remote sensing data.

With the most recent developments the RGI has been transformed from a loose collection of glacier shapes to a complete inventory providing various attributes (e.g. area, length, min./max. elevation, aspect, thickness). Future efforts should focus on further homogenizing the global snapshot of glacier outlines by adding most recent data, and by including information on source imagery.

IACS (Cryosphere)

C01a - C01 GLIMS and the Randolph Glacier Inventory: where Do We Go from Here?

IUGG-2846

The GAMDAM Glacier Inventory: A quality controlled inventory of Asian glaciers

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Glacier inventories are significant and basic information for water resources, glacier mass balance and ice volume at continental areas. Although, glaciers in the Asian mountain have an important role for water resources, glacier inventories in this area provided by previous studies (Randolph glacier inventory) have wide-ranging quality.
Our GAMDAM (Glacier Area Mapping for Discharge in Asian Mountains) project have conducted to make glacier inventory and covers the high Asian mountains between 67.4° and 103.9° E longitude and 27.0° and 54.9° N latitude.
Glacier outlines are delineated by perfect manual procedures using more than 350 of LANDSAT images from 1999 to 2003. Thermal infrared band (Band 6) images of LANDSAT scene also used to delineate termini of debris-covered glaciers. Google Earth with high resolution images also supported to judge glacier area. A digital elevation model (SRTM) was used to divide individual glacier by watershed analysis. Each glacier polygons have attribute data, which shows ID number of referred LANDSAT scene to delineate glacier outline. Operation work of manual delineation have taken more than two years by 5-7 persons.
Total glacier area of our inventory in Hindu-Kush-Himalaya range reached to 93% of ICIMOD inventory. Regional glacier area have discrepancies, which mainly caused by passing over some glaciers at shadow part in both inventories. Whereas, our inventory represents significantly less surface area (–24%) than a recent global glacier inventory (Randolph Glacier Inventory, RGI ver. 4.0) at entire high Asian Mountains.

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C01a - C01 GLIMS and the Randolph Glacier Inventory: where Do We Go from Here?

IUGG-3715

Extending the GLIMS Glacier Database to global completeness and new data types

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Global glacier databases are used by the modeling and assessment communities to estimate present and future contributions from glaciers to sea level, to assess hazard potential, and to gain insight into processes affecting the thickness and extent of glaciers. There are currently two global collections of glacier outlines: the glacier database of the Global Land Ice Measurements from Space (GLIMS) initiative and the Randolph Glacier Inventory (RGI). The GLIMS Glacier Database is rich in source metadata and contains time series for thousands of glaciers, while the RGI is a single snapshot and has less of the crucial metadata. However, the RGI has nearly complete global coverage, while the GLIMS database is currently at about 80% coverage.

This contribution describes how we are working toward merging the RGI into GLIMS; extending the range of data types stored in GLIMS to include more glacial lakes, snow lines, velocities, elevation data; and creating new tools to download these data in a choice of data models and formats, including both GLIMS and RGI data models. The result of this work will be an improved glacier database that will be useful for tracking changes in water resources, hazards, and changing mass balance processes. We describe the challenges involved with this merge and the estimated time line for completion.

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C01a - C01 GLIMS and the Randolph Glacier Inventory: where Do We Go from Here?

IUGG-5464

A retrospective and future perspective on global land ice measurements from space

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A global glacier mapping task—now known as Global Land Ice Measurements from Space (GLIMS)—was conceived by H. Kieffer in the early 1990s as an ASTER Science Team project. The goal was annual imaging and repeat mapping of the world's glaciers. GLIMS was directed first by Kieffer at the US Geological Survey, while I built an international consortium of analysts and then took leadership of GLIMS in 2003. A GLIMS glacier database was established by Bruce Raup at the National Snow and Ice Data Center. Several major innovations in glacier measurement and much energy for GLIMS came from Europe. Though various problems slowed progress, the initiative's original vision has been largely achieved through the efforts of GLIMS and the Randolph Glacier Inventory (RGI); GLIMS and RGI databases are now being merged. A powerful new capability has emerged recently: satellite stereo imaging is being used to directly measure glacier elevation changes (hence, mass balance). That ability is needed to address global change measurement priorities on sea level rise and water resources. GLIMS measurement goals should include the global subdecadal assessment of changes in glacier area and surface elevation (mass balance), surface flow speed, debris cover, albedo, and lake distribution; and globally sampled seasonal changes in glacier albedo and snowlines. GLIMS should extend interactions with applications science communities, to include: (1) glacier forecasting through empirical and theoretical evaluation of glacier dynamics, including response times, related to evolving global to local climates and nonclimatic forcings; and (2) assessment of changing downstream socioeconomic vulnerabilities to shifting glacier hazards and water output.

IACS (Cryosphere)

C01p - C01 GLIMS and the Randolph Glacier Inventory: where Do We Go from Here?

C01p-097

A new inventory of the glaciers in the Pyrenees (southwest Europe).

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The Pyrenees mountain range hosts the southernmost glaciers in Europe (south of 43°N). Some of these glaciers were studied by scientists since the end of the 19th century. However, a comprehensive and accurate inventory of their present-day extent was still missing up to now. The Pyrenean glaciers were classified as "nominal glaciers" in the Randolph Glacier Inventory (RGI Release 4.0). Nominal glaciers are those which are known to exist but are recorded only collectively or approximately in the source inventories. Here we present a new inventory of the Pyrenean glaciers. We used aerial ortho-images with a ground resolution of 0.5 m from the Spanish and French National cartographic institutes acquired in summer 2010 and 2012 to outline all known glaciers in the Pyrenees. This resolution was adapted to the small size of the glacier in the area (< 1 km²). In addition, field surveys helped us to determine or modify glaciers front positions at the end of the 2011 hydrological cycle (i.e. 1st October 2011). From the 107 nominal glaciers that were listed in the RGI v4.0 only 31 glaciers are actual glaciers in 2011. In 1850, the total glaciated area in the Pyrenees was around 20 km2, in 2011 it was 3 km2 according to our latest inventory. This dataset provides a basis to study the fate of the glaciers in the Pyrenees, including the 80 Pyrenean glaciers that vanished from the previous inventories.

IACS (Cryosphere)

C01p - C01 GLIMS and the Randolph Glacier Inventory: where Do We Go from Here?

C01p-098

Challenges in creating a glacier inventory for the Karakoram-Pamir region

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High-quality glacier inventories in a digital format are required to determine glacier changes and model their reaction to climate change. In particular, for several regions in High Mountain Asia such a glacier inventory is missing. To improve this situation, we have mapped all glaciers in the Karakoram-Pamir region to create a consistent and freely available dataset. Glacier mapping was performed using automated mapping and manual editing of Landsat TM/ETM+ imagery acquired around the year 2000. The mapping is challenging due to frequent seasonal snow at high elevations, debris-covered glacier tongues, steep terrain with shadows and several surging glaciers. We tackled the seasonal snow issue by utilizing multi-temporal imagery and debris-covered glacier tongues were manually corrected using ALOS PALSAR coherence images. Drainage divides were derived from the ASTER GDEM II and manually corrected to calculate topographic parameters. Slow disintegration of glacier tongues after a surge (leaving still connected dead ice) results in a difficult identification of the terminus and assignment of entities. All glaciers larger 0.02 km^2cover an area of about 21,700 km^2 in the Karakoram and about 11,800 km^2 in the Pamir region. A comparison with other recently published inventories reveals differences in the interpretation of glacier extents (mainly accumulation region) that would lead to huge area changes if unconsidered for change assessment.

IACS (Cryosphere)

C01p - C01 GLIMS and the Randolph Glacier Inventory: where Do We Go from Here?

C01p-099

Practical examples from Greenland of the importance of accurate glacier outlines for high resolution regional climate modelling and weather prediction

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Regional climate and numerical weather prediction (NWP) models use ice masks to define important surface properties that are significantly different from surrounding ice free land. Accurate outlines are particularly important in Greenland where local populations are keen to benefit from advanced weather forecasts. Similarly, in RCMs surface mass balance (SMB) estimates from models can vary very substantially if incorrect or out of date ice masks are used, as shown in previous work by Vernon et al. (2012).

A newly updated ice mask in the regional climate model HIRHAM5, run at very high resolution (0.05 and 0.03 degrees) shows the importance of using accurate outlines to derive accurate SMB output as a result. The HIRLAM and HARMONIE NWP models used to produce weather forecasts in Greenland likewise suffer from an inaccurate glacier outline and we present results here to indicate that improved land ice cover in models can also significantly improve local and regional weather products, including the daily SMB estimates for the Greenland ice sheet available from DMI. The ice mask is based on both input from GLIMS and the Randolph glacier inventory for Iceland and Arctic Canada, as well as satellite and aerial imagery processed by the PROMICE group at GEUS for the ice sheet and peripheral glaciers in Greenland. These ice masks are now available for download and the underlying vector data will be incorporated into GLIMS/RGI shortly.

IACS (Cryosphere)

C02a - C02 Advances in Estimating and Measuring Glacier Ice Thicknesses

IUGG-0607

A worldwide database of glacier thickness observations

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One of the grand challenges in glacier research is to assess the total ice volume and its global distribution. Over the past few decades the compilation of a world glacier inventory has been well-advanced both in institutional set-up and in spatial coverage. The inventory is restricted to glacier surface observations. However, although thickness has been observed on many glaciers and ice caps around the globe, it has not yet been published in the shape of a readily available database. Here, we present a standardized database of glacier thickness observations compiled by an extensive literature review and from airborne data extracted from NASA's Operation IceBridge. This database contains ice thickness observations from roughly 1100 glaciers and ice caps including 550 glacier-wide estimates and 750,000 point observations. A comparison of these observational ice thicknesses with results from area- and slope-dependent approaches reveals large deviations both from the observations and between different estimation approaches. For glaciers and ice caps all estimation approaches show a tendency to overestimation. For glaciers the median relative absolute deviation lies around 30% when analyzing the different estimation approaches. This initial database of glacier and ice caps thickness will hopefully be further enlarged and intensively used for a better understanding of the global glacier ice volume and its distribution.

IACS (Cryosphere)

C02a - C02 Advances in Estimating and Measuring Glacier Ice Thicknesses

IUGG-0794

A comparison of measured and modelled ice thickness distributions as a basis for future glacier scenarios in the Ötztal Alps

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Glaciers are an integral part of the Alpine mountain landscape. Besides the historic and cultural importance of glaciers, in the past and presence tourism and the use of the headwaters for energy production show their influence on socioeconomics. Glacier changes are an indicator for climate change in and progressive glacier shrinking can be expected if climate warming continues in the Alps. Therefore, scientific issues mainly concerning future changes in mountain hydrology are investigated using models of different complexity, which require i.a. surface elevations and glacier outlines for the simulation of runoff from glacier melt. On the basis of the same information, ice thickness distributions can be determined. In this study we compare ice thickness estimations from GPR measurements and numerical methods in the Austrian part of the Ötztal Alps (Tyrol, Austria). This mountain range includes 205 glaciers with a total area of 139 km². Mean determined ice thickness is 60 m with maximum ice thickness up to 290 m valid for 1997. Spatially distributed ice thicknesses and observed glacier area and volume changes derived from the Austrian glacier inventories were used to calculate scenarios of future ice thickness distributions. We present spatially distributed differences of the ice thickness estimations in an entire mountain range with respect to differences in measured and modelled ice thickness. Different methods to account for future changes in glacier volume based on observed glacier changes result in different ice thickness distributions particularly at the lower elevated parts of valley glaciers.

IACS (Cryosphere)

C02a - C02 Advances in Estimating and Measuring Glacier Ice Thicknesses

IUGG-2507

Advances in helicopter radio echo sounding for the Swiss glacier inventory

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A detailed inventory of the glacier surface area and of long-term mass balance observations exist in Switzerland, but only a rough estimate of the present ice volume is available. After the successful recording of more than 1500 km of helicopter ground penetrating radar (GPR) profiles on Swiss glaciers during the last four years, the Swiss Competence Center for Energy Research (SCCER) and the Swiss Geophysical Commission (SGPK) started an initiative to improve the estimate of the total ice volume located in the Swiss Alps. Steps towards this goal include the delineation of a 3D bedrock topography model underneath glacerized regions. The final ice volume estimation will comprise an ice flux computation model constrained by a dense network of helicopter-borne GPR profiles.

Different radar systems have been tested for their ability to receive sharp glacier bed reflections on Swiss glaciers, including towed and rigidly mounted systems, all in the frequency range of 15 to 70 Mhz. Some measurements were ground truthed with the same GPR antenna systems. Analyses of these data sets revealed a wealth of useful information on the glacier bed topography but also of technical nature. For instance the orientation of the antennas is utterly important. Therefore, a new towed radar system is being constructed at ETH Zurich, working with two orthogonal antenna pairs in axial and transverse direction relative to glacier flow. In addition to an adapted antenna design, the application of adequate processing steps improves the quality of glacier bed reflections enormously. Ringing noise for instance, can be removed by a singular value decomposition (SVD) filter and negative influences of strong topography can be handled with the right migration algorithm.

IACS (Cryosphere)

C02a - C02 Advances in Estimating and Measuring Glacier Ice Thicknesses

IUGG-3349

A better than nothing estimate for the thickness of an ice cover

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This work concentrates on a GPR dataset acquired at Antarctic Peninsula where no radar reflections from the bedrock could be seen on the reflection sections. Notwithstanding we have sought a rough local estimate for the ice thickness to help in future field campaigns planned for the area, a better than nothing perspective. To achieve that we have relied upon the rich firn stratigraphy displayed in the sections, characterized by reflectors with a curvature concave downward, the curvature becoming more pronounced the deeper the reflectors are. Their apexes align to each other, a phenomenon resembling radar observations observed at ice divides. We have heuristically hypothesized the observed increasing concavity with depth is linked to the quasi-static flow of the ice toward the outlet of a glacier more than 10 ice thicknesses away. We have formulated and sought the solution to an independent problem from the real situation, namely the one referring to the ice thickness of a static ice plate hanging from the top of the plateau, being deformed due to the loading of its overburden combined to its own weight. We have inverted the reflectors bending for the 14 most energetic reflectors, to produce an effective thickness of 233m of a proxy plate having the same total strength and bending moment of the integrated contributions from the ductile and brittle fractions of the ice cover. That estimate is compatible to independent estimates in the same generic area.

IACS (Cryosphere)

C02a - C02 Advances in Estimating and Measuring Glacier Ice Thicknesses

IUGG-3449

Estimation of total ice volume of Nordenskiöld Land glaciers, Svalbard, using radio-echo sounding and modeling

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The individual and total ice volumes of 210 glaciers in Nordenskiöld Land, Svalbard, were estimated using radar data for 15 glaciers, modeling of glacier thickness distribution with GlabTop model (Linsbauer et al., 2012) and volume-area (V-A) scaling procedure. Ice volume of 15 test glaciers in western part of Nordenskiöld Land was calculated using ANUDEM interpolation from detailed ice thickness measurements conducted in 1999, 2007 and 2010-2013 and satellite imagery for the same periods. Glacier outlines for the rest 195 glaciers were taken from Randolph Glacier Inventory. ASTER GDEM V.2 with horizontal resolution of ~30 m was used. Surface topography and ice thickness data of selected glaciers allowed us to calculate an average shear stress (τ) along manually digitized flow lines. It was found that τ correlates well with glacier length L (R^2=0.85) rather than altitude range. Tidewater Fridtjovbreen (5.08 km^3) did not follow this relationship most likely due to its surging behavior. This (τ =0.0002*L-0.0196, max τ =1.7 kPa) relationship was used to modify GlabTop model and to reduce the average difference between measured and modelled glacier volumes from initial 40% down to 15%. Total ice volume of 15 glaciers was estimated as 10.22±0.2 km^3 using ice-thickness measurements; 9.45±1.4 km^3 by modified GlabTop model; and 10.65±1.6 km^3 using A-V scaling. The total volume of Nordenskiöld Land glaciers of 22.25±3.3 km^3 was calculated with the modified GlabTop model while A-V scaling gave 28.73±4.3 km^3.

IACS (Cryosphere)

C02a - C02 Advances in Estimating and Measuring Glacier Ice Thicknesses

IUGG-3723

A catalogue of Svalbard radio-echo sounded glaciers and its use to derive a regional volume-area relationship

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We have compiled a catalogue of radio-echo sounded glaciers on Svalbard (http://svalglac.eu/publications.htm). The catalogue has a total of 314 entries in the inventory, corresponding to 154 different glaciers (many glaciers have been surveyed more than once or have been surveyed using distinct radar equipment). For 60 of these glaciers we were able to get a sufficiently accurate volume estimate. The selected sample consists of glaciers for which the net of ground-penetrating radar profiles covers most of the glacier basin and is dense enough. We have used the corresponding volume-area pairs to build a regional volume-area relationship for Svalbard glaciers, which has allowed to estimate the total volume for Svalbard glaciers, excluding Austfonna and Vestfonna ice caps, for which the ice volume has been estimated directly from ice-thickness data retrieved from ground-penetrating radar measurements. The resulting total volume estimate for Svalbard glaciers (including Austfonna and Vestfonna) is 6700 ± 835 km^3, or 17 ± 2 mm in sea-level equivalent.

IACS (Cryosphere)

C02b - C02 Advances in Estimating and Measuring Glacier Ice Thicknesses

IUGG-0198

Bed topography of fast-flowing glaciers and fine-resolution mapping of internal layers

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Our team at the University of Kansas developed radar instrumentation for sounding and imaging ice sheets and fine-resolution mapping of internal layers. We have been operating these radars on long-range and short-range aircraft for almost a decade and have collected a large volume of data over the Greenland and Antarctic ice sheets. The radar suite includes a 195-MHz radar, referred to as the Multi-Channel Coherent Radar Depth Sounder/Imager (MCoRDS/I), has been successfully used to sound fast-flowing glaciers and ice-sheet margins in Greenland. It uses Synthetic Aperture Radar (SAR) processing in the along-track direction and array processing in the cross-track direction to reduce surface clutter for detecting weak ice-bed echoes masked by clutter. We also developed signal and image processing algorithms to enhance and identify ice-bed echoes.

The MCoRDS/I has been used to collect a large volume of data over several key glaciers in Greenland, including Jakobshavn, Helhiem, and Kangerlussuaq glaciers. After reprocessing data collected over these three glaciers, new bed maps were generated. We also reprocessed data from southern Greenland to obtain ice thickness information for key areas. In this presentation we will provide an overview of the radars and our signal and image processing algorithms. We will show sample echograms to illustrate and discuss challenges involved in sounding fast-flowing glaciers and ice-sheet margins. We will show new bed maps along with associated error analysis. Finally, we will discuss what must be done to obtain the required information on bed topography and basal conditions for key glaciers and areas in Greenland and Antarctica.

IACS (Cryosphere)

C02b - C02 Advances in Estimating and Measuring Glacier Ice Thicknesses

IUGG-0545

Modeling Ice thickness and Bedrock topography using surface velocities and slope

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Himalayan glaciers are an important source of water for a large population residing in India. Ice thickness distribution serves as an important parameter in assessing the glacier's health and future evolution. Harsh climatic conditions and rough terrain render field measurements difficult. In this paper, we model the ice thickness of Gangotri glacier using surface velocities, slope and flow law of ice. Surface velocities were estimated using Landsat TM imagery. In the accumulation region, velocities range from ~17–80m/yr and <30m/yr near the snout. Using surface velocities and shallow ice approximation, ice thickness was estimated. The ice thickness was maximum along the central flowline and minimum at the edges. It ranged from ~400-540m in the central part of the glacier and near the snout it was ~45-55m. Bed rock topography was then estimated by differencing the ice thickness from a Digital Elevation Model. It ranged ~3900-4100m near the snout, ~4200-4700m in the central part and ~4900-6900m in the uppermost reaches. The elevation values were the lowest along the central flowline and progressively increased as one moved towards the glacier's flanks. The same method was also applied to two other glaciers in the Himalaya and ice thickness was estimated. This method proved to be very useful in the glaciers where mass balance data is not available.

IACS (Cryosphere)

C02b - C02 Advances in Estimating and Measuring Glacier Ice Thicknesses

IUGG-1344

Ice thickness measurements and volume estimates of Elbrus glaciers (Caucasus) using airborne radio-echo sounding

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Mount Elbrus is the largest glaciated massif in the Caucasus, in southern Russia. With an area of 112.6 km^2, it accounts for 10% of the total glacier area in the region. Elbrus glaciers are the source of fresh water for local communities as well as for the region's biggest rivers, the Kuban and the Malka.

Elbrus is a dormant volcano and historical records show the possibility of catastrophic debris flow in case of eruption. The formation of ice-dammed proglacial lakes has intensified recently due to increased rates of glacier recession. Therefore it is important to have a detailed ice thickness distribution map for hydrological modelling and risk assessments.

Here we present the results of ice thickness measurements of the Elbrus glaciers. Airborne radio-echo sounding was conducted during 2013-2014. The specially designed airborne modification of the VIRL-6 GPR (20MHz) was used. GPR with GPS was suspended under the helicopter on a wooden frame with vertical stabilizer. Measurements were conducted in automatic mode with a frequency of 0.2 seconds, a horizontal speed of about 70 km/h, and at an elevation of 10 to 500 m above the glacier surface. In total, 340 km of radio-echo sounding profiles were obtained, and 70% of them contained reliable bedrock reflection signal. Detailed ice thickness and bedrock topography maps were completed. The mean ice thickness is 49.5 m, while the maximal reaches 250 m at the elevation above 5000 m near the western summit. Ice thickness distribution map shows that about a half of the total glaciers volume concentrated between 3500-4000 m. The total volume of the Elbrus glaciers was estimated as 5.5±0.6 km^3 of ice.

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IACS (Cryosphere)

C02b - C02 Advances in Estimating and Measuring Glacier Ice Thicknesses

IUGG-1979

Peering into deep blue ice: achievements and challenges

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Ice-penetrating radar has been a viable method to map ice thickness and englacial structures of glaciers and ice sheets. Continuous reflectors in polar ice caps and ice sheets are accepted as isochrones and have been used to decipher their evolution using ice-flow models. Shallower reflectors in firn with little melt-water penetration are often used as proxies of past surface mass balance. Mountain glaciers less often have such stratified structures, but radar has been used to map hydraulic structures and crevasses. Beyond the use of range information, analysis of radar signals has led insights into bed conditions and physical properties of ice. Airborne surveys are filling major data gaps in Greenland and Antarctica, but still absence of data in some regions is a major barrier to understand current status and future behavior of glaciers and ice sheets. This talk provides brief overview of historical achievements of radar applications for glacier and ice-sheet research and discusses more recent development in radar instrument, data processing, and theoretical background of data interpretation. Finally I highlight several key challenges that we are facing now.

IACS (Cryosphere)

C02b - C02 Advances in Estimating and Measuring Glacier Ice Thicknesses

IUGG-2796

Time series of measured mountain glacier volumes from Little Ice Age to today as a playground for model validation

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The area of Austria's mountains glaciers decreased from 941 km² to 471 km² between the LIA and 1998. The area covered by glaciers during the Little Ice Age (LIA) maximum has been mapped from high resolution surface elevation data, orthophotos, and field surveys. Interpolating the glacier surface elevation manually with the help of the LIA glacier margins derived from LiDAR data and historical maps allows estimating the LIA surface elevation. For 66 glaciers covering ~ 50% of the total glacier area in 1998 (225 km²), measured ice thickness, area and surface elevation data are available. With the ice-free topography derived from this volume data set, the LIA ice thickness distribution was calculated.

The radar surveyed glaciers cover 358 km² during the LIA maximum, with a volume of 30 km³, corresponding to mean ice thickness of 84 m. The maximum of glacier area is found in elevations between 3050 and 3100 m a.sl., the maximum ice volume between 2950 and 3000 m.a.s.l..

In 1998, the radar surveyed glaciers stored an ice volume of 11 km³ (-64%), corresponding to a mean ice thickness of 52 (-38%) m. The elevation of the maximum of glacier area decreased to 3000-3050 m.a.s.l., the maximum volume increased to 3000-3050 m.a.sl. Mean ice thickness decreased from 84 m during LIA maximum to 52 m in 1998, i.e. a reduction office thickness by 38%.

As the HISTALP records provide high quality gridded climate data, these two glacier volume inventories provide an excellent data base for validating or comparing various approaches for modelling changing glaciers in the Alps.

IACS (Cryosphere)

C02p - C02 Advances in Estimating and Measuring Glacier Ice Thicknesses

C02p-100

Ice thickness measurements and volume estimates for glaciers in Norway

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Glacier volume and ice thickness distribution are important variables for the water resources management in Norway and for the assessment of future glacier changes. Here we present a detailed assessment of thickness distribution and total glacier volume for mainland Norway based on data and modelling. Glacier outlines from a Landsat-derived inventory from 1999-2006 covering an area of 2692 ± 81 km^2 were used as input. We compiled a rich set of ice thickness observations collected over the last thirty years. Altogether, interpolated ice thickness measurements were available for 986 km^2, or 37%, of the current glacier area of Norway with a total ice volume of 149 ± 28 km^3. Ice thickness data were used to calibrate a physically-based distributed model for estimating ice thickness of unmeasured glaciers. The results were also used to calibrate volume-area scaling relations and revealed that scaling was sensitive to how the glacier complexes were divided into units. The calibrated total volume estimates for all Norwegian glaciers ranged from 247 to 300 km^3.

IACS (Cryosphere)

C02p - C02 Advances in Estimating and Measuring Glacier Ice Thicknesses

C02p-101

Analysis of ice volume and its characteristics at .the glacier Baishui No.1 in mt. Yulong, Southwestern China

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Selecting the glacier Baishui No.1 on Mt. Yulong in southwestern China, theice thickness contour map of the glacier has been drawed and the thickness-measured area and its volume have been calculated, based on the detected results of its ice thickness by a ground penetrating radar (GPR),combined with the GPS data of measurement point on the glacier and the discrete element method (DEM) in 2009,as well as Landsat images in 2009 and 2013with the support of GIS technology and kriging interpolation methods. In addition, thecorrection factors in the V-S empirical formulaapplied to calculating the glacier’s area and ice thickness were also analyzed and revised. The corrected formula has been used to estimate the total volume of theglacier and the results show thatmaximumice thickness appeared at the altitudesbetween 4700 and 4750 msurrounding the mainstream line near the central area of the glacier. The average thickness is 87 m and Ice reserves is about? m^3,equal to a water equivalent of? m^3.
Combinedthe DEM map and completeddiagram of ice thickness and topographic map of the glacier surface, the internal characteristics of the glacier has been analyzed in details and drawed a topographic map. These results show the concave shape of glacier’s bed incontrastto the relativelyflatof glacier surface in the maximum ice thickness area.Glacier interior exist some special forms such as empty caves, caveswith water, crack under the ice,channels beneath the ice. There are also some debris layers between bedrock and iceand the edge of glacier.

IACS (Cryosphere)

C02p - C02 Advances in Estimating and Measuring Glacier Ice Thicknesses

C02p-102

Ice volume and characteristics analysis for representative temperate glacier - White River No.1 glacier, Mt. Yulong, China

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In this study, take the Yulong snow mountain glacier white river NO.1 ground penetrating radar (GPR) to detect the image in 2013 as an example, based on the obtained radar thickness results, combined with the measurement point of GPS data and the discrete element method (DEM) in 2009, as well as Land sat TM/ETM+ images in 2009, with the support of GIS technology, adopted the kriging interpolation method,interpolation calculation the thickness of the no thickness area. Draw the ice thickness contour map and calculated the area of the region and ice reserves of this glaciers measurement area, analysis of the correction factor which apply to glacier area of experience formula and ice reserves in this region, correction of V - S empirical formula, use correction formula estimate the total volume of the white river No. 1 glacier. The results show that ice thickness appeared at an altitude of 4722 m gravitate towards mainstream line position in Yulong snow mountain white river NO.1 glacier mainstream line central area,the average thickness is 87 m. Ice reserves of ? m3,water equivalent to ? m3.

Combined the glacier surface DEM of and ice thickness distribution to draw comprising topographic map of the glacier in this region. Analysis the internal characteristic of the glacier in this region. The results indicating that the glacier bed presents the concave shape which contrast to its relatively flat glacier surface topography in the largest ice thickness area. Part of the section in Yulong snow mountain white river NO.1 glacier, exist geomorphologic shape such as caves, caves with water, crack under the ice, channels beneath the ice ,there also exist debris layers between ice bedrock interfaces and the edge of glacier.

IACS (Cryosphere)

C03a - C03 Glacier Monitoring from In-Situ and Remotely Sensed Observations

IUGG-1537

Evolution of Ossoue glacier (Pyrenees, Southwest Europe) since the end of the Little Ice Age

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The Pyrenees mountain range hosts the southernmost glaciers in Europe. Ossoue glacier (42.46°N, 0.45 km^2), the second largest glacier in the Pyrenees, is an East-oriented glacier mainly fed by direct snowfall. We present here the reconstruction of its evolution since the Little Ice Age. Glacier length, area, thickness and mass changes indicators were generated from historical datasets, topographic survey, glaciological measurements (2001-2013), ground penetrating radar (GPR) survey (2006) and Pléiades satellite high-resolution stereoscopic images (2013). The glacier has strongly receded since the end of the LIA (40% of length and 60% of area). Three periods of marked ice depletion can be highlighted: 1850-1890; 1928-1950 and 1983-2013 as well as two periods of stabilization or slightly growth: 1905-1928; 1950-1983. These periods are consistent with local observations of air temperature and precipitation, and the larger-scale climatic indices of the North Atlantic Oscillation (NAO) and the Atlantic Multidecadal Oscillation (AMO). The geodetic mass balance rate over 1983-2013 is -1 m w.e.y^{-1}. The glaciological mass balance rate over 2001-2013 is 1.45 m w.e.y^{-1}. This indicates that the mass loss accelerated over the last decade. Assuming the current ablation rate as constant and given the maximum ice thickness registered in 2013 by GPR (59 m ±10), Ossoue glacier would disappear by the half of the 21th century.

IACS (Cryosphere)

C03a - C03 Glacier Monitoring from In-Situ and Remotely Sensed Observations

IUGG-2180

Reanalysing Norwegian long-term mass balance series

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Reanalysing glacier surface mass balance series is recommended as standard procedure for every mass balance monitoring programme, with increasing importance for long time series. The Norwegian mass balance record is extensive and more than 40 glaciers have been observed for shorter or longer periods. Of these, 10 glaciers have series longer than 20 years, all of which are part of today's monitoring programme. Repeated geodetic surveys are available for all these long-term glaciers and have been used to calculate geodetic mass balance.

Here we compare glaciological (field based, direct) mass balance observations with geodetic mass balance observations for 10 glaciers with long-term series. We show examples of how glacier mass balance data have been reanalysed including homogenization, assessment of uncertainty and calibration of glaciological mass balances. For four of the glaciers (Nigardsbreen, Engabreen, Ålfotbreen and Hansebreen) the difference between the methods are substantial for several of the geodetic survey periods, whereas for the remaining glaciers results are in better agreement. We discuss the challenges in the homogenization procedure; how to assess and quantify the uncertainties in both methods with varying metadata available, to what level of detail homogenization should be carried out, how to calibrate the glaciological mass balance series, and finally, how to communicate the resulting original, homogenized and calibrated mass balance series.

IACS (Cryosphere)

C03a - C03 Glacier Monitoring from In-Situ and Remotely Sensed Observations

IUGG-2231

Present changes in extent and thermal regime of Swedish glaciers

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During the last decade the recession speed of most Swedish glaciers has dramatically increased. The dynamics of the glaciers is influenced both by changes in thermal regime and by thinning. On several glaciers we have successive digital terrain models covering the period 1960-2008 and shorter time series of thermal regime changes. Between 1963 and 2008 the annual mass balance of Storglaciären was on average -0.1 m/y w.e while Pårteglaciären lost approximately 0.5 m w.e. Though very high mass losses the thermal regime of Pårteglaciären is rather stable showing only a slight thinning of the cold surface layer over the last 18 years, though the geometry of the tongue is changing significantly.. The corresponding annual mass balance of Mikkaglaciären was -0.4 m w.e. and its thermal regime has changed significantly over the years causing very high recession rates over the last decade. On a significant number of glaciers, nunataks have appeared close to the fronts influencing glacier flow and thus temperature regime and recession rates. The little summit glacier still acting as the highest point of Sweden on mount Kebnekaise is slowly shrinking and in current climate conditions another summit on the same mountain will become the highest peak. In this paper we will make an over view of the present state of the glaciers and discuss differences in glacier response in a thermal perspective.

IACS (Cryosphere)

C03a - C03 Glacier Monitoring from In-Situ and Remotely Sensed Observations

IUGG-2704

Adequate representation of snow accumulation distribution in a mass balance series re-analysis

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Glacier mass changes are monitored around the globe in order to better understand glacier response to climatic change. Typically, measuring networks are sparse, particularly regarding the complex distribution of winter snow. Thereby, one major drawback in current mass balance evaluation schemes is the representation of snow accumulation distribution that controls melt patterns and spatio-temporal surface albedo variations.

We present a re-analysis of ten years of glacier mass balance measurements on Findelengletscher, a 13km^2 temperate valley glacier in Switzerland. In 2004, a network of 13 ablation stakes and two accumulation measurements was established. Winter mass balance is regularly measured since 2009, consisting of snow probings and snow density pits. Complementary helicopter-borne ground-penetrating radar (GPR) surveys in 2012 to 2014 provided measurements of snow depth along regular 500m x 500m grid lines. The two-way travel time between the snow surface and the snow-ice or snow-firn interface was converted to depth using a density-based estimate of the wave velocity. The geodetic volume change of Findelengletscher is available for the period of 2005 to 2010.

We used the available measurements to constrain a distributed glacier mass balance model and to assess the model sensitivity to different assumptions on the winter snow accumulation. We demonstrate that an adequate implementation of the snow depth distribution is indispensable to derive glacier-wide mass balance from glaciological measurements. This can be achieved by means of annual GPR surveys or by using a normalised snow depth grid obtained from a different year with sufficient data.

IACS (Cryosphere)

C03a - C03 Glacier Monitoring from In-Situ and Remotely Sensed Observations

IUGG-3487

Efforts to improve glacier monitoring from in situ and remotely sensed observations in different mountain regions: Strategies and datasets

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Today, world-wide monitoring of glaciers and ice caps is organized by the Global Terrestrial Network for Glaciers (GTN-G), which is in charge of collecting and distributing glacier measurements.

Several online databases containing a wealth of diverse data types having different levels of detail and global coverage provide fast access to continuously updated information on glacier fluctuation and inventory data. Glacier front variations with about 42,000 entries since the 17th century and about 5,200 glaciological/geodetic mass/volume change observations back to the 19th century are available. Both datasets reveal evidence that glacier retreat and mass loss is a global phenomenon with a strong enhancement since the beginning of the 21st century. With version 4 of the Randolph Glacier Inventory (RGI), the mapping of glaciers has become close to globally complete. Current efforts are now underway to further improve the quality of the dataset regionally, integrate them into the Global Land Ice Measurements from Space (GLIMS) database.

To answer current important research questions related to the contribution of glaciers and ice caps to sea level rise or to estimate current and future runoff in dry regions, a combination of traditional observations with datasets from new technologies such as remote sensing is required. While the latter provide a wealth of data that yet have to be standardized, in situ measurements on reference glaciers have been declining since the mid-1990s. Current efforts are to re-establish or complement former measurements in different regions of the world to establish a well-distributed baseline for sound estimates of climate-related glacier changes.

IACS (Cryosphere)

C03b - C03 Glacier Monitoring from In-Situ and Remotely Sensed Observations

IUGG-0903

In-site Glacial Monitoring Network in Northwestern China

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Mountain glaciers are sensitive to climate change, making them important indicators for global warming. Although their water storage is small comparing to polar ice-sheets, mountain glaciers contribute significantly to sea-level rise because of their short turnover time. Even with remote sensing quite popular nowadays, in-site observation/measurement is still an important approach to study glaciers. One reason for that is some data required by glaciological studies cannot be obtained from remote sensing images. In northwestern China, an extremely dry region, more than 20,000 mountain glaciers are developed. Glacial melt water is vital for local water resources, ecosystem in the lower reaches, peoples' living and city development there. To obtain the general idea on glaciers in that region, Tianshan Glaciological Station, Chinese Academy of Sciences selected 9 glaciers in six sub-regions along Altai Mountain, Sawuer Mountain, Tianshan and Qilian Mountain, respectively, doing in-site observations and measurements on them every year. Based on those glaciers, "Glacial Monitoring Network in Northwestern China" was initially established in 2009. For most glaciers selected, mass balance, surface motion and retreat/advance rate were measured annually. Topography surveys and GPR thickness measurements were carried out every two or three years. Automatic Weather Stations were set up at relatively broad and flat open area nearby glacier snouts. Till now, five glaciers in the network have data series longer than three years. Based on them, a general overview on mass balance, movement, thermal condition and historical changes of mountain glaciers in Northwestern China is reported in this study.

IACS (Cryosphere)

C03b - C03 Glacier Monitoring from In-Situ and Remotely Sensed Observations

IUGG-2146

Mass balance reconstruction for Glacier Number 354, Inner Tien Shan, from 2003 to 2014

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Glaciers in Central Asia are strongly underrepresented in the worldwide glacier monitoring activities. Under the subject of climate change and today's water stress, interest in re-establishing the historical monitoring sites has increased. A monitoring programme for Glacier No. 354, Akshiirak range, Inner Tien Shan, Kyrgyzstan was initiated in 2010 within the projects Central Asian Water (CAWa) and Capacity Building and Twinning for Climate Observing System (CATCOS) and annual mass balance data has been measured since then. This study presents a reconstruction of the seasonal mass balance from 2003 to 2014 of Glacier No. 354 by the use of a distributed accumulation and temperature-index melt model driven by daily air temperature and precipitation data from a nearby meteorological station. The model is calibrated with in-situ measurements of annual mass balance collected from 2011 to 2014 and with winter accumulation measurements taken in May 2014. The snow-cover depletion pattern observed using satellite imagery provides additional information on the dynamics of mass change throughout the melting season. Two digital elevation models derived from high-resolution satellite stereo images acquired in 2003 and 2012 are used to calculate glacier volume change for the corresponding period. The so-derived geodetic mass change is used to validate the modelled cumulative glacier-wide balance. By combining the above methods, robust mass balance series at high temporal resolution for Glacier No.354 could be produced for a decade for which only little is known about glacier mass changes in the Akshiirak range. For the period 2003 to 2012 we found a cumulative

mass loss of -3.59 ±0.79 m w.e. This result agrees well with the geodetic balance of -4.45 ±0.67 m w.e. over the same period.

IACS (Cryosphere)

C03b - C03 Glacier Monitoring from In-Situ and Remotely Sensed Observations

IUGG-3411

"Changes in glaciation of balkhash-alakol basin over the past 60 years"

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The changes of glaciation in Balkhash-Alakol basin over the last half-century and their impact on river runoff are considered. The report is based on an analysis of data unified glaciers inventories of Zailiyskiy-Kungey (as of 1955, 1975, 1979, 1999, 2008), Jungar (as of 1956, 1972, 1990, 2000, 2011) glacier systems and data of similar glacier inventories of Chinese part of the Ili River basin (as of 1963 and 2011). Used also mass balance monitoring data of Tuyuksu glacier for the period since 1957 by 2014.

Comparative analysis of repeated glacier Inventories data allows concluding that:

- The ratio of the glaciers area of the individual basin to the glaciation area of corresponding glacial system is stable over time. This opens up possibilities for the operational monitoring of a state of glacial systems of various sizes, ranging from groups of basins with similar conditions for glaciers existence to glacier systems of mountain countries.
- From the mid of 1950s the glaciation of the region remained in a stage of degradation and in the average for the period was reduced with a rate about 0,8% a year on the area of open part of glaciers and about 1% a year on ice volume;
- The maximum rate of glaciers area reduction (up to 1.2 -1.3% a year) were observed in the first half of 1970s and coincided on time with a sharp reduction in maximum snow storage and sustained positive anomaly of average annual and summer air temperatures. During the subsequent period, the rate of glaciers area reduction steadily declined and now makes up no more than 0.65% a year.

- Glacial systems of large basins, like the Balkhash-Alakol, change simultaneously, linearly and with similar rates.

IACS (Cryosphere)

C03b - C03 Glacier Monitoring from In-Situ and Remotely Sensed Observations

IUGG-4267

Characteristics of surge-type glaciers in the Karakoram

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Several regions with clusters of surging glaciers have been identified globally, with the Central Karakoram being among the most prominent ones. In the recent past, the development of Karakoram's glaciers has been investigated by observing glacier flow velocities as well as length and surface elevation changes from satellite data. However, most studies have analysed only few glaciers or not consistently distinguished surging tributaries, which hampers the determination of glacier response to climate change. Since the causes of the frequent surges are still poorly understood, it is crucial to expand our knowledge about the characteristics of surging in comparison to non-surging glaciers.

For this purpose we have created a new high-quality glacier inventory over the whole Karakoram with surging glaciers or surging tributaries being separately indexed. An analysis of available satellite imagery back to 1961 reveals glacier changes over the past 50 years and has further enabled us to extend the number of known surge-type glaciers in this region. Moreover, we traced the changes in topographic parameters during a surge cycle and contrasted them with those from non-surging glaciers.

In total we mapped ~12,000 glaciers covering ~21.700 km², of which one fifth is larger than 1 km² (~90% of the glacierized area). While many non-surging glaciers have changed their extent only slightly, some of them have clearly retreated. The vast majority of the surging glaciers are tributaries of larger glaciers or independent glaciers that are mostly debris free, comparably steep and of medium size – in contrast to findings in previous studies. During a surge, glaciers can almost double their length while reducing their mean slope and mean elevation.

IACS (Cryosphere)

C03c - C03 Glacier Monitoring from In-Situ and Remotely Sensed Observations

IUGG-0788

Changes of glaciers and lake on Tibetan Plateau using GRACE and ICESat data

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Tibetan Plateau (TP) is covered with thousands of glaciers and lakes, which feed into Asian major rivers and provide billions of people with fresh water for living. Climate change affects directly Glaciers and lakes variation. Therefore, observing terrestrial water on the TP is essential for water management and study of climate change. Due to the harsh environment, it’s difficult to get large-scale, continuous field observation data. Gravity Recovery and Climate Experiment (GRACE) and Ice, Cloud, and land Elevation Satellite (ICESat) provide an effective method to monitor water mass balance on the TP

Using Space Domain Inverse method, mass budget from GRACE shows two negative signals beside and one positive signal within the Tibetan Plateau. The two negative signals are caused by glacier melting and underground water depletion. The positive signal may be owing to precipitation increase. Because GRACE estimates an integrated signal, including various contributions from glaciers, plate motion, and terrestrial water change. Therefore, mass balances of lakes and glaciers are derived respectively by recalculating Lake water level and glacier elevation changes from ICESat, which is beneficial to verify GRACE method. By comparing results from gravimetry and altimetry, their relevance in time evolution and spatial distribution is further discussed.

IACS (Cryosphere)

C03c - C03 Glacier Monitoring from In-Situ and Remotely Sensed Observations

IUGG-1691

Comparison of measured glacier mass balance data in the Tian Shan and Pamir Mountains, Central Asia

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The Tian Shan and Pamir Mountains are very heterogeneous concerning glacier coverage and glacier behavior due to a climate gradient from West to East. Glacier mass balance data in this area have been calculated by different methods including the GRACE satellites in previous studies with differing results. In contrast to most other remote sensing devices, GRACE measures changes in Earth's gravity and, hence, changes in Earth's mass distribution directly on a global scale. On a local scale, glacier mass balance is also measured directly by in-situ measurements. The aim of this study is to link these two methods because both methods measure mass balance directly. The largest challenges are the great differences in resolution and mapping methods. We used glacier mass balance data of the Tian Shan and Pamir Mountains measured by the glaciological method between 2003 and 2012 and GRACE GFZ RL05a-L2 data solutions. It is not possible to detect the cause of the mass change by GRACE itself. Therefore, in this study, the hydrological model WaterGAP 2.2 is used to calculate the total water storage that is subtracted from the GRACE data (glaciers are not simulated). Measured glacier mass balance data are prepared in four different ways. They are compared with GRACE-WaterGAP data to verify the possibility of using glaciological mass balance data for regional comparisons. Annual mass balance data between GRACE-WaterGAP and the measured glaciers show different signs in most years, but the temporal trend gives reliable results. By comparing our results with results from previous studies, it remained unclear which method for the measured glacier mass balances fits best. Therefore, more measurements are necessary to identify reliable results for this area.

IACS (Cryosphere)

C03c - C03 Glacier Monitoring from In-Situ and Remotely Sensed Observations

IUGG-3147

Mountain glaciers on the territory of Russia: Results on inventorying and an assessment of glacier changes

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Mountain glaciers being dynamically unstable systems reveal rapid reaction on climate change. Glacier recession implies the landscape changes in the glacial zone, origin of new lakes and activation of natural disaster processes, catastrophic mudflows, ice avalanches, outburst floods, and etc. The presence of glaciers in itself threats to human life, economic activity and growing infrastructure. Economical and recreational human activity in mountain regions requires relevant information on snow and ice objects. Absence or inadequacy of such information results in financial and human losses. One of the urgent aims is to study the current trends in development of mountain glaciation of the Earth in conditions of global climate warming. The unbiased assessment of current and future development of glaciers requires effective system of monitoring including in-situ and remotely sensed studies. In the paper we give an overview of recent results on mountain glaciers inventorying and mountain glacier changes on the territory of Russia received both by surface measurements and remote sensing observation.

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C03c - C03 Glacier Monitoring from In-Situ and Remotely Sensed Observations

IUGG-3714

Geodetic mass balances of Himalayan glaciers from SPOT5, Pléiades and ASTER stereo-images

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Glacier mass balances remain poorly documented throughout the Himalayas. Remote sensing estimates based on ICESat, GRACE have focused on large scale assessments but cannot capture accurately the mass budget for individual glacier bodies. In situ glaciological mass balances are limited to a few glaciers and, ideally, should be re-analyzed every 5 to 10 years using independent geodetic mass balance estimates. This is especially critical in Himalaya because the highly-elevated, often avalanched-fed accumulation areas are difficult to survey in the field. We use the differencing of SPOT5 (2004 and 2005) and Pléiades (2014) DEMs to compute the 10-yr mass balance of Chhota Shigri, Hamtah glaciers and of the 'iconic' Gangotri Glacier, all in the western Himalaya. Elevation changes are measured with an uncertainty of ~1 m. Our 2004-2014 mass balances are used to evaluate region-wide mass balances inferred from multi-temporal ASTER DEMs (ordered thanks to GLIMS) and confirm the continuing mass loss of glaciers in the western Himalayas.

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IUGG-4880

Snow and ice melt contributions from a temperature index model and an energy balance model in the Hunza River basin

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In mountainous regions of High Asia, snow and glacier ice both contribute to streamflow, but few in-situ observations exist that can help distinguish between the two melt components. We used MODIS-derived data sets to distinguish three surface types at daily resolution: 1) exposed glacier ice, 2) snow over ice and 3) snow over land in the Hunza River basin, a sub-basin of the Upper Indus. We compared two melt models that use this surface classification scheme, a temperature index model and an energy balance model. Downscaled reanalysis data is required for both models. For our temperature index model, we used ERA-Interim-derived lapse rates to downscale temperatures to 500m and aggregate by elevation bands. Lapse rates derived from reanalysis do not always match well with station-derived lapse rates. Consequently, this model is most sensitive to errors from downscaling (lapse rates) and errors in temperature (reanalysis). In contrast, our spatially-distributed energy-balance model requires shortwave, longwave and temperature data, which are downscaled to 500m from GLDAS NOAH surface simulations. Physically-based methods to downscale shortwave radiation are robust when forest cover is not a compounding factor to solar and terrain geometry. Shortwave radiation is the biggest driver of melt, so this model is most sensitive to accuracy of incoming shortwave radiation and albedo. We compared results from the two models with measured streamflow, and evaluated the models computation time, accuracy and ease of diagnosing errors output. We include comparisons of model results using different remote sensing products (MCD43, MOD10A1, MODSCAG, MODDRFS) to partition surface types.

IACS (Cryosphere)

C03d - C03 Glacier Monitoring from In-Situ and Remotely Sensed Observations

IUGG-0201

Ultra-wideband microwave radar for measurements of snow accumulation rate

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Ultra-wideband microwave radars have been demonstrated as a valuable tool for obtaining accurate estimates of snow accumulation rates in the polar ice sheets (Medley and others, Geophys. Res. Lett., Vol. 40, 2013). Accurate determination of snow accumulation is critical to improving numerical ice sheet models. At the Center for Remote Sensing of Ice Sheets, we are developing an ultra-wideband radar with enhanced capabilities for snow accumulation measurements. The radar operates in the Frequency-Modulated Continuous Wave (FMCW) mode over the 2-18 GHz frequency range with less than 1 W of transmit power. It is designed to combine and expand the capabilities of our earlier 2-8 GHz and 12-18 GHz radars, which are now flown simultaneously and routinely onboard various aircraft (Rodriguez-Morales and others, IEEE Trans. Geosci. Remote Sens., Vol. 52, No. 5, May 2014). The new 2-18 GHz radar is designed to provide a vertical resolution close to 1.5 cm in snow, and new polarimetric capabilities will enable estimation of key parameters, such as snow water equivalent and density. The system will also be capable of measuring snow thickness on sea ice, another vital indicator of climate dynamics.

We will present an overview of the capabilities of our current 2-8 GHz and 12-18 GHz radars, including some sample results from recent field campaigns. We will discuss considerations and challenges involved in the design of the new 2-18 GHz radar as well as its new capabilities. Finally, we will present some test results of the system and discuss our plans for deployment in the near future.

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C03d - C03 Glacier Monitoring from In-Situ and Remotely Sensed Observations

IUGG-1049

Potential of Moderate Resolution satellite imagery from MODIS and VIIRS for monitoring of perennial snow/ice cover over land

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The snow and ice are important hydrological resources. In this regard, the land snow and ice fields, which corresponds to a minimum spatial extent and called here as perennial snow/ice (PSI), play very important role as indicator of long-term changes and baseline capacity for surface water storage. The high-resolution imagery (<30m) can provide accurate estimates of PSI extent, but clouds, long revisit period (several weeks) and relatively small size of the imaging area are well-known limitations of this approach. On the other hand, moderate resolution sensors, such the Moderate Resolution Imaging Spectroradiometer (MODIS) and Visible Infrared Imaging Radiometer Suite (VIIRS) can provide imagery with 250m-375m spatial resolution at daily refresh rate from multiple overpasses. Successful application of this approach was demonstrated by Fontana et al. (JGR Surface, 2010). The study utilized the long-term MODIS time series at 250m spatial resolution processed at the Canada Centre for Remote Sensing (CCRS). It reported significant interannual PSI variations in the Arctic circumpolar land area and important biases in the global land cover datasets. Current paper will describe extension of this method for new VIIRS sensor onboard Suomi NPP satellite with focus on PSI over Canadian landmass. The details of VIIRS processing technology will be provided. Consistency between MODIS and VIIRS results will be discussed.

References:

Fontana, F.M.A., Trishchenko, A.P., Luo, Y., Khlopenkov, K.V., Nussbaumer, S.U., Wunderle, S., 2010: Perennial snow and ice variations (2000-2008) in the Arctic circumpolar land area from satellite observations. J. Geophys. Res., 115(4), F04020, doi:10.1029/2010JF001664, 11pp.

IACS (Cryosphere)

C03d - C03 Glacier Monitoring from In-Situ and Remotely Sensed Observations

IUGG-3357

A high-resolution sensor network for monitoring glacier dynamics at the Helheim glacier, south-east Greenland

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Iceberg calving is a key mass loss mechanism for tidewater glaciers, and has been the major contributor to increased contribution to sea-level rise from several regions of Greenland, including the south-east. In summer 2013 we installed a network of 19 GNSS sensors at the margin of Helheim Glacier in south-east Greenland together with 5 oblique cameras instrumenting an area of ~16 km^2. By design the network was robust to the loss of sensor nodes as the glacier calved. Data collection covered 55 days during July through to early September 2013, with data at rates of up to every 7 seconds providing velocity and elevation data of unprecedented resolution in time and space. The observation period included a number of significant calving events, with total glacier retreat approaching ~1.5 km. The glacier was seen to calve by a process of buoyancy-force-induced bottom-crevassing in which the ice downglacier of flexion zones rotates upwards because it is out of buoyant equilibrium. Calving then occurs back to the flexion zone and the data collected supports a explanation of this process. Theoretical considerations suggest the process of bottom crevasse propagation is strongly enhanced when the glacier base is deeper than buoyant equilibrium and GNSS and oblique camera image tracking analysis in combination allows us to place constraints on the geometry of the basal cavity that forms beneath the rotating ice downglacier of the flexion zone before calving.

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C03d - C03 Glacier Monitoring from In-Situ and Remotely Sensed Observations

IUGG-4953

Freeboard changes on Drygalski and Mertz ice tongue, east Antarctica from altimetry data

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Both Mertz and Drygalski ice tongue are floating extensions of land-based glaciers. Mertz glacier stretches about 140 km to the sea from the grounding line, with ice front of about 34 km in width before 2010. Drygalski ice tongue stretched from David glacier is about 20 km wide and 70 km long. Both ice tongues experienced iceberg collision in recent years and lost mass in the way of ice disintegration. Because of development of high accurate laser altimetry, the freeboard changes for large ice tongues are more feasible, complementing information directly in the vertical direction. In this study, we will show freeboard changes in both ice fronts with ICESat/GLAS data/ICE-Bridge Riegl laser altimetry data, differences in freeboard changing rate with or without considering footprints relocation and precision differences of freeboard extraction for G-C correction of ICESat/GLAS.

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C03p - C03 Glacier Monitoring from In-Situ and Remotely Sensed Observations

C03p-400

COSMO-SkyMed data in classification (bare ice and wet snow surfaces) of the glacier Polar Club in Potter Peninsula, Maritime Antarctica

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Over the last 50 years, ice masses retreats have been observed in King George Island concomitantly to a regional climate warming. In this context, it is necessary to monitor this environment to know the consequences of these changes and to estimate future trends. The study uses remote sensing techniques to evaluate the potential of SAR data for monitoring the surface dynamics in Potter Peninsula, 62° 14' south and 58° 38' west, King George Island, Maritime Antarctica. Backscatter values of surface targets were extracted from a COSMO-SkyMed satellite imagery obtained on February 1st, 2011. Subsequently, a supervised classification was made using the maximum likelihood statistical classifier to delimit surface cover classes. Average backscattering by surface water bodies have high similarity, making it impossible to distinguish different turbidity conditions. On the other hand, bare ice and wet snow surfaces have different backscatter values, which allowed classifying the glacier surface in five classes,, with kappa index 0.65 and 0.75 for the ice free-areas and the glacier surface classification, respectively. This study highlights the importance of the data generated by COSMO-SkyMed satellite and remote sensing techniques for monitoring periglacial environments.

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C03p - C03 Glacier Monitoring from In-Situ and Remotely Sensed Observations

C03p-401

Response of land-terminating King George Island Glaciers to climate change on a multi-decadal timescale

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This work investigates the response of land-terminating King George Island glaciers, located off the Antarctic Peninsula, to climate change on a multi-decadal timescale. SPOT, ASTER, Landsat satellite images and COSMO-SkyMed (Constellation of Small Satellites for Mediterranean Basin Observation) images in spotlight mode (1 meter of the spatial resolution) with HH and VV polarization were used to interpret behavior of the glaciers between 1979 to 2014. Topography and in-situ glaciological data, obtained in the fields in 2007, 2010, 2011, 2013 and 2014 summers, evidenced terminus and snow line fluctuations. Due to its small size and thermal conditions, these glaciers responded rapidly to climatic changes. Small land-terminating glaciers, as Dragon (lost 55% of their total area between 1979–2014), Professor (40%), Ecology (more than 22%) and Wanda Glaciers (32%) retreat faster than others glaciers, as Collins Glacier (12% since 1989), despite a regional warming climate. Three-dimensional model of the Wanda glacier surface and the Ground Penetration Radar survey to deliver information about the internal structure and indicated temperate ice with high liquid water content. The results evidenced changes of the outlet glaciers for land-terminating conditions (Znosco Glacier is the land-terminating glacier since end of the 1990 decade and have a retreat rate of the 20% of the total area in last decade), effectively making them more vulnerable to the warm temperatures trend. Annual positive surface air temperatures and rainfall events, registered from a meteorological station for the analyzed period, lead to increased wet snow and soaked snow zones in the glaciers.

IACS (Cryosphere)

C03p - C03 Glacier Monitoring from In-Situ and Remotely Sensed Observations

C03p-402

Variability of Antarctic proglacial lakes through numerical and remote sensing investigations, King George Island

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This work investigates multi-decadal and seasonal (spring and summer) variability of lakes associated to liquid precipitation, cloud condition, wind speed, solar radiation and annual melting variations in Fildes Peninsula, King George Island (KGI). The method combines in-situ measurement with remotely sensed and meteorological data analysis. We present an evolution of the Fildes Peninsula lakes for the1986–2014 period. We detected an area increase of 71% (0.034 km^2) from 1986 (0.013 km^2) to 2014 (0.047 km^2) for 9 proglacial lakes, being 7 new lakes (data base of 2014). The evolution of these lakes is related to the land-terminating Collins Glacier retreat, which lost 1.09 km^2 (of the 8.39 km^2 total area in 1986). The number of lakes has increased since 1986 (new 6 proglacial lakes in 2014) resulting in a maximum melting in the last days of February and beginning of March. The increase in the number of lakes is more evident in Southwest and South sectors and can be related to spatial variations in the radiation. Seasonal and diurnal processes (e.g. cloudy conditions, wind speed, radiation, liquid precipitation, air temperature) affect the meltwater production of the Collins Glacier and the development of the proglacial drainage. The interannual proglacial drainage evolution and retreat processes of Collins Glacier follow the annual liquid precipitation, solar radiation, and melting degrees days variation. The results indicate that the lakes and glacier areas are sensitive to the surface air-warming trend in KGI.

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C03p - C03 Glacier Monitoring from In-Situ and Remotely Sensed Observations

C03p-403

THE RESULTS OF MONITORING GLACIERS DESTRUCTION AND ICEBERGS FORMATION PROCESSES BY SEISMIC–INFRASONIC METHOD.

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In late 2010, the Geophysical Survey, Kola Branch, Russian Academy of Sciences installed a system of constant seismic and infrasonic monitoring on the Spitsbergen archipelago. To date, this system is the only tool to implement joint monitoring of seismic and infrasonic events in this part of the Arctic. This paper provides the results of a 3-years experiment for seismic–infrasonic monitoring of the glaciers located on the northern coast of Isfjorden Bay, Svalbard.

The experiment shows that glaciers produce a seismic emission, which is enhanced from the second part of July to the end of September. The diurnal variations of the seismic emission are close to the behavior of the air temperature near the Earth surface. The seismic–infrasonic events produced by the glaciers destruction have been revealed in Svalbard for the first time.

Funding for this research was provided by Ministry of Education and Science of the Russian Federation Project RFMEFI61014X0006, Agreement no. 14.610.21.0006 “Development of new methods and techniques for monitoring of geophysical and hydrometeorological state of Spitsbergen and Russian West Arctic.”

IACS (Cryosphere)

C03p - C03 Glacier Monitoring from In-Situ and Remotely Sensed Observations

C03p-404

The increase of debris cover of glaciers in eastern side of the Northern Patagonia Icefield in the last 70 years

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Precipitation decrease and temperature rise since the end of LIA have resulted in a generalized down-wasting trend in Patagonian Glaciers. Glacier retreat and thinning has exposed unstable bedrock and debris-mantled slopes to subaerial erosion increasing mass movement activity. Mass movements can travel onto glaciers covering ice with a sheet of debris that could modify the glacier dynamics. An increase in the debris covered area has been observed (e.g. Himalaya), however, changes in the debris covered areas of NPI glaciers have not been quantified.

We analyze the evolution of the debris covered area of 18 glaciers located on eastern side of the NPI from 1944 to 2014. Glacier debris-covered areas were interpreted and draw manually over Trimetrogón oblique aerial photographs (1944) and Landsat OLI TIRS (2014) images. The following glaciers were studied: Grosse, Exploradores, Bayo, U6, Fiero, Cristal, Leones, Soler, Nef, U5, Cachet Norte, Cachet, Colonia, Arco, U4, Pared Norte and Sur, Piscis.

The debris covered area of glaciers on the east side of the NPI increased ~68% (74.8 to 125.6 ± 4 km^2). This trend is coincident with glaciers retreat. The increase in debris cover was more pronounced on the southern glaciers. For example, the debris covered surface of Colonia Glacier increased from 9.37 to 19.94 km^2. Other glaciers that experienced significant changes in the debris covered areas were Pared Norte (2.4 to 11.9 ± 0.3 km^2) and Pared Sur (2.96 to 8.7 ± 0.3 km^2). This is the first quantification of changes in the debris covered area of the eastern NPI glaciers. The documented increase in the areas covered by debris in the last 70 years highlights the need of taking into account the effects of debris cover changes on the glaciers response to climatic changes in Patagonia.

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C03p - C03 Glacier Monitoring from In-Situ and Remotely Sensed Observations

C03p-405

Short-term elevation change in the accumulation area of the Northern Patagonia Icefield, Chile

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The Northern Patagonia Icefield (NPI), covering ca. 3.950 km^2, is the second largest ice-mass in the Southern Hemisphere outside Antarctica. In spite of its importance as a climate change indicator in mid-latitudes areas, the absence of ground-truth mass balance data leads to high uncertain in glacier response to global warming and sea-level rise contribution. Glaciological observations in its accumulation area are still lacking due to mainly its harsh environment and logistics costs involved.

We carried out three airborne laser altimetry (LIDAR) campaigns (2011, 2012, and 2013) in the gentle accumulation areas of three large neighbor outlet glaciers: San Rafael, San Quintín and Colonia. Surface elevation change of –6.4 ± 0.28 m a^{-1} for San Rafael, –3.78 ± 0.9 m a^{-1} for San Quintin and –2.3 ± 0.1 m a^{-1} for Colonia glaciers, was obtained from 2010 to 2014, by comparing LIDAR data and repeated ground-based GPS surveys (2010, 2011, 2012, 2013, and 2014) in a profile of ~ 40 km. In addition, at San Rafael Glacier was obtained a seasonal change of –3.74 ± 0.28 m (August 2012/February 2013), and an annual change of –1 ± 0.3 m a^{-1} (August 2012/August 2013), indicating high variability in the snow-height. Similar differences were also found at San Quintin and Colonia glaciers.

However, two accumulation-masts show year-to-year (2013/2014) variations in the snow-height from 1.8 m at San Rafael to 7.48 m at Colonia. This large annual snow-height difference is even larger than the elevation change obtained for the period 2010-2014. In glaciers with high precipitation rates, inter-annual variations in snow-height and changes in accumulation rates may explain short-term surface elevation change rather than ice-thinning in response to climate forcing if sparse data is available.

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C03p-406

Surface elevation change of Andean glaciers in Central Chile, based upon airborne laser altimetry and ground-truth GPS measurements

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Negative long-term glacier mass-balance is an indicator of global warming, and changes in runoff are expected as a result of high thinning rates in glacier response. Maipo basin (33° S / 70° W), with about 397 km^2 of glaciers, is one of the main glacierized areas of the Chilean Andean glaciers outside Patagonia.

At Echaurren Norte (ca. 0.4 km^2, 3.750 m asl), a small mountain glacier, mass-balance measurements by the glaciological method indicates a marked thinning trend since 1975 (-15.6 m w. e.). In spite of this glacier is sensitive to inter-annual variations in rainfall due to El Niño Southern Oscillation (ENSO), very little is known on the response of different type of glaciers (i.e., large area, high altitude and debris-cover) of the same basin.

Based upon airborne laser altimetry (LIDAR) carried out in 2009 and 2012, and global positioning system (GPS) in 2014, we estimated the surface elevation change in four clean-ice glaciers: Yeso (ca. 2.03 km^2, 4.400 m asl), Bello (ca. 4.21 km^2; 4.400 m asl), San Francisco (ca. 1.69 km^2, 3.350 m asl) and Echaurren Norte (0.25 km^2, 3.750 m asl), and in one debris-covered glacier: Pirámide (ca. 4.39 km^2; 3.600 m asl).

Higher thinning rates were found in glaciers with both lower elevation and mostly clean-ice surface (-2.27 m a^{-1} at San Francisco and -2.47 m a^{-1} at Echaurren Norte) whereas melting rate decrease over the 4000 m layer (-0.17 m a^{-1} at Yeso Glacier and -0.24 m a^{-1} at Bello Glacier). However, the insulating effect of thick debris yields to almost negligible melting rate in the debris-covered glacier (no change at Pirámide) independently of its lower elevation. Debris-covered glaciers are widespread at Maipo basin (47%) and they may alter spatial patterns of mass loss.

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C03p-407

Surface elevation change of Andean glaciers in Central Chile, based upon airborne laser altimetry and ground-truth GPS measurements

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IACS (Cryosphere)

C03p - C03 Glacier Monitoring from In-Situ and Remotely Sensed Observations

C03p-408

Ice front and flow speed variations of marine-terminating outlet glaciers along the coast of Prudhoe Land, northwestern Greenland

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The Greenland ice sheet is losing mass under the influence of flow acceleration and retreat of marine-terminating outlet glaciers. Recently, ice mass loss is increasing particularly in northwestern Greenland, thus it is important to study outlet glaciers in this region. We analyzed satellite images to measure frontal positions and ice speeds of 19 marine-terminating outlet glaciers along the coast of Prudhoe Land over the period from 1988 to 2014. Ice front positions were delineated using 266 images and ice speed was measured using 1017 image pairs by feature tracking method. All of the glaciers retreated over the study period by a distance between 0.23 and 5.34 km, with the median and mean retreat distance of 1.02 and 0.63 km, respectively. Ice speed near the front of each individual glacier in 2013 ranges from 19±5 to 1720±60 m a^{-1}. Ice speed was greater than 400 m a^{-1} near the front of five glaciers located in the eastern part of the study area. Our results indicate that the retreat of the glaciers began in 2000. In northwestern Greenland, the positive degree day sum (PDDsum) and summer sea surface temperature significantly increased after 2000. Thus, we hypothesize that warming after 2000 triggered the glacier retreat. The retreat rate of each individual glacier is strongly correlated with ice speed increase between 2000–2014. Because there is no clear relationship between ice speed and PDDsum, the observed recent speed-up was probably caused by back-stress reduction due to rapid ice-front retreat.

IACS (Cryosphere)

C03p - C03 Glacier Monitoring from In-Situ and Remotely Sensed Observations

C03p-410

Geomorphic characteristics and classification of peninsula Fildes lakes, King George island, maritime antarctic

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The South Shetland Islands and the West Antarctic Peninsula region are currently experiencing one the fastest rates of temperature increase on Earth. The regional average temperature rose by 3°C over the last 60 years, and the glacier retreat widespreads a set of features and deposits which contains considerable information about climate and environmental history at Holocene scale. Fildes Peninsula is the largest deglaciated area of King George Island, Southern Shetland Islands. The area has the largest number of lakes and ponds (more than 60), that receive amount of sediments from different processes: glacial, glaciofluvial, periglacial and marine. In this work we analyze the regional geomorphological features, and mineralogy and biogeochemistry of the lake-bottom sediments to study the influence of glacial and non-glacial processes on the lakes origin. Quickbird (2010), Landsat 8 (2013) images and Surface Elevation Models (DEM) were used for recognition of geomorphological features, and to delimit the lake basins. Short cores of lake-bottom sediments were acquired during fieldwork carried out in December 2013, and were kept frozen until sampled in the laboratory. Particle size and mineralogical analysis were performed with laser granulometer and X-ray diffraction. Organic C concentrations were measured with Costech CHN Analyzer. We propose a typology of lakes formed by the retreating glacier and by other processes. Lake-bottom sedimentary records and geomorphological features of the surrounding areas are important tools for the proposed classification, since they reflect the climatic variability in the area. The lakes were preliminarily classified in: proglacial lake, meltwater lake, temporary lake, mixed-origin lake and wetland.

IACS (Cryosphere)

C03p - C03 Glacier Monitoring from In-Situ and Remotely Sensed Observations

C03p-411

Sub-regional climate influences on the mass balance and proglacial discharge of two small glaciers in Svalbard

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In the frame of the project "Cryosphere reactions against the background of environmental changes in contrasting high-Arctic conditions in Svalbard" two small glaciers (about 2 km square of ice coverage) were investigated within two years with the use of the same set of methods. The glaciers are separated one from another with the distance of 104 km from the western coast of the island of Spitsbergen inland. The measurements covered the comparison of glaciers extents archive data acquired since the end of Little Ice Age, meteorological, ice mass balance and water discharge observations compared for years 2013 and 2014. The climate of the island is changing from maritime on the western coast, where the Waldemar Glacier is located to more continental, named "quasi-continental", in the inland, in the vicinity of the second under study Pollock Glacier. The difference of environmental interactions is observed in the amount of precipitation, mostly influencing winter mass balance prevailing twice in the maritime area. Comparing the net mass balance, the Pollock Glacier is showing values by about 21% higher than the Waldemar Glacier. The structure of proglacial discharge of the two glaciers differ mainly in terms of its seasonal intensity and represents relations in sub-regional climatic variability.

IACS (Cryosphere)

C03p - C03 Glacier Monitoring from In-Situ and Remotely Sensed Observations

C03p-412

Separating snow and ice on glacier surfaces using remote sensing for the Hunza basin: Towards an automated method?

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Separating snow and ice on glacier surfaces is needed for calculating glacier snow lines altitudes (SLAs), for inferring stable-state glacier equilibrium line altitudes (ELA), and for calculating the specific mass balance of glaciers where field-measurements exist. Furthermore, partitioned snow and ice on glaciers is needed as input for parameterizing melt models and estimating snow and ice runoff components at regional or watershed scales. Direct measurements of snow lines are rarely possible particularly in high altitude glacierized terrain, and remote sensing data are often used to as a tool to separate snow and ice. Snow lines are generally visible on optical satellite images so the delineation is often done manually, and is subjective to digitization errors. Models based on Snow Covered Area and Grain size/albedo (SCAG), which detect snow cover at sub-pixel resolution may provide an automated alternative to manual digitization.

Here we evaluate the potential of Landsat 8 using the SCAG model at 30-m resolution to 1) separate glacier surfaces (snow/ice) from surrounding terrain and 2) within the glacier surface, separate snow (accumulation area) from ice (ablation area). For each of these steps, SCAG outputs are compared to standardized semi-automated algorithms used commonly: a) band ratios with threshold and b) supervised classification schemes, respectively. Algorithms are evaluated in terms of accuracy based on manual digitization of snow lines on selected glaciers, processing time and algorithm complexity. The goal is to develop an automated method for distinguishing snow/ice and to find snowlines to input into melt models at large scales.

IACS (Cryosphere)

C03p - C03 Glacier Monitoring from In-Situ and Remotely Sensed Observations

C03p-413

Surface elevation change of Andean glaciers in Central Chile, based upon airborne laser altimetry and ground-truth GPS measurements

G. Barcaza[1], *A. Segovia*[1], *D. Farias*[1], *J. Huenante*[1], *B. Varela*[1], *D. Gonzalez*[1], *A. Vergara*[1]
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Negative long-term glacier mass-balance is an indicator of global warming, and changes in runoff are expected as a result of high thinning rates in glacier response. Maipo basin (33° S / 70° W), with about 397 km^2 of glaciers, is one of the main glacierized areas of the Chilean Andean glaciers outside Patagonia.

At Echaurren Norte (ca. 0.4 km^2, 3.750 m asl), a small mountain glacier, mass-balance measurements by the glaciological method indicates a marked thinning trend since 1975 (-15.6 m w. e.). In spite of this glacier is sensitive to inter-annual variations in rainfall due to El Niño Southern Oscillation (ENSO), very little is known on the response of different type of glaciers (i.e., large area, high altitude and debris-cover) of the same basin.

Based upon airborne laser altimetry (LIDAR) carried out in 2009 and 2012, and global positioning system (GPS) in 2014, we estimated the surface elevation change in four clean-ice glaciers: Yeso (ca. 2.03 km^2, 4.400 m asl), Bello (ca. 4.21 km^2; 4.400 m asl), San Francisco (ca. 1.69 km^2, 3.350 m asl) and Echaurren Norte (0.25 km^2, 3.750 m asl), and in one debris-covered glacier: Pirámide (ca. 4.39 km^2; 3.600 m asl).

Higher thinning rates were found in glaciers with both lower elevation and mostly clean-ice surface (-2.27 m a^{-1} at San Francisco and -2.47 m a^{-1} at Echaurren Norte) whereas melting rate decrease over the 4000 m layer (-0.17 m a^{-1} at Yeso Glacier and -0.24 m a^{-1} at Bello Glacier). However, the insulating effect of thick debris yields to almost negligible melting rate in the debris-covered glacier (no change at Pirámide) independently of its lower elevation. Debris-covered glaciers are widespread at Maipo basin (47%) and they may alter spatial patterns of mass loss.

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IACS (Cryosphere)

C04a - C04 Modelling of Mountain Glaciers, Past and Future

IUGG-0535

Twenty-first century changes in the hydrology, glaciers, and permafrost of Susitna Basin, Alaska

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Future climate change will impact the quantity and seasonality of river flow in the upper Susitna Basin in South-Central Alaska, USA. We present field measurements and results from hydrological modeling for this 13,289 km² basin. The basin is 4% glacierized and is characterized by sparse vegetation, discontinuous permafrost, and little human development.

Traditional glacier mass balance measurements show that glaciers in the Upper Susitna lost more mass in 2012, 2013, and 2014 than previous work showed for 1981, 1982, or 1983. Springtime snow radar surveys of the glaciers allow us to extrapolate from point measurements of snow depth to the whole glacier area. Snow depth measurements at tundra sites as well as tundra vegetation and soil characterizations help us choose appropriate model parameters for the tundra portions of the basin. Meteorological data (T, RH, P) from over 20 stations in the basin show the summertime temperature lapse rate to be smaller over glacier surfaces than ice-free surfaces. Precipitation is highly variable across the basin.

We run a physically-based hydrological model (WaSiM) to project 21st century river discharge. Climate inputs come from a CCSM CMIP5 RCP6.0 scenario downscaled to a 20km-5km nested grid using the Weather Research and

Forecasting (WRF) Model. From 2010-2029 to 2080-2099 the basin-wide mean-annual temperature will rise 2.5 degrees and total precipitation will rise 2%, with a 13% decrease in snowfall and a 20% increase in rainfall. WaSiM runs indicate that glaciers will retreat, evapotranspiration will increase, and permafrost will thaw. Annual runoff will remain relatively steady, but the timing of the peak spring runoff will shift to an earlier date.

IACS (Cryosphere)

C04a - C04 Modelling of Mountain Glaciers, Past and Future

IUGG-1842

Climate sensitivity of Svalbard glaciers

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Simple geometric considerations reveal that the sensitivity of regularly-shaped glaciers to changes in the equilibrium-line altitude is inversely proportional to the mean slope. Seen in a global perspective, the larger glaciers on Svalbard have remarkably small slopes (0.05 or less). Presumably this is the consequence of sediment beds with low resistance, and the effectiveness of surges imposing an upper linit to the surface slope that glaciers can attain. As a consequence, the larger glaciers on Svalbard appear among the most sensitive in the world. Typically, a long-term change in the equilibrium-line altitude of 100 m may lead to a 5 km change in glacier length or more, although it may take a long time to achieve this.

Very small slopes and calving fronts make that Svalbard glaciers may react in a strongly nonlinear way to climatic changes, even if these changes are small. The nonlinearity stems from the altitude - mass balance feedback, and from the dependence of calving rates on bed geometry. A study with a simple glacier model, in which these feedbacks are represented, shows bifurcations in the solution diagram and the possibility of multiple steady states. The results imply that many of the large tidewater glaciers present today would not reform under the current (post-LIA) climatic conditions. This finding is in line with the increasing evidence that during the mid-Holocene climatic optimum the degree of glaciation on Svalbard was much smaller than today.

IACS (Cryosphere)

C04a - C04 Modelling of Mountain Glaciers, Past and Future

IUGG-4009

Power law scaling and efficient assessment and modeling of glacier populations

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Volume-area power law scaling, one of a set of analytical scaling techniques based on principals of dimensional analysis, has become an increasingly important and widely-used method for estimating the future response of the world's glaciers and ice caps to environmental change. Over sixty papers since 1988 have been published in the glaciological and environmental change literature containing applications of volume-area scaling, mostly for the purpose of estimating total global glacier and ice cap volume and modeling future contributions to sea level rise from glaciers and ice caps. Originally posited as an empirical relationship, the theoretical basis of volume-area scaling for glaciers was established by Bahr et al. in 1997, and elaborated in subsequent papers.

We discuss the essential properties of power law scaling in the context of regional glacier mass balance assessments. While power law scaling must be applied to populations of glaciers, rather than to individuals, the number of glaciers in a population does not need to be exceptionally large, and in fact certain advantages can be exploited when specific cases are being treated.

Power law scaling is a powerful and theoretically validated tool for modeling and prediction of future states of glaciers. Numerical modeling strategies can be framed in a power law context, and the necessity of modeling a large number of glaciers explicitly can be avoided. Such strategies can be especially effective when exhaustive measurements in a region are impractical, and future changes in state expressed in aggregate form, such as future net volume change over time, are satisfactory.

IACS (Cryosphere)

C04a - C04 Modelling of Mountain Glaciers, Past and Future

IUGG-4627

Challenges in modelling regional and global glacier response to climate change

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Glacier dynamics and glacier-climate processes are well understood for individual ice masses, where in situ field studies and sophisticated local models provide a detailed picture of glacier sensitivity to climate change. Where bed topographic information is available, such models are able to depict 3D glacier flow dynamics; similarly, distributed surface energy balance models provide realistic estimates of glacier melt patterns, but typically require good knowledge of local snowpack and meteorological conditions. Once one moves to uninstrumented glacier sites, as is necessary at the scale of mountain ranges, model skill deteriorates because of a lack of local ice thickness, snowpack, and meteorological data. Even high-resolution numerical weather models face a steep challenge to quantify the complex meteorological patterns that characterize mountain regions. Hence, 'downscaling' strategies are required to model glacier mass balance from remote station data, reanalyzed climatology, or, for the future, climate model fields.

I discuss different strategies to tackle these challenges at the regional scale, to provide estimates of glacier change and associated impacts on water resources and global sea level. In particular, I examine the potential for enhanced glacier flowline models and an energy balance sensitivity approach to simulate 'ensembles' of glaciers at the mountain range scale. The approach requires detailed knowledge of the regional energy balance regime, which can then be perturbed for different climate scenarios. These methods are developed and examined in the Canadian Rocky Mountains, with testing against available mass and energy balance data at Peyto and Kwadacha Glaciers.

IACS (Cryosphere)

C04a - C04 Modelling of Mountain Glaciers, Past and Future

IUGG-4681

Modelling glacier mass changes on global and regional scale: How precise can the models be?

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Changes in mass contained by mountain glaciers and ice caps can modify the Earth’s hydrological cycle on multiple scales. On a global scale, the mass loss from glaciers contributes to sea-level rise. On regional and local scales, glacier meltwater is an important contributor to and modulator of river flow. Until recently, the lack of basic inventory data was a major impediment in global mass balance assessments and projections. The recently completed Randolph Glacier Inventory, the first globally complete glacier inventory, is a major forward step towards reducing uncertainties in global-scale studies. In this talk I will review some of the recent attempts to model glacier mass changes on regional and global scales, and discuss the main challenges these models face. In particular I will focus on two models of different complexities and compare their performance in simulating present-day and future mass changes of glaciers in western Canada.

IACS (Cryosphere)

C04b - C04 Modelling of Mountain Glaciers, Past and Future

IUGG-1268

Dynamic response of Urumqi Glacier No.1, Eastern Tianshan, to climate forcing over the last decade

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Glaciers in the eastern Tianshan, northwest China, provide important water resources both for ecosystems and local population. The glaciers are summer-accumulation-type glaciers, that are highly vulnerable to the overall warming trend. Glaciers in the eastern Tianshan are experiencing rapid shrinkage. In short-term, this may result in an increase in stream flow, however, as glaciers reduce in number and disappear, water supply from glacial melt will decline. The reduction in magnitude and changes in the seasonal pattern of glacial runoff are the most important hydrological consequences of future climate change in the study region.

The spatial pattern of surface energy and mass balance, glacial dynamics and glacier hydrology in the eastern Tianshan has not yet systematically been addressed. In this study we couple a 'COupled Snowpack and Ice surface energy and MAss balance model' (COSIMA) to a Shallow Ice Approximation ice flow model to assess the dynamic response of Urumqi glacier No.1 in the Tianshan mountains to climate forcing over the period 2000-2012. COSIMA is forced by atmospheric model data from the High Asia Refined analysis (HAR). The coupling allows quantifying the difference between this approach and COSIMA runs using static glacier geometry over the same study period. Further, with this approach we identify the characteristic patterns in glacier surface energy and mass balance and improve our understanding of atmosphere-cryosphere interactions in this region. The importance of subsurface refreezing and sublimation as relevant processes of glacier mass balance are evaluated in comparison to findings from other study sites in High Asia. The results may allow for a better understanding of the future response of glaciers in the Tianshan to climate forcing.

IACS (Cryosphere)

C04b - C04 Modelling of Mountain Glaciers, Past and Future

IUGG-1622

High Mountain Asia contribution to sea level rise by 2100

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We estimate individual glacier area and volume change in High Mountain Asia (HMA) by 2100 using five different methods using different glacier inventories, and methods of assessing sensitivity to summer temperatures driven by a regional climate model and the IPCC A1B radiative forcing scenario. The Randolph Glacier Inventory version 4.0 separates individual glaciers from the complexes present in version 2, leading to a 22% increase in glacier numbers but a 30% decrease in total volume in the year 2000 this reduced ice volume lowers the HMA sea level rise contribution by 2100 by about 20%. An even larger range of sea level rise variation comes from varying equilibrium line altitude (ELA) sensitivity to summer temperatures. We use regionally prescribed sensitivities based on energy balance models, sensitivities estimated from Chinese meteorological stations, and also from $1°\times1°$ gridded temperatures in the Berkeley Earth database. The ELA sensitivity to temperature using the gridded database temperatures produces least sea level rise, and prescribed sensitivities the highest. The mean of the three estimates of sea level rise from HMA using RGI 4.0 is consistent with tuning models to match surface elevation changes from satellite altimetry.

IACS (Cryosphere)

C04b - C04 Modelling of Mountain Glaciers, Past and Future

IUGG-1660

Future projection of the surface mass balance of Altai Glaciers Using WRF Meteorological Data and CMIP5 models

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The Altai Mountains, located in the southern periphery of the Asian Arctic basin, contain 1281 glaciers with an area of 1191 km^2. These glaciers are at the headwaters of many prominent rivers, which affects the water discharge of large rivers such as the Ob and Yenisei Rivers. These glaciers experienced considerable mass loss during past decades, especially in the western part of the region. Here, we implement a temperature index-based glacier model that considers the feedback between the surface mass balance and changing glacier hypsometry to project the surface mass balance of all the individual glaciers of the Altai Mountains. The model is forced by the outputs of the latest 10 general circulation models (GCMs) participating in the fifth phase of the Coupled Model Intercomparison Project (CIMP5) under two representative concentration pathway scenarios (RCP4.5 and RCP8.5), which are bias-corrected by a Weather Research and Forecasting (WRF) model simulations with 5 km resolution. The model is validated against 66 observed annual mass balances of 5 glaciers in the region. Despite large differences in the surface mass balance from site to site, we project an increase in negative mass balance in the Altai Mountains for two RCPs, which is caused primarily by an increase in air temperature. In particular, changes are more remarkable under RCP8.5, under which most of all small glaciers are projected to be disappear by the end of this century.

IACS (Cryosphere)

C04b - C04 Modelling of Mountain Glaciers, Past and Future

IUGG-3959

The energy and mass balance of tropical Lewis Glacier, Mount Kenya, and its sensitivity to climate

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If their interaction with the atmosphere is understood, and their changes are documented or reconstructed, glaciers in the tropics can provide information about regional climate, its dynamics, and its evolution over decadal and centennial time scales. The glaciers on Mount Kenya capture a climate signal from the mid troposphere at about 5 km a.s.l., where our knowledge of climate change is scarce and controversial.

We use in-situ meteorological and glaciological observations to optimize and validate a physically-based, process-orientated energy and mass balance model to quantify the exchange processes between the glacier surface and the atmosphere above and to explore the sensitivity of energy and mass exchanges to changing climatic conditions. Atmospheric reanalysis data and long term glaciological observations provide a baseline against which the results of the sensitivity study are interpreted over climatological time scales.

IACS (Cryosphere)

C04b - C04 Modelling of Mountain Glaciers, Past and Future

IUGG-4272

Modeling strategies to assess the response of western Canadian glaciers to past and future climate change

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Glaciers in western Canada cover a small fraction of the landscape, but they represent a vital component of the region's cryosphere. These ice masses are primarily nourished by winter snowfall and depleted by summer melt. An imbalance of these factors allows these glaciers to grow and shrink in response to climate change. We examine the response of glaciers to climate variability for three different time periods using a vertically integrated model of ice flow driven by surface mass balance fields derived through three approaches relevant to the available forcing data. In the first experiment, we explore the response of the decaying Cordilleran Ice Sheet to abrupt climate change during the latest Pleistocene (14-11 ka). Climate fields from the TRACE experiment are downscaled and used to derive distributed fields of surface mass balance that are in turn used to run our simulation. In the second experiment, we use TRACE to examine the Holocene variability and long-term trends in the area, length, and volume change of mountain glaciers in the southern Coast Mountains. Our final experiment considers the evolution of glaciers throughout the Canadian Cordillera under present and future climate change. This work's novel contribution is the simulation of the full Holocene through 2100 C.E. evolution of glaciers in the region within a consistent process modelling framework. As such, it will put the present and future state of glaciers in western Canada within the context of near-glacial through Holocene climatic optimum conditions which spans the largest and smallest glacial extents in the recent geologic record.

IACS (Cryosphere)

C04p - C04 Modelling of Mountain Glaciers, Past and Future

C04p-291

Mass-balance modelling of Chhota Shigri and Patsio glacier in western Himalaya, India

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Projections of glacier mass-balance evolution in the Himalayas are afflicted with high uncertainty due to the diversity of the climatic conditions and the extremes in topographical relief. Large spatial variations in glacier mass balances are connected with the diverse precipitation patterns. While there are indications of recent glacier retreats in the Himalayas, only few glaciers have been monitored over long periods.

In 2002, a long term continuous monitoring programme of glacier mass balance was started on Chhota Shigri glacier (15.7 km²). During the period 2002-2013, measurements show an average glacier-wide mass balance of -0.59±0.12 m w.e. after near zero annual mass balances in the 1990s. On Patsio glacier (2.3 km²) mass-balance studies were initiated in 2010.

We apply a mass-balance model for the glaciers Chhota Shigri and Patsio using gridded data from two different regional climate models: 1) the Weather Research and Forecasting (WRF) Model for the periods 1970-2005 and 2000-2012, and 2) the regional climate model REMO for the periods 1989-2008 and 2000-2012. The data are downscaled from its grid resolution (27 km) to the glacier grid (300 m). As refinement method for precipitation distribution over the glacier areas we apply an orographic precipitation model. The mass-balance model calculates snow accumulation, melt and runoff on a sub-daily (6h) timescale. Calibration and validation data are the available seasonal and annual mass-balance measurements together with point data of snow accumulation. Additional runoff measurements are available close to the glacier fronts.

The study presents first results within the project “Water related effects of changes in glacier mass balance and river runoff in western Himalaya, India: past, present and future (GLACINDIA)”.

IACS (Cryosphere)

C04p - C04 Modelling of Mountain Glaciers, Past and Future

C04p-292

Towards an integrative, automatic tool for glacier flowline modelling

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Most models of global scale glacier evolution rely on volume-area scaling to account for glacier size change in time. This rather simple, empirical approach was long considered to be the only viable method for global scale applications: its nearest alternative in terms of complexity, glacier flowline modelling, requires significantly more information about the glacier geometry and bed topography. However, a number of independent recent studies provide the necessary components for an automated, integrated approach to glacier flow modelling. This work aims to develop a set of coherent numerical tools for computing glacier evolution, which are applicable to any individual glacier, and which rely only on the globally available glaciers outlines, digital elevation model, and climate observations as input. It is mainly composed of i) the determination of glacier centerlines, ii) the computation of glacier bed topography, and iii) a multi-branch 1D flowline model along the centerlines handling intersections and merging of glacier tributaries. With selected examples in the European Alps, we explore the different levels of complexity needed to reach this objective and demonstrate the feasibility of the approach.

IACS (Cryosphere)

C04p - C04 Modelling of Mountain Glaciers, Past and Future

C04p-293

Spatial and temporal variability of winter mass balance on four french alpine glaciers.

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In the Alps, annual glacier mass balance is mainly driven by ablation. However, understanding accumulation processes and distribution is an essential concern to simulate past and future changes of glaciers. Due to strong topographic effects, the distribution of accumulation at the glacier surface can significantly vary in space and time. As a consequence modelling accumulation a the glacier surface is challenging. On the basis of net accumulation (i.e. winter mass balance) measurements, made on 4 french alpine glacier since 1995 within the GLACIOCLIM observatory, this study presents the relationship between net accumulation and three topographic variables: altitude, slope, curvature. Elevation appears to be the primary factor controlling the spatial distribution of net accumulation at the glacier scale, and correlations with the two other variables are not statistically significant. However the elevation dependency is not sufficient to fully explain the spatial variability. In order to improve the understanding of this variability, other topographic variables or index have been tested (Topographic Position Index, Winstral parameter Sx) and a field campaign has been conducted during winter 2014-2015 on the Mer de Glace accumulation area involving repeated LiDAR measurements at monthly scale over a 4 km^2 flat area. These measurements were combined with snow depth, snow density and meteorological measurements. Firn compaction and vertical velocities have been considered to retrieve snow depth measurements presented in this study.

IACS (Cryosphere)

C04p - C04 Modelling of Mountain Glaciers, Past and Future

C04p-294

Application of the mass balance model to the Hurlbut Ice Cap in northeastern Greenland

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Many of ice caps and glaciers exist at the margin of the Greenland and their contribution rate to sea level rise by recent temperature warming is large. The northeastern Greenland is one of the the areas in which a little of in-situ mass balance observations were conducted. Saito et al. (2014) revealed with satellite images that the surface level change of some ice caps in northern Greenland is three times as large as that revealed by Bolch et al. (2013). We estimated surface mass balance of Hurlbut Ice Cap in northern Greenland by the mass balance model of Hock (1999). The model shows spatial variation of surface mass balance for each ice caps. The 100m - gridded DEM and surface condition of the ice cap as input of the model were derived from modified ALOS (Advanced Land Observing Satellite) data. The climate data as input of the model was global radiation, air temperature and precipitation at Thule climate station (77.2N, 68.4W), which is one of the long-term running climate stations in Greenland and situates about 100 km south to the Hurlbut ice cap. The result of the calculation is dependent on the tuning factors for both accumulation and ablation. The result was compared with the change of the surface height by Saito et al (2014). The air temperature at the Thule was increasing after 1990, and this is one of the reasons that mass balance of Hurlbut ice cap was negative.

IACS (Cryosphere)

C04p - C04 Modelling of Mountain Glaciers, Past and Future

C04p-295

Thresholds for growth and decay of Hans Tausen Iskappe (Greenland)

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Hans Tausen Iskappe (Greenland), situated at 82.5°N, 27.5°W, is the world's northernmost ice cap. During several field campaigns in the 70s and 90s, its ice thickness was measured, mass balance and meteorological measurements were made, and a 345 m deep ice core was drilled. From this ice core it is known that the ice cap (largely) disappeared during the Holocene Thermal Maximum. The present-day ice cap started building up some 3500-4000 years ago in a wetter and slightly warmer climate than at present.

Here we present first 3-D thermo-mechanical ice flow modelling results of the ice cap's fundamental climate sensitivity. We use field measurements and combine these with satellite derived surface velocities and palaeoclimatic reconstructions to understand thresholds for growth and decay during the Holocene. In our analysis we also investigate the effect of higher-order dynamics (compared to the Shallow Ice Approximation) and pay particular attention to what these thresholds in the system could entail for (partial) decay of the ice cap in the future.

IACS (Cryosphere)

C05a - C05 Impacts of Dust and Black Carbon on Snow and Glaciers

IUGG-0914

The recent darkening of the Greenland Ice Sheet from space and modelling

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The surface energy and mass balance of the Greenland Ice Sheet largely depends on the albedo of snow. The Greenland ice sheet albedo has declined over the past decade and this decrease has been attributed to enhanced snow metamorphism. However, satellite data from the multispectral sensors MODIS and MERIS revealed that the albedo at high elevation (i.e. accumulation area) in springtime has significantly dropped between 2008 and 2009 and lower albedo have persisted since then compared to the previous decade. This abrupt change in springtime is unexplained. Using spectral analysis and a snow model, our study shows that this decrease can be explained by an increase in light-absorbing impurity content in snow. Remote-sensing results are compared to recent in-situ measurements of snow impurity content. The impact of the albedo decrease on Greenland Ice Sheet mass balance is estimated using a detailed snow model.

IACS (Cryosphere)

C05a - C05 Impacts of Dust and Black Carbon on Snow and Glaciers

IUGG-1066

Glacier mass balance modelling: Improvements using imaging spectroscopy derived ice surface material composition and spectral albedo

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Glaciers are neither clean nor homogeneous. In fact, they represent diverse surfaces with different materials and structures. Although organisms living on ice surfaces, in-situ sampling of cryoconite and the use of local automatic weather stations to observe glacier surface albedo have received considerable interest, there is still only little known about the presence and distribution of light absorbing impurities on glacier surfaces and their impact on albedo and, hence, mass balance.

In this study, we apply an approach combining airborne and in-situ observations together with numerical models to characterize glacier surfaces, in particular the distribution of ice surface materials and their influence on glacier mass balance. The APEX (Airborne Prism EXperiment) image spectrometer was used to acquire spatial and spectral high resolution radiation measurements over Glacier de la Plaine Morte and Findelengletscher in the Swiss Alps. In-situ radiation measurements were acquired with an ASD field spectrometer. Further, data of seasonal glacier mass balance over the last five years is available to calibrate a distributed model for calculating glacier-wide surface mass balance.

We present results of surface classification including estimated abundances of different materials and derive spectral albedo maps representing the spatial variability in ice surface albedo. Furthermore, we demonstrate the added value of using actual ice surface albedo information for reproducing observed melt rates, by implementing such data products into a distributed mass balance model.
Our results contribute to a better understanding of the spatial distribution of glacier melt, which is important to improve models to study future glacier evolution.

IACS (Cryosphere)

C05a - C05 Impacts of Dust and Black Carbon on Snow and Glaciers

IUGG-1238

Long range transport of dust and soot from Indo-Gangetic Plains and their impacts on Himalayan snow and glaciers

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The Indo-Gangetic plain (IGP) is a valley in the northern part of India, home of 900 million people. The valley is surrounded by the towering Himalaya in the northern side of the IGP. The valley suffers with long range transport of dusts and anthropogenic emissions. The dusts are prevalent during pre-monsoon season and during winter months (December – January) anthropogenic emissions are high in the IGP and during October-November the greenhouse emissions due to crop residue burning in the western parts are transported to the eastern parts of the IGP. Depending upon the meteorological conditions (air temperature, relative humidity, water vapor) and wind speed and wind direction, the greenhouse emissions reaches towards the foothills of the Himalaya and also the anthropogenic emissions of the IGP and long range transport of dust depending upon the favorable meteorological conditions above 500 hPa the Himalayan snow/glaciers covered by the dust and soot in different seasons. The air mass reaching to the Himalaya even further cross over the towering Himalayan region which is clearly seen from the back trajectories of the air mass which are also clearly seen from the multi sensor images/data. The dust and soot particles both are the cause for melting of snow/glaciers in the Himalayan region. Detailed observations over the years are needed to quantify the role of dust and soot in melting of snow/glaciers in the Himalayan region.

IACS (Cryosphere)

C05a - C05 Impacts of Dust and Black Carbon on Snow and Glaciers

IUGG-2302

Light absorbing snow impurity concentrations measured at Sapporo, Japan during the 2007–2013 winters

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The mass concentrations of elemental carbon (EC) and organic carbon (OC) and dust in snowpack at Sapporo, Japan, were measured during six winters from 2007 to 2013. EC and OC concentrations were measured with the thermal optical method, and dust concentration was determined by filter gravimetric measurement. Adding $NH_4H_2PO_4$ coagulant to melted snow samples improved the collection efficiency for EC particles by a factor of 1.45, meaning that the collection efficiency (69%) of a quartz fiber filter without the coagulant is higher than that reported in the previous study (< 38%). The mass concentrations of EC, OC, and dust in the top 2-cm layer ranged in 0.007–2.8, 0.01–13, and 0.14–260 ppmw, respectively, during the six winters. The mass concentrations and their short-term variations were larger in the surface than in the subsurface. The snow impurity concentrations varied seasonally, that is, they remained relatively low during the accumulation season and gradually increased during the melting season. Although the surface snow impurities showed no discernible trend over the six winters, they varied from year to year, with a negative correlation between the snow impurity concentrations and the amount of snowfall. The surface snow impurities generally increased with the number of days elapsed since snowfall and showed a different rate for EC (1.44), OC (9.96), and dust (6.81). The possible processes causing an increase in surface snow impurities were dry deposition of atmospheric aerosols, melting of surface snow, and sublimation/evaporation of surface snow.

IACS (Cryosphere)

C05a - C05 Impacts of Dust and Black Carbon on Snow and Glaciers

IUGG-2328

Multi isotope approach to dynamics of impurities in snow and ice on the Greenland Ice Sheet

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Supraglacial impurities are one of the most significant factors to determine surface albedo and have been reported to affect substantial melting of glacier ice and snow. They usually consist of inorganic and organic material accreted on the ice surface by wet precipitation or Aeolian deposition. Microbes and organic matter are also dominant biotic constituents of impurities. Microbes and their derivative organic matter often aggregate with mineral particles and form spherical granules called cryoconite. Cryoconite and some pigmented algae usually display a higher light absorbency compared with pure snow and ice, thus they can efficiently reduce surface albedo. However, these changes are currently unconstrained because we have still only limited information of impurities, in particular, biological impurities. Stable isotopes of various elements in impurities could provide a means to determine sources and redistribution process of each constituent. We report multi stable isotopes in soluble and insoluble impurities in supraglacial ice (87/86Sr and 143/144Nd for mineral fraction; 13C and 15N for organic faction; 18O and 15N for nitrate) collected in the north- and mid-west Greenland Ice Sheet. Sr and Nd isotopes of the impurities varied geographically, suggesting that mineral dust is derived locally. C and N isotopes of organic fraction varied among elevations, suggesting a range of microbial production and nutrient conditions on the surfaces. O and N isotopes of nitrate showed that it is mostly supplied from atmosphere derived from both natural and anthropogenic origins. Results suggest that abundance of impurities on Greenland Ice Sheet are mostly determined by supply of local mineral dust and microbial photosynthetic production controlled by nutrients.

IACS (Cryosphere)

C05a - C05 Impacts of Dust and Black Carbon on Snow and Glaciers

IUGG-5355

Mineral dust and spectral reflectance of snow and glacier ice in the Caucasus and northern Tien Shan

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Field measurements of spectral reflectance were conducted on Djankuat glacier (Caucasus Mountains) and Tuyuksu glacier (northern Tien Shan) in the summer of 2013. Samples of snow containing light absorbing impurities, such as cryoconite and mineral dust, and samples of surface glacier debris were collected. The abundance of organic material was determined by weighing samples before and after combustion. Geochemical and mineral composition of the samples was determined by X-ray diffraction ad X-ray fluosrescence analyses. Mineral dust of desert origin was present on both glaciers and identified through mineral composition of samples that was significantly different from the local debris material and contained kaolinite and palygorskite associated with material of desert origin. Spectral reflectance of snow containing desert dust was 20-30% lower than spectral reflectance of aged snow that did not contain dust and cryoconite.

IACS (Cryosphere)

C05p - C05 Impacts of Dust and Black Carbon on Snow and Glaciers

C05p-086

Characteristics of dust deposition at high elevation sites recorded in shallow ice cores, Mt. Elbrus and Mt. Kazbek, Caucasus, Russia

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In the snow-covered and glaciated regions, mineral dust changes reflectance of the surface and melt rates. The nature and extent of both radiative and geochemical impacts of mineral dust on snow pack and glaciers depend on physical and chemical properties of dust and its deposition rates. These, in turn, are a function of dust concentrations, size distribution, meteorological conditions, topography and surface characteristics and are highly variable at local and regional scales. One glaciated region experiencing influx of mineral dust from the Sahara and deserts of the Middle East is the Caucasus Mountains. Our previous studies evaluated climatology of dust deposition events, the source regions and transportation routes and revealed strong seasonality in dust deposition events. Here we present a study of two shallow ice cores obtained at Mt Elbrus in 2013 (drilling site elevation 5115 m asl) and at Mt. Kazbek in 2014 (4500 m asl) located in the central sector of the Greater Caucasus. Samples were analysed for chemistry, concentrations of dust and black carbon, and particle size distributions. Individual dust particles from the Kazbek core samples were analysed using SEM. Both cores were analysed using the same methodology and sampling protocol which allowed to compare two sites and to evaluate regional characteristics of dust deposition. Annual dust flux in the Caucasus Mountains was estimated as ~300 $\mu g/cm^2\ a^{-1}$. In was shown that particle size distribution depends on individual characteristics of dust deposition event and also on the elevation of the drilling site. The contribution of desert dust deposition was estimated as 35-40 % of the total dust flux in 2007-2014 period with the highest share in 2008 when desert dust deposition accounted for 55%.

IACS (Cryosphere)

C05p - C05 Impacts of Dust and Black Carbon on Snow and Glaciers

C05p-087

Not only on the snow. The impact of debris and black carbon depositions on glacier ice as well

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In this work we show the results of a pilot study we performed to detect and quantify fine debris coverage at the melting surface of an Alpine debris-free glacier to evaluate its seasonal variability and its influence on ice albedo. Despite the abundant literature dealing with dust and black carbon deposition on glacier accumulation areas only a few studies on the distribution and properties of fine debris in the ablation areas are available. Furthermore, guidelines are needed to standardize field samplings and lab analyses thus permitting comparisons among different glaciers. We proposed a novel integrated method to describe fine debris occurring at the surface of a debris-free glacier and we found a linear relation between the surface covered by debris and the natural logarithm of ice albedo. An innovative approach based on the semi-automatic analysis of high-resolution images (describing sample areas with a size of 1m x 1m) was developed in order to quantify the surface area covered by debris. The procedure was tested on the Forni Glacier (Italian Alps). Debris analyses generally indicate a local origin of debris and dust with a locally high organic content. Nevertheless, the finding of some cenospheres also suggests an anthropic contribution. In addition, for a more exhaustive albedo analysis the effect of the water (originating from both ablation and liquid precipitation) was considered as well. In particular, we observed that the rainfall has a non-negligible effect on ice: in almost all events we analyzed the mean daily albedo is found increasing slightly higher than 20% after the rain occurrence. However, the incidence of the washing out effect and the consequent reflectivity increase is found to be short lasting (ranging from 1 to 4 days).

IACS (Cryosphere)

C05p - C05 Impacts of Dust and Black Carbon on Snow and Glaciers

C05p-088

Evaluation of MODIS albedo product over Vatnajökull and Langjökull ice caps (Iceland) and impact of volcanic eruptions on albedo

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Albedo is a key variable in the glacier mass balance because it defines the amount of solar radiation absorbed by the glacier surface. It depends on various factors including the content of impurities in the surface layer. Information about seasonal and inter-annual evolution of albedo is important for improvement of glacier surface energy balance models embedded in climate models. Over large glaciers and ice caps, mid-resolution satellite remote sensing enables to monitor the albedo with a reasonable frequency. Here we present an evaluation of the MODIS (Aqua/Terra combined) broadband shortwave albedo product MCD43A over Vatnajökull and Langjökull ice caps in Iceland. We compared these data with in situ daily albedo data from five automatic weather stations located on both ice caps during the period 2009-2012. The results show a good agreement between both datasets, with Pearson's correlation coefficients higher than 0.85 at three AWS for which there are enough comparison data (N>40). The biases are also low and range from 0.033 to less than 0.001. There is remarkable large variability in the albedo on Icelandic glaciers due to the mixing of fresh snow with dark tephra layers. We further quantify the impact of tephra deposition on the glacier albedo following the eruption of Eyjafjallajökull in April 2010 and Grímsvötn in May 2011. We show a widespread albedo drop of 0.4 over all Icelandic ice caps following these eruptions.

IACS (Cryosphere)

C05p - C05 Impacts of Dust and Black Carbon on Snow and Glaciers

C05p-089

Spatial and temporal patterns of albedo changes on Icelandic ice caps as a result of the 2010 Eyjafjallajökull volcanic eruption

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The energy balance at a glacier surface is the major driving factor of ablation and thus for mass balance. In many parts of the world, solar radiation provides the most substantial part of the energy gain at the glacier surface. Albedo is thus a key factor controlling the amount of available melt energy. Explosive volcanic eruptions are able to cover vast areas with fine grained ash deposits. These deposits have the potential to considerably reduce the albedo of glacier surfaces and to substantially alter energy and mass balance.

In April 2010 the eruption of the Eyjafjallajökull volcano spread ash deposits over large parts of two major ice caps, Myrdalsjökull and Vatnajökull, in southeast Iceland. The MODIS sensors onboard the Terra and Aqua satellites provide observations of snow and ice albedo at daily resolution. In this study we use these data to analyse changes in the surface albedo of Myrdalsjökull and Vatnajökull that occurred as a result of the deposition of the ashes from the Eyjafjallajökull eruption.

A geostatistical approach is employed to identify areas of statistically significant albedo decreases and to track the evolution of these areas over time. We find that the ash-induced albedo changes occur most widely in the year of the eruption. Throughout the accumulation areas no changes were evident anymore after the first winter season while throughout the ablation areas the decrease of albedo is traceable until four years after the eruption.

IACS (Cryosphere)

C05p - C05 Impacts of Dust and Black Carbon on Snow and Glaciers

C05p-090

Snow cover sensitivity to black carbon deposition in the Himalayas: From atmospheric and ice core measurements to regional climate simulations

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We applied a climate-chemistry global model to evaluate the impact of black carbon (BC) deposition on the Himalayan snow cover from 1998 to 2008. Using a stretched grid with a resolution of 50 km over this complex topography, the model reproduces reasonably well the remotely sensed observations of the snow cover duration. Similar to observations, modelled atmospheric BC concentrations in the central Himalayas reach a minimum during the monsoon and a maximum during the post- and pre-monsoon periods. Comparing the simulated BC is more challenging because of their high spatial variability and complex vertical distribution. We simulated spring BC concentrations in surface snow varying from tens to hundreds of μg kg^{-1}, higher by one to two orders of magnitude than those observed in ice cores extracted from central Himalayan glaciers at high elevations (> 6000 m a.s.l.), but typical for seasonal snow cover sampled in middle elevation regions (< 6000 m a.s.l.). In these areas, we estimate that both wet and dry BC depositions affect the Himalayan snow cover reducing its annual duration by 1 to 8 days. In our simulations, the effect of anthropogenic BC deposition on snow is quite low over the Tibetan Plateau because this area is only sparsely snow covered. However, the impact becomes larger along the entire Hindu-Kush, Karakorum and Himalayan mountain ranges. In these regions, BC in snow induces an increase of the net short-wave radiation at the surface with an annual mean of 1 to 3 Wm^{-2} leading to a localised warming between 0.05 and 0.3°C.

IACS (Cryosphere)

C05p - C05 Impacts of Dust and Black Carbon on Snow and Glaciers

C05p-091

Scanning electron microscopy (SEM) analysis of black carbon in Arctic snow

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Snow and ice in the Arctic contain various atmospheric aerosols, such as black carbon and mineral dust. These light-absorbing impurities can reduce surface albedo and affect melting of seasonal snow cover and glaciers. Thus, it is important to understand optical characteristics of the impurities in snow deposited in the Arctic. In this study, we analyzed structure and surface chemistry of black carbon in snow collected from Greenland and other Arctic sites as well as that from Sapporo (Japan) with a Scanning Electron Microscope (SEM, QUANTA FEG 450) equipped with an Energy Dispersive X-ray Spectrometer (EDS).

Microscopic observation revealed that snow samples from Greenland, Alaska, and Sapporo contained black carbon particles with chain-like structures and compact aggregate structures as shown in a previous study. However, the proportion of these black carbon structures were different among the samples. For example, snow from Greenland showed higher abundance of chain-like particles, while that from Alaska showed higher number of compact particles coated by membrane like material. These results indicate that the differences in the structure of the black carbon particles between the samples likely reflect their origins.

IACS (Cryosphere)

C05p - C05 Impacts of Dust and Black Carbon on Snow and Glaciers

C05p-092

Impact of BC and dust on the seasonal snowpack of the high altitude regions of the Himalayas

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Small amounts of black carbon (BC) in snow have a strong impact on snow albedo, melting, and local climate. To study this effect we implemented a radiative transfer scheme into the snowpack model Crocus. This new version is capable of simulating the effect of absorbing impurities like BC and dust on the albedo of and the transfer of radiation inside the snow. We applied this new model version to conditions encountered at the Nepal Climate Observatory-Pyramid GAW station located in the upper Khumbu valley during the three winter seasons from 2004 to 2007. The simulations were performed with a variety of BC and dust concentrations corresponding to previously observed concentrations in snow and ice cores from the Himalayas. For example, the addition of 100 ppb BC reduced the average snow albedo by around 0.03 compared to the albedo of pure snow causing an earlier melting of the snow between 3 and 10 days. As a result, an annual local radiative forcing between 3 and 4.5 W m^{-2} was obtained mainly caused by the earlier melting of the snow. Similar trends were also found in the presence of dust or the combination of dust and BC. The results indicate that the sensitivity for the albedo regarding the addition of BC is highest for pure snow, while the sensitivity for the melting accelerates in the presence of absorbers. This accelerated melting is caused by a faster metamorphism during the entire winter season leading to increased snow grain sizes. The cumulative effect of absorbing material has important implications since a reduction of BC in the snow would have more pronounced positive impact on the local radiative forcing if large amounts of other absorbers are present making a reduction of BC in the snow an even more important target for local climate mitigation strategies.

IACS (Cryosphere)

C05p - C05 Impacts of Dust and Black Carbon on Snow and Glaciers

C05p-093

Quantification of impacts of black carbon on snow via bidirectional reflectance measurements

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In order to quantify the effects of absorbing material on snow and define its contribution to climate change, we have conducted a series of dedicated bidirectional reflectance measurements. Chimney soot, volcanic sand, and glaciogenic silt were deposited on snow in a controlled way. The bidirectional reflectance factors of these targets and untouched snow have been measured using the Finnish Geodetic Institute's field goniospectrometer FIGIFIGO. It has been found that the contaminants darken the snow, and modify its appearance mostly as expected, with a clear directional signal and a modest spectral signal. A remarkable feature is the fact that any absorbing contaminant on snow enhances the metamorphosis under strong sunlight. Immediately after deposition, the contaminated snow surface appears darker than the pure snow in all viewing directions, but the heated soot particles sink down into the snow within minutes. When the snow melt rate gets faster than the diffusion rate (under condition of warm outside temperatures), as was observed at the end of the experiment reported here, dark material starts accumulating into the surface. Thus BC deposited on snow at warm temperatures initiates rapid melting and may cause dramatic changes on the snow surface. The nadir measurement remains darkest, but at larger zenith angles the surface of the soot-contaminated snow changes back to almost as white as clean snow. Thus, for an observer on the ground, the darkening by impurities can be completely invisible, overestimating the albedo, but a nadir looking satellite sees the darkest points, now underestimating the albedo.

IACS (Cryosphere)

C05p - C05 Impacts of Dust and Black Carbon on Snow and Glaciers

C05p-094

Optical properties and climate forcing of Icelandic dust

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Iceland is an active source of dust originating from glaciogenic and volcanic sediments. The frequency of days with dust suspension exceeded 34 dust days annually in 1949-2011. This figure represents a minimum value as many dust storms occur without the dust passing the weather stations recording the events. Comparison of meteorological synoptic codes for dust observation and direct particulate matter mass concentration measurements in 2005-2013 showed that the mean number of dust days in Iceland can increase up to 135 dust days annually. Dust events in NE Iceland occur mostly in May-September, while almost half of all dust events in SW Iceland were at sub-zero temperatures or in winter.
Icelandic dust is different from the crustal dust; it is of volcanic origin and dark in colour. It contains sharp-tipped shards and is often with bubbles. Such physical properties allow large particle suspension and transport to long distances, e.g. towards the Arctic. To estimate the further impacts of dust transport, both laboratory and field measurements were done using the Finnish Geodetic Institute Field Goniospectrometer FIGIFIGO. The albedo, bidirectional reflectance factor and other snow properties were monitored on the clean snow and areas affected by the dust deposition through the following melting period. This experiment showed that the Icelandic dust may both directly and indirectly act as a positive climate forcing agent. We suggest that Icelandic dust may be a contributor to the Arctic warming.

IACS (Cryosphere)

C06a - C06 Ice Sheet and Ocean Interactions on Multiple Scales

IUGG-0764

Modeling Greenland ice sheet present-day and near-future runoff contribution

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The last IPCC report [AR5, IPCC] has shown an increasing contribution from Greenland melting to global sea-level over the last decade, increasing from 0.09 mm/year (period 1992-2001) to 0.59 mm/year (period 2002-2011). Given its strategic location, i.e. close to the main North Atlantic ocean convection sites, it is therefore of importance to better assess ice sheet melting and its impact on regional ocean processes. So far, runoff estimate from ice sheet has been poorly constrained (e.g. [Hanna et al., 2005], [Hanna et al., 2008]) and most of the time the few estimates comes from regional atmospheric models or general circulation models (e.g. [Edwards et al., 2013], [Fettweis et al., 2013]).
Here, we present the results from the implementation of a routing scheme, which is based on the ``multiple flow direction" method developed by [Quinn et al., 1991], into the 3D thermo-mechanical ice sheet-ice shelves model GRISLI [Ritz et al, 2001]. This model is applied to the Greenland ice sheet mass evolution over the 20th and 21st centuries, with a 5km horizontal resolution. The future projections are based on two representative concentration pathways (RCP) scenarios: RCP 8.5 and RCP 4.5 [Moss et al., 2010]. GRISLI is forced by using a set of seven simulated air surface temperature and precipitation fields from CMIP5 atmosphere-ocean coupled general circulation models (AOGCM).
The ablation scheme gives us an estimate of the meltwater in Greenland, while the routing scheme allow us to obtain an estimate of the total amount of freshwater reaching the Greenland coasts and its spatial distribution. This runoff distribution will be used as forcing in an ocean model to evaluate the ocean response to this freshwater input and to its spatial distribution.

IACS (Cryosphere)

C06a - C06 Ice Sheet and Ocean Interactions on Multiple Scales

IUGG-2496

A simple parameterisation of ice shelf basal melting and its implementation in the ice sheet model SICOPOLIS

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Ice shelf basal melting, and its change with time, plays a crucial role for the past and future evolution of the Antarctic ice sheet and its contribution to global sea level. Since integrating coupled ocean and ice sheet models for long time periods at high resolution is hard to achieve within a reasonable amount of time using present-day computers, long-term simulations of the Antarctic ice sheet require that ice shelf basal melting is parameterised. Here we describe a simple, physically-based parameterisation that calculates the basal melting of ice shelves as a function of both the depth of ice below mean sea level and far-field ocean temperatures. The parameterisation is tuned differently for eight Antarctic sectors in order to achieve reasonable agreement with the modern spatial distribution of ice shelf basal melting. It is then implemented in the Antarctica module of the dynamic/thermodynamic, large-scale ice sheet model SICOPOLIS (www.sicopolis.net). We discuss several future climate runs over the next centuries in order to explore the sensitivity to various forcings. The model will help provide new insight into estimating both past and future contributions of the ice sheet to both sea level rise and the heat budgets of the ocean.

IACS (Cryosphere)

C06a - C06 Ice Sheet and Ocean Interactions on Multiple Scales

IUGG-2864

Coupled ice sheet-ocean simulations with the POPSICLES model

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We present idealized and realistic simulations using the POPSICLES coupled ice sheet-ocean model. POPSICLES couples the POP2x ocean model—a modified version of the Parallel Ocean Program (Smith and Gent, 2002)—and the BISICLES ice-sheet model (Cornford et al., 2012). POP2x includes sub-ice-shelf circulation using partial top cells (Losch, 2008) and boundary layer physics following Holland and Jenkins (1999) and others. BISICLES makes use of adaptive mesh refinement and a momentum balance similar to the L1L2 model of Schoof and Hindmarsh (2009) to accurately model regions of dynamic complexity, such as ice streams, outlet glaciers, and grounding lines.

We show that POPSICLES produces similar results to Goldberg et al. (2012a,b) in an idealized setup comparable to Pine Island Glacier/Ice Shelf. We present results from a new set of idealized, coupled experiments, the Marine Ice Sheet-Ocean Model Intercomparison Project (MISOMIP). We propose the MISOMIP experiments, together with their standalone ocean (ISOMIP+) and ice-sheet (MISMIP+) companions as standard test cases for coupled ice sheet-ocean models.

In a realistic configuration, our POPSICLES simulations cover the full Antarctic Ice Sheet and the Southern Ocean and span the period 1990 to 2010. Simulations are performed at 0.1 deg. (~5 km) ocean resolution and with adaptive ice-sheet model resolution as fine as 500 m. We explore the influence on basal melting and system dynamics resulting from two different choices of climate forcing: a mean climatology and the interannually varying CORE v. 2 forcing data (Large and Yeager 2008). We also point out the influence of uncertainties in ice shelf cavity

thickness (due to a lack of observations of sub-ice-shelf bathymetry) on melt rates and grounding-line dynamics.

IACS (Cryosphere)

C06a - C06 Ice Sheet and Ocean Interactions on Multiple Scales

IUGG-3335

East Antarctic deglaciation and the link to global cooling during the Quaternary: Evidence from geomorphology of the Sør Rondane Mountains

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While it is broadly accepted that the Antarctic ice sheets play a major role in the Earth's global climatic system, many questions remain due to the multitude of processes and timescales involved. Reconstructing past variability of the Antarctic ice sheets is essential to understand their stability and to anticipate their contribution to sea level change as a result of future climate change in a high-CO_2 world. Recent studies have reported a significant decrease in thickness of the East Antarctic Ice Sheet (EAIS) during the last several million years. However, the geographical extent of this decrease and subsequent isostatic rebound remain uncertain and a topic of debate. In this study, we reconstruct magnitude and timing of ice sheet retreat at central part of the Sør Rondane Mountains in Dronning Maud Land, East Antarctica, based on detailed geomorphological survey, cosmogenic exposure dating, and glacial isostatic adjustment modeling. Three distinct deglaciation phases during the Quaternary for this sector of the EAIS are identified, based on rock weathering and ^{10}Be surface exposure data. We estimate that during the Plio-Pleistocene the ice sheet thinned by at least 500 m. This thinning is attributed to the reorganization of Southern Ocean circulation associated with the global cooling into the Pleistocene, which reduced the transport of moisture from the Southern Ocean to the interior of EAIS. The data also show that since the Last Glacial Maximum the ice surface has lowered less than ca.50 m and probably started after ca. 14 ka. This suggests that the EAIS in Dronning Maud Land is unlikely to have been a major contributor to postglacial sea-level rise and Meltwater pulse 1A.

IACS (Cryosphere)

C06a - C06 Ice Sheet and Ocean Interactions on Multiple Scales

IUGG-3698

Modeling ice front Dynamics of Greenland outlet glaciers using ISSM

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The recent increase in the rate of mass loss from the Greenland Ice Sheet is primarily due to the acceleration and thinning of outlet glaciers along the coast. This acceleration is a dynamic response to the retreat of calving fronts, which leads to a loss in resistive stresses. These processes need to be included in ice sheet models in order to be able to accurately reproduce current trends in mass loss, and in the long term reduce the uncertainty in the contribution of ice sheets to sea level rise. Today, the vast majority of ice sheet models that include moving boundaries are flow line and flow band models, that are not adapted for complex geometry of Greenland outlet glaciers, as they do not accurately capture changes in lateral stresses. Here, we use the levelset method to track moving boundaries within a 2D plane view model of the Ice Sheet System Model (ISSM), and investigate the sensitivity of Greenland outlet glaciers to increase in ocean induced melting at the calving front. We rely on a new simplified calving law adapted from von Mises yield criterion. We show that bed topography is one of the main controls on ice front retreats and new bed topography maps based on mass conservation make it possible to model more accurately the behavior of Greenland outlet glaciers compared to other mapping techniques.

IACS (Cryosphere)

C06a - C06 Ice Sheet and Ocean Interactions on Multiple Scales

IUGG-3952

Ice sheet model intercomparison project for CMIP6

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We present the framework for a new effort, ISMIP6, the Ice Sheet Model Intercomparison Project for CMIP6. The primary goal of ISMIP6 is to improve projections of sea level rise via improved projections of the evolution of the Greenland and Antarctic ice sheets under a changing climate, along with a quantification of associated uncertainties (including uncertainty in both climate forcing and ice-sheet response). This goal requires an evaluation of AOGCM climate over and surrounding the ice sheets; analysis of simulated ice-sheet response from standalone models forced “offline” with CMIP AOGCM outputs and, where possible, with coupled ice sheet-AOGCM models; and experiments with standalone ice sheet models targeted at exploring the uncertainty associated with ice sheets physics, dynamics and numerical implementation. A secondary goal is to investigate the role of feedbacks between ice sheets and climate in order to gain insight into the impact of increased mass loss from the ice sheets on regional and global sea level, and of the implied ocean freshening on the coupled ocean-atmosphere circulation. These goals map into both Cryosphere and Sea-Level Rise Grand Challenges relevant to Climate and Cryosphere (CliC) and the World Climate Research Program (WCRP).

IACS (Cryosphere)

C06p - C06 Ice Sheet and Ocean Interactions on Multiple Scales

C06p-184

Parametrization of melting along the calving face of Jacobshavn Glacier, Greenland.

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Ocean models at climate resolution O(1-10 km) are not able to compute the melt rate driven by subglacial discharge along the calving face of a tidewater glacier such as Jacobshavn Glacier. The reasons are simple: the processes along the calving face need a very high horizontal resolution O(1-10m) to be explicitly simulated, and subglacial discharge is neglected.

However, this deep input of freshwater has two major consequences. The first one is that the waters confined within the overdeepened basin of a fjord can be renewed in summer by a vigorous overturning circulation driven by the subglacial discharge and the glacier terminus melting. The second one is that the elevated melt rates may contribute to glacier recession in Greenland.

In order to incorporate these processes in a relatively coarse-resolution ocean model (~ 5 km), we implement a parameterisation based on the theory of buoyant plumes in unstratified environments. Although Greenlandic fjords are far from unstratified, their structure is more accurately approximated using two or three well-mixed layers separated by sharp interfaces than by a constant linear stratification. In an unstratified environment there are two length scales that govern plume behaviour: one based on the ratio of the initial input of buoyancy to the buoyancy input by melting; the other based on the change in the freezing point with depth. Suitable nondimensionalisation of the plume equations using these length scales allows the melt rate to be approximated by polynomial functions. The melt rates computed by these parametrizations and the subglacial runoff are included in an ocean model. As a proof of concept, this method is implemented and validated in an idealized fjord configuration at coupled climate model resolution (~ 5 km).

IACS (Cryosphere)

C06p - C06 Ice Sheet and Ocean Interactions on Multiple Scales

C06p-185

Effect of tides and eddies on Ross Ice Shelf basal melt from a regional ocean model

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Understanding the processes that affect ice shelf basal melt is key in predicting the future of ice shelves and the Antarctic Ice Sheet. We use a regional ocean model (ROMS) to investigate the effect of smaller scale processes on basal melt and the fate of Ice Shelf Water (ISW), a precursor to the Ross Sea version of Antarctic Bottom Water (AABW). Using simulations with and without tidal forcing at eddy permitting and eddy resolving horizontal resolutions, we find that tides, rather than eddies, have an effect on ice shelf-ocean interactions in the Ross Sea. We see an ~10% increase in ice shelf basal melt in simulations with tidal forcing, and the same increase in the amount of ISW that is exported across the ice shelf front. The time series of basal melt shows a strong seasonal cycle with a significant contribution from the fortnightly spring-neap tidal cycle. Spatially, the largest absolute changes in basal melt between simulations with and without tidal forcing occur near the ice shelf front, while the largest relative changes occur on the eastern side of the ice shelf near the grounding line. Despite recent emphasis on the necessity of eddy resolving models for Antarctic continental shelves and some evidence in our model that eddies can cross the ice shelf front, we find the contribution from mesoscale eddies is negligible under the Ross Ice Shelf.

IACS (Cryosphere)

C06p - C06 Ice Sheet and Ocean Interactions on Multiple Scales

C06p-186

Response of the cryosphere to ocean warming below Filchner Ronne Ice Shelf

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Simulations of ice shelf - ocean interaction for several IPCC future climate change scenarios have revealed the potential of a rapidly increasing basal mass loss for the Filchner-Ronner Ice Shelf (FRIS) in the Weddell Sea. This sensitivity has been found to be consistent between two independent sea ice - ice shelf - ocean models forced with identical atmospheric data sets. However, both models assume a steady-state ice shelf geometry. To study ice-ocean interaction in a more consistent way, the ice flow model RIMBAY has been configured in a model domain that comprises the FRIS and the grounded ice in the relevant catchment area up to the ice divides. At the base of the model ice shelf, melt rates from the finite-element sea ice – ice shelf – ocean model FESOM are prescribed. For present-day conditions with ice shelf basal melting obtained from a 20th-century simulation with FESOM, the ice model yields a quasi-steady state with an ice shelf geometry and grounding line location very close to the presently observed configuration. With FESOM's increasing melt rates modelled for future climate warming scenarios, the ice model predicts an accelerated grounding line retreat between the Möller and Institute Ice Streams. Simulated discharge of (formerly) grounded ice is converted to an estimated contribution to global sea level rise. The sub-ice shelf cavity geometry in FESOM is adjusted according to the ice thickness evolution in RIMBAY to investigate the effect of a dynamically varying ice shelf topography on simulated basal melt rates. A two-way coupling between the two models will be conducted as a natural next step.

IACS (Cryosphere)

C06p - C06 Ice Sheet and Ocean Interactions on Multiple Scales

C06p-187

Paleoenvironments analysis based on marine microfossils, admiralty bay, King George island, antarctica maritime

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This work aims to analyze the paleoenvironment features in marine sediments cores sampled during the Operantar XXXII (2013/2014 summer season) in Admiralty Bay, King George Island, Antarctica Maritime: ALM-P12 (62º 16.0778’ N, 58º 15.9022’ W, 720 m depht), ALM-P13 (62º 11.4’ N, 58º 22.2’ W, 520 m depth) and ALM-P14 (62º 07.7016’ N, 58º 25.8337’ W, 420 m depth). Sediment and submarine features show evidence for extensive glaciation in Admiralty Bay, with rapid retreat events and re-advances of the glaciers. Standard methods of calcareous microfossils extraction was applied to the analysis: (a) wet weight of the sample; (b) sediment dried at 60°C and subsequent weighed; (c) separated sediment of 20gr dried weighted; (d) sediment washed with fresh water over a 63-µm mesh sieve and subsequent dried at 60°C; (e) separation of sediments into different size fractions (125, 250 and 500 microns); (f) observation under stereoscopic microscope for extraction of microfossils in the fractions > 63,> 125,> 250 and> 500 microns. After that, the sediments are examined under a compound microscope, in order to identify the microfossils present in the fractions. The microfossils are separated for identification according to their taxon. Once the foraminifera is identified (planktonic and/or benthic), it is classified according to specific references. According to initial results it has been possible to verify the presence of calcareous and agglutinated foraminifera at different levels, and other microfossils such as diatoms, radiolarians and sponge spicules, which indicate a biologically rich environment. The quantification and classification of microfossils (in progress) can yield a better characterization of the environment and climate changes occurred in the study area.

IACS (Cryosphere)

C07a - C07 Understanding Linkages between Different "Elements" of the High-Latitude Cryosphere

IUGG-1053

Arctic lake ice in a changing climate: radar remote-sensing and numerical modelling data analysis

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Air temperature and winter precipitation changes over the last five decades have impacted the timing, duration, and thickness of the ice cover on Arctic lakes. For shallow tundra lakes, many of which are less than 3-m deep, warmer climate conditions could result in thinner ice covers and consequently, in a smaller fraction of lakes freezing to their bed in winter. The analysis of a 20-year time series of European remote sensing satellite ERS-1/2 synthetic aperture radar (SAR) data and a numerical lake ice model were employed to determine the response of ice cover on shallow lakes of the North Slope of Alaska (NSA) to recent climate conditions. Given the large area covered by these lakes, changes in the regional climate and weather are related to regime shifts in the ice cover of the lakes. Analysis of available SAR data from 1991 to 2011, from a sub-region of the NSA near Barrow, shows a reduction in the fraction of lakes that freeze to the bed in late winter. This finding is in good agreement with the decrease in ice thickness simulated with the Canadian Lake Ice Model (CLIMo), a lower fraction of lakes frozen to the bed corresponding to a thinner ice cover. Observed changes of the ice cover show a trend toward increasing floating ice fractions from 1991 to 2011, with the greatest change occurring in April, when the grounded ice fraction declined by 22% (α = 0.01). Model results indicate a trend toward thinner ice covers by 18-22 cm (no-snow and 53% snow depth scenarios, α = 0.01) between 1991-2011 and by 21-38 cm (α =0.001) from 1950 to 2011. The longer trend analysis (1950-2011) also shows a decrease in the ice cover duration by ~ 24 days consequent to later freeze-up dates by 5.9 days (α = 0.1) and earlier break-up dates by 17.7-18.6 days (α = 0.001).

IACS (Cryosphere)

C07a - C07 Understanding Linkages between Different "Elements" of the High-Latitude Cryosphere

IUGG-1391

Link between Arctic Sea Ice Loss and Greenland Melt?

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The shrinking sea ice cover is one of the most striking features of Arctic climate change. Since the late 1970s, the ice cover has declined by more than 40% in September, with smaller, yet statistically significant negative trends in other months. The negative trends in sea ice are likely a result of a combination of decadal-scale variability combined with rising temperatures from increases in atmospheric greenhouse gases. At the same time, the Greenland ice sheet has experienced increased summer melt, and an increasingly negative mass balance. While earlier studies suggested that the Greenland mass loss was approximately balanced between ice discharge and ice melt, newer evidence suggests that surface melting is now contributing 84% to the mass loss since 2009. Similar to the sea ice environment, an anthropogenic signal has been identified in the observed changes of the Greenland surface mass balance. Given that both the reductions in the sea ice cover and enhanced melting over the Greenland ice sheet are likely responding to anthropogenic warming it is not surprising that increased melting over Greenland, as defined by melt intensity is inversely correlated to reduced ice loss ($r=-0.83$ from 1979 to 2014). This strong correlation is dominated however by the large trends in both time-series. Detrended data reveal a weaker inverse relationship ($r=-0.30$). Nevertheless, year-to-year variability between September sea ice extent and Greenland melt remains highly correlated ($r=-0.72$), suggesting that atmospheric processes fostering a high Greenland melt year also tend to foster more summer sea ice loss and vice versa. Additionally, both the sea ice extent and ice sheet melt indicate that strong negative year-to-year changes are followed by positive year-to-year changes and vice versa. Given that both the year-to-year September sea ice extent and the Greenland melt intensity changes from exhibit significant negative lag-one autocorrelation (-0.51 and -0.63, respectively) further suggests negative feedbacks prevent self accelerating trends in both fields. Changes in sea ice have strong influences on the Arctic climate through enhanced transfer of heat and moisture between the ocean and atmosphere and have been shown to have an impact on amplified warming in the Arctic. Thus, one may expect that variations in open water fraction around Greenland will impact on the local climate around the ice sheet, and therefore potentially influence the mass balance of the Greenland ice

sheet through the transfer of heat and moisture fluxes to the ice sheet. In fact several studies have found atmospheric warming driven by sea ice loss impacts surrounding areas. Thus is it plausible that changes in the sea ice/open water regime surrounding the ice is capable of modulating Greenland surface melt and precipitation. Here, we investigate relationship between Arctic summer sea ice cover and Greenland surface melting using a combination of remote sensing observations, atmospheric reanalysis geopotential heights, and outputs from a regional climate model for the period. Our results point to a strong covariability between Greenland surface melt and sea ice, particularly in Baffin Bay and much of the Beaufort Sea earlier in the summer. Most of this covariance appears due to simultaneous influence of atmospheric circulation anomalies on both the sea ice and Greenland melt, rather than a local atmospheric response from sea ice retreat. Nevertheless, some regional response may exist within the Baffin Bay region.

IACS (Cryosphere)

C07a - C07 Understanding Linkages between Different “Elements” of the High-Latitude Cryosphere

IUGG-2251

Cryospheric contribution of small lakes in climate models

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The presence of small lakes has a substantial impact on the simulation of winter surface fluxes in climate models. Neglecting the presence of these lakes will necessarily introduce a bias in the simulations, whether the lake coverage is ignored and effectively considered as part of the bare soil fraction of the grid cell (leading to an anomalously early buildup of the snow pack), or the various land cover components are normalized by the sum of the non-lake covers (causing a low wintertime albedo bias). A realistic simulation also depends on a reasonable representation of the formation of winter ice cover and the subsequent snow pack on the surface of the lakes.

Recent work will be presented using a one-dimensional small lake model that has been developed for use as a 'tile' within the Canadian Land Surface Scheme ('CLASS'), the operational land surface model in the Canadian regional and global climate models. The effect of including the lake model, and the surface lake ice and snow models, will be demonstrated over a regional modelling domain covering eastern Canada, where the coverage of lake within model grid cells can exceed 40%. Validation of the simulations against a variety of datasets derived from remote sensing and field-based observations will also be presented.

IACS (Cryosphere)

C07a - C07 Understanding Linkages between Different “Elements” of the High-Latitude Cryosphere

IUGG-3199

Influences of the changing Arctic terrestrial freshwater on Arctic sea ice

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Increases in surface air temperatures in the Arctic have been exceptionally fast over recent decades. The increased temperature resulted in a number of changes in the Arctic terrestrial freshwater system during the period. The representative examples are increases in river discharge, changes in river-ice phonological dates, increases in river water temperature, and etc. However, there are significant knowledge gaps in our understanding for their changes. Therefore, a land surface model (CHANGE), coupling biophysical and biogeochemical processes, was applied to the terrestrial Arctic during the period of 1979–2009 in order to evaluate changes in the terrestrial Arctic freshwater system and to explore influences of the terrestrial freshwater on the Arctic Ocean. The model simulated increasing river discharge (7.3 $km^3\ yr^{-1}$, $p=0.13$) and water temperatures in the terrestrial Arctic, consistent with the observations, which resulted in increasing trend in heat flux (167.7 PJ yr^{-1}, $p=0.23$) flowing to Arctic Ocean. While the increases were significant in eastern Eurasia rivers, the trends in North America were negative. River ice in the Eurasian rivers also tended to be thinner thickness and earlier breakup. Our analysis exhibited that the heat fluxes of the eastern Eurasian rivers were significantly correlated with sea surface temperature and sea ice concentration of the nearshore, providing an insight about influence of the terrestrial freshwater on the declining Arctic sea ice.

IACS (Cryosphere)

C07a - C07 Understanding Linkages between Different “Elements” of the High-Latitude Cryosphere

IUGG-5161

Researches on linkages between Greenland ice sheet and sea ice in the Baffin Bay

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Relationships between sea ice and ground condition are challenging target of science. Japanese GRENE Arctic Climate Change Research Project “Rapid Change of the Arctic Climate System and its Global Influences” expanded observation sites in the Arctic regions and set AWS at many sites. Arctic Environment Research Center (AERC) in the National Institute of Polar Research (NIPR) in Tokyo contracted Arctic Data archive System (ADS). Passive microwave data is available for observations on both sea ice coverage and ice sheet melting. Satellite microwave data of SSM/I, AMSR-E and AMSR2 are available in ADS and used for observing ice cover, SST, ice sheet melting and freezing.

Last thirty years observation on melting of Greenland ice sheet and sea ice conditions in the Baffin Bay shows synchronized variations. These components are compared also in the seasonal scale. Significant decrease in the freezing day in the southern Baffin Bay has been reported by previous studies. These trends are associated with sea ice variations in the northern Baffin Bay. Daily, seasonal and long-term associations are visible among sea ice and coastal ice sheet melting/freezing.

IACS (Cryosphere)

C07b - C07 Understanding Linkages between Different "Elements" of the High-Latitude Cryosphere

IUGG-1095

Small scale variability of snow density on Antarctic sea ice

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Snow on sea ice plays an important role in air-ice-sea interactions, as snow accumulation may for example increase the albedo. Snow is also able to smooth the ice surface, while at the same time it may generate roughness elements by interactions with the wind. Snow density is a key property in many processes, for example by influencing the thermal conductivity of the snow layer, radiative transfer inside the snow as well as the effects of aerodynamic forcing on the snowpack. By comparing snow density from snow pits and snow micro penetrometer (SMP) measurements, augmented by terrestrial laser scanning (TLS) on an area of 50x50 m^2, highly resolved density profiles and surface topology were acquired at a horizontal resolution of approximately 30 cm. Average snow densities are about 300 kg/m^3, but the analysis also reveals a high spatial variability in snow density on sea ice in both horizontal and vertical direction, ranging from roughly 150 to 500 kg/m^3. This variability is expressed by coherent snow structures over several meters. A comparison with TLS data indicates that the spatial variability is related to deviations in surface topology. This suggests a strong influence from surface processes, for example wind, on the temporal development of density profiles. The fundamental relationship between density variations, surface roughness and changes therein as investigated in this study are interpreted with respect to larger-scale ice-movement and ice mass balance.

IACS (Cryosphere)

C07b - C07 Understanding Linkages between Different “Elements” of the High-Latitude Cryosphere

IUGG-2583

Coincident circumpolar mapping of Antarctic coastal polynyas and landfast sea ice; their relationship and linkage

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Sinking of dense water from Antarctic coastal polynyas produces Antarctic Bottom Water (AABW), which is the densest water in the global overturning circulation and is a key player in climate change as a significant sink for heat and carbon dioxide. Very recent studies have suggested that landfast sea ice plays an important role in the formation and variability of the polynyas and possibly AABW. However, they have been limited to regional and case investigations only. This study provides the first coincident circumpolar mapping of Antarctic coastal polynyas and landfast sea ice. The map reveals that most of the polynyas are formed on the western side of landfast sea ice, indicating an important role of landfast sea ice in the polynya formation. Winds diverging from a boundary comprising both coastline and landfast sea ice are the primary determinant of polynya formation. The blocking effect of landfast sea ice on westward sea-ice advection by the coastal current would be another key factor. We evaluate these effects on the variability in sea-ice production for 13 major polynyas quantitatively. Furthermore, we demonstrate that a drastic change in landfast sea ice extent, which is particularly vulnerable to climate change, causes dramatic changes in the polynyas and possibly AABW formation that can potentially contribute to further climate change. These results suggest that landfast sea ice and precise polynya processes should be addressed by next-generation models to produce more accurate climate projections. This study would give the boundary and validation data of landfast sea ice and sea-ice production for such models.

IACS (Cryosphere)

C07b - C07 Understanding Linkages between Different “Elements” of the High-Latitude Cryosphere

IUGG-3188

Landfast sea ice: A key factor affecting sea ice production in Antarctic coastal polynyas.

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Antarctic coastal polynyas are key formation sites of dense water, owing to the high rates of sea ice production in these spatially-limited regions. Recent results have shown strong variability and trends in sea ice production rates within several Antarctic coastal polynyas, which cannot be adequately accounted for by atmospheric forcing alone. Using a new state-of-the-art landfast ice dataset based on visible/thermal infrared satellite imagery (resolution: 15 day, 1 km) and 6.25 km resolution daily sea ice production estimates from passive microwave satellite data, we investigate the close relationship between landfast sea ice, perhaps the most dynamic element of the coastal cryosphere, and adjacent sea ice production in the Cape Darnley and Barrier Polynyas, East Antarctica. The Cape Darnley Polynya is of global climatic significance as an area of Antarctic Bottom Water formation. Here, we emphasise the importance of the morphology of the landfast ice. In particular, we show that the component of landfast ice extent perpendicular to the wind vector is a strong factor controlling polynya size in these regions. This important linkage between cryosphere and the polar ocean has hitherto been under-appreciated. This work highlights the importance of including realistic landfast ice distribution in regional and global ocean models, and of better understanding of cross-cryosphere interactions as they affect ice-ocean-atmosphere processes.

IACS (Cryosphere)

C07b - C07 Understanding Linkages between Different "Elements" of the High-Latitude Cryosphere

IUGG-3366

Climate, sea ice, and ocean precursors to the Larsen Ice Shelf disintegrations

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Ice flux in this region surged 2- to 6-fold after two ice shelf disintegration events in 1995 and 2002, and glacier imbalance in the region has remained approximately twice the rate of accumulation (Scambos et al., 2014, TCryo). The disintegration events were driven by a group of processes arising from the presence of extensive melt lakes and hydrofracture. However, precursor changes in the ice shelves beginning more than a decade before the disintegrations have been identified, beginning around 1990, and coincide with a trend towards reduced sea ice cover and increased foehn winds. These are linked to climate changes, e.g., frequency of positive Southern Annular Mode conditions and increased foehn wind events. Examination of satellite images spanning 1963 - 2014 shows that shear margins and suture zone features evolved significantly prior to shelf retreat. Rifts in the area increased in number and expanded, and ice flow speed increased. These changes suggest either increased ocean-driven basal melt or effects of increased surface meltwater on grounded glacier outflow are a cause of early shelf weakening that led eventually to disintegration. The reduced sea-ice extent in the 1990s- early 2000s in the NW Weddell Sea suggests that wind traction on the ocean surface may have influenced sub-shelf ocean circulation. Available ocean profiles show that modified Weddel Deep Water, having potential temperature 0.1-0.2°C above freezing, is present near the former ice fronts in 1995-2012 data. Moreover, reduced sea ice cover permitted long-period ocean waves to reach the ice front and flex the ice shelf. A wave train in early March, 2002, (~14s period, NOAA WaveWatch data) may have triggered the 2002 disintegration of the Larsen B Ice Shelf.

IACS (Cryosphere)

C07b - C07 Understanding Linkages between Different "Elements" of the High-Latitude Cryosphere

IUGG-4096

Change in snow distribution patterns over an Antarctic ice floe following a snow storm event

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Sea ice, snow and atmosphere interactions are major drivers of the spatial distribution of snow over sea ice in polar regions. Here, we quantify changes caused by a snow storm in the spatial distribution of snow over an Antarctic ice floe at resolutions of 1-10 cm and over 100 m x 100 m. The snow/ice elevations were obtained using a Terrestrial Laser Scanner during the SIPEX-2 in 2012. The pre-storm surface (2012-10-20) exhibits multi-directional elongated snow dunes behind aerodynamic obstacles likely formed during previous snow storms. The post-storm surface (2012-10-23) exhibits clear new deposition dunes elongated along the predominant wind direction. The new deposition areas amount to 38% of the total surveyed area. Patterns of erosion are less evident but cover a larger portion of the area. This results in a total volume of change near zero with a mean elevation difference of 0.02 m. After the storm, the statistical distributions of elevation and the 2D correlation functions remain similar to those of the pre-storm surface. The pre- and post-storm surfaces also exhibit power-law relationships in the power spectrum with little change between pre- and post-storm slopes. These observations suggest that despite the significant change observed in the snow surface patterns, the change does not translate into significant changes in the spatial statistical and scaling properties of the surface morphology. Such an observation is important for sea-ice model representations of the sub-pixel variability of sea ice surfaces, particularly between snow storm events, although more datasets will be required to extend these results to a wider range of sea ice surface morphologie

IACS (Cryosphere)

C07p - C07 Understanding Linkages between Different "Elements" of the High-Latitude Cryosphere

C07p-282

Frequency and distribution of winter melt events from passive microwave satellite data in the pan-Arctic

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Observed and projected warming in the Arctic are likely to drive an increase in the frequency and duration of winter melt events. These events can have important impacts on the soil thermal regime, climate, hydrology and ecology through the formation of ice layers, changes in the physical properties of snow and the generation of winter runoff. Satellite passive microwave data are very sensitive to the appearance of liquid water in snow and have been used for melt detection over various components of the Arctic cryosphere. Here we developed an algorithm to detect winter melt events in the northern high latitudes (>50°N).

The algorithm is based on temporal variations in the difference of 19 and 37 GHz brightness temperature from SSM/I. Evaluation with pan-Arctic weather station data shows the algorithm clearly captures days with above freezing air temperature. Further evaluation using snow survey data shows the algorithm is useful for detecting actual snow melt events that result in changes in the physical properties of the snowpack (melt crusts/ice layer development). Short duration events with air temperatures above 0°C are not detected as they do not typically result in enough snow melt to produce liquid water within the snowpack detectable at the satellite scale. These results suggest that the satellite-detected winter melt events should be more closely linked to prominent and expansive changes to the physical properties of snow than those derived from air temperature based on surface observations or Reanalysis. We present the spatial and temporal variability and examine the changes of winter melt frequency over the 1989-2014 period. The results of this work can also be used to assess the representation of Arctic snowpack melt dynamics in climate models.

IACS (Cryosphere)

C07p - C07 Understanding Linkages between Different “Elements” of the High-Latitude Cryosphere

C07p-283

Understanding interactions between different polar cryosphere elements: A new WCRO CliC (Climate and Cryosphere) initiative.

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Major change is occurring across the high-latitude cryospheres of both polar regions, yet little is known about the inter-relationships between the different component “elements” of the polar cryosphere - sea and river ice, ice sheet/glaciers, icebergs, snow and permafrost (connected by oceanic and atmospheric processes) - and how change in one may affect others. Tantalizing new/recent studies suggest that these linkages may be complex and involve subtle and previously-unconsidered feedbacks. The aim of this new initiative is to:

- encourage a more holistic, integrated approach to cryosphere-climate research that crosses boundaries, bridges the disciplines, and links observations, process studies and modelling, “looking outside the box” and linking both polar regions in the process;
- synthesize existing work, identify key gaps, provide new insights and raise awareness of (potentially) important cross-cryosphere interactions;
- foster and facilitate cross-disciplinary and –polar collaboration, discussion and coordination; and
- provide input towards inclusion of cross-cryosphere interactions and feedbacks in models (Earth System, coupled regional high-resolution, ice sheet and ice shelf-ocean).

This cross-cutting initiative forms a new “targeted activity” of the WCRP CliC (Climate and Cryosphere) Project (http://www.climate-cryosphere.org/activities/targeted). As defined by CliC, a targeted activity is a focussed 3- to 5-year research activity designed to increase understanding of the relationship between climate and cryosphere.

IACS (Cryosphere)

C08a - C08 Ice Cores and Climate

IUGG-0203

Arsenic concentration variability in West Antarctic ice core and its relationship with copper mining in Chile

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Arsenic compounds are emitted naturally by many sources, e.g., volcanoes, forest fires, and minerals deposit erosion. This element is present in non-ferrous metals that are melted (e.g., Cu, Zn, Pb) and is eliminated out of smelters as residue. Copper mine residues have been dispersed into the atmosphere and significantly affected the natural geochemical cycles in many regions of the Earth's surface. The variability records of As are preserved in snow and ice cores and this can be utilized to reconstruct the history of air pollution.
The Mount Johns ice core (79º55'S; 94º23'W and 91 m depth) was collected in the West Antarctic Ice Sheet in the 2007/08 austral summer. Here we report the As concentration variability determined in 2137 samples from the upper 45 m of this core using an ICP-MS (CCI, Maine, US). The record covers approximately 125 years (1883–2008) showing a mean concentration of 4.32 (±3.52) pg/g. The As concentration along the core follows the evolution of copper mining in the world, especially in Chile (the largest producer of Cu), showing an increase from 1900 to 1930. In the 1930s, world As emission fluctuated significantly, showing a downward trend. Initially this could be attributed to reduction of mining investments during the Great Depression. From 1940 to 1990, mining production increased as well as arsenic emissions (about 4.5 times when compared to 1900).In the last two decades, environmental regulation for As have been implemented, forcing smelters to treat their gases to respect national and international environmental standards. In Chile, decontamination plants required by the government started operating from 1993 to 2000. Following, As emission levels declined while Cu production more than doubled. The same reduction is seen in the core.

IACS (Cryosphere)

C08a - C08 Ice Cores and Climate

IUGG-0886

Decapitation of high-altitude glaciers on the Tibetan Plateau revealed by ice core tritium and mercury records

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Two ice cores were retrieved from high elevations (~5800 m a.s.l.) at Mt. Nyainqentanglha and Mt. Geladaindong in the southern to inland Tibetan Plateau. The combined analysis of tritium (^{3}H), ^{210}Pb, mercury tracers, along with other chemical records, revealed that the two coring sites had not received net ice accumulation since at least the 1950s and 1980s, respectively, implying an annual ice loss rate of more than several hundred millimeter water equivalent over these periods. Both mass balance modeling at the sites and in situ data from nearby glaciers confirmed a continuously negative mass balance (or mass loss) in the

region due to the dramatic warming in the last decades. Along with a recent report on Naimona'nyi Glacier in the Himalaya, the findings suggest that glacier decapitation (i.e., the loss of the accumulation zone) is a wide-spread phenomenon from the southern to inland Tibetan Plateau even at the summit regions. This raises concerns over the rapid rate of glacier ice loss and associated changes in surface glacier runoff, water availability, and sea levels.

IACS (Cryosphere)

C08a - C08 Ice Cores and Climate

IUGG-1383

The debate on the basal age of Kilimanjaro's plateau glaciers

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Radiocarbon dating can be a powerful tool when the counting of annual layers in the lowermost segments of high altitude ice cores is constrained by ice flow-induced thinning limits. Nevertheless the amount of organic material contained in the ice can be a limiting factor. We present a novel radiocarbon dating approach using carbonaceous aerosols enclosed in the ice to help resolve the controversy about the age of the Kilimanjaro's plateau glaciers. Paleoclimate reconstructions based on six ice cores drilled in 2000 assigned a basal age of 11'700 years. A recent study claims recurring cycles of waxing and waning controlled primarily by atmospheric moisture and an absence of the ice bodies was suggested for 1200 AD. Resolving the dispute of the time frame for the extinction of the Kilimanjaro ice might have implications for the understanding of the climate variability in the tropics.
A stratigraphic sequence of 45 horizontal short cores was collected in 2011 from the exposed vertical ice cliffs at the margins of the Northern Ice Field (NIF). Additionally, 3 samples were taken from the glacier surface to investigate a potential age offset. The insoluble carbonaceous particles were filtrated and combusted by means of a thermo-optical OC/EC analyser and ^{14}C was analysed using a compact radiocarbon AMS system 'MICADAS' at the University of Bern, Switzerland.
The results of ^{14}C calibrated ages span between modern ages on surface to 1200 AD at the bottom, thus supporting the hypothesis that the ice on Kilimanjaro's plateau has come and gone repeatedly throughout the Holocene. It is possible that the cores collected further from the margin of the NIF contained older, relict ice, implying hiatuses, and a non-continuous record.
Therefore, further investigations are necessary.

IACS (Cryosphere)

C08a - C08 Ice Cores and Climate

IUGG-2047

Climate and environment back to the Eemian interglacial viewed from ionic records at NEEM, Greenland

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A 2540 m-long ice core was drilled during 2008-2012 by an international ice coring project NEEM (North Greenland Eemian Ice Drilling). Discrete samples were collected from the CFA (Continuous Flow Analysis) melt fractions during the field campaign carried out at NEEM in 2009-2011, and were distributed to different laboratories. Ionic species were analyzed at National Institute of Polar Research (Japan) and Alfred Wegener Institute for Polar and Marine Research (Germany). At NIPR, minor ions as well as major ions were analyzed. Fluoride, oxalate, and acetate show variations associated with Dansgaard–Oeschger (DO) events, as do calcium, sodium, chloride, sulfate, sodium, potassium and magnesium. On the contrary, nitrate, ammonium, and MSA do not show large variations, as was previously reported for other deep ice cores from Greenland. During Holocene and Eemian, ammonium, acetate and formate show coherent variations. During early to mid Eemian, ammonium, acetate and formate concentrations show decreased concetrations. Since these terrestrial biogenic species are likely originated from North America, this suggests either a mid-Eemian cold/dry spell in North America or a change in atmospheric circulation. The evident surface melting during Eemian did not seem to have a strong impact on concentrations of these ions. During cold stadials, dust and sea-salt species concentrations show relationship with Greenland temperature slightly different from that during interglacials and interstadials. These results would give insight into the past atmospheric circulations.

IACS (Cryosphere)

C08a - C08 Ice Cores and Climate

IUGG-4492

Results from the recent Greenland deep drill project NEEM

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As "North Greenland Eemian Ice Drilling – NEEM" suggest the goal of the project was recovering the Eemian period. Opposed to the expectations we did not recover a continuous record over the Eemian, however, we managed to puzzle the scrambled record back together and have a reconstructed, continuous record to about 128 kyr BP. By that NEEM provided insight into glaciological features that were so far not recognized.

In the course of the Eemian period the ice sheet decreased by 400±250 meters, reaching surface elevations 122,000 years ago of 130±300m meters lower than today. Over the Eemian period we find frequent indications of surface melting which is not the case over the present warm period.

IACS (Cryosphere)

C08b - C08 Ice Cores and Climate

IUGG-0205

Meteorological and snow accumulation gradients across an antarctic dome

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In situ observations show that snow accumulation is ~10% larger 25 km north than south of the summit of Dome C on the east antarctic plateau. The mean wind direction is southerly. Although a slight slope-related diverging catabatic flow component is detectable, the area is an essentially flat homogeneous snow surface. Meteorological analyses data reproduce a significant accumulation gradient and suggest that 90% of the the mean accumulation results from the 25% largest precipitation events. During these events, air masses originate from coastal areas in the north rather than from inland in the south. Radiative cooling condensation occurs on the way across the dome and as the moisture reservoir is depleted less snow is dumped 25 km south than north, with little direct impact from the local topography. Air masses are warmer on average, and warmer north than south, when originating from the coast. This marginally affects the mean temperature gradients, more so atmospheric moisture which non linearly relates to temperature: the mean atmospheric moisture is larger north than south. Significant meteorological and hydrological gradients over such relatively small distances (50 km) over locally flat region may be an issue when interpreting ice cores: although cores are drilled at the top of domes and ridges where the slopes and elevation gradients are minimal, they sample small surfaces in areas affected by significant spatial gradients of meteorology and hydrology.

IACS (Cryosphere)

C08b - C08 Ice Cores and Climate

IUGG-0749

Mt. Elbrus ice core, the Caucasus: a high altitude paleoclimate and environmental record for the South of Eastern Europe

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An intermediate depth up to the glacier bottom ice core (181.8 m) has been recovered on the Western Plateau of the Mt. Elbrus (43°20’53.9” N, 42°25’36.0” E; 5150 m a.s.l.) in the Caucasus, Russia in 2009. This is the first ice core for the region, representing practically un-disturbed by seasonal melting paleoclimate record, with the amount of snow accumulation allowing to analyze the intra-seasonal climate proxies variability with high temporal resolution. The ice core has been analyzed for stable isotopes (δ^{18}? and δD), micro-particle concentration, major ions (K^+, Na^+, Ca^{2+}, Mg^{2+}, NH_4^+, SO_4^{2-}, NO_3^-, Cl^-), black carbon (BC) and tritium content. The mean annual net accumulation derived from distinct annual oscillations of δ^{18}?, δD, and NH_4^+ is 1200 mm w.e. Temperatures were measured in the boreholes on the of the Western Elbrus Plateau in 2009 and ranged from −17°C at 10 meters depth and −2.4°C at 182 m. Detailed radio-echo sounding shown glacier thickness ranged from 45 meters near marginal zone of the plateau to 255 m at the central part. The detailed analysis of whole the ice core is still an on-going process. The paper presents the content of the obtained and of the expected data and the first conclusions from the completed parts of the data evaluation. Ice core dating was made by counting annual layers on the basis of isotopic and chemical stratigraphic records (δ^{18}?, NH_4^+, succinic acid). Annual layer counting was achieved down to 85 m w.e. and is in agreement with the tritium 1963 time horizon and 1912 (Katmai) sulfate peak.

IACS (Cryosphere)

C08b - C08 Ice Cores and Climate

IUGG-2118

Reconstruction of El Niño-Southern Oscillation (ENSO) from the Mercedario ice core

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South America is a key region for the understanding of climate dynamics in the Southern Hemisphere. With winter precipitation amounts in Central Chile being significantly correlated to the Southern Oscillation Index, high altitude Andean glaciers located between 28 and 35°S can be expected to record a signal related to the El Niño-Southern Oscillation (ENSO).

We present new results from an ice core drilled in 2005 at La Ollada glacier on Cerro Mercedario, Central Argentinean Andes (31°58‘S, 70°07‘W, 6100 m asl). Measured borehole temperatures, ranging from -16.7 °C at 104 m to -18.5 °C at 10 m depth, are the lowest englacial temperatures measured in Andean glaciers to date. The result is a well preserved ice archive with complete absence of melt features. Another notable characteristic of this ice core is the lack of seasonal variability in the records of water stable isotope ratios ($\delta^{18}O$, δD). Dating was performed by a combination of independent tools such as annual layer counting based on chemical dust tracers, nuclear dating with ^{210}Pb, ^{14}C of particulate organic carbon and tritium, measurements of trace gases (CH_4, N_2O, CFCs) trapped in the ice enclosed air bubbles and glacier flow modelling. We determined a mean annual accumulation rate of 0.27 m weq, principally allowing seasonal to sub-seasonal resolution. With the different dating techniques applied a consistent chronology of the past 350 years was obtained for the 104 m of ice core recovered. As expected for the location, we find $\delta^{18}O$ and most chemical impurities to be strongly modulated by

the ENSO. We will discuss source regions and transport of chemical impurities and the relation between them, $\delta^{18}O$ and tropical eastern Pacific sea surface temperatures resulting in a new ENSO reconstruction back to ~1700 AD.

IACS (Cryosphere)

C08b - C08 Ice Cores and Climate

IUGG-2742

Volcanic synchronization of Dome Fuji and Dome C Antarctic deep ice cores over the past 216 kyr

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Two deep ice cores, Dome Fuji (DF) and EPICA Dome C (EDC), drilled at remote dome summits in Antarctica, were synchronized to better understand their chronology. A total of 1401 volcanic tie points were identified covering the past 216 kyr. DFO2006, the chronology for the DF core characterized by strong constraining by the O_2/N_2 age markers, was compared with AICC2012, the chronology for 5 cores including the EDC core, and characterized by glaciological approaches combining ice flow modelling with various age markers. The age gaps between the two chronologies are within 2 kyr, except at Marine Isotope Stage (MIS) 5. DFO2006 gives ages older than AICC2012, with peak values of the gap of 4.5 kyr and 3.1 kyr at MIS 5d and MIS 5b, respectively. Accordingly, ratios of duration DFO2006/AICC2012 are 85% at a period from the late stage of MIS 6 to MIS 5d and 114% at a period from MIS 5d to 5b. We then compared the DFO2006 with another chronology of the DF core, DFGT2006, characterized by glaciological approaches with weaker constraining by age markers. Features of the DFO2006/DFGT2006 age gaps are very similar to those of the DFO2006/AICC2012 age gaps. This fact lead us to hypothesize that a cause of the systematic DFO2006/AICC2012 age gaps at MIS 5 are associated with differences in the dating approaches. Besides, ages of speleothem records from China agreed well with DFO2006 at MIS 5c and 5d but not at MIS 5b. Thus, we hypothesize at least at MIS 5c and 5d, major sources of the gaps are systematic errors in surface mass balance estimation in the glaciological approach. Compatibility of the age markers should be carefully assessed in future.

IACS (Cryosphere)

C08b - C08 Ice Cores and Climate

IUGG-4601

First shallow ice core drilling at Kazbek Mt., Caucasus: results and prospects

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Glacierized massif of the Kazbek volcano (5033 m a.s.l.) is one of the dangerous places in Caucasus in terms of natural and particularly glacier hazards. A number of catastrophes associated with volcanic activity and surging behaviour of Kolka and Devdorak glaciers happened here a number of times. At the same time flat Maily glacier plateau at the upper part of the Kazbek volcano potentially could contain a long paleoclimate record. However there was a lack of glaciological studies at the accumulation zone of Kazbek glaciers. A complex glaciological field campaign took place in the summer of 2014 in order to assess potential of the Maily plateau (4500 m) for the deep ice core drilling and paleoclimate reconstructions. A detailed GPR survey showed that a maximum ice thickness reaches 250 m. First shallow ice core drilling was conducted. Borehole temperature was measured -2.7 C at the depth of 18 m. Stratigraphy shows presence of melt features in summer layers. A number of layers in spring-summer horizons contained visually distinguishable desert dust. ?ce core was sampled on site into precleaned vials for chemical and isotopic analysis, samples were transported in frozen state to the LGGE laboratory. Samples then were analysed for soluble ions using Dionex Dual ICS- 3000. Dust particles were analysed using Coulter Counter Multisizer 3. Dust layers were sampled and filtered for SEM analysis. Results show that shallow ice core covers 4 years of accumulation. Substantial melting occurred here during one of the summers which affected chemical composition of the previous year. Isotopic composition and dust record was not changed. Surface and bedrock topography as well as chemical composition emphasize potential and limitations of the paleoclimate studies at the Kazbek Mt.

IACS (Cryosphere)

C08b - C08 Ice Cores and Climate

IUGG-5467

State dependence of climatic instability from long Antarctic ice-core records and climate modelling

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Climatic variability on 10^3- to 10^4-year timescales and an associated bipolar seesaw pattern during the last glacial period has been documented in palaeoclimatic records. However, their frequencies in older glacial periods are still not firmly established. Here we investigate the long-term characteristics of such variability using a 700-kyr ice core record from Dome Fuji, East Antarctica. Combining with the Dome C record, we identify 10^3- to 10^4-year warming events over the past eight glacial cycles. They are most frequent and abundant when Antarctic temperature is slightly below average, equivalent to an intermediate climatic state during glacial periods. We also observe events with long periodicity ($>10^4$ years) and large magnitude during early stages and terminations of glacial periods, when Northern Hemisphere summer insolation is highly variable, suggesting a role of orbital forcing in the inter-hemispheric seesaw. With a fully coupled climate model, we show that inter-hemispheric seesaw response of temperature and precipitation, characterized by abrupt changes in Northern North Atlantic region and gradual changes in Antarctica, can occur easier under glacial climate than interglacial climate, associated with moderate fresh water anomaly in the North Atlantic and resulting change in Atlantic meridional overturning circulation (AMOC). Together with the ice core data, this suggests that the prerequisite for the most frequent climate instability with bipolar seesaw pattern during the late Pleistocene is not only the extent of continental ice sheets but also low CO_2. North Atlantic cooling sets high sensitivity of AMOC and climate to small perturbations such as moderate freshwater anomaly.

IACS (Cryosphere)

C08c - C08 Ice Cores and Climate

IUGG-0853

The WAIS Divide ice core: the phasing of the bipolar seesaw inferred from high-resolution climate records

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The West Antarctic Ice Sheet (WAIS) Divide core is a newly drilled, high accumulation Antarctic ice core that provides climate records over the last 68 ka at unprecedented temporal resolution. In the first part of this presentation, we will review several of the key climatic records from the WAIS Divide ice core. For the last deglaciation, water isotopes as well as $d^{15}N$ of N_2 provide evidence for an early onset of deglacial warming starting at least 2 ka earlier than the continent-wide warming at 18 ka. The high-resolution WAIS Divide CO_2 record shows unambiguously that a large fraction of the total deglacial CO_2 rise occurred in three centennial-scale jumps of 10 to 15 ppm each. The abrupt CO_2 changes show a clear relationship with abrupt climate changes in the Northern Hemisphere high latitudes.

In the second part of the presentation we will show that WAIS Divide climate records can be used to investigate the phasing of the bipolar seesaw at sub-centennial precision. We show that on average abrupt Greenland warming leads the corresponding Antarctic cooling onset by 221 ± 92 years (2s) for DO-events, including the Bølling event; Greenland cooling leads the corresponding onset of Antarctic warming by 196 ± 95 years. Our results demonstrate a north-to-south directionality of the abrupt climatic signal, which is propagated to the Southern Hemisphere (SH) high latitudes by oceanic rather than atmospheric processes. The similar interpolar phasing of warming and cooling transitions suggests that the transfer time of the climatic signal is independent of the AMOC background state.

Our findings confirm a central role for ocean circulation in the bipolar seesaw, and provide clear criteria for assessing hypotheses and model simulations of DO dynamics.

IACS (Cryosphere)

C08c - C08 Ice Cores and Climate

IUGG-1396

A precise ice-core chronology from Antarctica for the past 31,000 years

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Here we present a new chronology for the upper part (0-2850 m, 31200 years BP) of the West Antarctic Ice Sheet (WAIS)-Divide ice core which is based on layer counting of distinctive annual cycles preserved in the elemental, chemical and electrical conductivity records. These cycles are caused by the seasonally varying impurity concentrations in snowfall reflecting source strength of emissions, transport and deposition efficiency. A new ice core chronology has been developed using manual interpretation as well as by using a layer detection algorithm based on Hidden Markov Models taking advantage of the large suite of sub-annually resolved and co-registered aerosol records from high-resolution continuous measurements. The age model is validated against the absolute dated radiocarbon calibration curve IntCal13 using ice-core Berillium-10 measurements for proxy synchronization revealing an unprecedented accuracy of the new ice core chronology since the Last Glacial Maximum. The new chronology can become a reference chronology for ice cores with synchronization to other ice cores achievable through the unique high-resolution sulfur record indicating hundreds of volcanic signals common to many other deep ice cores in Antarctica.

IACS (Cryosphere)

C08c - C08 Ice Cores and Climate

IUGG-2783

Can we use 20th Century climate reanalysis products to support Antarctic ice core interpretation?

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Ice cores are useful proxies for interpreting past climate, particularly for those areas where instrumental data are short and/or scarce, such as Antarctica. However, ice core proxies cannot be used in complete isolation and interpretation of proxy data is often complemented by an examination of the climate through instrumental observations or reanalysis data. In Antarctica, much of the instrumental data, including reliable reanalysis data, is limited to the post-satellite era (~post-1978). This poses problems when decadal-to-multidecadal scale features are being examined.

Recently, several reanalysis products have become available that assimilate only surface measurements, thereby extending reanalyses throughout the 20th Century. This extension helps with the interpretation of ice core proxies for decadal-to-multidecadal scale features, but is reliant on the skill of these reanalysis products over Antarctica, which we test here for the first time.

This study examines the skill of one of the newer 20th Century reanalysis data sets, the ERA-20C by comparing it to radiosonde measurements of temperature, geopotential height, wind speed and direction over Antarctic stations from 1957–2010. The radiosonde data provides an independent comparison as only surface measurements have been assimilated into the ERA-20C reanalysis. The results demonstrate variation in skill with meteorological variable, with season and over time, which are attributable to a number of factors.

IACS (Cryosphere)

C08c - C08 Ice Cores and Climate

IUGG-4551

Atmospheric teleconnections between the tropics and high southern latitudes during millennial climate change.

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Rapid climate changes, known as Dansgaard-Oeschger (DO) events, are ubiquitous over the last glacial period. DO climate anomalies are propagated globally through climatic teleconnections that are incompletely understood and insufficiently constrained by paleoclimatic data. Here we use a high-resolution deuterium excess record from the new West Antarctic Ice Sheet Divide ice core, to show that changes in the moisture sources for Antarctic precipitation occurred in-phase with the DO shifts in Northern Hemisphere (NH) climate and tropical hydrology. These results support the hypothesis that the Southern Hemisphere (SH) storm tracks migrate northwards during NH warm periods, in parallel with the well-established northward migration of the intertropical convergence zone.

Variability in the deuterium excess record also suggests that Southern Ocean sea surface temperatures (SST) followed the pattern of Antarctic surface temperatures, out of phase with NH climate, as expected from conceptual and numerical models of the ocean bipolar 'seesaw' mechanism. Furthermore, using a new, physically-based definition of the deuterium excess parameter, we show that many Antarctic records are highly coherent over these events, indicating that the SST changes are zonally uniform. Our data demonstrate that both atmospheric and oceanic teleconnections couple climate variations between the NH and SH high latitudes, and constrain the timescales on which they operate.

IACS (Cryosphere)

C08p - C08 Ice Cores and Climate

C08p-095

A new East Antarctic (Northern Victoria Land) ice core record and its tephrochronology

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During the 2013-14 Italian Antarctic Expedition, multiple firn/ice drilling down to 250 m depth has been carried out at the GV7 site, at the eastern edge of the East Antarctic Plateau. Based on previous field and core surveys, this near coastal site (70°41'S, 158°52'E; elevation 1950 m, Tmean= –31.8°C) is characterised by an average snow accumulation of ca. 240 mm w.eq. (during the last 150 years), a good signal/noise ratio and an excellent chemical and isotopic stratigraphy. A preliminary age/depth model estimates that the upper 500 m could cover more than two thousands years. The aim of this drilling project, funded by PNRA with KOPRI cooperation, is to contribute to the SCAR-PAGES International effort "The IPICS 2k Array: a network of ice core climate and climate forcing records for the last two millennia".

A single macroscopic tephra layer occurs at ca. 183 m depth. We performed geochemical analysis (major elements by electron microprobe and trace elements by LA-ICP-MS) of single glass shards and compared the results with data from Antarctic rocks and known englacial tephra, with the purpose of providing a first constraint for the core chronology. The geochemical signature suggests correlation with the tephra originated in the nearby Pleaides volcanoes and dated 1254±2 AD. This is a continental-scale volcanic marker already detected in a number of cores from the West and East Antarctic ice sheets. Our finding further extends the known area of ash fallout and offers the prospect of stratigraphic correlation with other palaeoclimatic records.

At the moment of the writing isotopic, mineral dust and glaciochemical measurements of ice core samples are in progress. The data will be combined with the tephra time constraint to develop the age scale for the whole record.

IACS (Cryosphere)

C08p - C08 Ice Cores and Climate

C08p-096

Water stable isotope records from the GV7 drilling site (Oates Coast, East Antarctica): Preliminary results

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Here we present the $d^{18}O$, dD and deuterium excess records obtained from a snowpit (4 m) and two firn cores (5.6 m and 12 m long respectively) drilled together with a 245 m ice core at a near coastal site in East Antarctica, during the 2013-2014 Italian Antarctic Expedition. This drilling project, funded by PNRA with KOPRI cooperation, represents a contribution to the IPICS theme “The 2k Array”. The drilling site (GV7, 70°41’S, 158°52’E; elevation 1950 m, T= –31.8°C), located on the ice divide extending from the Oates Coast to Talos Dome, is characterised by a relatively high snow accumulation rate (240 mm w.eq during the last 150 years). Previously, a 55 m-length firn core was retrieved in the same area, during the 17th Italian Antarctic Expedition (2001-2002). The obtained data, combined in a multicore-approach, will be used to produce a stacked climate record of the past centuries with at least an annual resolution.
At the moment of the writing the isotopic measurements of the high-resolution samples (3-4 cm) are still in progress. The preliminary data show a very good signal/noise ratio and seasonal stratigraphy thanks to the high snow accumulation rate of the GV7 site.

IACS (Cryosphere)

C08p - C08 Ice Cores and Climate

C08p-097

Characteristics of spacial distributions of ions and trace metals concentration in the snows on Lambert Glacier, East Antarctica

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Oxygen isotope, ions and trace metals composition were analyzed, and compared with seasonal variations and spatial patterns from the coast to the inland of Antarctic Continents. Snow samples collected from four snow pits at Lambert Glacier basin on the way to from Chinese Zhongshan Station to Dome A (Pit 1; 70°50´S, 77°04´E, Pit 2; 69°31´S, 76°17´E , Pit3; 72°00´S, 77°55´E, Pit4: 73°15´S, 75°30´E). The correlation coefficients of the snow samples in pit 2, which is 20km far from the coast, show strong positive correlation between Cl with Na, K, Mg, Ca ions (0.92 to 1) and weak negative or positive correlation with almost of trace metals (-0.34 to 0.27) except U, Rb and As (0.94, 0.98 and 0.64 respectively). On the contrary, in pit 4, 450km far from the coast, show weak correlation between Cl with Na and K (0.12 and 0.43) and strong correlation with Ca and Mg (0.52 and 0.79), and no clear correlation with trace metals.

IACS (Cryosphere)

C08p - C08 Ice Cores and Climate

C08p-098

Modelling the isotopic response to antarctic ice sheet change during the last interglacial

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Ice sheet changes can exert major control over spatial water isotope variations in Antarctic surface snow. Consequently a significant mass loss or gain of the West Antarctic Ice Sheet (WAIS) would be expected to cause changes in the water isotope record across Antarctic ice core sites. Analysis of sea level indicators for the last interglacial (LIG), around 125 to 128 ka, suggest a global sea level peak 6 to 9 m higher than present. Recent NEEM Greenland ice core results imply that Greenland likely provided a modest 2 m contribution towards this global sea level rise. This implies that a WAIS contribution is necessary to explain the LIG sea level maxima. In addition, Antarctic ice core records suggest that Antarctic air temperatures during the LIG were up to 6°C warmer than present. Climate models have been unable to recreate such warmth when only orbital and greenhouse gas forcing are considered. Thus changes to the Antarctic ice sheet and ocean circulation may be required to reconcile model simulations with ice core data. Here we model the isotopic response to differing WAIS deglaciation scenarios, freshwater hosing, and sea ice configurations using a fully coupled General Circulation Model (GCM) to help interpret Antarctic ice core records over the LIG. This approach can help isolate the contribution of individual processes and feedbacks to final isotopic signals recorded in Antarctic ice cores.

IACS (Cryosphere)

C08p - C08 Ice Cores and Climate

C08p-099

Laboratory experiments on frozen aqueous solutions and artificial snow: Spectroscopy and microscopy

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The location of impurities in ice and snow strongly influences their speciation and spectroscopic properties as well as their environmental lifetimes. We conducted laboratory experiments with a few molecular probes in frozen aqueous solutions and on artificial snow to model natural conditions. In particular, the aggregation and self-organization for the gas phase deposition was compared to the solution freezing. [1] Changes of the absorption properties, mostly caused by the solute aggregation, were found to be compound specific and lead to the bathochromic shifts of absorption spectra only in certain cases. [2,3] Environmental scanning electron microscopy coupled with fluorescence spectroscopy revealed the impurities aggregated on the grain boundaries at nearly environmental conditions (temperatures above 250 K and pressures below 700 Pa). [4] The results showed that the impurities are vapor deposited on the ice surface, but freezing places them mostly into the veins between the ice crystals.

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IACS (Cryosphere)

C08p - C08 Ice Cores and Climate

C08p-100

Nevado Illimani (Bolivia) accumulation rate as a proxy for Amazon precipitation

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Andean tropical glaciers have shown a clear shrinkage throughout the last few decades. However, it is unclear how this decline is associated with variations in the rainfall patterns in the Amazon basin. We compared the annual net accumulation variations derived from an ice core from the Nevado Illimani (16°37'S, 67°46'W), with climatic series (mean annual temperature and precipitation volume) of several weather stations in the Amazon basin since 1961. The annual accumulation at the ice core site showed the following pattern of change: an increase from 1960 to 1981, a decrease from 1981 to 1999. Our analysis shows that, after 1999, the mean annual temperature kept on rising (0.26ºC/decade between 1961 and 2009) and there was also a rise in the altitude of the 0°C isotherm in the Cordillera Real - Bolivia, probably explaining the glacier shrinkage after 1999. The Amazonia forest region that best reflects changes in accumulation rates of Bolivian glaciers is the Northern Amazonian Rainfall (NAR). Our proposal is based on three points: 1) This area shows a reduction in the rainfall during the positive phase of the Pacific Decadal Oscillation PDO, associated with more frequent and intense El Niños. During the opposite phase of PDO contrary conditions prevail (greater precipitation volume), and La Niña events are more frequent, and the accumulation rate increase at Nevado Illimani; 2) Comparing the ice core record with the NAR variations, we identified the same trend for the two variables with a change in the early 1980s, represented by a decrease in the accumulation rates and standard deviations data, probably indicating the same cause; 3) The Pacific sea surface temperature can

remotely control the accumulation of ice core, influencing the Bolivian glaciers mass balance.

IACS (Cryosphere)

C08p - C08 Ice Cores and Climate

C08p-101

Natural periodicities and Northern-Hemisphere - Southern-Hemisphere connection of temperature changes during the last glacial period: EDML and NGRIP revisited

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The European Project for Ice Coring in Antarctica Dronning Maud Land (EDML) and North Greenland Ice-Core Project (NGRIP) data sets are investigated to study both the time evolution of the so-called Dansgaard-Oeschger events and the dynamics at longer timescales during the last glacial period. Empirical mode decomposition (EMD) is used to extract the proper modes of both the data sets. It is shown that the time behavior at the typical timescales of Dansgaard-Oeschger events is captured through signal reconstructions obtained by summing five EMD modes for NGRIP and four EMD modes for EDML. The reconstructions obtained by summing the successive modes can be used to describe the climate evolution at longer timescales. Using EMD signal reconstructions and a simple model based on the one-dimensional Langevin equation, it is argued that the occurrence of a Dansgaard-Oeschger event can be described as an excitation of the climate system within the same state, while the longer timescale behavior appears to be due to transitions between different climate states. Finally, on the basis of a cross-correlation analysis performed on EMD reconstructions, evidence is presented that the Antarctic climate changes lead those of Greenland by a lag of about 3.05 kyr.

IACS (Cryosphere)

C09a - C09 Water Stable Isotopes as Tools to Elucidate Atmosphere, Hydrosphere and Cryosphere Interactions

IUGG-1164

Stable isotopes and precipitation mechanisms at Dome Fuji and Dome Concordia, Antarctica

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The temperature derived from stable isotope ratios measured in Antarctic firn and ice cores is strongly dependent on moisture origin, moisture transport and precipitation mechanisms. At the Japanese Antarctic base Dome Fuji, a year of daily precipitation measurements including stable isotope ratios of the corresponding snow samples are available. At the French-Italian base Dome C, daily precipitation measurements and sampling have been initiated in 2006, and with a few interruptions have been continued until today. Both locations are deep ice core drilling sites. Therefore it is highly valuable to have these data sets to study precipitation processes in order to get a better understanding and thus better interpretation of the ice core data. Using data from the AMPS (Antarctic Mesoscale Prediction System) archive, we investigated moisture origin for precipitation events at both sites (with back-trajectories) and analysed the synoptics of weather situations that led to precipitation. Basically, three types of precipitation are considered: Diamond dust, snowfall and hoar frost. Snowfall was usually associated with warm air advection from lower latitudes combined with orographically forced lifting of the air masses. The local cycle of sublimation/deposition is still far away from being understood, and it is even harder to quantify. Unusually high amounts of diamond dust and/or hoar frost can be observed after snowfall events, when there is still a higher amount of moisture than on average. This moisture is not of local origin (as usually assumed for deposition), but related to the preceding warm-air advection.

IACS (Cryosphere)

C09a - C09 Water Stable Isotopes as Tools to Elucidate Atmosphere, Hydrosphere and Cryosphere Interactions

IUGG-2709

An investigation of local and synoptic-scale processes driving deuterium excess variability in continental near-surface atmospheric water vapour

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The quantification of the continental surface evaporation flux in the midlatitudes water cycle is an important research task, especially in view of recent studies predicting substantial changes in soil moisture regimes, which will affect regional temperature and precipitation patterns and extremes. Deuterium excess in water vapour (dv) is a measure for non-equilibrium fractionation and as such represents an instructive research tool to investigate surface evaporation. An analysis of the local and large-scale drivers of near-surface dv at the hourly to daily time scale is presented here. A combination of high time resolution measurements of dv and other local meteorological variables as well as a Lagrangian moisture source diagnostic is used. dv measurements were performed with a Picarro cavity ring-down laser spectrometer at a field site in the Swiss prealps in the summer and autumn 2011. The relation between dv and the relative humidity (h) conditions at the moisture source is characterised at the daily time scale. It is shown that the intensity of continental moisture recycling and the transpiration part of the continental evaporation flux can be estimated from the dv-h relation of continental moisture. At the subdaily time scale dv exhibits characteristics that are attributed to local effects of evapotranspiration and boundary layer mixing with the free atmosphere. Typical daily cycles of dv are compared to local measurements of h, temperature, soil moisture and the surface latent heat flux.

IACS (Cryosphere)

C09a - C09 Water Stable Isotopes as Tools to Elucidate Atmosphere, Hydrosphere and Cryosphere Interactions

IUGG-2892

Deciphering influences of temperature, moisture sources, post-deposition effects and stratospheric inputs in records of stable isotopes in East Antarctic snow

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The isotopic composition of ice enables reconstruction of past climate from the straightforward relationships observed between the oxygen or deuterium isotopic composition in the precipitated snow and temperature. However several processes may affect the isotopic composition of snow after precipitation: the wind may blow away and redeposit the uncompact snow, and therefore affects the chronology of the record. Various origins of the moisture source, including possible stratospheric inputs may also affect water isotopic composition. Finally the isotopic signal is also modified by diffusion of isotopes in the solid phase, local sublimation and condensation, and water vapor transport between snow layers.

In order to assess the effect of these mechanisms on the snow isotopic composition in East Antarctica, we follow a data-model approach. First, we present combined water vapor and surface snow isotopic compositions during a summer season at the Dome C station. Second, the incorporation of water vapor and water isotopic composition in a snow model enables prediction of the effect of post-deposition on surface and sub-surface snow isotopic composition. Finally we compare the results of the analyses in $^{18}O/^{16}O$, $^{17}O/^{16}O$, D/H and ^{10}Be of four snow pits from the East Antarctica plateau: two from Vostok, one from Dome C and one from S2. Because the different water isotopes are affected differently by equilibrium and diffusive

processes and because stratospheric inputs are expected to leave a significant signature in ^{10}Be and ^{17}O-excess, the combination of the isotopic profiles permits to identify different origins for $\delta^{18}O$ or δD variations at the different sites with a stratospheric signature at Vostok only.

IACS (Cryosphere)

C09a - C09 Water Stable Isotopes as Tools to Elucidate Atmosphere, Hydrosphere and Cryosphere Interactions

IUGG-2900

Stable water isotopes in an idealised extratropical cyclone

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Numerical model simulations of stable water isotopes help to improve our understanding of the complex processes driving isotopic variability in water vapour and precipitation. They provide information on the full four-dimensional structure of the isotopes in atmospheric moisture and can be used for sensitivity studies to identify relevant mechanisms involving fractionation. We use the recently developed isotope-enabled version of the numerical weather prediction model COSMO to study the isotopic evolution of an idealised extratropical cyclone in a baroclinic channel. We show results from four times four simulations comprising different initial isotopic compositions of the water vapour (uniform, vertical gradient only and/or a horizontal gradient of $\delta^{18}O$) and different fractionation processes (evaporation from the ocean, cloud microphysics, and equilibration and evaporation of rain). The simulations reveal in which regions of the cyclone the effects of the initial conditions, vertical and horizontal transport, and the fractionation processes are important and how they interact. Cloud microphysics shapes the isotope signal at the upper levels and in the centre of the cyclone, while evaporation from the ocean dominates close to the surface and in the cold air behind the cold front. Rain evaporation and equilibration are important near the cold front. This idealised framework gives valuable new insight into how stable water isotopes are affected by weather systems on the mesoscale and may help in the interpretation of high-resolution isotope measurements in water vapour and precipitation.

IACS (Cryosphere)

C09a - C09 Water Stable Isotopes as Tools to Elucidate Atmosphere, Hydrosphere and Cryosphere Interactions

IUGG-4701

The annual change in the isotopic composition of wet precipitation on the territory of Altai (South-West Siberia, Russia)

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Samples of wet atmospheric precipitation were collected during cold (November-March) and warm (April-August) seasons 2013-2014 in the plain part of the Altai territory (Barnaul city). Sampling point was located on the roof of the Institute building. Analysis of samples was carried out using IR laser absorption spectroscopy (Picarro L2130-i equipped with WS-CRDS system).
During the study period volume weighted mean isotopic values were $\delta^{18}O$=-19.4 ‰, δD=-147.2‰, d_{exc}=8.4‰ for cold season and $\delta^{18}O$=-12.0 ‰, $\delta^{2}D$=-88.0 ‰, d_{exc}=7.4 ‰ for warm season.
Isotope composition of wet atmospheric precipitation for cold period (07.11.2013-04.03.2014, 20 individual snowfalls) has good correlation with mean surface air temperature during precipitation (R^2=0.75 for $\delta^{18}O$ and R^2=0.74 for δD). Linear relationship between $\delta^{18}O$ and surface air temperature (T,^{0}C) is approximated by the equation: $\delta^{18}O$=0.58T - 16.9 ‰, which is very similar to the linear regression of annual average precipitation - $\delta^{18}O$ value and annual average surface air temperature at nine GNIP weather stations in Central Asia for the year 1990: $\delta^{18}O$= (0.55 ± 0.26)T_{sfc} - (16.9 ± 3.2), ‰ [Henderson et al., 2006].
In contrast to the cold season isotope composition of precipitation for the warm season (11.04.2014-15.08.2014, 29 individual rains) has no correlation with surface air temperature (R^2=0.13 for $\delta^{18}O$ and R^2=0.06 for δD). We attribute this to the fact that in the winter, there is one major source of moisture in study area - the Atlantic, since all internal reservoirs are ice-covered and soils are frozen under snow. In the summer there are a lot of moisture sources and every time their contributions to water precipitation may be different, so the correlation between isotopic composition and temperature is not observed.

IACS (Cryosphere)

C09a - C09 Water Stable Isotopes as Tools to Elucidate Atmosphere, Hydrosphere and Cryosphere Interactions

IUGG-5170

The influence of boundary layer stability on Greenland Ice Sheet accumulation

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Over long timescales, there is a close correlation between snow accumulation and temperature at high altitudes on the Greenland Ice Sheet. The response of accumulation to temperature does not follow thermodynamic prediction, which has been interpreted to reflect a predominantly atmospheric circulation-driven control on ice sheet accumulation. Continuous in situ measurements of vertical profiles of the isotopic composition of water vapor at Summit Camp, the highest observatory on the Greenland Ice Sheet, are used here to study water fluxes within the shallow and predominately stable boundary layer. Surface temperature inversions during the summertime are associated with a positive moisture flux onto the surface through condensation. In winter, there is a net tendency for export of water vapor away from the ice sheet due to persistent sublimation, but this moisture condenses and settles back to the surface below the inversion layer leading to a balance of sublimation and condensation fluxes. Given the persistence of these processes, any significant or sustained shift in atmospheric stability can have an impact on accumulation at this arid site. Wintertime inversion frequency has increased over the last decade, and the greater isolation of the ice from the atmosphere can limit the ability for the ice sheet to behave like a cold trap, which can explain the observed decreasing trend of winter accumulation in spite of recent warming.

IACS (Cryosphere)

C09p - C09 Water Stable Isotopes as Tools to Elucidate Atmosphere, Hydrosphere and Cryosphere Interactions

C09p-284

Isotopic composition and sources of atmospheric precipitation in Central Yakutia in 2013-2014

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Stable isotope ratios of atmospheric precipitations, meteorological data and backward trajectory analyses were used for identification of moisture sources responsible for atmospheric precipitations in Central Yakutia. We analyzed isotopic ratio ($\delta^{18}O$ and δD) of the daily collected atmospheric precipitation in Yakutsk city (Central Yakutia, Russia) from October 2013 till August 2014.

During the cold period (October-March) δD values of the precipitation range from -203.64‰ to −295.98‰, while $\delta^{18}O$ varies between -27.56‰ and−38.45‰. During the domination of the Siberian High in the region, the main sources of winter precipitation is the locally formed occluded cyclones. These local cyclones were formed due to warm moist air masses came to Central Yakutia from the Mediterranean and the Aral-Caspian regions. It was shown that unfrozen water reservoirs of Eastern Siberia can also be the sources of atmospheric moisture for winter precipitation.

During the warm period (April-July) δD values of the precipitation range from -88.35‰ to −198.31‰ and $\delta^{18}O$ values - from -9.15‰ to −23.93‰. Summer precipitation has the mixed sources of origin, and come to Central Yakutia mostly from the West and North. It’s worth noting that the sources of the most heavy summer precipitation were the air masses came from the Sea of Okhotsk (i.e., from the East)

IACS (Cryosphere)

C09p - C09 Water Stable Isotopes as Tools to Elucidate Atmosphere, Hydrosphere and Cryosphere Interactions

C09p-285

A weather system-based investigation of midlatitude isotope meteorology in the period 1979-2000 in a millennium simulation

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Extratropical cyclones and their fronts are an essential feature of the synoptic-scale atmospheric motion and play a primary role in the midlatitude water cycle as an efficient transport mechanism of moisture. Furthermore, extratropical precipitation extremes with a huge impact on society have been shown to be often directly related to cyclones and fronts. These dynamical systems are also thought to be responsible for a large part of the synoptic timescale variability of the isotope signals in near-surface atmospheric water vapour and precipitation in the midlatitudes. Here we present a weather system-based investigation of midlatitude isotope meteorology in the present climate (1979-2000) using data from a millennium simulation at a spectral resolution T31 with the isotope enabled version of the Max Planck Institute for Meteorology Earth System Model COSMOS-wiso. Cyclones are identified in the 6-hourly model data in an objective way using an existing algorithm. Patterns of surface evaporation and precipitation associated with these systems are detected. The influence of these features on the variability of isotopes in meteoric waters is investigated for different regions like continental central Europe, Scandinavia, Greenland, Eastern China, and Western Siberia. For the present day climate we show results from a comparison of i) the synoptic timescale variability in isotope signals from the simulation with available water vapour and precipitation isotope measurements, ii) the identified cyclone characteristics from the simulation with the ones found in atmospheric reanalysis data (ERA-Interim). Furthermore, we discuss the possibility to extend our analysis to time slices with different climatic conditions in the last millennium.

IACS (Cryosphere)

C09p - C09 Water Stable Isotopes as Tools to Elucidate Atmosphere, Hydrosphere and Cryosphere Interactions

C09p-286

Quantification of factors impacting seawater and calcite d18O during Heinrich Stadials 1 and 4

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We perform idealized experiments of a Heinrich Stadial with an Earth System Climate Model which includes oxygen isotopes. Our results compare relatively well with the planktic and benthic δ18O records of Heinrich Stadial 1 (HS1) and 4 (HS4). We find that changes in planktic δ18Oc can be equally attributed to the 'temperature effect' due to fractionation during calcification; the 'circulation and climate effect' due to changes in circulation, precipitation, evaporation, sea ice, and river discharge; and the 'meltwater effect' due to the addition of depleted freshwater from continental ice sheets. In contrast, changes in benthic δ18Oc are mainly governed by the 'temperature effect'. Finally, we simulate a ~1permil δ18Oc decrease in the deep North Atlantic at the end of the Heinrich Stadial which is caused by the resumption of North Atlantic Deep Water formation. We therefore suggest an alternative to the 'sea ice brine hypothesis' to explain the depletion seen in Atlantic sediment cores during Heinrich Stadials.

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C09p - C09 Water Stable Isotopes as Tools to Elucidate Atmosphere, Hydrosphere and Cryosphere Interactions

C09p-287

Reconstructing paleosalinity from d18o: Coupled model simulations of the last glacial maximum, last interglacial and late holocene

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Reconstructions of salinity are used to diagnose changes in the hydrological cycle and ocean circulation. The most widely used method of determining past salinity uses oxygen isotope (δOw) residuals, relying on a constant relationship between δOw and salinity throughout time. An isotope-enabled fully coupled General Circulation Model (GCM) has been used to assess how the relationship between δOw and surface salinity varies in response to past climate changes. We undertake simulations of the Late Holocene (LH), Last Glacial Maximum (LGM), and Last Interglacial (LIG) focussed on 0 ky, 21ky, and 125 ky respectively. The results show considerable variability in the δOw-salinity relationship, with large differences observed between spatial and temporal δOw-salinity gradients. We find that the largest sources of uncertainty in salinity reconstructions are caused by changes in regional freshwater budgets, ocean circulation, and sea ice regimes. These can cause reconstruction uncertainties exceeding 4 psu. We find that paleosalinity reconstructions in the South Atlantic, and Indian Oceans should be most robust, since these regions exhibit relatively constant δOw-salinity relationships across spatial and temporal scales. Largest uncertainties will affect North Atlantic and high latitude paleosalinity reconstructions. Finally we show that it is very difficult to generate reliable salinity estimates for regions of dynamic oceanography, such as the North Atlantic Current, without additional constraints. Paleosalinity is a good example where combining models and data can help constrain the terms affecting δOw and thus improve the interpretation of δOw in relation to past climate change.

IACS (Cryosphere)

C09p - C09 Water Stable Isotopes as Tools to Elucidate Atmosphere, Hydrosphere and Cryosphere Interactions

C09p-288

Comparison between air temperature and stable isotope ice core data recorded at the Mount Ortles drilling site (South Tyrol, Italy)

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The ice core oxygen and hydrogen isotopic composition has been widely used for reconstructing past temperatures. However, the conditions in which snow layers are formed, and the effects of post-depositional processes, must be taken into account when using stable isotopes as climate proxies, especially at medium and low latitude sites.
In autumn 2011 four ice cores were drilled (three down to bedrock) in the top part of the Alto dell'Ortles glacier (3859 m a.s.l., South Tyrol, Italy), where the mass balance is still largely positive. For the first time an ice core project reached the bedrock of a glacier in the Eastern European Alps. Several snow pits were also dug, and two 10 m deep shallow cores were retrieved in the same area, between 2008 and 2014.
During the drilling operations, an Automatic Weather Station (AWS) was placed in proximity of the drilling site, at 3830 m a.s.l., providing air temperature, relative humidity, wind speed and direction, incoming and outgoing longwave and shortwave radiation, and snow height data since 2011. A reconstructed (via lapse rate) Ortles temperature dataset, based on the surrounding meteorological stations, is also available since 1864. These data have been compared with the temperatures provided by two gridded observational datasets, E-Obs (spatial resolution: 0.25°) and HISTALP (spatial resolution: 0.09°), for the Ortles area.

Temperature data are used to calibrate the isotope thermometer, compared with oxygen-18 and deuterium oscillations from snow pits and deep and shallow cores. The analysis is aimed at better understanding the sensitivity of the isotopic composition to temperature variations at this site, in order to estimate the feasibility of a reconstruction of past climatic conditions in this Alpine region.

IACS (Cryosphere)

C09p - C09 Water Stable Isotopes as Tools to Elucidate Atmosphere, Hydrosphere and Cryosphere Interactions

C09p-289

Stable water isotopes in the Arctic Circle: a review of existing data.

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The isotopic signal in climatic archives usually refers to the ratio of “heavy” isotopomers ${}^{1}H_2{}^{18}O$ or ${}^{1}H^{2}H^{16}O$ over its “light” counterpart, ${}^{1}H_2{}^{16}O$. Following the seminal work of Dansgaard (1964), these stable water isotopes (SWI) have been employed as a first order climatic proxy for temperature and a second order isotopic signal, the deuterium excess d linked to humidity.

These signals contribute to our understanding of the processes related to moisture fluxes between the atmosphere and the cryosphere, biosphere, hydrosphere. The recent enhancement in isotope spectrometry technology provides an additional set of data: continuous water vapor. This supplements existing liquid and solid samples; enhancing our understanding of the mechanisms at work between atmospheric signal and their subsequent ice core. This opens up a new avenue in direct comparison between observation and simulations, at the global and regional scale. The goal is to identify model defects as well as a sharpening our physical parameterization.

In this study the aim is to generate a synthesis of existing stable isotope records for the Arctic Circle, comprising solid, liquid and vapor signals. Furthermore it includes a comparison of the records, in particular their temporal and spacial features.

IACS (Cryosphere)

C09p - C09 Water Stable Isotopes as Tools to Elucidate Atmosphere, Hydrosphere and Cryosphere Interactions

C09p-290

What controls the isotopic composition of surface snow?- understanding the processes influencing the surface snow isotopic composition.

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For the purpose of understanding the processes creating the ice core isotope signal, monitoring of the isotopic composition d^{18}O and dD at several height levels of near-surface water vapor, precipitation, and surface snow has been conducted at NEEM, NW Greenland (Summer 2010-2012) and Kohnen station, Antarctica (Austral summer 2013/2014). We support our field observations with specifically designed laboratory experiments targeting the processes controlling the interaction between the snow pack and interstitial water vapor.

During several periods between precipitation events in Greenland, our data demonstrate parallel changes of d^{18}O and d-excess in surface snow and near-surface vapor. The changes in d^{18}O of the vapor are similar or larger than those of the snow d^{18}O. Comparisons with atmospheric models show that day-to-day variations in near-surface vapor isotopic composition are driven by synoptic variations and changes in air mass trajectories and distillation histories. We suggest that, in-between precipitation events, changes in the surface snow isotopic composition are driven by these changes in near-surface vapor isotopic composition.

However, for Antarctica, we do not observe the same magnitude in snow surface isotope changes as we document for Greenland. Instead, we find that the uptake of the water vapor isotopic signal by the surface snow depends on the structure of the surface snow. We further more speculate that the lower temperatures at Kohnen, Antarctica, limit the uptake of the atmospheric water vapor isotope signal by the surface snow compared to NEEM, Greenland. Our laboratory experiments supports this hypothesis as they show that for higher temperatures the snow pack isotopes take up at a faster rate the interstitial water vapor isotopes.

IACS (Cryosphere)

C09p - C09 Water Stable Isotopes as Tools to Elucidate Atmosphere, Hydrosphere and Cryosphere Interactions

C09p-291

Understanding climatic controls on Svalbard water vapour andprecipitation isotopic composition

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We investigate the meteorological and climatic controls on the isotopic composition of vapour and precipitationat Ny Alesund, Svalbard. This is based on the IAEA database of monthly precipitation isotopic composition dataspanning 1993-2012 as well as new measurements performed using a PICARRO CRDS analyzer deployed sinceJune 2014 at Ny Alesund. The precipitation data depict a strong decoupling between oxygen 18 and temperatureat the seasonal scale and for monthly anomalies. While a relationship is observed between winter precipitationisotopic composition and temperature, this disappears during summer, at the inter-annual scale. Moreover, thedeuterium versus oxygen 18 relationship depicts different meteoric water lines in winter and summer, consistentwith the strong seasonal cycle of deuterium excess, and indicating shifts in moisture origin. The continuous watervapour data (investigated from July to December 2014 so far) show in contrast a tight relationship between hourlyoxygen 18 data and surface temperature and humidity, as well as strong antiphase between deuterium excess andoxygen 18. No significant diurnal variability is observed. We show how precipitation intermittency strongly altersthe sampling provided by precipitation data and distorts the relationship with local temperature. The surface vapourdeuterium data are compared with FTIR retrievals. The importance of changes in air mass origins is also assessedby comparison with moisture back trajectories.

IACS (Cryosphere)

C11a - C11 Climate Downscaling for Modelling Glacier Mass Balance

IUGG-0721

Monsoon energy fluxes for snow and ice melt at Yala Glacier, Langtang Valley, Nepal

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The contributions of snow and ice melt to streamflows in the Himalayas have impacts on local water resources, hydroelectric power generation, and flood mitigation. However, given the difficulties in establishing and maintaining on-glacier meteorological stations, our understanding of snow and ice melt processes are limited. Field-based studies that quantify high-altitude energy fluxes for snow and ice melt during the monsoon are rare, and comparisons between field observations and dynamically downscaled climate fields are even rarer. This study details initial results from a meteorological station installed at an elevation of 5350 m a.s.l. on south-facing Yala Glacier in the Langtang Himalaya of central-eastern Nepal. The station operated continuously from May to October 2014, and recorded air temperature, humidity, incoming and outgoing shortwave and longwave radiation, wind speed and direction, atmospheric pressure, and surface height change (from May to July). We use a simple energy balance approach with bulk turbulent flux parameterisations and a shallow snowpack heat storage routine to close the surface energy balance, and evaluate the model against co-located observations of net glacier mass balance. The relative contributions of the radiative and turbulent energy fluxes to surface melt are quantified and compared against time-series extracted from 1 km and 5 km fields of the Weather Research and Forecasting (WRF) model, and implications for future changes in snow and ice melt contributions are discussed.

IACS (Cryosphere)

C11a - C11 Climate Downscaling for Modelling Glacier Mass Balance

IUGG-1769

Modelling the surface mass balance of South Georgia glaciers using a high-resolution atmospheric model

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South Georgia is a mountainous island in the subantarctic Southern Ocean. Much of the island is covered with permanent snow and ice, with a number of alpine and tidewater glaciers draining both sides of the main mountain chain. Aerial photography and satellite observations indicate that most glaciers have retreated at accelerating rates in recent decades but also show an asymmetric pattern to this retreat – the acceleration of retreat is greater for glaciers draining towards the northeast (climatologically downwind) coast of the island than for those draining towards the southwest (climatologically upwind) coast. We hypothesise that this asymmetry is the result of strengthening prevailing westerly winds interacting with the island's orography.

No long-term in-situ measurements of glacier surface mass balance (SMB) have been made on South Georgia so we have investigated our hypothesis using SMB maps produced from a 21 month run of the Weather Research and Forecasting (WRF) regional atmospheric model. We ran WRF on three nested domains, the innermost of which covered the central part of South Georgia at 900 m horizontal resolution and was thus able to represent individual drainage basins for 14 glaciers. Basin-scale calculations from WRF output show clear contrasts between glaciers on opposite sides of the mountain divide in both mean SMB and its response to changing atmospheric circulation.

IACS (Cryosphere)

C11a - C11 Climate Downscaling for Modelling Glacier Mass Balance

IUGG-1855

"First steps towards the nesting of a glacier mass balance algorithm in the Canadian regional climate model"

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This project aims at nesting the ensemble of glaciers of western and Arctic Canada in the Canadian Regional Climate Model (CRCM5) to assess interactions of glaciers in the climate system through atmospheric feedback mechanisms, taking into account glacier geometric adjustments caused by a warming climate. Such attempts have long been pushed to a side due to the lack of data in highly glacierized areas to run the ice model and to the complexity of mountain regions. However, advances in glacier inventories, the increasing resolution of RCMs, and the development of improved models and techniques to downscale meteorological fields to finer resolution present new opportunities.

As a first step, a glacier mass balance model that has been developed to be driven by observed in-situ meteorological data has been adapted and optimized to be run on each cell of a 0.003° resolution grid for western and northern Canada. Validation of the glacier mass balance simulated by the model is done at three study sites in the Rocky Mountains where long series of data exist (Haig, Peyto and Place glaciers) in an uncoupled mode. The atmospheric data to drive the model were provided in a first experiment by NCEP-NCAR reanalyses and in a second by CRCM5 fields. These data were redistributed for each high-resolution grid cell for the three glacier sites to account for the terrain properties (elevation, slope, aspect and shading recomputed from the Canadian Digital Elevation Data, Geobase). Simulated and observed glaciers mass balances are presented, and we discuss the calibration parameters and procedures necessary to provide realistic mass balance fields.

IACS (Cryosphere)

C11a - C11 Climate Downscaling for Modelling Glacier Mass Balance

IUGG-3835

Interactively coupled, high-resolution modelling of the atmosphere and alpine glaciers at the regional scale

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For simulations of glacier climatic mass balance (CMB), high-resolution distributed meteorological data are required as forcing. In mountainous terrain, obtaining such data is hindered by the coarse spatial resolution of many atmospheric datasets, by a scarcity of observations, in particular at high-altitudes, and by the complexity of interactions between the atmosphere and the orography. Using case studies from the Karakoram and central Himalaya, we illustrate the utility of an interactively coupled, high-resolution model of the atmosphere and glacier CMB for process-based and explicit simulations of mountain glaciers at the regional scale. Our discussion focuses on the challenges introduced by the coupled modelling approach, the insights this method offers into atmosphere-glacier feedbacks, and its potential for understanding regional atmospheric and local drivers of glacier change.

IACS (Cryosphere)

C11a - C11 Climate Downscaling for Modelling Glacier Mass Balance

IUGG-5038

Surface Mass Balance of Renland Ice Cap, East Greenland using very high resolution regional climate modelling from HIRHAM5

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Ice sheet models require accurate surface mass balance forcing in order to represent both surface topography and ice dynamics. The Renland ice cap is the target of a new ice coring campaign, for which accurate bed topography, derived from an inversion of an ice sheet model study, is essential for identifying appropriate field sites. Renland is a small ice cap in Eastern Greenland at high elevation and surrounded by a fjord landscape which presents a large challenge to surface mass balance calculated with a conventional regional climate model. In addition, there is very little local climate data to assist in refining model estimates.

The very high resolution (0.05 degrees) HIRHAM5 regional climate model outputs climate and surface mass balance variables at a uniquely high resolution which captures the essential patterns of seasonal and interannual variability in this area. Evaluation against data from similar field sites in other locations indicates that HIRHAM, forced by ERA-Interim reanalysis, is able to accurately calculate glacier surface mass balance but for a finer resolved pattern of SMB, further statistical downscaling is necessary. For the Renland ice cap, HIRHAM output is scaled statistically to a resolution of a few hundred metres to further refine SMB estimates in order to compare the ice sheet topography derived from Pism with estimates derived from remote sensing and earlier geophysical investigations.

IACS (Cryosphere)

C11b - C11 Climate Downscaling for Modelling Glacier Mass Balance

IUGG-1037

Precipitation downscaling in complex terrain for modelling glacier mass balance: Principles, challenges and open scientific issues

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While the large-scale climate conditions play an important role in shaping the environment in which glaciers exist, the mass and energy balance of each individual glacier is dictated by local conditions. Given the complex mountain topography around alpine glaciers it is not trivial to find a direct link between the large-scale atmospheric state, which is usually provided by coarse models, and the local-scale weather conditions at an individual glacier. Distributed alpine glacier models usually require high resolution climate forcing to adequately represent the ablation and accumulation processes. In particular resolving the scale-discrepancy of precipitation in complex terrain has proven to be critical and remains a major challenge also in future. Bridging the scale gap requires appropriate assumptions about the spatial and temporal distribution, and the pertinent question is what assumptions are appropriate given the nature of the specific problem addressed. This is reflected by the vast number of downscaling algorithms and methods which rely on fundamentally different assumptions. Which approach best fits the specific problem depends on the local characteristics, data availability and computational cost. Moreover, the generality of the downscaling techniques cannot sufficiently be verified due to the sparsity of monitoring activities on the glacier and its surroundings. This talk reviews commonly used precipitation downscaling techniques in complex terrain, its challenges and limitations. Open scientific issues will be discussed, along with issues related to glacier mass balance modelling studies.

IACS (Cryosphere)

C11b - C11 Climate Downscaling for Modelling Glacier Mass Balance

IUGG-1749

Statistical downscaling for data-sparse, glaciated mountain environments

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The scarcity of atmospheric data near and on mountain glaciers is a primary factor that inhibits area-wide glacier mass simulations over longer periods. In this study, we review statistical downscaling techniques for variables required in process-based glacier mass modelling. The importance of predictor selection is outlined for the different variables, and “a priori” versus data-based selection concepts are presented. Particular emphasis is put on appropriately considering the pitfalls of short observational data records that are typical of high mountains.
We show application examples with short-term, high-resolution target variables measured in the glaciated Cordillera Blanca, Peru (e.g., daily air temperature, relative humidity and precipitation), and various reanalysis data sets as the predictors. Our results show that accounting for natural periodicity in the downscaling procedure is vital in order to eliminate seasonality in the model error, and to avoid spuriously high performances of certain predictors. In the case of air temperature, at least 40 to 140 training observations are required - within each calendar month - to obtain statistically significant skill with regard to intra-seasonal and inter-annual variability. The selection of the appropriate reanalysis data set strongly affects the performance of the developed downscaling model.

IACS (Cryosphere)

C11b - C11 Climate Downscaling for Modelling Glacier Mass Balance

IUGG-2480

A new statistical downscaling tool to retrieve glacier surface energy balance fluxes from large-scale atmospheric data

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Glacier surface energy and mass balance (SEB/SMB) modelling requires in-situ meteorological measurements as well as complex and computationally expensive numerical models. The available time series of SEB fluxes are therefore very short, and the existing models not applicable on decadal or even longer timescales. Some glaciers (especially at high altitude in the tropics) are shown to be less sensitive to temperature than for example mid-latitude glaciers, thus standard approaches based on temperature only may be inappropriate for glacier mass balance variability studies. The starting point of this work is a four-year long time series of distributed SEB/SMB at Shallap Glacier, southern Cordillera Blanca, calculated using a process-based model driven by in-situ observations. We use these data to calibrate a fully automated regression-based statistical downscaling tool, developed especially to downscale the individual SEB/SMB fluxes from large-scale gridded atmospheric data on a monthly basis (in this study, ERA-Interim). Albeit some limitations inherent to the mass balance model and to the statistical downscaling strategy, the skill of the model evaluated by robust cross-validation allows a comprehensive evaluation of the ENSO influence on glacier SEB/SMB fluxes for the longer period 1980-2013. The presented open-source downscaling tool, written in the Python programming language and relying on widely used machine-learning libraries, can be applied easily to other glaciers and/or atmospheric datasets, providing a new way to extend observed SEB/SMB time series to much longer time scales.

IACS (Cryosphere)

C11b - C11 Climate Downscaling for Modelling Glacier Mass Balance

IUGG-4350

Lapse rate based versus fully-dynamical meteorological downscaling for high-resolution modelling of snowpack and glacier mass balance in alpine terrain

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In regions of complex topography, the spatio-temporal variability of meteorological conditions governs the evolution of seasonal snowpack over glacierized and non-glacierized areas. Capturing this variability at fine scale is necessary for modelling snowpack and glacier mass balance. In this study, we compare two downscaling methods of varying complexity to generate high-resolution atmospheric forcing (500-m grid spacing) for distributed snowpack simulations applied over the French Alps (200*200 km²) for winter 2011-2012. The first method is a simple downscaling technique based on fixed lapse-rates and applied to operational outputs of the atmospheric model AROME at 2.5-km grid spacing. Such method is suitable for the downscaling of RCM outputs. The second method relies on a fully dynamical approach using a version of AROME at 500-m grid spacing.

Atmospheric forcings (air temperature and humidity, longwave and shortwave radiation) produced by the two methods are firstly compared against a network of automatic weather stations. Results are analysed as a function of station location (valley, mid- and high-altitude). The spatial pattern of seasonal snowfall and its dependency with elevation are then evaluated against output from the SAFRAN precipitation analysis specially developed for alpine terrain. Finally, results of snowpack simulations driven by the two kind of forcing are evaluated against (i) ground-based measurements of snow depth, (ii) maps of snow covered areas estimated from optical satellite data (MODIS) and (iii) measurements of winter mass balance of four glaciers.

Results of this study illustrate the benefit of using high-resolution atmospheric model to evaluate downscaling method of lower complexity for modelling snowpack and glacier mass balance.

IACS (Cryosphere)

C11b - C11 Climate Downscaling for Modelling Glacier Mass Balance

IUGG-5151

Generating high-resolution, gridded fields of near-surface air temperatures for the High Asia region.

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Near-surface air temperatures are necessary to estimate snow and ice melt whether temperature index or energy balance approaches are used. However, observations of these air temperatures in the mountains of High Asia are sparse, especially at elevations with seasonal snow cover and glaciers. Temperatures must either be extrapolated from valley stations that are often below the elevations of seasonal snow lines and glacier termini or derived from air temperatures from global or regional numerical weather prediction models. Biases between modelled surface temperatures and observations can be on the order of -4 C. Moreover, free-air lapse rates derived from upper air temperatures from weather models tend to be steeper than near-surface temperature gradients estimated as differences between nearby meteorological stations. Biases of this magnitude can have a substantial impact on melt estimates.

In this paper, we investigate differences between ERA-Interim, MERRA and CFSR reanalysis temperatures and observed near-surface temperatures, and explore methods to correct biases and modify free-air lapse rates to better estimate near-surface temperature gradients. We present a method that combines observed air temperatures and reanalysis temperatures to produce a “best estimate” of near-surface air temperature at 500 m resolution for the High Asia region. The approach assumes that near-surface temperature gradients result from a linear combination of free-air lapse rates and heating from the underlying land surface. Free-air lapse rates are derived from reanalysis temperatures. Surface heating terms are estimated from multivariable linear relationships between station temperatures and reanalysis variables. The approach is evaluated for the three reanalyses.

IACS (Cryosphere)

C11p - C11 Climate Downscaling for Modelling Glacier Mass Balance

C11p-292

HiRSvaC-500: Towards a high-resolution surface climatology for glacier mass-balance modelling on Svalbard

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Glacier mass-balance modelling on a regional-scale requires spatially distributed input data that reliably reproduce the variability of climate elements across different terrain situations. The spatial resolution of these data has to be chosen according to the degree of terrain complexity such that all major terrain features are accounted for sufficiently.

The glacierized areas on the Arctic archipelago of Svalbard are characterized by a highly variable terrain shape that reaches from large, flat and evenly formed ice caps to small, steep and narrow valley glaciers. This implies that the climate data that are intended to be used as input to mass-balance models needs to show horizontal resolutions in the order of hundreds of meters. However, due to the high level of complexity and variability of the terrain shape any downscaling that is aimed to result in data covering all glaciers and ice caps of the archipelago is especially challenging.

The newly developed HiRSvaC-500 (High Resolution Svalbard Climatology - 500 m) dataset is a combined product that shall provide surface albedo, solar radiation, air temperature and precipitation on one consistent 500 m grid covering all glaciers and ice caps on Svalbard. It is created by a combination of geostatistical modelling and statistical downscaling that is based on remote sensing data (MODIS), reanalysis data (ERA-Interim), regional climate modelling data (WRF) and a wealth of in situ measurements. The final version of the dataset will cover the period 1979-2014.

IACS (Cryosphere)

C11p - C11 Climate Downscaling for Modelling Glacier Mass Balance

C11p-293

A high-resolution view on Greenland Ice Sheet surface mass balance: Regional differences and trends

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We analyze the surface mass balance (SMB) in a 5 km horizontal resolution HIRHAM5 regional climate model simulation over Greenland. The simulation covers 1980-2014 and is forced by ERA-Interim reanalysis on the domain boundaries. The ice sheet is divided into 293 hydrological drainage basins (Lewis and Smith 2009) which are then grouped into four regions. This allows for a partitioning of the SMB and its components into positive and negative contributions from the individual basins and for analyses of regional differences.

Over the last decade of the simulation, an increased occurrence of negative-phase NAO summers leads to increased warm advection and declining cloud cover along the western coast. This results in a decreasing trend in the simulated annual total SMB, dominated by an upward trend in runoff with only a small negative trend in accumulation.

The southeast (SE) is the primary location for cyclone landfall in Greenland, and stands out as the region with the highest accumulation rates and occurrence of positive basin total SMBs. Due to a general warming, all regions see increasing runoff during the simulation. Particularly in the north, basins with near-zero runoff become less prevalent. This indicates that basins previously able to refreeze almost all summer melt are being eroded in cold content, and the northern runoff distributions change to look more like those in the south.

Refreezing is high in the north due to colder temperatures and in the SE due to high snowfall. Due to increasing temperatures and rain fractions, refreezing tend to decrease in all parts of Greenland. Accumulation generally decreases slightly across Greenland but in the SE there is an approximately equal number of basins that experience increases and decreases in accumulation.

IACS (Cryosphere)

C12a - C12 Coupling Processes between the Atmospheric Boundary-Layer and Snow/Ice Surfaces: Observations and Modelling

IUGG-2968

Downscaling regional wind forecasts to high resolution snow model forcings

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High resolution model forcings are required to adequately simulate snow accumulation, melt, and streamflow in mountain environments. Wind has been shown to play a vital role in these processes. Yet wind observations are sparse and rarely capture the large variability present in alpine regions. High resolution (1-10km grid scale) climate data is becoming more readily available but even these data are too coarse to properly represent alpine snow processes. Much attention has been focused on downscaling precipitation and air temperature for fine resolution modeling. However there is very little in the literature that has addressed techniques for downscaling wind speeds. Here we test the feasibility of inverting a proven technique for upscaling wind speeds from point observations to a high resolution grid (Winstral et al., 2009) for downscaling purposes. First, high resolution climate-model wind data were downscaled to a very high resolution grid (10m grid scale) for comparison to point data from the Reynolds Creek Experimental Watershed (RCEW) in Idaho, USA. The usefulness of this technique was then assessed by using a downscaled product (100m grid scale) to capture sub-grid variability of wind speeds in a 1km grid scale operational snow model applied across Switzerland. Seasonal and event-based comparisons of simulations with this model showed that accounting for the sub-grid variability of wind speeds using this method improved snow and melt simulations.

IACS (Cryosphere)

C12a - C12 Coupling Processes between the Atmospheric Boundary-Layer and Snow/Ice Surfaces: Observations and Modelling

IUGG-3242

High-resolution large eddy simulation of snow accumulation in alpine terrain

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Snow accumulation in alpine terrain is controlled by three main processes that act at different scales: (i) orographic precipitation; (ii) preferential deposition of snowfall and (iii) wind-induced snow transport of previously deposited snow. The relative importance of these processes in controlling snow accumulation in complex terrain remains largely uncertain. This study presents how high-resolution coupled snowpack/atmosphere simulations help quantifying the effects of these processes. The simulation system consists of the detailed snowpack model Crocus coupled to the meso-scale atmospheric model Meso-NH used in Large Eddy Simulation (LES) mode. Dedicated routines allow the coupled model to explicitly simulate wind-induced snow transport.

Our case study is a snowfall event that occurred in February 2011 in the Grandes Rousses range (French Alps). Three nested domains at 450-, 150- and 50-m grid spacing allow the model to simulate the complex 3D precipitation and wind fields down to fine scale. We firstly assess the ability of the coupled model to reproduce meteorological conditions during the event (wind speed and direction, snowfall amount and blowing snow fluxes). The spatial variability of snowfall and snow accumulation is then considered. At 50-m grid spacing, snowfall shows local maxima on the leeside of mountain crests because of interactions between the near-surface flow field and cloud dynamics. Variograms show that the resultant spatial variability of snowfall is lower than the variability of snow accumulation when considering snow transport.

IACS (Cryosphere)

C12a - C12 Coupling Processes between the Atmospheric Boundary-Layer and Snow/Ice Surfaces: Observations and Modelling

IUGG-3621

Numerical simulations of drifting snow and drifting snow sublimation in the turbulent boundary layer

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Abstract: Drifting snow is a special process of mass-energy transport in the hydrological cycle of cryosphere. It can not only change the snow distribution, but also result in phase change of ice crystal into water vapor, which is so called drifting snow sublimation. Here, we take the coupling effects between wind and snow particles into account and present a 3-D drifting snow model with mixed grain size in the turbulent boundary layer. Then the drifting snow model was combined with balance equations for the heat and moisture of the atmosphere to simulate the physical process of drifting snow sublimation in the saltation layer. The results indicate that the drifting snow in the turbulent boundary layer has apparent a 3-D structure and snow streamers, which leads to an intermittent transport of the snow particles and spatial inhomogeneity, and the motion trajectories of snow particles, especially the small snow particles, are obviously affected by the turbulent fluctuation. The macro statistical results show that the average sublimation rate of drifting snow particles near surface increases linearly with the friction velocity; the snowdrift sublimation of saltating particles is greater than that of suspended particles when the friction velocity is less than 0.525 m/s, which indicates that the drifting snow sublimation in the saltation layer also plays a very important role in the whole snow sublimation.

IACS (Cryosphere)

C12a - C12 Coupling Processes between the Atmospheric Boundary-Layer and Snow/Ice Surfaces: Observations and Modelling

IUGG-4752

3-D simulations of snow transport, erosion and deposition using a Large Eddy Simulation coupled with a Lagrangian Stochastic Model

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The development of reliable models of near surface snow-atmosphere interactions from small to large scale is motivated by the need for a better understanding of the fluid- and morpho-dynamic processes in Polar environments. These interactions drive observed spatial patterns of snow distribution, ice deformation, travel and distribution of sea ice, among many others. However, challenges arise when representing the detailed sequence of processes involved, such as aerodynamic entrainment, particle dynamics, feedback on fluid momentum and particle impact on the surface. Here, we test a Lagrangian Stochastic Model of snow particle transport coupled to a Large Eddy Simulation to represent particle dynamics in turbulent flows and momentum extraction caused by suspended particles. An Immersed Boundary Method is adopted to effectively reproduce surface erosion and deposition, both of which influence surface drag and turbulence statistics. The model is implemented to represent snow redistribution over an Antarctic sea ice floe over which pre- and post- storm snow distribution patterns were successfully quantified using a terrestrial laser scanner. The dataset collected in October 2012 as part of the SIPEX-2 indicates marked changes in the snow distribution as a result of particle transport processes, providing valuable testing grounds for the model. The modeled snow surface pattern and the spatially variable shear stress evolve and reciprocally interact, generating areas of preferential deposition and erosion consistent with the observations. Model results and future improvements are discussed.

IACS (Cryosphere)

C12a - C12 Coupling Processes between the Atmospheric Boundary-Layer and Snow/Ice Surfaces: Observations and Modelling

IUGG-4761

How to quantify particle numbers and mass flux in drifting snow?

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Several methods to quantify particle number flux and mass flux were presented in the past, such as snow traps, snow particle counter (SPC), a laser diode based particle detector or methods such as particle tracking velocimetry based on digital shadowgraph imaging (SG), which record a two dimensional image of saltating particles. The current study compares two of the most common methods, SPC and SG. The two methods were correlated to each other based on particle number flux and mass flux. For the SPC measurements, the device was calibrated by the manufacturer beforehand. The SG setup is based on a digital shadowgraph imaging setup.

A calibration study with artificially scattered sand particles and glass beads allowed finding suitable settings for the SG as well as getting a first correlation of the two methods in a controlled environment. In addition, using snow collected in trays during snowfall periods, several experiments were performed to observe drifting snow events in a cold wind tunnel. First results demonstrate good correlation between the mass flux signals for the calibration studies (r between 0.6 and 0.8) and moderate to low correlation for the drifting snow experiments (r approx. 0.45). This decreased correlation in mass flux originates from the fact that the processing of the drifting snow experiments with the SG detects a higher number of particles with large diameter compared to the SPC. This study addresses several topics. It discusses general advantages and disadvantages of the two systems with respect to quantifying saltation. Furthermore it helps to optimize the settings of the digital shadowgraph imaging system for both, acquisition and processing of particles in a drifting snow event.

IACS (Cryosphere)

C12b - C12 Coupling Processes between the Atmospheric Boundary-Layer and Snow/Ice Surfaces: Observations and Modelling

C12p-504

MeteoIO: A Pre-Processing Library for Numerical Models

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The MeteoIO library has been designed to offer robust and flexible meteorological data pre-processing to numerical models allowing the models developers to focus on core modeling issues while still enabling the direct use of raw measurements data. The whole task of data pre-processing has been delegated to this library, namely retrieving, filtering and re-sampling the data if necessary as well as providing parametrizations and spatial interpolations. The focus has been to design an Application Programming Interface (API) that (i) provides a uniform interface to meteorological data in the models; (ii) hides the complexity of the processing taking place; (iii) guarantees a robust behavior in case of format or transmission errors, erroneous or missing data. A strong emphasis has been put on simplicity and modularity in order to make it extremely easy to support new data formats or protocols and to allow contributors with diverse backgrounds to participate. This library is released under an Open Source license and is available at https://models.slf.ch/p/meteoio .

Several of the advanced, physically based data filtering and correction algorithms implemented in this library as well as several important parametrizations that can be used to generate missing measured parameters are evaluated and compared in the context of energy balance modeling of snow. This leads to recommendations on the usage of such algorithms as well as highlights their limitations.

IACS (Cryosphere)

C12b - C12 Coupling Processes between the Atmospheric Boundary-Layer and Snow/Ice Surfaces: Observations and Modelling

IUGG-1363

Seasonal variations of the air-snow drag coefficients in coastal Adélie land, East Antarctica

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Neutral stability 10-m air-snow drag coefficients CDN10 has been computed from more than 5,300 half-hourly averaged, six-level wind speed profiles collected in coastal Adélie Land from December 2012 to December 2013. Values range from 0.8 x 10^-3 to 5 x 10^-3. The whole dataset shows a clear seasonality of the CDN10; despite stronger wind speeds due to the enhanced katabatic forcing in winter, the CDN10 remains substantially lower compared to the summer situation. Our measurement site experienced drifting snow more than 60% of the time during the observational period, so that the wind frequently reshaped the snow surface, building and/or eroding sastrugi-like snowdrifts in the main wind direction and thus altering its aerodynamic roughness. Wind-deposited snow is often densely packed, providing a large number of contact points and hence bonds. Snow particles bonding is monotonically related to temperature. Consequently, during winter, the aerodynamical adjustment of the snow surface efficiently reduces the total surface drag. In contrast, when the temperature reaches its maximum values in summer, the snowpack resistance determining the threshold condition for aeolian snow transport increases more rapidly through the enhanced formation of ice bonds. This leads to a more cohesive surface which tends to inhibit snow erosion. The implication is that the snow surface is not smooth, and then CDN10 remains high. Substantial precipitation events can partly compensate this effect.

IACS (Cryosphere)

C12b - C12 Coupling Processes between the Atmospheric Boundary-Layer and Snow/Ice Surfaces: Observations and Modelling

IUGG-1828

Snow Surface Roughness Quantification from Geometry Using Various Methods

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The snow surface is the interface between the atmosphere and the earth. It is very dynamic, and varies spatially and temporally. Its roughness influences turbulence and is used to estimate the sensible and latent heat fluxes to and/or from the snow surface to the atmosphere. We used different metrics, including the random roughness, autocorrelation, and fractal dimension, geometric roughness length, curvature, and power spectrum density to characterize the roughness of a typical snow surface. The data for the surface come from airborne lidar measurements taken during from the NASA Cold Land Process Experiment in late March 2003 at the Fraser Alpine intensive study area. The surface elevation data were rotated to be parallel to the dominant wind direction and were interpolated to a 1-m resolution. We provide a comparison of methods and present their possible applicability for other datasets.

IACS (Cryosphere)

C12b - C12 Coupling Processes between the Atmospheric Boundary-Layer and Snow/Ice Surfaces: Observations and Modelling

IUGG-2615

Assessment of turbulent flux parametrizations over snow using different stability corrections

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Modeling turbulent fluxes over snow is challenging because atmospheric stability has often a strong influence on turbulent mixing in the boundary layer that is difficult to quantify. The aim of this study is the assessment of the validity of Monin Obukhov theory and the evaluation of the performance of different stability corrections by comparing measured and modeled turbulent sensible heat fluxes.

For that purpose, we first conducted a comprehensive analysis of the existence of a constant flux layer (CFL) by analyzing the vertical evolution of turbulent sensible heat fluxes at the four different test sites in the Swiss Alps and Eastern Antarctica. Measured sensible heat fluxes were then compared against modeled fluxes using the physics-based model SNOWPACK. Turbulent fluxes are calculated using the Monin Obukhov bulk formulation with different stability corrections. Three already published stability corrections were evaluated and compared with the assumption of a neutrally forced boundary layer. The findings of our study were classified in events with and without a CFL.

The analysis of all data sets shows that the CFL totally occurs in 10 % of the time, particularly in the morning. The CFL was most frequently observed for situations characterized by high wind speeds (> 3 m/s) and/or large differences between the snow surface and air temperature.

The mean errors are up to 10 W/m² larger for situations without measured CFL compared to cases with an existing CFL. The mean error of the sensible heat flux is lowest applying the stability correction of Holtslag and de Bruin (1988) and highest assuming a neutral boundary layer. The stability correction of Stearns and Weidner (1993) (modified by Michlmayr et al. 2008) performs worse than a simple Log-Linear approach.

IACS (Cryosphere)

C12b - C12 Coupling Processes between the Atmospheric Boundary-Layer and Snow/Ice Surfaces: Observations and Modelling

IUGG-5200

GABLS4: an inter-comparison case to study the stable boundary layer on the Antarctic plateau

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Within GABLS (GEWEX Atmospheric Boundary Layer Study), inter-comparison studies focus on boundary-layer parametrisation schemes in use by numerical weather prediction and climate models. In polar regions and under stable stratifications, models still present large biases that are dependent on the parametrisations used for the surface and the boundary layer (Holtslag et al, 2013). The GABLS4 case aims at studying the interaction between the boundary layer and the surface in strong stability and during the diurnal transition focussing on the decrease of the turbulence. For those topics, a surface with a low conductivity and a high cooling potential, such as snow, is more accurate. The site of DomeC on the Antarctic Plateau was chosen for the availability of the in-situ measurements, the flat topography and the homogeneity of its surface. The boundary layer observations are retrieved from a 45m tower with 6 levels of sensors measuring temperature, wind and humidity (Genthon et al, 2013) and turbulent fluxes. The radiative fluxes and the temperature in the snow pack are also available. In fact, the case will consist of 3 inter-comparisons : Single Column Model (SCM), Large Eddy Simulation (LES) and land-snow model (LSM). It is organized in two phases. The first one is dedicated to the LSM and the SCM with an interactive surface (snow) scheme. Then, in the second one, the observed surface temperature will be prescribed in the SCM and in the LES models. Results from LES, SCM, LSM will be evaluated with the observations. Additionally, results from LES with their variability (or uncertainties) and with specific diagnostics, will be also used to evaluate SCM results.

IACS (Cryosphere)

C12c - C12 Coupling Processes between the Atmospheric Boundary-Layer and Snow/Ice Surfaces: Observations and Modelling

IUGG-3070

Ultra-low surface temperatures in East Antarctica and boundary layer air and snow interaction: The coldest places on Earth

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A new analysis of satellite thermal-band data over Antarctica has revealed sites where the wintertime surface skin temperature is frequently below -90°C, and can reach -93°C (-135°F) in isolated low pockets near the highest portion of the East Antarctic Ice Sheet. These appear to be the lowest surface temperatures on Earth. Strong near-surface gradients in air temperature are characteristic of the East Antarctic Plateau. We identify several sites near the East Antarctic ice divide crest that have had multiple low temperature events of <-90° C (<183.15 K, <-130°F) using satellite thermal-band data sets spanning 1983 to 2014. The low-temperature sites lie within small (typically 10 to 50 km^2) topographic basins of ~1 to 3 m closure, above 3800 m. The coldest measured temperature using the MYD11 MODIS Land Surface Temperature data set is -93.2°C (10 August, 2010, 81.80°S, 59.3°E). However, ~65 sites along the Dome A – Dome F divide have minimum temperatures within 2°C of this value, suggesting an external control. Temperature gradients of 6°C km^{-1} horizontally, and 3°C m^{-1} elevation, are seen at cold site margins, using Landsat 8 thermal-band data. A conceptual model of regional radiative surface cooling approaching equilibrium with a high-altitude thermal minimum and cloud layer, modified by local gravity-driven flow of near-surface air, and pooling of air in the topographic lows leading to further cooling, is presented.

IACS (Cryosphere)

C12c - C12 Coupling Processes between the Atmospheric Boundary-Layer and Snow/Ice Surfaces: Observations and Modelling

IUGG-3148

Modelling the distribution of surface hoar layers

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Surface hoar crystals form when water vapour from the atmospheric boundary layer sublimates on the snow surface. Avalanche forecasters track the distribution of surface hoar layers in mountainous terrain, as they are prone to releasing slab avalanches. Their distribution is affected by atmospheric and micro-meteorological conditions. We evaluate maps of modelled surface hoar produced by forcing the snow cover model SNOWPACK with gridded data from a numeric weather prediction (NWP) model. Surface hoar layers were mapped over two winters with forecast data from Environment Canada's high resolution NWP model (2.5 km). The maps were verified with field studies in 2013-2014. The maps resolved regional patterns (roughly 20 km wide) caused by different atmospheric conditions such as cloud cover and humidity. Changes over elevation within these regions were also resolved, such as less surface hoar at higher elevations because of higher wind speed. We also modelled variations caused by slope angle and aspect with SNOWPACK, but found inconsistent agreement with field observations. Modelling the distribution of surface hoar layers in complex terrain is clearly challenging, but general regional and elevation patterns can be adequately resolved with NWP data. Accordingly, operational maps were produced in 2014-2015 to help members of the Canadian Avalanche Association forecast the distribution of surface hoar layers in western Canada.

IACS (Cryosphere)

C12c - C12 Coupling Processes between the Atmospheric Boundary-Layer and Snow/Ice Surfaces: Observations and Modelling

IUGG-3694

The value of observations of atmospheric-snow chemical exchanges in the interpretation of boundary layer processes over Antarctica

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A number of boundary layer chemistry experiments have been carried out in Antarctica at the South Pole. These include the Investigation of Sulfur Chemistry in the Antarctic Troposphere (ISCAT: 1998 and 2000); and the Antarctic Tropospheric Chemistry Investigation (ANTCI: 2003, 2005 and 2006) (Eisele et al. 2008). At the South Pole, the chemistry at the surface associated with the photolysis of nitrate in the snow, its release into the BL and its subsequent recycling have been found to be strongly influenced by the cycle in BL turbulence and depth (Davis et al. 2008; Neff et al. 2008, Atmos. Env.). Here we use observations from the multi-year ISCAT and ANTCI programs to analyze the interplay of chemistry and meteorology in the boundary layer at the South Pole in the context of meso- and synoptic-scale variability. We highlight how seasonal changes and variability in the large scale dynamics of the atmosphere over Antarctica can be reflected in surface chemistry in the following ways: 1) with the breakup of the ozone hole in the spring, radiative forcing of photolysis changes, 2) transport regimes over the continent change as the thermal tropopause reforms, 3) from spring into summer, high winds, blowing snow, accumulation and strong surface inversions typically give way to periods of ablation, weaker surface inversions, and higher temperatures. As these transitions occur we find significant changes in boundary layer depth, fetch, and resulting changes in NOx concentrations. These analyses show how the chemistry measurements help to interpret the behavior of the boundary layer and associated surface exchange processes.

IACS (Cryosphere)

C12c - C12 Coupling Processes between the Atmospheric Boundary-Layer and Snow/Ice Surfaces: Observations and Modelling

IUGG-4667

Measurements and modelling of surface energy balance at a glacier in the Interior Mountains, British Columbia

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Energy balance melt models provide the most physically-based method to model surface mass balance for a glacier since they account for radiative and turbulent exchanges occurring at the snow or ice surface. Direct measurements of turbulent fluxes, however, are uncommon given the complexity of making reliable measurements of turbulent energy exchange on alpine glaciers. Most studies thus rely on the bulk aerodynamic method used to parameterize turbulent fluxes; an approach that may be inaccurate due to poorly specified empirical coefficients. Here we present measurements of radiative and turbulent energy fluxes for an alpine glacier in the Interior Mountains of British Columbia for ablation season in 2010 and 2012. We evaluate the performance of an energy balance model in simulating the in-situ surface melting on sub-daily scales and validate the performance of bulk methods in simulating the turbulent fluxes relative to directly measured fluxes by eddy covariance method.

IACS (Cryosphere)

C12c - C12 Coupling Processes between the Atmospheric Boundary-Layer and Snow/Ice Surfaces: Observations and Modelling

IUGG-5299

Large-eddy simulation of downburst events over a mid-latitude Alpine valley glacier

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The development of a persistent shallow downslope wind above glaciers is a well know phenomena, and commonly referred as glacier wind. Triggered by strong wind shears in the low-level jet region, bursts of turbulence can occur causing vertical mixing of heat and momentum. The episodic entrainment of warm air from the free atmosphere acts as an important “heat pump” for the glacier surface. Non-local dynamic effects due to the surrounding complex topography can significantly modify the spatial and temporal occurrence of these downburst events. We perform highly resolved and properly designed case experiments by large-eddy simulations with real topography to determine the sensitivity of the mixing process to the prevailing flow conditions at the head of Martell Valley in the central Ortler-Cevedale Group, Italy. The analysis of the turbulent kinetic energy budget highlight the importance of non-local processes on the local microclimates. In particular, lee rotors and enhanced valley winds promote the development of downburst events. The gain of heat in the stable boundary layer by vertical mixing of warm air at predestinated regions locally affects the surface fluxes. It is shown, that turbulent heat fluxes may be very different from one site to another and can have a profound effect on the local energy balance. Therefore, inferences from individual point-measurements on the spatial distribution of turbulent fluxes, as suggested by most studies, are hardly practicable in complex terrain.

IACS (Cryosphere)

C12c - C12 Coupling Processes between the Atmospheric Boundary-Layer and Snow/Ice Surfaces: Observations and Modelling

IUGG-5619

Enhanced heterogeneous nitrates photolysis on ice and potential impacts on NOx emissions

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Nitrates photolysis plays a key role in the chemistry of the polar boundary layer and of the lower troposphere over snow-covered areas (1). Using a combination of vibrational (2) and photo-absorption spectroscopies (3), we show that nitric acid is mostly dissociated upon its adsorption onto, and its dissolution within ice at temperatures as low 20K. Using amorphous solid water as a model substrate for the disordered surface layer at the interstitial air-ice interface, UV irradiation in the environmentally relevant n-pi* transition uncovers the fact that the photolysis rate are significantly higher for surface-bound nitrates compared to those dissolved within the bulk. The complex coupled interfacial transport and reaction kinetics result in the formation of a thin photochemically active layer at the surface of ice which may magnify the impact of surface-enhanced nitrates photolysis rates on ice thereby providing a significant contribution to the intense photochemical NO_x fluxes observed to emanate from the sunlit snowpack upon polar sunrise.

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IACS (Cryosphere)

C12p - C12 Coupling Processes between the Atmospheric Boundary-Layer and Snow/Ice Surfaces: Observations and Modelling

C12p-495

The low-level jet : a hint for understanding the turbulent structure of the summer boundary-layer above the antarctic plateau

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Observations along the 45m tower at Concordia station, Dome C (75°06 S, 123° E), Antarctica, have recently revealed a nocturnal low-level jet within the summer atmospheric boundary layer. This jet has been shown to be a climatological feature (present more than 90 % of the last 5 years December and January nights). It can appear down to 10m above the surface and its peak speed reaches 7-12m/s. Its formation has been attributed to an inertial oscillation which takes place in the nocturnal stable boundary-layer, at a height where the turbulent flux divergence starts to be negligible in the momentum budget in the evening.
While the height of the jet nose is a good indicator of where the surface shear turbulence is dissipated, its timing and its strenght are simple but robust clues to analyse the day-night transition and the associated turbulence cut-off. On one hand, this means that looking at the jet in the observations is a simple way to get an estimation of the nocturnal boundary layer height over the Dome C. On the other hand, the modelling of such a jet in very stable nocturnal boundary layers like antarctic ones could significantly help in evaluating the turbulence scheme of an atmospheric model.
A fourth case of the models intercomparison project GABLS (Gewex Atmospheric Boundary Layer Study 4) has started in July 2014 and is precisely focused on the summer boundary layer at Dome C. The simulations are currently dissected and the correct representation of the low-level jet is a key criterion of the analyses.

IACS (Cryosphere)

C12p - C12 Coupling Processes between the Atmospheric Boundary-Layer and Snow/Ice Surfaces: Observations and Modelling

C12p-496

Study of the upper boundary condition for a permafrost thermal model in the Qinghai-Tibet Plateau

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Global warming and engineering activities tend to warm the permafrost in the Qinghai-Tibet Plateau and make it susceptible to thaw. The upper thermal boundary condition is a key factor to determine the development of the underlying permafrost. Therefore, to protect the environment and develop effective designs for vital infrastructure in permafrost regions of the Qinghai-Tibet Plateau, it is very necessary to study the upper boundary condition for a permafrost thermal model in modeling possible permafrost degradation. In this study, the air, nature surface and ground temperatures have been observed for a long time in the different permafrost regions of the Qinghai-Tibet Plateau, and the relations among the air, nature surface and permafrost temperatures are analyzed. Furthermore, we use the output from a widely-used atmospheric forecast model to predict time series of air, nature surface and shallow ground temperatures, and then stepwise multiple regression is used to develop an equation that provides a best fit prediction of observational data using output from the atmospheric model. This approach bridges the scale difference between atmospheric models and permafrost thermal models, and allows for a wider range of factors to be used in predicting the thermal boundary condition. The upper boundary condition model can be used to predict future changes in boundary condition parameters under different scenarios of global warming factors. Future work will improve the upper boundary condition model with additional data sets from more cold regions sites, and on linking model output to permafrost thermal models used in evaluating the degradation of permafrost and guiding the engineering construction design.

IACS (Cryosphere)

C12p - C12 Coupling Processes between the Atmospheric Boundary-Layer and Snow/Ice Surfaces: Observations and Modelling

C12p-497

Observational studies seasonal frozen area of black soil hills of gently sloped farmland variation of available phosphorus during freeze-thaw period

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The research background is middle-deep (-2±1 m) seasonal frozen soil area in black soil in northeast China. In fall, the phosphorus contents in the postharvest black soil increased each year. The black soil hills of gently sloped farmland occupy 60% of the arable land. Thus further research on the variation of available phosphorus during the freeze-thaw period of black soil hills of gently sloped farmland topsoil is needed. The black topsoil was subjected to temperatures of from low -15.5 degree centigrade to 17.2 degree centigrade for 155 days. In freezing thawing period of black soil farmland systems were significantly different in soil before freezing, in freezing, freezing-thawing cycle period 3 times, after thawing at the same sampling position different depth sampling observation study. In this study analyzed the wild black soil slope farmland slope length of 168 m from its base at 100 m samples tested. The results show: available phosphorus content in the black soil hills of gently sloped farmland underground 0-1 cm / 1 cm-5 cm / 5 cm-10 cm soil at different depths by the freeze/thaw cycles were slightly increased after thawing, by cold front affecting after thawing underground 0-1 cm soil moisture content slightly decreased compared with before freezing, underground 1 cm-5 cm and 5 cm-10 cm soil moisture has been increased. Underground 15 cm-20 cm, 20 cm-30 cm, 30 cm-50 cm available phosphorus and soil moisture content have not changed much. It is suggest further research directions on the theoretical problems of black soil hills of gently sloped farmland available phosphorus and soil moisture content variation under effects of freeze/thaw event at different sampling location.

IACS (Cryosphere)

C12p - C12 Coupling Processes between the Atmospheric Boundary-Layer and Snow/Ice Surfaces: Observations and Modelling

C12p-499

Comparison of snow depth on the sea ice between buoys and CFSR data

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To understand snow depth distribution on Arctic sea ice, we compared the snow depth data on the Arctic multiyear sea ice obtained by Ice Mass Balance (IMB) buoys developed by CRREL (Cold Region Research and Engineering Laboratory) with reanalysis data of the Climate Forecast System Reanalysis (CFSR) provided by National Centers for Environmental Prediction (NCEP). In this study, we examined 23 buoys in 2002-2013. Although mean annual cycle of snow depth from the CFSR was reproduced well, the reanalysis data has a positive bias during winter and spring, and a negative bias during summer and autumn. Because the correlation coefficients between the reanalysis and observation are around 0.70 between October and December. Sea-ice thickness in the reanalysis was approximately 1 m thicker than the observations during all seasons. We investigated recent changes in snow depth and sea-ice growth rate during autumn and early winter using the reanalysis data. Due to enhanced cyclone activity and enhanced surface evaporation from the ice-free ocean, the increases in precipitation (i.e., snow depth) are seen over Chukchi and Beaufort seas, resulting in reduction of growth of thin ice during November. However, ice thickness anomaly in the CFSR reduced an insulating effect of the snow depth on sea-ice growth. We will discuss about sea ice thickness mass change using the 1-D thermodynamic model.

IACS (Cryosphere)

C12p - C12 Coupling Processes between the Atmospheric Boundary-Layer and Snow/Ice Surfaces: Observations and Modelling

C12p-500

Mass balance and runoff simulations for glacierized catchments in the Ötztal Alps (Austria)

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Assessing the amount of water resources stored in mountain catchments as snow and ice as well as the timing of meltwater production and the resulting runoff is of high interest for glaciological and hydrological applications and hydropower production. With the project MUSICALS (Multiscale Snow/Icemelt Discharge Simulations into Alpine Reservoirs) an attempt is made to identify and quantify water availability and runoff in alpine headwater catchments for time scales ranging from mid- to long-term (seasonal predictions to climate scenarios).

The hydroclimatological, process-based model AMUNDSEN is set up to simulate the energy balance at snow and ice surfaces, the glacier mass balance, and runoff for the catchments of the Gepatsch reservoir (Ötztal Alps, Austria). In AMUNDSEN, different types of snow and ice layers are distinguished and their distinct properties are accounted for. The initial ice thickness distribution is modeled with the digital elevation model and glacier outlines from the Austrian glacier inventory 1997. Meteorological forcing fields are derived by interpolating station recordings, while a novel parameterization for wind-induced snow redistribution based on topographic openness is applied to accurately describe the heterogeneous snow distribution in high Alpine terrain. Discharge generation from calculated meltwater production and precipitation is simulated using a linear reservoir cascade model.

Model performance is evaluated by comparing snow cover distributions derived from airborne laserscan measurements, as well as using glacier mass balance and runoff observations. As part of future research, a glacier evolution model will be coupled to the hydroclimatological model in order to apply the model framework for climate change scenarios.

IACS (Cryosphere)

C12p - C12 Coupling Processes between the Atmospheric Boundary-Layer and Snow/Ice Surfaces: Observations and Modelling

C12p-501

Particle transport property of snow particles using random-flight model of blowing snow

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It is known that massive particle transports such as the blowing snow and dust storm hold and develop through four physical sub-processes: aerodynamical entrainment, blown particle dynamics, splash caused by particle-bed collision, and wind modification. Also, the particle transport in the saltation layer is an important particle source to the suspension layer. In this study, we conduct numerical simulations using the random-flight model of blowing snow to reveal the turbulent transport property near the saltation layer.
This model considers four physical sub-processes in the aeolian particle transport. Fluid is treated as the boundary-layer turbulence, whereas dynamics of particle obey Newton’s equation of motion. Additionally, the interaction between fluid and particle is realized by the momentum exchange based on air drag and aerodynamical entrainment.
According to the total mass flux, longitudinal data of numerical simulations are divided into three phases: developmental stage, relaxation process, and steady state. A distinct transition height emerges on the vertical profile of friction velocity, and it quantitatively corresponds to mean saltation height. Further, the skin-friction velocity keeps roughly constant (< fluid threshold) despite initial conditions and upper boundary condition, whereas the friction velocity above the saltation layer accurately reflects the friction velocity at the upper boundary.

IACS (Cryosphere)

C12p - C12 Coupling Processes between the Atmospheric Boundary-Layer and Snow/Ice Surfaces: Observations and Modelling

C12p-502

The influence of air and tree temperature on sub-canopy incoming longwave radiation modelling

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Snowmelt in forested environments contributes substantially to spring surface runoff and is largely controlled by the surface radiation budget. In mid-latitude forested regions, the shading, absorption, and emission of incoming radiation causes significant spatial and temporal variation of incoming longwave radiation to the snow surface that is markedly different from unforested areas. Improved simulations of the sub-canopy energy fluxes will therefore reduce current uncertainty in snowmelt modeling in forested regions. Simulated incoming longwave radiation commonly uses a two-part model that partitions the up-looking hemispherical view between radiation coming from the sky (the sky-view fraction, SVF) and the forest (1-SVF), using estimates of emissivity and temperatures. This method was evaluated at two mid-latitude, forested, alpine sites in Switzerland between 2004 and 2014. Using air temperature as a proxy for canopy temperature, errors in simulations of incoming longwave radiation show similar diurnal patterns between six modelled years during the snowmelt period. Furthermore, sub-canopy vertical air temperature profiles lead to further uncertainties in the use of air temperatures as a proxy for canopy temperatures which are again similar between four modelled snowmelt seasons. In response to these long term simulations of sub-canopy longwave radiation, measurements of air and tree temperatures as well as incoming longwave radiation with increasing distances to tree trunks were collected at a third site between January and April 2014. Results show that simulations of sub-canopy incoming longwave radiation were improved by explicitly incorporating the trunk-view fraction (TVF) and its temperature into the traditional two-part model.

IACS (Cryosphere)

C12p - C12 Coupling Processes between the Atmospheric Boundary-Layer and Snow/Ice Surfaces: Observations and Modelling

C12p-503

A computation research of the snow deposition over complex terrains

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Abstract: The variations of snow distribution in time and space profoundly affect the hydrological cycle, climate system, and ecological and evolutionary change as well as other natural processes. Current studies concentrate on the effects of drifting and snowmelt on the distribution of snow on the ground. Here, we present a numerical study of the snowfall process involving snow particles of mixed grain size over complex terrain. A three-dimensional large eddy simulation (LES) code is used to predict the wind field by considering the fluid-solid coupling effect, and the Lagrangian particle tracking method is employed to track the movement of each snow particle. Our results suggest that the velocity of movement of snow particles in the air follows the Poisson distribution law, and the mean velocity increases with particle diameter. The vertical rate of descent of the snow particles plays a decisive role in the observed changes in the resultant velocity. The blocking effect of terrain with high relief is the principal factor that contributes to an uneven distribution of snow. The nonuniform wind field due to undulating topography will aggravate the phenomenon. Snow particles accumulate more readily on the windward slope than on the leeward slope, and the difference in snow depth between windward slope and leeward slope potentially increases as a result.

IACS (Cryosphere)

C12p - C12 Coupling Processes between the Atmospheric Boundary-Layer and Snow/Ice Surfaces: Observations and Modelling

C12p-505

Cooling by the melting of snowfall on the Toyama Plain during the winter monsoon

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The peaks of the appearance frequency of the surface air temperature during precipitation are clearly observed near the melting point of water on the Toyama Plain during the winter monsoon. The peaks could be explained by the hypothesis that the melting of snowfall is the primary cause of the cooling on the Toyama Plain. To verify this hypothesis, we investigated the relation of temperature between the inland and the coast using observed data in January from 1990 to 2009 and applied a simple estimation method of the cooling due to the melting of snowfall. The temperature on the Toyama Plain tends to remain around the melting point when the surface air temperature on the coast is higher than 273.15 K and lower than 277.15 K, which almost corresponds to the changeover from snowfall to rainfall. The relation is unclear when hardly any precipitation is observed. The simply estimated cooling by the melting of snowfall using the observed precipitation can also represents the cooling on the Toyama Plain. Accordingly, the local climatic temperature could be greatly influenced by advection of the air mass cooled by the melting of snowfall until the air mass reaches the Toyama Plain during the winter monsoon.

IACS (Cryosphere)

C12p - C12 Coupling Processes between the Atmospheric Boundary-Layer and Snow/Ice Surfaces: Observations and Modelling

C12p-506

Potential impact of glacier surface on local precipitation study based on microclimate observations in a continental glacier valley

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To study the potential impacts of glacier surface on local precipitation, we set up 12 Automatic Weather Stations (AWS) in a continental glacial valley in northwest China. Basic meteorological data were collected for more than one year and short-term radiosonde measurements were carried out to study the vertical structure of glacier and non-glacier surface boundary layer. The microclimate characteristics in the glacial valley were analyzed for elements such as temperature, relative humidity, wind direction and some rainfall events in the summer season. Atmospheric temperature inversion exists all the day on glacier surface while it only appears at night on non-glacier surface in the front of the glacier tongue. Temperature lapse rate reaches the maximum near the glacier tongue- the interface of glacier and non-glacier surface. The monthly total precipitation displays an interesting pattern in summer. If only light rain (<=10mm, most are convective rainfall here) were considered, the precipitation seems to increase with the distance closer to the glacier tongue. Three days of GPS radiosonde measurements also indicate obvious difference of inverse humidity layer and wind direction of boundary layers between glacier and non-glacier surface. Above results implied that the cooling effect of glacier surface may plays an important role on local microclimate in the glacier area, which have impact on local temperature, humidity, wind direction and even on local convective precipitation. While the ration of glacial cooling effect on local precipitation need some modeling work in the future.

IACS (Cryosphere)

C12p - C12 Coupling Processes between the Atmospheric Boundary-Layer and Snow/Ice Surfaces: Observations and Modelling

C12p-508

A high density observation station network in the Berchtesgaden Alps for snow hydrological model evaluation.

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Modeling the spatio-temporal distribution of snow cover properties (SWE and SD) in alpine environments is still very challenging. Frequently used model algorithms were often developed in regions and climatic conditions (e.g. flat, low-elevated and open terrain), different to them they are finally applied to (e.g. steep, high-elevated, wind-exposed, or forested). Snow model verification and validation in complex terrain are crucial in order to improve snow hydrological modeling in diverse mountainous landscapes. However, this requires high quality datasets with a high spatial distribution and temporal resolution.
We present an observation network providing data from 34 climate stations in the region of the Berchtesgaden Alps in southeastern Germany. Additionally a network of 25 snow monitoring stations (SnoMoS) and 10 time-lapse cameras was established in the investigated catchment (433 km^2) including paired stations at open and forested sites.
Measured SD and SWE data in different elevations and expositions, as well as at forested and open sites were analyzed to characterize the seasonal snow cover distribution. The data was then used to evaluate the snow cover distribution simulated by the physically based distributed hydrological models AMUNDSEN and WaSiM. Preliminary results show that the observed timing of seasonal snowfall and melt out dates as well as SD and SWE values are well reproduced by the models throughout a large range of elevations and expositions. The models are able to simulate the meteorological conditions and snow amounts inside forests but have shown to require very accurate input data characterizing the forest canopy.

IACS (Cryosphere)

C14a - C14 Snow: Physical Properties and Impact on the Cryosphere

IUGG-0548

Temporal trends of the ionic composition in the wintertime snow cover of two high alpine sampling sites over three decades

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Major element chemistry of snow packs was investigated at two high altitude glaciers, Wurtenkees and Goldbergkees (Hoher Sonnblick, 3106m a.s.l., Austrian Eastern Alps) over the time period 1987-2014. The sampling was carried out every spring (at the beginning of May) when winter accumulation generally ends and melting processes in the snow are still negligible. Concentrations of the major ions such as NH_4^+, SO_4^{2-}, NO_3^-, Ca^{2+}, Mg^{2+}, K^+, Na^+ and Cl^- were determined using ion chromatography (IC). Acidity, expressed through the concentration of H^+, was calculated from the measured pH of the samples. Source identification of the ions was performed using principal component analysis (PCA) and calculation of non-sea-salt proportions. Two anthropogenic clusters (Na^+, K^+, Cl^- and SO_4^{2-}, NO_3^-, NH_4^+) originating mainly from biomass burning, traffic or fossil fuel combustion as well as animal husbandry and one crustal cluster (Ca^{2+}, Mg^{2+}) originating from Saharan dust events or local geological input were found. Temporal trends in concentration for all major ions were analyzed using Kendall´s tau rank correlation coefficient. Significant decrease of SO_4^{2-}, NO_3^- and H^+ concentration at both sites were detected. This suggests that emission reductions of their precursor gases SO_2 and NO_x are effective. The snow pack concentrations were compared to concentration data measured with a wet-and-dry-only-sampler (WADOS) located at the summit of Sonnblick and to freshly fallen snow. Interestingly, concentrations of all ions measured in the snow pack are 2-5 times lower than in the WADOS but in freshly fallen snow, the differences are only significant for SO_4^{2-}, NO_3^- and NH_4^+. Possible reasons for these differences will be discussed.

IACS (Cryosphere)

C14a - C14 Snow: Physical Properties and Impact on the Cryosphere

IUGG-0920

Snow microstructure and modelling in support of permafrost science

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Permafrost underlies ~22% of the Northern Hemisphere ground surface and has been observed and projected to undergo severe degradation in the context of global warming. Yet, permafrost modelling is still a challenging task, even at monitoring stations where observations of ground properties exist. One of the main problems is the representation of the thermal properties of snow, which very much depend on snow microstructure and accumulation depth.

Here, we present the results of a spring campain lead on Samoylov Island, Lena Delta (72.4°N, 126.5°E), Siberia, where snow was investigated in terms of stratigraphy and microstructural parameters. Several snow profiles and transects were measured in order to characterise the snow over the polygonal tundra landscape. Cast snow samples were analysed by micro-computed tomography in the cold laboratory at SLF, Davos in order to calculate physical properties for relevant transport processes in the snowpack, such as thermal conductivity and permeability.

Additionally, the snow cover model SNOWPACK is applied at Samoylov, to assess its capability to represent a high-arctic snowpack. Overall, SNOWPACK predicts realistic profiles of physical and structural properties similar to the observed ones. This is an encouraging step for the application of snow modelling in support of the permafrost science community.

IACS (Cryosphere)

C14a - C14 Snow: Physical Properties and Impact on the Cryosphere

IUGG-2228

Modelling snow as a granular material with a microstructure-based discrete element approach

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While the evolution of the snow microstructure with metamorphism is fairly well known, the relation between snow microstructure and its mechanical properties is still poorly understood because of the complexity and the variability of the microstructure. To decipher this relation, we propose to conduct numerical mechanical experiments on snow samples whose microstructure is captured by tomography. We developed a model which takes advantage of the granular nature of snow under rapid and large deformations. The three-dimensional microtomographic images of the scanned samples are first decomposed into an assembly of grains, using geometrical criteria on curvature and contiguity. Second, the grains are used as geometrical inputs of a discrete element model accounting for grain re-arrangements through the failure of cohesive bonds and the creation of new contacts. The model is applied to different samples, spanning the different seasonal snow types, loaded under confined compression. The simulations show that the compression behaviour of snow is mainly dependent on density. Indeed, the simulated stress-density relationships follow a main trend with little variability. However, the mechanical behaviour observed during the first phase of the compression, which is due to the prime failure of bonds, cannot be accurately parameterized by density, but depends on the initial bonding system of the microstructure. The model appears thus capable of accounting for the role of the microstructure on the mechanical properties. It opens perspective for a better interpretation of the characterization of the snowpack with an indenter, and the investigation of the failure of weak layers under combined shear and compression.

IACS (Cryosphere)

C14a - C14 Snow: Physical Properties and Impact on the Cryosphere

IUGG-4992

Temporal evolution of weak layer and slab properties – and consequences for snow instability

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If a weak snow layer below a cohesive slab is present in the snow cover snow slab avalanches can be triggered by over-snow travellers such as skiers. In the case of persistent weak layers the unstable situation can prevail for days or even weeks – representing a formidable challenge for public avalanche forecasting as well as people travelling in avalanche terrain. In December 2014 a layer of faceted crystals was buried und subsequently was responsible for widespread avalanching in the region of Davos (Eastern Swiss Alps) – initially natural releases and subsequently human-triggered avalanches. We followed the evolution of this weak layer as well as the overlaying slab layers over almost two month at the location of an automatic weather station (AMS) in our field site above Davos. Whereas the slab thickness, and hence the load, steadily increased the weak layer only slowly gained strength. Several weeks after burial results of propagation saw tests indicated that propagation propensity was still relatively high. However, due to the increasing depth of the weak layer failure initiation propensity decreased. Repeated snow micro-penetrometer measurements allowed quantifying the temporal evolution of the weak layer as well as the slab properties. We then compared a newly developed measure of instability derived from the repeated SMP profiles with the results of the concurrently performed instability tests. The unique dataset provides for the first time a comprehensive time series of quantitative measures of snow instability. As the measurements were taken in the near vicinity of an AMS the data can be compared to the temporal evolution of the snow cover as provided by the numerical snow cover model SNOWPACK and its stability estimates can be validated.

IACS (Cryosphere)

C14a - C14 Snow: Physical Properties and Impact on the Cryosphere

IUGG-5749

Snow, vegetation, permafrost: On the relevance of snow processes and potential feedbacks in a thawing Arctic

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The Arctic is warming faster than other regions, due to the action of efficient feedbacks, such as the snow-albedo feedback, whereby the replacement of snow by darker surfaces positively feedbacks on climate. Another crucial feedback with global consequences is the thawing of permafrost, and the subsequent release of its organic compounds as CO_2 and CH_4 to the atmosphere. Since permafrost stores twice as much carbon as the atmosphere, the effects could be dramatic. Predicting how fast permafrost will thaw is the first step in understanding its carbon release. The relationship between permafrost and air temperatures is complex, because variations in vegetation and snow cover strongly impact energy exchanges between the atmosphere and the ground. Snow physical properties, such as albedo, thickness and thermal conductivity modify these energy exchanges by a factor of 10 or more in winter. Here, we focus on how interactions between climate, vegetation and snow affect heat fluxes through snow. In the Arctic, the warming-induced growth of higher vegetation such as shrubs lead to snow trapping, increased snow depth and the shielding of snow from wind erosion. Snow physical properties also change, with the partial replacement of wind slabs by layers of depth hoar of lower thermal conductivity. This limits winter ground cooling, accelerating permafrost warming. Other effects of shrubs include the decrease in snow albedo due to absorption of radiation by shrubs covered by the snow. These point heat sources also modify snow metamorphism and therefore its physical properties. Several examples will be detailed to illustrate the complexity of snow-vegetation-climate interactions, and the need to study them before reliable predictions of the rate of permafrost thawing can be made.

IACS (Cryosphere)

C14b - C14 Snow: Physical Properties and Impact on the Cryosphere

IUGG-0616

Stratigraphy and snow properties of polar snowpacks: requirements from a modelling perspective

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This paper reviews the problem of how to develop models of polar snow which are physics-based, internally-consistent, can be validated and provide information in a useful form. Such models are needed in a wide-range of applications, for example to determine the age difference between a gas bubble and the ice in which it is trapped (important for determining past climate from ice cores), to interpret remote sensing data (important in polar regions where ground data are sparse) and to predict the future behaviour of the global climate system. Physics-based models treat snow as a continuum, with conservation laws supplemented by constitutive equations describing the bulk properties of the snow. These are derived either by a microscale approach, focussing on the physics of individual snow grains, with up-scaling to the differential volume of the model, or by a macroscale, phenomenological approach. In both cases, the challenge is to ensure that essential details of the complex behaviour of snow are not lost by averaging and that the various simplifying assumptions made in deriving different part of the snow model are all consistent.

IACS (Cryosphere)

C14b - C14 Snow: Physical Properties and Impact on the Cryosphere

IUGG-2908

Densification of layered firn of the ice sheet at Dome Fuji, Antarctica

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In order to better understand the densification of polar firn, firn cores from three sites within approximately 10 km of Dome Fuji, Antarctica, were investigated, using surrogates of density: dielectric permittivities ε_v and ε_h at microwave frequencies with electrical fields in the vertical and the horizontal planes, respectively. Dielectric anisotropy $\Delta\varepsilon(= \varepsilon_v - \varepsilon_h)$ was then examined as a surrogate of the anisotropic geometry of firn. Firn was found to become denser as a result of complex effects of two phenomena that commonly occur at the three sites. Basically, firn with initially smaller density and smaller geometrical anisotropy deforms preferentially throughout the densification process due to textural effects. Second, layers having a higher concentration of Cl^- ions deform preferentially at depths from the surface to approximately 30 m. We argue that Cl^- ions dissociated from sea salts softened firn due to modulation of dislocation movement, but that the layered deformation ceases when Cl^- is smoothed out by diffusion. Moreover, firn differs markedly between the three sites in terms of strength of geometrical anisotropy, mean rate of densification, and density fluctuation. We suggest that these differences are caused by textural effects resulting from differences in depositional conditions within various spatial scales.

IACS (Cryosphere)

C14b - C14 Snow: Physical Properties and Impact on the Cryosphere

IUGG-3732

Stratigraphy and microstructure of Antarctic snow

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The stratigraphy in Antarctica is a complex product of depositional and metamorphic processes. The depositional process is dominated by frequent re-deposition and rare atmospheric precipitation. Metamorphism is a ubiquitous and significant process occurring at the near surface of snow and firn. Relatively little is known about how snow metamorphism affects the physical and mechanical properties of snow in Antarctica, and observations are difficult by traditional means. One reason for the lack of knowledge is that depositional and metamorphic processes occur concurrently. Near-infrared photography, quantitative translucent profiles, high-resolution penetrometry and micro-tomography are modern methods capable to improve knowledge of Antarctic snowpacks. These instruments gather detailed stratigraphic information at multiple scales. We applied these methods at three different sites in Antarctica: Allan Hills, Pointe Barnola and Kohnen Station. The characteristic stratigraphy and microstructures found at these locations is presented and interpreted. The new methods are very efficient to reveal the complex structures and to characterize layer thickness and variability. Based on our observations, we show that alternating temperature gradient metamorphism, which is the dominant type of metamorphism at the surface, has a strong effect on the re-mobilization of the hard snow surface during austral summer, and temperature gradient metamorphism is important during winter. Large erosional events, removing multiple years of deposition, can occur, and have a marked impact on stratigraphy.

IACS (Cryosphere)

C14b - C14 Snow: Physical Properties and Impact on the Cryosphere

IUGG-3864

Polar snow and firn – Linking in-situ data and model requirements

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Polar snow and firn is studied on very different scales using a variety of methods. Spatial and temporal scales of the observations range from lab-studies on the micro-scale, snow pit and firn core analyses on a cm-scale up to km- and continental scale analyses using ground penetrating radar, airborne and satellite remote sensing. However, synthesizing the information obtained on the different scales is a continuous challenge. The spatial and temporal representativeness of single snow pit and firn core data is under debate, as is the use of too simplified statistics of snow and firn properties in radiative transfer models for the analysis of remote sensing data. Aim of this study is to bridge the gap between the different scales and methods. Using in-situ measurements of specific surface area and high-resolution density records, we discuss, how snow and firn can be better represented in and by (radiative transfer) models considering microstructure and stratigraphy.

IACS (Cryosphere)

C14b - C14 Snow: Physical Properties and Impact on the Cryosphere

IUGG-4425

Linking snow microstructure to its macroscopic elastic properties: A 3D numerical homogenization method and its application to tomographic images

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Snow is a highly porous material that exhibits a complex microstructure constantly evolving in time. Because overall mechanical properties of snow are strongly influenced by its density (Mellor 1974) and the topology of its microstructure (Shapiro et al. 1997), a correct multi-scale modeling of its mechanical properties is of great interest when it comes to avalanche risk forecasting.

We propose a modeling of the homogeneous behavior of snow based on the combined use of microtomography imaging and the resolution of Kinematically Uniform Boundary Condition (KUBC) problems derived from the homogenization theories. Snow is modeled as a porous cohesive material, and its 3D macroscopic mechanical behavior is explored within the framework of the elastic behavior of ice (Schulson et al. 2009). Based on the integral range theory (Lantuejoul 1991, Kanit et al. 2003), a convergence analysis is performed in terms of physical and not only geometrical parameters. This provides an accurate definition of the representative elementary volume to be used in numerical simulations.

A wide range of snow densities is explored (100 – 600 kg/m^3) and a simple power law is proposed in order to link the Young and shear moduli of snow to its density. Thanks to the study of three temporal series, the influence of the main types of metamorphism (temperature gradient, wet snow and isothermal metamorphism) on the macroscopic elastic properties of snow is recovered in details through numerical simulations.

Finally, the proposed methodology can be easily applied to investigate a more complex behavior of the snow such as its 3D viscoplastic behavior. Such a work is currently in progress and preliminary results will be shown.

IACS (Cryosphere)

C14p - C14 Snow: Physical Properties and Impact on the Cryosphere

C14p-019

Macroscopic modeling for heat and water vapor transfer with phase change in dry snow by homogenization

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At the microscopic scale, i.e. pore scale, dry snow metamorphism is mainly driven by the heat and water vapor transfer and the sublimation-deposition process at the ice-air interface. Up to now, the description of these phenomena at the macroscopic scale, i.e. snow layer scale, in the snowpack models used for avalanche forecast, climate studies…, has been proposed in a phenomenological way. Differences can be found between these models, concerning e.g. the phenomena taken into account or the definition of the effective properties.
In this work, we used an upscaling method, namely the homogenization of multiple scale expansions, to derive theoretically the macroscopic equivalent modeling of heat and vapor transfer through a snow layer from the physics at the pore scale. The phenomena at the pore scale under consideration are heat transfer by conduction and convection, vapor transport by diffusion and convection, and phase change. The method is based on dimensionless numbers that characterize the relative intensity of the physical phenomena at the pore scale, and thus drive the expression of these phenomena at the macroscopic scale. Accordingly, we show that three main macroscopic modeling must be considered, depending mostly on the air flow intensity, i.e. the pore Reynolds and Péclet numbers. The definition of all terms arising in these modeling is provided, in particular the effective properties (effective diffusion tensor, intrinsic permeability tensor...) and the macroscopic source terms of heat and vapor arising from the phase change at the pore scale. We show that such source terms can have a significant influence on transfers when the snow layer undergoes large temperature gradients. Finally, we illustrate the macroscopic modeling through 2D numerical simulations.

IACS (Cryosphere)

C14p - C14 Snow: Physical Properties and Impact on the Cryosphere

C14p-020

Annual evolution of snow albedo in the Pyrenees and Sierra Nevada (Spain): implications for snow modelling.

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Albedo is a key component of the radiative balance in snow covered environments. However, little research has been conducted about the evolution of albedo during the snow season and about the suitability of decay functions for Mediterranean areas. In this study, we use albedometers of two automatic meteorological stations located in the Spanish Pyrenees (42ºN) and Sierra Nevada (37ºN) at 2056 and 2100 m as.l respectively. Both stations present contrasted climatic conditions that lead to a continuous snowpack in the former from late autumn to late spring, and a more ephemeral snowpack in the latter. These data are used to analyze the main characteristics of albedo in both sites, and to identify events of albedo decay after snowfall in order to identify the initial albedo, the daily rate of albedo decay and the best function that fits such decay. Those indicators are related with the air temperature, occurrence of rainfall events and incoming solar radiation during those days. Results inform that generally albedo is lower and albedo decay is faster in Sierra Nevada compared to Pyrenees as a consequence of faster snow metamorphism after snowfalls. In general, a linear decay provide very similar accuracy compared to negative exponential functions, but the slope of the function varies noticeably among events, with a tendency to be steeper as the snow season advance. Results show that using single approaches to parameterize albedo evolution may induce non-negligible errors in the simulation of the radiative balance of snowpack but this is not always the major source of uncertainty when the whole energy balance of the snowpack is simulated.

IACS (Cryosphere)

C14p - C14 Snow: Physical Properties and Impact on the Cryosphere

C14p-021

Investigating spatio-temporal forest-snowpack interactions

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The spatial deposition of snow and following metamorphism determines snowpack stratigraphy, the layering within seasonal snowpacks with varying microstructural properties such as hardness, grain size, and grain shape. Forests modify precipitation, wind, radiation and temperature regimes and therefore snowpack properties compared to open non-forested areas, resulting in a much different snowpack stratigraphy over time and space. Bark beetle outbreaks cause drastic changes in canopy structure, composition, and function of forests with little known consequences for, e.g. avalanche hazards and snow dominated hydrology regimes.

Snowpack observations in forested terrain are rare and typically describe layering and related microstructural properties by point observations with snow pit profiles, which do not adequately describe spatio-temporal forest-snowpack interactions. To increase our understanding of the spatial and temporal patterns of these interactions, we examined the stratigraphy of the subcanopy snowpack. Weekly Snow Micro Penetrometer (SMP) measurements were recorded along 10 m transects at 0.3 m intervals during three winter months beneath canopies of (1) undisturbed forests, (2) forests 3^{+}years after a spruce beetle infestation, and (3) harvested Engelmann spruce stands in the central Rocky Mountains in Utah, USA.

The collected spatio-temporal data combined with meteorological observations allows us to characterize the evolution of the snowpack stratigraphy as a function of tree-to-tree spacing, canopy type and disturbance history. We expect to gain a quantifiable representation of the subcanopy snowpack which will contribute to assessing consequences of a changing forest cover due to natural disturbances or forest management for snow hydrology and natural hazards.

IACS (Cryosphere)

C14p - C14 Snow: Physical Properties and Impact on the Cryosphere

C14p-022

A point of problem in estimating snow strength related to brittle fracture

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Strength of snow that is an important factor to evaluate a snow fracture such as a snow avalanche is estimated commonly using an expression related to snow density. Although many expressions for estimating the snow strength have been obtained by previous studies, the relation between each expression should be examined because snow strength is affected by conditions of measurement and snow structure. To make a point of problem in the estimation of snow strength clear, the expressions obtained from previous studies were examined by comparing with each expression.
Although many compression tests of various snow grain types were conducted, there are only few expressions of compressive strength related to density. Moreover, compressive strength estimated by each expression differs to that estimated by other and the relation of compressive strength to water content have not yet be clarified. To estimate the compressive strength, however, snow hardness that was measured by penetration test like a compression can be used because the relations of snow hardness to density and water content were investigated enough.
Tensile strength of dry snow can be estimated by using the expressions corresponding to various snow grain types. For wet snow, however, there are only few expression of tensile strength related to density but not water content. In the same way to compressive strength, snow hardness would be used to estimate the tensile strength of wet snow.
Many expressions of shear strength for various snow grain types exist, so the shear strength of both dry and wet snow can be estimated by using the density and water content. For snow with density of 400 kg m-3 or greater, however, we have to pay attention to difference of shear strength obtained by each expression.

IACS (Cryosphere)

C14p - C14 Snow: Physical Properties and Impact on the Cryosphere

C14p-023

Structural evolution of snow under alternating temperature gradients

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The traditional view of snow metamorphism is that equi-temperature metamorphism causes rounded grains and temperature-gradient metamorphism causes faceted grains. However, the temperature conditions in a snowpack are often more complex. For example the diurnal cycle of solar insolation leads to alternating temperature gradients in a snowpack (Pinzer and Schneebeli, 2009). We investigated experimentally the structural change of snow caused by alternating temperature gradients by means of time-lapse micro-computed tomography in a cold laboratory. We imposed sinusoidal temperature gradients with an amplitude of +-70K/m and periods of 24, 48 or 72h on snow samples. The residence time of snow grains shows that the changing direction of the mass flux within the snow leads to grains consisting of a young shell and an old core, which is as old as the experiment (up to 3 weeks). Even though the large amplitude of the alternating temperature gradient caused a large mass turnover within the snow, almost no faceting occurred. The initially large rounded grains and isotropic snow microstructure changed into large vertically oriented structures. On these grains little fingers grew, which are a sign of unstable growth. Such small structures have a large SSA, leading to a temporally constant overall SSA. A possible link between the growth of these fingers and preferential growth due to different crystal orientations will be discussed. We conclude that the inversion of the direction of the temperature gradient is a necessary extension to current snowpack models, especially concerning the SSA evolution.

Pinzer, B. R., & Schneebeli, M. (2009). Snow metamorphism under alternating temperature gradients: Morphology and recrystallization in surface snow. Geophys. Res. Lett., 36, L23503.

IACS (Cryosphere)

C14p - C14 Snow: Physical Properties and Impact on the Cryosphere

C14p-024

Can interfacial curvatures predict the missing size metric in the characterization of snow microstructure?

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The two-point correlation function as a measure of density fluctuations has become an important quantity for the prediction of various physical properties such as thermal conductivity, permeability or electromagnetic properties of snow. The simplest approach to relate the correlation function to measurable quantities is to use the optical equivalent diameter (or the inverse specific surface area) as a single length scale to characterize the decay of structural fluctuations in the lowest order. This has turned out to be insufficient since physical properties in fact probe the tails of the correlation function and thereby depend at least on yet another length scale. To overcome merely statistical fitting exercises of the tails and work towards a predictive means for their time evolution in snowpack models it is necessary to relate the second length scale to familiar parameters of snow microstructure. To this end we assess a higher order term in the expansion of the correlation function which bears another structural length scale different from the optical diameter. This length scale can be related to moments of the interfacial curvature, which have been used previously in other studies to characterize snow microstructure. We have employed VTK-based image analysis to compute the relevant curvature terms for a large set of 3D images reconstructed by micro-computed tomography and assessed their potential of predicting the tail of the correlation function. A best-fit relation of the curvature parameter to the statistical parameters in common functional forms for the correlation function, such as the bicontinuous Teubner--Strey form, are given.

IACS (Cryosphere)

C14p - C14 Snow: Physical Properties and Impact on the Cryosphere

C14p-025

Field experiment on liquid water flow in snow accumulated on slope

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Rain-on-snow events will cause disasters such as wet-snow avalanches and floods due to runoff of much water from snowpack on slopes. To evaluate the disasters caused by rain-on-snow events, liquid water flow pattern in snowpack is an important factor. To clarify the nature of water infiltration within snowpack on a slope, we carried out a field experiment to evaluate the relationship between water infiltration and snowpack structure.
The results of experiments showed clearly the differences in water infiltration caused by various snowpack structures on the slope. In the case of snowpack that consisted of rounded fine grains below the freezing point on the slope, liquid water tended to flow along snow layers and/or water-ponding layer to lower part of the slope and did not reach the bottom of the snowpack. However, in the case of snowpack that consisted of melt-form coarse grains at the freezing point on the slope, liquid water flowed along a water-ponding layer, also penetrated vertically, and reached the ground surface. The differences in water infiltration due to snow stratigraphy will affect the type of wet-snow avalanche, such as a surface or full-depth avalanche.
The results of the experiments indicated also differences in water infiltration and timing of reaching the ground between the level ground and the slope. These characteristics of liquid water infiltration through snowpack on the slope have to be considered when estimating avalanche occurrence by using a numerical analysis. However, quantitative evaluation of the liquid water flow along snow layer and the vertical flow through snowpack on slope is a future task.

IACS (Cryosphere)

C14p - C14 Snow: Physical Properties and Impact on the Cryosphere

C14p-026

3D growth rates from tomographic images: local measurements for a better understanding of snow metamorphism

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Once deposited on the ground, snow forms a complex porous material whose microstructure constantly transforms over time. These evolutions, which strongly impact the physical and mechanical properties of snow (e.g. Srivastava et al, 2010; Calonne et al, 2014) need to be considered in details for an accurate snowpack modeling. However, some of the physical mechanisms involved in metamorphism are still poorly understood.

To address this problem, several investigations combining X-ray tomography and 3D micro-modeling have been carried out (e.g. Flin et al, 2003; Kaempfer and Plapp, 2009; Pinzer et al, 2012) but precise comparisons between experimentation and modeling remain difficult. One of the difficulties comes from the lack of high resolution time-lapse series for experiments occurring with very well-defined boundary conditions, and from which precise measurements of the interfacial growth rates can be done.

Thanks to a recently developed cryogenic cell (Calonne et al, AGU2013), we conducted in situ time-lapse tomographic experiments on several snow and ice samples under various conditions (isothermal metamorphism at -7°C, temperature gradient metamorphism at -2°C under a TG of 18 K/m, air cavity migration in a single crystal at -2°C under a TG of 50 K/m). The non-destructive nature of X-ray microtomography yielded series of 8 micron resolution images that were acquired with a 2-12 h time step. An image analysis method was then developed to estimate the normal growth rates on each point of the ice-air interface and applied to the series obtained.

The analysis of the results and their comparison to those of existing models (e.g. Flin et al, 2003; Flin and Brzoska, 2008) give interesting outlooks for the understanding of the physical mechanisms involved in snow metamorphism.

IACS (Cryosphere)

C14p - C14 Snow: Physical Properties and Impact on the Cryosphere

C14p-027

Difference of water infiltration through channels in snowpack between on flatland and on a slope

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In wet snow regions, snowpack properties such as layer structure, grain type, density, and water content, which are important factors in wet avalanche formation strongly characterized by the effect of water infiltration into snowpack. The effects of water infiltration into snowpack may differ between flat land and slopes, because water flow has a directional component parallel to the slope in snowpack on slopes. We conducted snow pits observations on flat land and on a slope (40° incline; NE aspect) for three winters of 2011-12, 2012-13 and 2013-14 to clarify the difference water infiltration into snowpack. There were some vary for each winters, however we found the tendency that MFr (the ratio of the total thickness of the layers composed of Melt Forms to the thickness of all layers of the snowpack) was higher for the snowpack on the slope than for the snowpack on flat land, despite the slope's being a shaded side slope. We analyzed these observations using a one-dimensional multi-layer snowpack model included parameterization of the vertical water-channel process in snowpack. Our results show that to represent the MFr at each site and winter, the amount of water infiltrating through vertical water channels was estimated at 5 % of the total amount of water provided from the snow surface for the slope and 36 % for the flat land on the average. Our results indicate that in wet snow regions, differences in the water infiltration process can generate the differences between snowpack on a slope and that on flat land.

IACS (Cryosphere)

C15a - C15 Cryosphere, Atmosphere and Climate: Evaluation of the Cryosphere in CMIP5 Models

IUGG-0183

CMIP5 Climate models evaluated against the first climatology of antarctic precipitation

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Climate models in the CMIP5 / IPCC5 archive all predict that antarctic precipitation will increase with climate warming. This will result in a moderation of sea-level rise due to other contributions. However, for a given scenario, the models disagree as to the amplitude of this moderation (increase?). It is a common practice to attribute a higher level of confidence in those models that most closely reproduce the current climate. Current antarctic precipitation in the CMIP5 archive ranges over a factor of 2. The climate change prediction by the 2 most extreme models implies a ~5 mm/yr sea level difference. The 1st model-independent climatology of antarctic precipitation, which has recently been obtained using space borne cloud radar data (Palerme et al., The Cryosphere, 2014), can be used for assessing the reliability of the simulations for the contemporary period. It indicates an overestimation of precipitation amount of all CMIP5 models. The models which less disagree with the new climatology predict a larger increase of antarctic precipitation with climate warming and thus a larger impact on sea-level.

IACS (Cryosphere)

C15a - C15 Cryosphere, Atmosphere and Climate: Evaluation of the Cryosphere in CMIP5 Models

IUGG-0630

Present-day evaluation and future projections of radiative fluxes, clouds, and snow cover in CMIP5 models

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Radiative fluxes are critical for understanding the energy budget of the Arctic region, where the climate has been changing rapidly and is projected to continue to change. This work investigates causes of present-day biases and future projections to top-of-atmosphere Arctic radiative fluxes in the CMIP5 models. An assessment of the ability of CMIP5 models to represent present-day climate is conducted by comparing net shortwave flux biases, outgoing longwave radiation biases, snow cover area, and cloud amount to appropriate observations. Biases are quantified over various surfaces (open ocean, sea ice, land areas with snow, and land areas without snow) to quantify the impacts that surface type has on model performance. A similar analysis is conducted on modeled projections of climate change: net shortwave flux changes, outgoing longwave radiation changes, snow cover area changes, and cloud amount changes are quantified over each of the different surface types. These results help identify the causes of model biases with representing present-day Arctic climate, and the contributions of surface albedo, surface type, and cloud amount to projected changes in Arctic climate.

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IUGG-1508

Falsifiability of earth system models

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Using the example of sea ice, I examine the three aspects of falsifiability that are most commonly applied to an Earth-System-Model (ESM) context.

Falsifiability as a requirement for any research to be termed scientific is trivially fulfilled for any ESM simulation, and I here show that it is in particular given for the simulated timing of Arctic summer sea-ice loss.

The falsification of ESM simulations to narrow down the range of policy-relevant climate projections is, in contrast, very challenging, because standard metrics are often too variable to allow for a straight-forward model falsification given the short observational record. This is shown here to be the case for sea-ice area and sea-ice volume. A probabilistic view on the timing of an ice-free Arctic as introduced in this presentation is therefore possibly more informative than an absolute one.

Finally, it is shown that falsification of ESM simulations to examine model shortcomings for scientific purposes is often easily possible because of the large variety of non-policy relevant metrics with low internal variability that can be used for this purpose. Such direct falsifiability of a simulation result does, however, not necessarily imply the falsifiability of a particular model component, since usually many different model components influence the evolution of any specific observable.

These findings point towards the need for an in-depth analysis of the suitability of specific metrics for any study that aims at an analysis of model quality. In particular, given the current change of climatic conditions for many metrics 30-year long averages are not sufficient to obtain a representative average for direct model evaluation.

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IUGG-2458

Detection and attribution of multi-decadal 20th century Southern Ocean sea ice changes from satellite observations and proxy data

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The failure of coupled climate model ensembles to reproduce the increased Antarctic sea ice cover observed by satellites raises grave doubts about our ability to accurately predict the future of the Antarctic climate system, with important implications in the context of predicting Antarctica's contribution to future sea level rise. While the increase in total Antarctic ice cover is within the bounds of coupled model internal variability, the spatially heterogeneous pattern of trends indicates that Antarctic sea ice may have a response to anthropogenic forcings that is not replicated by the models. A complete understanding of this discrepancy is hampered by the relatively short satellite record. In this work, 20th century sea ice reconstructions from a number of ice cores are combined to give a synthesis covering about 75% of the circumpolar region. It is found that in sectors with the biggest SAM response, late winter sea ice cover has been decreasing since the 1960s, in qualitative agreement with CMIP5 models. In the Ross Sea the observed increase in ice cover has been a occurring since the mid 1960s, when it was preceded by a sharp, decade long reduction, outside the range of simulated natural variability. This work suggests that for many sectors of the Southern Ocean, CMIP5 simulations are consistent with observations. The Ross Sea sector remains a challenging region, both for proxy reconstructions and for models.

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IUGG-3090

The Antarctic sea ice concentration budget in climate models

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The Antarctic sea ice concentration budget of several models is computed and analyzed. Following a previously developed method, the sea ice concentration balance over the autumn-winter seasons is decomposed into four terms, including the sea ice concentration change during the period of interest, advection, divergence and a residual accounting for the net contribution of thermodynamics and ice deformation. Concurrently, the salinity, temperature and mixed-layer depth of the ocean below are compared to observations and correlated with the thermodynamic component of the sea ice concentration budget. Preliminary results from this method, applied first to the ocean-sea ice coupled model NEMO-LIM, show that the geographical patterns of all budget terms over 1992-2010 are in qualitative agreement with the observed ones. Sea ice thermodynamic growth is maintained by horizontal divergence near the continent and in the central ice pack, while melting close to the ice edge is led by sea ice advection. Quanti tatively however, the inner ice pack divergence and associated sea ice freezing are much stronger as compared to observations. The advection of sea ice in both the central pack and the marginal areas are likewise stronger. Those strong dynamic components in the sea ice concentration budget are due to ice velocities that tend to be biased high all around Antarctica and particularly near the ice edge. The method is then more generally applied to several fully coupled climate models from the CMIP5 archive and results are put forward against those previously obtained.

IACS (Cryosphere)

C15b - C15 Cryosphere, Atmosphere and Climate: Evaluation of the Cryosphere in CMIP5 Models

IUGG-0768

Forcing impact on Greenland surface mass balance estimates

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The last IPCC report [AR5, IPCC] has shown an increasing contribution from Greenland melting to global sea-level over the last decade, increasing from 0.09 mm/year (period 1992-2001) to 0.59 mm/year (period 2002-2011). Given its strategic location (i.e. close to the main North Atlantic ocean convection sites), Greenland is considered to be one of the components of the Earth system which might reach a “tipping point” [Lenton et al., 2008].
Here, we use a set of seven simulated air surface temperature and precipitation fields from CMIP5 atmosphere-ocean coupled general circulation models (AOGCM), to estimate present-day and projected Greenland surface mass balance (SMB). This is done by using two thermo-mechanical ice sheet-ice shelves models: GRISLI [Ritz et al., 2001] and SICOPOLIS [Greve, 1997] and using two different spatial resolutions, i.e. 5km and 20km. The future projections are based on two representative concentration pathways (RCP) scenarios: RCP 8.5 and RCP 4.5 [Moss et al., 2010].
Simulations performed over the 20th century are validated against estimates from regional atmospheric models or reanalysis (e.g. [Hanna et al., 2005], [Fettweis et al., 2013]). Simulations of the 21st century, instead, provide an estimate of the timing at which the overall Greenland ice sheet SMB passes the zero SMB threshold permanently, i.e. seen as a Greenland tipping point. Results show that the tipping point is approached towards the middle of the 21st century and it is slightly sensitive to the ice sheet model used, and that the timing at which the zero SMB threshold is reached does moreover slightly change depending on the spatial resolution considered.

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IUGG-2136

Masking of snow albedo by forests in CMIP5 models

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Analysis of CMIP5 models cited in the Intergovernmental Panel on Climate Change's Fifth Assessment Report has found large inter-model variations in snow albedo feedback that have persisted from CMIP3. The largest variations are found over the heavily vegetated boreal forest zone, so differences in how models represent the masking of snow albedo by vegetation is suspected as a source of spread. Differences can result not just from wide differences in model structure but also from differences in poorly constrained model parameters and crude characterizations of forest structure on climate model grid scales. This presentation will discuss how remote and in-situ observations can be used to attribute and reduce differences between models in predicting the albedo of snow-covered forest regions.

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IUGG-2925

Sensitivity of permafrost thaw and carbon loss to warming

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Permafrost-affected soils are uniquely vulnerable to climate change, and potentially may act as a powerful carbon cycle feedback to warming. Yet the magnitude of permafrost losses and the resulting greenhouse gas balance under future global warming remains highly uncertain. I will discuss the representation of permafrost processes and permafrost dynamics in the CMIP5 generation of Earth system models, as well as more recent progress to reduce the uncertainty in projections of permafrost thaw and carbon release. While the set of CMIP5 climate models agree on widespread permafrost losses with warming, they disagree on permafrost areal extent both under current and future climates, and on the sensitivity and timing of permafrost loss with warming. Much of this disagreement can be traced to biases in the representation of snow and ice in the models. Recent progress has been made both on improving the representation of soil and snow processes and also on the permafrost C cycle, through observationally constraining the magnitude and characteristics of the permafrost carbon reservoir and in representing its dynamics in numerical models, and support the assessment that permafrost soils represent a globally-relevant carbon cycle feedback that is likely to amplify climate change.

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IUGG-4908

The influence of canopy snow parameterizations on snow albedo feedback in boreal forest regions

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Variation in snow albedo feedback (SAF) among the fifth Coupled Model Intercomparison Project (CMIP5) models has been shown to account for much of the spread in projected warming over Northern Hemisphere land. Boreal evergreen needleleaf forests are capable of intercepting snowfall throughout the winter, which has a significant impact on seasonal albedo evolution. Prior studies have demonstrated both considerable spread in surface albedo, and a negative bias in the simulated strength of SAF, over snow-covered boreal forest. In this study, multiple satellite-derived datasets and tower based observations of albedo are compared with simulations from the NCAR Community Climate System Model version 4 (CCSM4) to investigate the causes of a weak bias in simulated SAF over the boreal forest. The largest bias occurs in April-May, when simulated SAF is one-half the strength of observed SAF. This is traced to two features of the canopy snow parameterization used in the land surface scheme. First, there is no mechanism for the dynamic removal of snow from the canopy when temperatures are below freezing, which results in albedo values in midwinter that are biased high. Second, when temperatures do rise above freezing, all snow on the canopy is melted instantaneously, which results in an unrealistically early transition from a snow-covered to a snow-free canopy. These processes combine to produce large differences between simulated and observed monthly albedo. However, evaluation of the larger CMIP5 group suggests that CCSM4 is an outlier throughout the melt period, as the other models tend to be biased high in SAF. This provides strong evidence that the treatment of canopy snow can have a profound impact on the seasonal cycle of albedo and influence a hemispheric climate response.

IACS (Cryosphere)

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IUGG-5181

Evaluation of CMIP5 models toward regional modelling of the Antarctic surface mass balance

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The Antarctic ice-sheet surface mass balance is a significant component of the sea level budget and may mitigate the rise in sea level in a warmer climate, but this term is still poorly known. On the one hand, the Antarctic surface mass balance cannot be directly deduced from global climate models (**GCM**) because of their too low resolution (~100 km) and their unadapted physic over cold and snow-covered regions. On the other hand, regional climate models (**RCM**) adapted for polar regions can compute surface mass balance components over the ice-sheet from large scale forcings at their boundaries. Consequently, a better estimation of the Antarctic surface mass balance require appropriate GCM fields used as an input for polar-oriented RCM.

We present here results of a careful evaluation of 38 CMIP5 GCM over Antarctica. We focus on GCM forcing fields for RCM runs, and particularly on those that may have the greatest impact on surface mass balance components. We consider ERA-Interim reanalysis as a reference, since previous studies shown that it is the most reliable reanalysis over the Antarctic region, but we also include the performance of 4 other reanalysis. Models efficiency is assessed by taking into account the multi-decadal variability of the fields. We also consider models sensitivity to climate change during the 21st century in relation to their state at the end of the 20th century for the rcp85 scenario. To conclude, we show that only few CMIP5 GCM outputs are suitable for RCM forcings over the Antarctic region for 20th and 21st century runs.

IACS (Cryosphere)

C15p - C15 Cryosphere, Atmosphere and Climate: Evaluation of the Cryosphere in CMIP5 Models

C15p-103

An analysis of present and future seasonal Northern Hemisphere land snow cover simulated by CMIP5 coupled climate models

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The 20th century seasonal Northern Hemisphere (NH) land snow cover as simulated by available CMIP5 model output is compared to observations. On average, the models reproduce the observed snow cover extent very well, but the significant trend towards a reduced spring snow cover extent over the 1979–2005 period is underestimated (observed: (−3.4 ± 1.1)% per decade; simulated: (−1.0 ± 0.3)% per decade). We show that this is linked to the simulated Northern Hemisphere extratropical spring land warming trend over the same period, which is also underestimated, although the models, on average, correctly capture the observed global warming trend. There is a good linear correlation between the extent of hemispheric seasonal spring snow cover and boreal large-scale spring surface air temperature in the models, supported by available observations. This relationship also persists in the future and is independent of the particular anthropogenic climate forcing scenario. Similarly, the simulated linear relationship between the hemispheric seasonal spring snow cover extent and global mean annual mean surface air temperature is stable in time. However, the slope of this relationship is underestimated at present (observed: (−11.8 ± 2.7)% $°C^{-1}$; simulated: (−5.1 ± 3.0)% $°C^{-1}$) because the trend towards lower snow cover extent is underestimated, while the recent global warming trend is correctly represented.

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C15p-104

Regional sea ice projection – An example of CMIP5 Model Evaluation and Application

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Model evaluation and selection approaches applied to the suite of CMIP3 and CMIP5 model results have gained some popularity. Statistical approaches to model selection, using different criteria and different variables, often result in different models being selected. Yet, we consider that prior information can be useful in reducing the potential negative impacts from including outlier models. Such information can consist of hindcast evaluations based on quality assessments of the underlying model physics. While not sufficient, model evaluation provides a necessary condition for credible results. We apply a two-step approach for regional projections, taking the Pacific and Atlantic Arctic as examples. The ice-free season north of Bering Strait is forecast to extend from 3 months now to 5 months by 2040 with reduced north-south gradient. CMIP5 based sea ice decadal forecasts for the Barents Sea are less reliable due to uncertainties in model ocean circulation. Thus, the use of CMIP5 model projections for societally relevant decadal forecasts is regionally and question dependent.

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C15p-105

"How implausible are CMIP5 sea-ice simulations?"

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Simulations from state-of-the-art global climate models show a considerable spread in modelled sea ice area and volume. Decomposing the contributions of model biases and internal variability to the spread is challenging as not all models provide ensemble simulations that could be used to estimate the system's internal variability. We here therefore evaluate the plausibility of the historical simulations available in the CMIP5 archive for both hemispheres based on an estimate of the model-specific internal variability that we compute from the pre-industrial control simulation. We find that there is a nearly one-to-one relationship between the variability of the control simulations and the spread of available ensemble simulations during the historical period which allows for a uniform treatment of all model runs. Using this approach, we find that for most models their internal variability cannot explain the models' deviation from observed summer trends in Northern-Hemisphere sea ice area, Southern-Hemisphere seasonal trends in sea ice area and winter trends in sea ice volume as well as the hemispheric mean states especially with respect to sea ice volume. In contrast, many models' internal variability is sufficiently high to explain the models' deviations from observed Northern-Hemisphere winter trends in sea ice area and seasonal trends in sea ice volume, Southern-Hemisphere summer trends in sea ice volume as well as the mean state of Northern-Hemisphere sea ice area. The approach of using estimates of internal variability from the control simulation might generally be useful for the evaluation of climate model output.

IACS (Cryosphere)

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C15p-106

Anthropogenic influence on recent Antarctic sea-ice changes: Why do models and observations disagree?

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Observations reveal an increase of Antarctic sea ice over the past three decades, yet global climate models tend to simulate a sea-ice decrease for that period. Here we combine observations with model experiments (MPI-ESM) to investigate causes for this discrepancy and for the observed sea ice increase. Based on observations and atmospheric reanalysis, we show that on multidecadal time scales Antarctic sea-ice changes are linked to intensified meridional winds that are caused by a zonally asymmetric lowering of the high-latitude surface pressure. In our simulations, this surface pressure lowering is a response to a combination of anthropogenic stratospheric ozone depletion and greenhouse gas increase. Combining these two lines of argument, we infer a possible anthropogenic influence on the observed sea-ice changes. However, similar to other models, MPI-ESM simulates a surface-pressure response that is rather zonally symmetric and has a too unstable Southern Ocean stratification, which explains why the simulated sea-ice response differs from observations.

IACS (Cryosphere)

C15p - C15 Cryosphere, Atmosphere and Climate: Evaluation of the Cryosphere in CMIP5 Models

C15p-107

Observed and modeled snow variability and change in Romania

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The main goal of our study is to investigate the snow variability and change over the Romanian regions, where the complex orography plays an important role in shaping local response to large-scale climate variability and change. We use snow observations from 113 meteorological stations covering Romania and model results from six regional climate models from the EuroCORDEX Programme under RCP 4.5 and RCP 8.5 scenarios. For the present climate, the analyzed time intervals are 1961-2010 and 1971-2000. We analyze future projections in the time intervals 2021-2050 and 2071-2100. Trends are identified in observed snow cover, which are consistent with future evolutions under climate change scenarios. We show how spatial patterns of snow cover change affect local climate due to feedbacks influencing surface energy and moisture fluxes. We also investigate the relation of snow cover in South Eastern Europe with large scale variability using 27 numerical experiments from CMIP 5 archive. Both observations and simulations show the relation between snow cover fluctuations and Arctic/North Atlantic Oscillation.

IACS (Cryosphere)

C15p - C15 Cryosphere, Atmosphere and Climate: Evaluation of the Cryosphere in CMIP5 Models

C15p-108

Assessment of the sea ice thickness-drift relationship in the CMIP5 climate models

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The previous generation of climate models used in the Climate Model Intercomparison Project (CMIP) 3 experiments, have shown an unrealistic physical sea ice thickness-drift relationship where thick and packed sea ice accelerates during the winter season and slows down during the summer melt contrary on the observed. Here we assess the coupling between the Arctic and Antarctic sea ice thickness and drift in the latest CMIP5 climate models. We evaluate the representation of the seasonal ice thickness and ice motion spatial distributions, as well as, annual cycles, compared to available observational data. To account for the uncertainty in the observations multiple data sets are used. The ultimate goal of the study is to assess the capability of the models to reproduce the observed trends of ice cover loss in the Arctic and slight increase in Antarctic and attempt to give further insights on the mechanisms lacking or misrepresented in the ice model physics. Preliminary results show that spatial ice thickness patterns are unrealistic in majority of the models, particularly the summer distributions in Antarctic where the model spread is largest. First look at the ice solutions of some of the CMIP5 members reveals that the uncoupling between the ice drift and the ice thickness still persist in the CMIP5 models, raising the demand for further model improvement of the representation of these important feedbacks.

IACS (Cryosphere)

C15p - C15 Cryosphere, Atmosphere and Climate: Evaluation of the Cryosphere in CMIP5 Models

C15p-109

Assessment of Arctic Climate and Greenland Ice Sheet processes in a fully coupled GCM – ISM (EC-Earth – PISM)

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Recently observed rapid changes in key elements of the cryosphere including sea ice, snow cover and glacier surface mass balance show that the Arctic region is currently experiencing a rapid transition. However, projections of both present day and future change, for example in sea ice extent, made by the CMIP5 models have a wide spread and a relatively poor fit to observations.

The EC-Earth GCM is fully coupled to the PISM ice sheet model to study feedback processes between the climate system and the Greenland ice sheet. Simulations show that including an interactive ice sheet model changes ocean circulation, sea ice extent and regional climate, e.g. coupled experiments show a dampening of the increase in Arctic temperatures under high RCP scenarios when compared with uncoupled experiments.

To assess the quality of the climate forcing from the GCM we compare the energy and surface mass balance (SMB) with a high resolution (0.05 degrees) simulation by the regional climate model (RCM) HIRHAM5. The RCM has been evaluated over a wide range of climate parameters for Greenland and gives a representative climate for the Greenland ice sheet. To make a fair comparison, we use downscaled simulations forced with both ERA-Interim and the EC-Earth RCP8.5 scenario to run an offline energy balance model (EBM) and compare with output from the same EBM forced directly with EC-Earth output.

The SMB forcing from the EC-Earth model is comparable overall to that provided by HIRHAM but important differences in the distribution of for example melt area extent also emerge. A cold bias in the Arctic within EC-Earth is carried through the HIRHAM downscaling and may therefore underestimate future mass loss from the Greenland ice sheet.

IACS (Cryosphere)

C15p - C15 Cryosphere, Atmosphere and Climate: Evaluation of the Cryosphere in CMIP5 Models

C15p-110

Evaluation of snow cover extent and surface air temperature relationships simulated by CMIP5 coupled climate models

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Seasonal snow cover in the Northern Hemisphere is the largest component of the terrestrial cryosphere and has important effects on climate due to snow albedo feedback. Correct representation of snow cover in climate models is required to simulate the important effects of seasonal snow cover on climate in contemporary climate system models. In this study, we investigate the snow cover extent (SCE) simulated by 23 CMIP5 coupled climate models in historical simulations. The 23 models simulate a spring SCE trend of (-1.2±1.4)% per decade over Northern Hemisphere land areas for the period 1979-2005, majority models simulate a negative SCE trend, but all simulate weaker than observed trends. Three models simulate a weakly positive SCE trend. For the simulations, the slope between spring SCE and global average annual mean surface air temperature (SAT) is about (-5.8±5.1)% per degree. Preliminary analysis suggests that snow model schemes and snow-vegetation interaction are important causes on biases in SCE and SAT relationships.

IACS (Cryosphere)

C15p - C15 Cryosphere, Atmosphere and Climate: Evaluation of the Cryosphere in CMIP5 Models

C15p-495

Changes in the Weddell Sea Warm Deep Water in CMIP5 models from the 20th into the 21st Centuries

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In the Southern Oceans (SO) the dense waters of the Antarctic Bottom Water (AABW) are formed predominantly in the Weddell Sea and then move along density surfaces with very little change due to vertical mixing. Thus water mass properties on these density surfaces (isopycnals) are a faithful representation of the source region surface heat and freshwater fluxes, which provides good indicators of climate change. Export of AABW constitutes a key component of the ocean's meridional overturning circulation (MOC) and thus has a great impact on the Earths Climate. Because of the intrinsic difficulties to observe water mass formation at high latitudes, numerical models become an essential tool for quantifying variations in water masses. This study aims to assess the representation and variability of the Southern Ocean water masses in CMIP5 models for the 20th and 21st Century. Considering the importance of the Weddell Sea in the formation and export of dense waters to the global ocean, its characteristics are investigated. Results show freshening and warming of the Warm Deep Water (WDW) for most models although their physical representation of the water mass distribution in the Weddell Sea is remarkably different. Issues relative to the lack of necessary physical processes in the CMIP5 models to adequately represent the changes in the Weddell Sea that affect the MOC are discussed.

IACS (Cryosphere)

C15p - C15 Cryosphere, Atmosphere and Climate: Evaluation of the Cryosphere in CMIP5 Models

C15p-496

Ocean Heat Content changes in the 20th and 21st Century in the Southern Ocean: a regional approach.

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The warming of the World Ocean and changes in Ocean Heat Content have been a hot topic during the past years, with many studies concerning model and observations. Here, we investigate the changes in Ocean Heat Content (calculations based on Antonov et al., 2004) in the South Atlantic and the Southern Ocean Atlantic Sector by looking at three well known ocean Reanalyses [SODA, ORAS4 and ECCO2] and nine CMIP5 models [CanESM, CCSM4, CESM1-CAM5, GFDL-CM3, Hadgem2-ES, IPSL-CM5A-MR,MIROC5, MIROC-ESM, MPI-ESM-MR]. The investigated period spans from Jan/1 960 to Dec/2005. CMIP5 models disagree on their representation of the Southern Ocean processes. The fact that the Sea Ice Extent on these models is decreasing while observations show it is increasing (IPCC, 201 3) combined with the results shown here make us believe that changes in the OHC might be one of the processes that contribute to the sea ice expansion, although we are not yet sure about how important it is.

IACS (Cryosphere)

C15p - C15 Cryosphere, Atmosphere and Climate: Evaluation of the Cryosphere in CMIP5 Models

C15p-502

Thermodynamics of slush and snow-ice formation on sea ice

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Snow-ice forms on top of sea ice under negative freeboard, once brine or seawater floods the base of snow and freezes there. Snow-ice is widespread in the spring Antarctic sea ice zone, because much snow falls on relatively thin ice. Here, we focus on the freezing process, using three approaches: (i) an isolated system model based on energy, water and salt conservation; (ii) laboratory experiments - a NaCl solution is poured, freezing into grated ice (a proxy for snow) in a cryogenic container -; and (iii) field observations at the SIMBA drift station (Bellingshausen Sea, Antarctica, 10/2007). Our analysis highlights three main conclusions. (i) A solid snow ice volume can form provided that the frozen ice amounts > 60% of the initial volume of snow+water. Otherwise, ice crystals are loose and rise above salt water, stratifying the system. (ii) Since the snow latent heat of fusion largely dominates the energy balance, snow-ice is generally warm (T>-3°C). T significantly depends on the salinity of salt water, but only marginally on the temperature of the pre-existing snow [-40, 0°C] or salt water [-1.8, 20°C]. (iii) In a closed system, the snow-ice salinity S would be >20 g/kg, for typical values of seawater salinity and snow density. In the field, however, S is much smaller (~10 g/kg), suggesting that salt quickly expells from forming snow-ice. We discuss the implications for the large-scale temperature field in Antarctic pack ice, the large-scale progression of flooding, and the detection of snow ice formation in the field.

IACS (Cryosphere)

C16a - C16 Cryosphere, Atmosphere and Climate: The Cryosphere and Polar Amplification of Climate

IUGG-1848

Arctic change/mid-latitude weather linkages

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Based on five workshops and five research reviews in the last 2 years, different researchers reach different conclusions on potential Arctic change/mid-latitude weather linkages from essentially the same data; we are in a pre-consensus period. Current scientific differences are philosophical (null hypothesis verses risk avoidance), procedural (different data types, using long or short durations, and small or large areas) and degree of reliance on climate models. Yet the issue is of societal importance leading to potentially improved extended range forecasts give future Arctic change. Recently, consensus has improved. Natural variability in chaotic atmospheric flow remains the main dynamic process, and it is difficult to determine whether Arctic forcing of a north-south linkage is emerging from the most recent period of Arctic change since 2007. There is general agreement that there will be no net mid-latitude cooling, only a potential for severe events. The community can make progress with the hypothesis that linkages are regional, episodic, and based on amplification of existing weather patterns such as Greenland blocking and the Siberian High. While not definitive, in the last five early winters (December-January 2009-10 through 2013-14), two record and four other negative Arctic Oscillation atmospheric circulation index events have been observed, with positive Greenland Blocking Indices. Positive geopotential height anomalies relate to both dynamics through vorticity advection, and thermodynamics through lower level advection of temperature anomalies and low level heating. Similar linkage results are found in the literature for east of the Ural Mountains and the Siberian High.

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C16a - C16 Cryosphere, Atmosphere and Climate: The Cryosphere and Polar Amplification of Climate

IUGG-3067

Variability of Northern Hemisphere terrestrial snow depth: Self-organizing maps and the Madden-Julian Oscillation

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In efforts to understand and quantify the rapidly changing Arctic climate, recent research has focused on the importance of intraseasonal variability of key parameters within this region. For example, Arctic sea ice concentration had been found to vary by phase of the Madden-Julian Oscillation (MJO) in both summer and winter, driven largely by variability in upper- and lower-tropospheric circulation and surface air temperature. Given that Northern Hemisphere terrestrial snow depth frequently responds to similar atmospheric variables, it seems reasonable to expect that snow depth, too, may have an intraseasonal connection to the MJO. In this study, daily changes in snow depth, from cutting-edge reanalysis datasets including the ERA-40 Interim, NASA-MERRA, NCEP/DOE II, and Japanese JAXA reanalyses, were examined for variability by phase of the MJO (as determined by the Wheeler and Hendon Real-time Multivariate MJO index). In addition to defining MJO phase using the Wheeler and Hendon index, Self Organizing Maps (SOMs), trained by outgoing longwave radiation fields, were also utilized to explore the robustness of this tropical-high latitude connection. Composite anomalies of daily snow depth change by MJO phase were then compared to composite anomalies of mid tropospheric circulation and surface air temperature. Multiple snow variables from multiple reanalysis products were chosen to fully explore variability on the intraseasonal time scale. Furthermore, because snow variables have “memory”, in that snow that falls and accumulates during one MJO phase may remain for several subsequent MJO phases, it was important to examine snow fields from multiple data records. Results of these experiments will be presented at the meeting.

IACS (Cryosphere)

C16a - C16 Cryosphere, Atmosphere and Climate: The Cryosphere and Polar Amplification of Climate

IUGG-3695

Using the twentieth century reanalysis to examine extremes, variability, and changes in the greenland climate system: 1871-2012

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[Neff et al., 2014, JGR] examined the 2012 Greenland melt episode and compared it with the last episode in 1889 finding similar factors at work using the Twentieth Century Reanalysis (20CR: [Compo et al., 2011, J. Royal Met. Soc.]). A key factor was the presence of an Atmospheric River (AR) that transported warm air from a mid-continent heat wave over the Atlantic Ocean and thence to the west coast of Greenland and then over the ice sheet (with a distinct water vapor isotopic signature – Bonne et al, in press JGR). Although these events with wide spread melting of the ice sheet surface are extremely rare, a question remained as to the frequency of less extreme transport events. Because the 20CR was based on an evolving surface pressure observing network, we found that while it captured the essential spatial structure of AR events, it underrepresented the magnitude of moisture transport in early decades. For this reason we used a threshold technique to examine the top 5% of strong moisture transport events for each decade beginning in 1871 and classified them into four categories: 1) Direct AR Greenland impact, 2) AR transport into the north Atlantic, 3) isolated surges of moisture near Greenland, and 4) local disorganized events with high IWV just west of Greenland. We found systematic increases in recent decades as well as significant decadal variability in all these moisture transport events over the last 142 years in addition to a higher incidence in the period 1880-1889.

IACS (Cryosphere)

C16a - C16 Cryosphere, Atmosphere and Climate: The Cryosphere and Polar Amplification of Climate

IUGG-4315

Temperature feedbacks dominate Arctic amplification in contemporary climate models

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Climate change is amplified in the Arctic in past warm and glacial climates, historical observations and climate model experiments . Although a wide range of feedback mechanisms has been suggested to contribute to Arctic amplification, the increased absorption of solar radiation due to retreating snow and ice or surface albedo feedback is often understood to be the main contributor. Yet, Arctic amplification is also found in models without snow and ice changes, and has been shown to be primarily caused by feedbacks affecting terrestrial longwave radiation, i.e. temperature, water vapour and longwave cloud feedbacks, rather than feedbacks affecting solar shortwave radiation. Using a feedback decomposition based on radiative kernels, we show that weaker Arctic temperature feedbacks are the largest contributors to Arctic amplification in climate models: Surface warming leads to a smaller increase in the energy radiated to space in the Arctic because of 1) the vertical structure of warming (lapse-rate feedback) and 2) the smaller increase of emitted blackbody radiation at colder temperatures (Planck feedback). The weak Arctic temperature feedback is most pronounced in the cold season and roughly doubles wintertime warming.

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IUGG-4853

Modeling the role of Arctic ocean in polar amplification using the regional arctic system model

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Understanding oceanic effects on warming Arctic climate is commonly reduced to diagnosing spatio-temporal variability of sea surface temperatures, while in fact it requires knowledge of the mean upper ocean hydrography, circulation and their variability. The western Arctic, where the sea ice cover has been most reduced, is strongly affected by the outflow of warm summer water from the Bering / Chukchi / East Siberian shelves and their interactions across the boundary current along the slope. According to observations and some models, the heat content due to advection of warm water and local insolation has increased in the western Arctic since the late 1990s.
We analyze multi-decadal results from the Regional Arctic System Model to understand the seasonal cycle and interannual to decadal variability of the upper ocean heat content and its impact on the sea ice cover and warming climate. We also examine processes governing the exchange of water from the western Arctic shelves into the basin and their impact on the sea ice cover. Our research suggests that a thinner ice cover promotes a positive feedback in the upper ocean, where the new ice regime, including increased ice drift, results in an increased ice-ocean stress, which acts to enhance turbulent mixing and upward heat entrainment, making it available to reduce ice growth in winter and more ice melt in summer. We argue that such processes and feedbacks must be realistically represented and diagnosed in global climate and earth system models to improve their simulation and prediction of arctic climate warming.

IACS (Cryosphere)

C16p - C16 Cryosphere, Atmosphere and Climate: The Cryosphere and Polar Amplification of Climate

C16p-296

Temperature-Humidity regime of Antarctica in the modern climate conditions

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The main attention is paid to changes of the glaciological and climatic indicators of icing in the area of Antarctica such as air temperature, moisture content and moisture transfer in the troposphere and so on. In the thesis the impact of the climate change on the components of the temperature-humidity conditions of the troposphere over Antarctica under global warming conditions is considered. The integrated estimation of the cloud conditions of Antarctica is given; spatial distribution of ratio of mean low cloud cover to total cloudiness is described. Characteristics of changeability of air temperature in the troposphere of Antarctica are determined over the last 30 years. Main quantative and qualitative tendencies in air temperature are revealed. Local inhomogeneity of air temperature near the surface, namely, a dipole, is discovered by means of joint analysis of the maps of correlation coefficient and maps of air temperature anomalies near the surface. Physical reasoning of conditions of the dipole formation and its movement over Antarctica is given.

Methodology calculation of moisture content and moisture transfer in the troposphere is adapted for Antarctica. Modern tendencies in the changes of moisture content of the troposphere are revealed, reasons of the changes are determined and moisture content of the Antarctica troposphere is calculated by means of using this methodology. Quantitative and qualitative characteristics of moisture advection in the troposphere of Antarctica are determined.

IACS (Cryosphere)

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C16p-297

Subsea climate change - challenges and first results from a coupled atmosphere-ocean-permafrost model

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Observations taken during recent expeditions indicate that the East Siberian Arctic Shelf (ESAS) is a source of methane in the global climate system. This methane stems from shallow hydrate seabed reservoirs and has been previously thought to be trapped under subsea permafrost, which underlies most of the ESAS. The total amount of carbon within the ESAS is so large that release of only a small fraction, for example via taliks, which are columns of unfrozen sediment within the permafrost, could have major implications for the global climate. For this reason, it is important to model the future fate of subsea permafrost with regard to changing atmospheric and oceanic circulation, but up to now only a few attempts to model subsea permafrost have been made and most of them have focused on the evolution of permafrost since the Late Pleistocene ocean transgression, approximately14000 years ago.

In contrast to land permafrost modeling, any attempt to model the future fate of subsea permafrost needs to consider several additional factors, in particular the dependence of freezing temperature on water depth and salt content and the differences in ground heat flux depending on the seabed properties. Also the amount of unfrozen water in the sediment needs to be taken into account. Using a system of coupled ocean, atmosphere and permafrost models allows us to capture the complexity of the different parts of the system and evaluate the relative importance of different processes.Here we present the first results of a novel approach by means of a dedicated permafrost model which has been coupled to a regional climate model for a region covering the Laptev Sea region in East Siberia.

IACS (Cryosphere)

C16p - C16 Cryosphere, Atmosphere and Climate: The Cryosphere and Polar Amplification of Climate

C16p-298

Arctic amplification and its impact on the hydro- and cryosphere of a Svalbard glacier basin

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Arctic climate is currently warming at a faster rate than observed elsewhere with numerous implications on cryosphere. Svalbard is one of the largest glaciated area and climate change will impact glaciers and ice caps across the archipelago playing an important role in sea level rise. Relations between large-scale climate evolutions, and thaw or glacier ice melting are one of the main uncertainties in assessing greenhouse effect on climate induced evolutions. Here we use large scale weather regimes and river discharge in Austre Lovénbreen glacier watershed to understand the control of climate change on the evolution of hydrology on Spitsbergen. River discharge since 1979 was modelled using a glacio-hydrological model. River flow show a major break in 1998, with an increase of water discharge related to an early snow melting in response to a recent warming. At the same time, 6 weather regimes over the Arctic North Atlantic are defined, showing an increase of warmer local temperatures due to a higher frequency of Greenland and Norwegian anticyclones. These findings show that global climate change on Spitsbergen leads to an intensification of anticyclonic conditions controlling the increase of meltwater discharge in the early summer.

IACS (Cryosphere)

C16p - C16 Cryosphere, Atmosphere and Climate: The Cryosphere and Polar Amplification of Climate

C16p-299

The contribution of sub-grid snow distributions to climate change and polar amplification in a quadrupled CO2 world using an AOGCM

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Snow cover evolution is an important factor in snow albedo feedback processes and thus “Polar amplification” within future climate projections simulated using general circulation models (GCMs). In the present study, we introduce a sub-grid snow distribution submodel (SSNOWD; Liston 2004) into the Minimal Advanced Treatments of Surface Interaction and RunOff (MATSIRO; Takata et al. 2003, Nitta et al. 2014) land surface scheme, which is coupled interactively with a GCM known as the Model for Interdisciplinary Research on Climate (MIROC; Watanabe et al. 2010).

By using this new version of MIROC GCM with SSNOWD, we compare and evaluate the warming in a quadrupled CO2 experiment with a pre-industrial control experiment. We also compared a quadrupled CO2 experiment with a control using the original version of MIROC which assumes a simple empirical relation between snow amount and snow cover in a grid-cell.

By introducing SSNOWD, distribution of snow cover fraction becomes more realistic in a control experiment. Quadrupled CO2 experiments show warming in the mid-latitude is amplified due to the introduction of SSNOWD. On the other hand, in the Arctic Ocean, response of sea ice weakens warming with SSNOWD. These two opposite effects compensate, so that the global warming and the

equilibrium climate sensitivity show very small change due to the introduction of SSNOWD. However, the polar amplification is weakened due to the latitudinal contrast of warming.

IACS (Cryosphere)

C16p - C16 Cryosphere, Atmosphere and Climate: The Cryosphere and Polar Amplification of Climate

C16p-300

Links between Arctic amplification and mid-latitude weather

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The rise in Arctic near-surface air temperatures has been almost twice as large as the global average in recent decades, but cold, snowy winters have been found over mid-latitude land areas. This phenomenon has been found both in the early 20th century warming period and the current warming period. Several studies suggested a possible link between the Arctic Amplification and the change of weather pattern in the mid-latitude. However, the physical mechanism of this link is still under debate. In this study, we analysed the dynamical features of those severe winters during both warming periods. The purpose is to provide better understanding and long term perspective of the drivers of temperature and precipitation variability in the mid-latitude.

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C16p-301

Investigating the spread of snow albedo in climate models in boreal forest regions

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Studies have found that a large spread in snow albedo feedback in CMIP3 and CMIP5 models, which adds to uncertainy in climate projections, is associated with the spread in simulated albedo in the presence of snow. Here we compare surface albedo and leaf area index (LAI) simulated by CMIP5 models with satellite observations at the high northern latitudes. The largest spread in models is found for evergreen needleleaf forest regions for both variables; LAI ranges from near 0 to 3.0, and surface albedo from 0.2 to 0.7 during the peak snow accumulation period (Feb - March). It appears that the spread in simulated surface albedo when snow occurs in forested regions is closely linked to the spread in simulated LAI. This is expected since LAI and canopy coverage are important parameters that control snow interception and radiation transfer in snow-canopies. Changes in LAI also affect the sky view fraction which affects snow accumulation falling through the canopy gaps. Sensitivity tests are performed with CanAM4.2 (a developmental version of the CCCma AGCM) to investigate how changes in LAI affect winter albedo in the boreal forest.

Biases in simulated LAI may be attributed to a number of factors, such as errors in plant functional type, canopy cover fraction, and canopy structural parameterizations. Preliminary results show that models that have relatively accurate LAI values in summer may not have realistic values in winter, suggesting incorrect land cover type specification or poor parameterization of phenology. Results suggest that improvements in simulated LAI in climate and Earth system models, and reduced spread across the models, will likely reduce the large spread in winter albedo and consequently the spread in snow-albedo feedback strength.

IACS (Cryosphere)

C17a - C17 Challenges in Cryospheric Sciences: Past, Present and Future

IUGG-0216

Challenges in the study of cryospheric changes and their impacts

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Cryospheric changes and their impacts are receiving wide attention from international scientific and social communities. Here, we summarize the present hotspots of international cryospheric sciences and hence conclude four major aspects of them. They are respectively (1) mechanism of cryospheric changes, (2) interaction of cryospheric and other spheres of climate /earth system, (3) impacts of cryospheric changes, and (4) adaptation methods and strategy to these changes. Among the four areas,mechanism study is the basis for cryospherc sciences, interaction between different spheres is the currently developing aspect of the field, impacts of cryospheric changes are increasingly studied and yet still have large gaps, while adaptation study is still an iniative nowadays. For the above four aspects, there are key issues for each of them. For instance, dynamic responses and the spatial /temporal differences are the key challenges in the mechanism studies.Rational and precise description on physical /chemical /geochemical processes of cryosphere is one of critical issues on improving the climate models. Scoping the spatial /temporal scales, as well as defining the influence degree is the key gaps in studying the cryospheric impacts. Methods and related index system for vulnerability assessment is the key issue in the study of the adaptation strategy of cryospheric impacts. Cryospheric sciences are developing towards, in the near future, the coupling of cryoshperic components into climate system in global scale, detecting the impacts of cryospheric changes using multiple and integrated methodology, and innovated approaches in adaptation.

IACS (Cryosphere)

C17a - C17 Challenges in Cryospheric Sciences: Past, Present and Future

IUGG-4144

Ice sheet responses to external forcing: Are we observing weather or climate?

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In the last two decades apparently dramatic changes have been observed, primarily from satellites, in mass trends, ice dynamics and grounding line retreat in both West Antarctica and Greenland. It has recently been suggested that, for West Antarctica, an irreversible threshold has been passed and grounding line retreat is unstoppable. The satellite record, however, is short-about 20 years- and curiously these changes appear to coincide with our ability to observe them. Is this coincidence or because the ice sheets are always behaving like this, long before the observations existed? A critical question for improving predictions is to what extent the changes seen are due to internal variability in the ice sheet-climate system (weather) or to external forcing (climate). Ice sheet models or coupled GCMs should not be expected to reproduce the former as this is a stochastic signal. Models tuned to internal variability will not be a reliable predictor of future behaviour. Understanding the time-scales and amplitudes of internal variability in the ice sheets is, therefore, a critical step in producing more robust predictions. Here I present some results from an expert elicitation exercise, the paleo-climate record and more recent, but pre-satellite, data that explores these issues and discuss the challenges in understanding the short, (20 year) satellite record of ice sheet change in the context of longer-term changes in the climate system.

IACS (Cryosphere)

C17a - C17 Challenges in Cryospheric Sciences: Past, Present and Future

IUGG-5237

Sea ice studies from the bi-polar perspectives and mid-high latitude connections

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Polar and sub-polar sea ice conditions shows general tendencies of decrease, however different variations in time and space. As sea ice coverages in the Arctic and Antarctic are showing both common and different seasonal, long-term trends, bi-polar perspective will be important for understanding sea ice change in the consequence of global climate change. Sea ice map often focuses extreme condition of sea ice and seasonal march and long-term trend. Sea ice information are indicated separately in the Arctic or Antarctic. This study tried to put together and summarized characteristics of their extent, seasonal differences, seasonal march and long-term trends. Summer sea ice decline in the Arctic was evidenced in the high Arctic latitudes, on the other hand winter sea ice variations were derived by the sub-Arctic sea ice variations. The discussion requires expanding to all season, connection to the middle latitudes and bi-polar perspectives. Sea ice area in the Antarctic can be separated in to several zones by latitude and season. Dynamic components are important factor in the Antarctic sea ice change due to its high mobility. Arctic sea ice was thick and mobility was not large, however recent decrease of ice area is making new condition of Arctic sea ice. Sea ice is showing high mobility in summer and also evidenced even in winter season. Recent study introduces importance of sea ice dynamics for the ice thickness change in the Arctic. Relationships between sea ice and land snow condition are also of interest. This presentations attempts to scan polar and sub-polar evidences and also bi-polar perspectives of sea ice researches. National and international efforts of observations will be introduced for future advance of sea ice studies.

IACS (Cryosphere)

C17a - C17 Challenges in Cryospheric Sciences: Past, Present and Future

IUGG-5782

The present and future challenges of modeling ice sheets in a changing climate

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Ice sheets are dynamic systems that interact with other components of the Earth System and are thestrongest contributor to present-day sea level rise. Observations over the last three decades haveshown that the Greenland and Antarctic Ice Sheets have been losing mass at an increasing rate. Howthe ice sheets respond to this negative mass balance has become today one of the most urgentquestions in understanding the implications of global climate change. Numerical modeling is the onlyeffective way of addressing this problem. Yet, despite significant improvements in ice sheet modelsover the past decade, the predictive skills of the new generation of models remain limited overshort time scales (tens to hundreds of years). The primary reason for this lack of reliability isnot missing physics in ice sheet models but rather the level of uncertainty in many important modelinputs, such as bed topography, geothermal heat flux or ocean induced melting patterns. With theadvent of remote sensing of the Cryosphere, we have been able to reduce some of these uncertainties,and ongoing and future missions such as Sentinel-1, ICESat-2, NASA's OMG, will help better constrainthese model inputs. However, as more and more data from different sources, different epochs anddifferent resolutions become available, it is not clear how ice sheet models will be able to ingestthis increasing amount of information. Over the next couple of decades, dealing with big data andlarge-scale temporal data assimilation will become an important challenge for this new generation ofmodels.

IACS (Cryosphere)

C17b - C17 Challenges in Cryospheric Sciences: Past, Present and Future

IUGG-0706

News from the IACS Working group on Glacier ice thickness

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The question about the ice thickness of a given glacier is amongst the oldest in glaciology, and knowledge of its distribution is essential for a number of applications. Despite this importance, the ice thickness of the majority of worlds' ice masses remains unknown. Recently, significant progress has been made in numerical methods that infer the ice thickness of glaciers from their surface characteristics and similarly, substantial advances have been achieved in the acquisition of in-situ measurements. So far, however, these efforts have been coordinated only marginally. This has led to a situation in which a series of modelling approaches are potentially available, but no assessment comparing their relative strengths and weaknesses exist, and in which a wealth of ice thickness data are spread across the literature or individual data bases, without being accessible in an unified manner.

The IACS Working Group (WG) on Glacier Ice Thickness is taking action in this field and aims at (A) perform a model intercomparison experiment, in which different methods estimating the ice thickness distribution from surface characteristics are compared against each other in a set of well constrained test cases, (B) associate an estimate of the ice thickness distribution to every glacier of the Randolph Glacier Inventory, in order to provide a reference estimate for the ice thickness distribution of every glacier around the globe, and (C) continue the effort initiated by the World Glacier Monitoring Service in centralizing the ice thickness measurements available worldwide.

In this contribution we will report on the progress made by the WG to date, give an overview of the ongoing activities, and discuss the challenges we have encountered so far.

IACS (Cryosphere)

C17b - C17 Challenges in Cryospheric Sciences: Past, Present and Future

IUGG-3730

Global glacier mass balance modeling – how can we do better?

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Glacier mass loss entails economic, societal, and ecological consequences resulting from changes in global sea level, fresh water availability, and other environmental conditions. Major advances have been made recently in modeling glaciers outside the ice sheets on a global scale. Results indicate continued glacier wastage throughout the century, and variable hydrological responses among different regions. The recent globally complete Randolph Glacier Inventory presents a major step forward but global glacier modeling remains challenging due to scarcity of validation data and crude representation of some processes in the current generation of global models. We investigate pathways to improve model parameter calibration using in-situ point mass balance data as well as glacier-wide geodetic balances derived from newly available large-scale topographic data.

IACS (Cryosphere)

C17b - C17 Challenges in Cryospheric Sciences: Past, Present and Future

IUGG-4849

IACS working group MicroSnow - From quantitative stratigraphy to microstructure-based modelling of snow: Motivation, progress, future.

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The IACS working group 'MicroSnow - From quantitative stratigraphy to microstructure-based modelling of snow' was initiated to foster 'the discussion on [...] newly developed instruments in view of necessity and sufficiency for an “optimal” description of physical properties of snow'. We detail our mission statement by providing an overview of current requirements and limitations of microstructure-based activities from both perspectives, modeling and measurement. We summarize outcomes and initiated activities of the working group in the previous two years and pose key questions to be answered in the future.

IACS (Cryosphere)

C17b - C17 Challenges in Cryospheric Sciences: Past, Present and Future

IUGG-5617

Mapping glaciers from space: Historical development and new challenges

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The potential use of satellite data for glaciological applications was recognized already in the early 1970s with the first images from the Landsat MSS sensor. The comparably low spatial resolution (~70 m), limited computer power and difficulties in separating snow from clouds were major obstacles for global glacier mapping with MSS data. This changed in the 1980s with the launch of the 30 m resolution Landsat TM sensor and increasing computer power. Even small glaciers were identifiable now and the new shortwave infrared band allowed distinguishing snow from clouds and map glaciers automatically. Data acquisition and processing was reduced during the commercial phase of data distribution in the 1990s, but this changed strongly after all Landsat data were made freely available; orthorectified and in a map projection. Now the major challenges for large-scale glacier mapping shifted to the required manual editing of debris-covered glaciers, clouds and seasonal snow. While the latter two will likely improve with the launch of the Sentinel 2a and 2b satellites (5 instead of 16 days repeat cycle), there is still no algorithm available for automated mapping of debris-covered glaciers with the required accuracy. Apart from this technical aspect, the discrimination of glaciers from rock glaciers and perennial snowfields also needs to be addressed. A new challenge will be the huge data stream coming from the Sentinels. The current set-up of globally distributed data processing as part of research projects will be unable to assimilate and process all data in a standardized and quality controlled way, likely independent of the debris-mapping problem. Hence, new ideas are required for efficient and automated processing lines converting the EO data into a useful product.

IACS (Cryosphere)

C17c - C17 Challenges in Cryospheric Sciences: Past, Present and Future

IUGG-0957

European network for a harmonised monitoring of snow for the benefit of climate change scenarios, hydrology and numerical weather prediction

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COST Action on SNOW which aims at building a better connection between snow measurements and models, between snow observers, researchers and forecasters, for the benefit of various stakeholders and the entire society will be presented.

Aim of the action is to enhance the capability of the research community and operational services to provide and exploit quality-assured and comparable regional and global observation-based data on the variability of the state and extent of snow.

Overall objectives and benefits are (1) Establish a European-wide science network on snow measurements for their optimum use and applications benefitting on interactions across disciplines and expertise, (2) Assess and harmonise practices, standards and retrieval algorithms applied to ground, air- and space-borne snow measurements => Foster their acceptance by key snow network operators at the international level, (3) Develop a rationale and long term strategy for snow measurements, their dissemination and archiving, (4) Advance snow data assimilation in European NWP and hydrological models and show its benefit for relevant applications, (5) Establish a validation strategy for climate, NWP and hydrological models against snow observations and foster its implementation within the European modelling communities, (6) Training of a new generation of scientists on snow science and measuring techniques with a broader and more holistic perspective linked with the various applications. There are 3 workings groups as listed below

Working group 1: Physical characterization of snow properties

Working group 2: Instrument and method evaluation

Working group 3: Snow data assimilation and validation methods for NWP and

hydrological models

IACS (Cryosphere)

C17c - C17 Challenges in Cryospheric Sciences: Past, Present and Future

IUGG-3678

Understanding and protecting snow in Antarctica: The goals SCAR Action Group "SnowAnt"

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Snow in Antarctica is a precious resource for current and future research and logistics. The intensified use of this resource and lack of the topic in the HorizonScan 2020 motivated us to put forward this subject and to form a SCAR Action Group. The key topics of the Action Group are to
(i) to investigate: Improve the knowledge on depositional and metamorphic processes in Antarctic snow and its feedbacks to the climate system, develop a snow classification for Antarctica
(ii) to protect: What is disturbed today will be in the ice core for the next ~ 1 My – reserve pristine snow areas: currently disturbed areas have to be mapped and coordinated with national logistic operators,
(iii) to implement and collaborate with the Antarctic Environments Portal and SnowReader to document disturbed areas, historic snow profiles, accumulation data from AWS, stake farms, surface radar profiles, shallow firn – snow cores,
(iv) to educate and coordinate: quantitative snow stratigraphy methods developed by the IACS working group MicroSnow should be implemented by snow schools, recognize the importance of snow for SCAR,
(v) to develop a proposal for an expert group on 'Snow in Antarctica' to be presented at the next SCAR meeting.

We present the current state of implementation of the goals and invite participation to this group.

IACS (Cryosphere)

C17c - C17 Challenges in Cryospheric Sciences: Past, Present and Future

IUGG-4407

Temporal dynamics of the snow cover in Russian Arctic

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The economic activity in the Russian Arctic region increased significantly in the last several years. New mineral deposits and corresponding transport infrastructure are under development. New military bases and Emercom centers along the Northern Sea Route are recently introduces. The increasing Polar tourism in coming years is actively discussed. The required scientific accompaniment to such activity is supported by the State and by the commercial companies. One of the announced State-supported actions is publishing of the “National Atlas of Arctic”, which would include all existent environmental, social, economic and resources information.

One of the most important component affecting Russian Arctic environment and economic conditions is seasonal snow cover. Despite numerous publications and databases containing the snow cover information, the published conclusions on the variability and possible scenarios of future changes in snowiness differ from region to region and from author to author. The presentation is an attempt to review the existent data and to analyze the variability in the duration of snow season in different parts of Russian Arctic.

IACS (Cryosphere)

C17c - C17 Challenges in Cryospheric Sciences: Past, Present and Future

IUGG-4598

Experimental investigation on intermittent drifting snow

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Drifting snow has a significant impact on snow distribution in mountains, prairies as well as on glaciers, ice shelves, and sea ice. In all these environments, the local mass balance is highly influenced by drifting snow. The most established formulations of the saltation mass flux consider the process as stationary. Nevertheless, experimental and numerical investigations suggest that drifting snow exhibits large intermittency with time-scales ranging from the inter-particle time-scale to scales larger than the largest flow time-scales.

It is hypothesized that drifting snow intermittency arises from the interplay between large coherent flow structures triggering the entrainment and splashing of snow crystals and snow-cover physical properties, the former affecting smaller-scale, the latter larger-scale variability of the mass flux.

Wind tunnel experiments of drifting snow over natural snow cover permit investigations under idealized boundary conditions (i.e. flat terrain, stationary and uniform approaching boundary layer flow), which allow to study in a fairly independent way the different causes of intermittency. We show time-series of mass flux as acquired by means of a snow particle counter. Further spatial information is gathered by employing digital shadowgraphy. The results suggest that intermittency in our wind tunnel environment is primarily caused by the non-linear flow-mass flux interaction. Additionally, measurements of the turbulence might be employed to correlate the mass flux intermittency to the turbulence time-scales, allowing a deeper insight into the mechanisms driving the mass flux time-variability of drifting snow at the smallest scales. Combined measurements of mass-flux and turbulence are crucial for the understanding of drifting snow intermittency.