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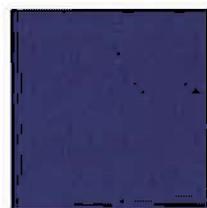
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Abstracts

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50A001

Effect of precipitation seasonality on glacier mass balance

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In the recent studies on the glacier shrinkage and their effect on sea-level rise, sensitivity of glacier against warming (climatic sensitivity) are considered to be associated with annual amount of precipitation. On the other hand, it has been pointed out that glaciers under the Asian summer monsoon were vulnerable against warming rather than those under the Euro-American winter accumulation climate. Under the summer-accumulation climate, warming will change precipitation phase from snow to rain. This alternation will induce not only reduce of accumulation but also lowering of surface albedo, which will cause drastic melt. Since many climatic variables will affect glacier mass balance and its climatic sensitivity, however, it has been questionable whether only precipitation seasonality dominated them. The author examined a comprehensive model calculation changing annual amount, degree of seasonal concentration and seasonality of precipitation under different latitudes using a simple periodic pattern of meteorological variables. The result clearly shows the assertion that climatic sensitivity of glacier mass balance strongly depends on seasonality and concentration of precipitation rather than the annual amount. This study shows that Asian glaciers located under the summer monsoon climate are potentially more vulnerable against the warming than previously thought.

50A002

Mass-balance modelling

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A mass-balance model is a model that generates the balance rate at a glacier surface from meteorological input data. The input data may be obtained from nearby weather stations, or from climate models. Once calibrated, mass-balance models can be used to study the sensitivity of the balance rate to climate change. Data from Automatic Weather Stations (AWS) are very helpful in designing mass-balance models which are based on an explicit description of the relevant processes that regulate the exchange of mass and energy between glacier surface and atmosphere. A scheme for the surface albedo, for instance, can be tested with AWS data. In this contribution a brief survey of mass-balance models will be presented. It will be argued that a plausible model has to consider at least air temperature and solar radiation as explicit variables. Some applications of mass-balance models will then be discussed. Consideration will also be given to the use of satellite data for construction/calibration of mass-balance models.

50A003

The importance of including variable near-surface temperature lapse rates when employing the degree-day method to estimate glacier melt

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The magnitude of glacier ablation depends on the energy balance at the glacier surface. For remote glacier locations, the large amounts of data required to determine this balance are often unavailable. For this reason, degree day models (DDM's) based on the strong observed relationship between glacier melt and near surface air temperatures are often used to estimate surface melt. Most studies that employ DDM's must downscale or interpolate climate model output and/or station observations to the area of interest. For spatially distributed models, temperature fields must be generated to reflect local conditions, which often include complex topography. This is most commonly done through the use of a digital elevation model and an assumed constant free air temperature lapse rate (often taken to be 6-7°C km⁻¹). The problem with this method is that temperature lapse rates measured over melting glacier surfaces can deviate greatly from standard free air values, for some glaciers by as much as 3°C km⁻¹. These deviations are mainly the result of temperatures over melting surfaces being fixed at 0°C and thus, can generate strong temperature gradients between the surface and overlying atmosphere. This can result in strong modification of near surface temperatures, principally through sensible heat flux to the surface. Recent investigations into near-surface temperature lapse rates in the Canadian High Arctic have found that lapse rates vary on both seasonal and daily time scales. During the melt season (JJA), observed fluctuations in lapse rates can be modelled using variations in lower tropospheric temperatures which, in this case, are derived from the National Centres for Environmental Prediction's North American Regional Reanalysis (NARR). In this study we examine the implications of including modelled variable near-surface lapse rates in DDM simulations of the surface mass balance of the Devon Island Ice Cap, Nunavut, Canada. Surface mass balance estimates are determined for the years 2004-06 during which time three automatic weather stations and 17 temperature loggers were in operation on the Ice Cap. These results are compared with estimates determined using the assumption that model temperatures can be downscaled using the moist adiabatic lapse rate. In addition, melt onset and freeze-up dates as well as melt duration and intermittent freeze-up events determined using variable and constant lapse rates are compared with those determined using QuikScat satellite scatterometer images, allowing for glacier wide validation of the temperature downscaling methods.

50A004

By how much do climate models underestimate snow accumulation on the Antarctic plateau? A re-evaluation of / from in-situ observations

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It has been suggested that meteorological and climate models underestimate snow accumulation on the Antarctic plateau because accumulation (or Surface Mass Balance, SMB) is dominated by clear-sky precipitation while this process is not properly taken into account in the models. Here, we show that differences between model and field SMB data are much reduced when the in-situ SMB reports used to evaluate the models are filtered through quality control criteria and less reliable reports are subsequently left out. We thus argue that, although not necessarily unsupported, model biases and their interpretations in terms of clear-sky versus synoptic precipitation on the Antarctic plateau may have been overstated in the past. To avoid such misleading issues, it is important that in-situ SMB reports of insufficient or un-assessed reliability are discarded even if this is at the cost of a strong reduction of spatial sampling and coverage.

**50A005 The surface accumulation and ablation of a coastal blue ice area near Cap Prudhomme,
Adélie Land, Antarctica**

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A record of accumulation and ablation along a 47-stake network at a coastal blue ice area in Adélie Land is presented and analyzed. The record covers early 2004 to early 2006, from 25 field surveys including in austral winter. The 2 years on record are very different, with a virtually null surface mass balance during the 2004 winter but large accumulation during the 2005 winter. A snow/ice energy and mass balance model is used to reproduce the accumulation and ablation record. A parameterization for snow erosion by wind is included. Input meteorology is from the ECMWF analyses and forecasts, corrected using one year of local meteorological observations from an automatic weather station. Model results agree reasonably well with the observations. Wind erosion is the largest contributor to ablation through removing much of the precipitation. Sublimation and to a lesser extent melt/runoff account together for more than 60 cm water equivalent of ablation in 2 years, mainly in summer. Although the record is short, it confirms high interannual variability and thus high sensitivity to meteorology and climate. Monitoring and understanding the mass balance of such coastal blue ice areas may help monitor and detect climate change at the Antarctic coasts.

50A006

Computation and mapping maximal altitude of snow line Z_{max}

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Spatial variability of snow line is function of balance accumulation and ablation processes on glaciers as well as outside of them, therefore it is necessary to unify data about Z_{max} for both of those types of basin surfaces. Main drainage boundaries of Turkestanskiy, Gissarskiy and Zeravshanskiy ranges presenting natural water divide are used as topography criteria at the first level of regionalization. Separation in general morphologically homogeneous groups of glaciers connected to the prevailing azimuth of macro-slopes of the above listed ranges is the next stage of bounding sub-basins. Thirty-four sub-basins were identified within Zeravshan river basin by this method and unified mean weighted value Z_{max} was computed for each of them. Ultimately the generalizing formula was obtained which describes spatial variability Z_{max} for Zeravshan river basin taking into account a peculiarity of this parameter within glacier areas and outside of them. In order to determine area where annual balance accumulation and ablation of solid precipitation is positive it is necessary to calculate a set of Z_{max} values and average them for the given shape of river basin. Local maximum of altitudes for the given shape should be computed also. It is not difficult to determine the annual balance of accumulation and ablation for the given shape by means of using method computation average layer of precipitation described in the paper.

50A007 Calculation of glacier mass balance and changes of mountain river basins glaciation using standard meteorological data

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The glacial runoff forms approximately 10-12 per cent of annual runoff of main rivers in the Central Asia within the limits of the former USSR. Hence, calculation of the mass balance of the glaciers is necessary in prediction of the runoff which is basis of life in Central Asia and destiny of Aral Sea also. On the available data, the area of glaciation was reduced as fast as 0.6-1.0 per cent a year in average for last half-centuries. Two problems are important for estimation of glaciation change: calculation of mass balance of individual glaciers and calculation of change in the whole glaciation of river basins, in other words integrated characteristics of set of glaciers. Regular measurements of the mass balance are carried out on a small number of mountain glaciers only. Therefore numerous attempts to find correlation between the mass balance and basic meteorological factors influencing it took place. The principal meteorological parameters determining the mass balance of mountain glaciers are annual or winter precipitation (a parameter of annual accumulation) and summer air temperatures (parameter of annual ablation). Many attempts to find the dependence between these values have been made. However in all cases it was necessary to have long enough series of the glacier mass balance evaluation, precipitation, and air temperature measurements at basic meteorological stations. Unfortunately these cases are rare. The method of specific mass balance approximate calculation which doesn't need direct measurements at a glacier is offered. The input data are annual precipitation and average summer air temperature air at basic meteorological stations and average long-term (climatic) equilibrium line altitude on a glacier or group of glaciers. Last value can be evaluated using standard topographic maps. The method was validated on mass balance data of the Abramov Glacier (Pamirs-Alay mountain system) and surrounding meteorological stations. The second problem (change of integral characteristics of the glaciation under climate change) is solved with use of statistical characteristics of the glaciation and their links with characteristics of the river basin. The offered technique allows calculation of change in ELA, numbers of glaciers, their total area and ice volume. Besides it is possible to calculate approximate fraction of glacial water in total runoff from a river basin having glaciation. The method was applied for calculation of possible glaciation change in several river basins located at Western Tien-Shan and the Pamirs.

50A008

Statistical analysis of the spatial and temporal variability of winter mass balance of Storglaciären

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Detailed mass balance measurements have been carried out on Storglaciären, a small valley glacier (3 km²) in northern Sweden, since the mid 1940s. The purpose of our study is to statistically analyse the spatial and temporal variations of the winter mass balance data of the period 1966 to 2005 when snow probings are available at about 300 points on a 100 m resolution grid. We use the statistical model by Lliboutry (1974) which assumes that the mass balance $b(j,t)$ at site j for year t , can be described with a linear function of two parameters depending on time and space. While previous studies have indicated that such a relationship is valid for net mass balance, we test the applicability of the model for winter mass balance. Results show that the model has a systematic bias. The residuals have a significant correlation with the winter mass balance, and the model sometime yields negative values especially when accumulation is low. The model was modified to an exponential function, instead of the linear one presented by Lliboutry. Results showed that the new model performs better as indicated by lack in correlation between the residuals and the measured winter balances. The standard deviation of the residuals for the linear model and exponential model are 0.40 m w.eq. and 0.32 m w.eq., respectively. The model proved to be a useful tool for estimating winter mass balances for years that lack detailed spatial coverage in snow depths measurements.

50A009 Comparing Climate Information as Derived from Mean Specific Glacier Mass Balance and Ablation Stake Records

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By comparing trends in the time series of (i) the mean specific mass balance of a glacier (b_m) and (ii) the ice ablation on a single point (b_{ia}) from three East Alpine glaciers (Hintereis- and Kesselwandferner in the Ötztal Alps, Weißbrunnferner/Ghiacciaio Fontana Bianca in the Ortler-Cevedale-Group) and by relating them to time series of (iii) positive degree days' temperature sums (ST+) and (iv) winter precipitation (P) from nearby stations, three phases of different climate-glacier relationships are identified: In Phase I (before 1978) b_m values are close to zero in a balanced climate-glacier relationship. b_m and b_{ia} show the same signal. In Phase II (1979 - 1991) b_m and b_{ia} drop into negative values which correspond to increasing ST+. Still, different trends in b_m and b_{ia} indicate a diverse reaction to the changing climate. The glaciers have started to shrink, extenuating the climate information from b_m . In Phase III (1992 - 2005) the trends of b_m and b_{ia} are oppositional. While a decrease of negative b_m values is strongly influenced by a rapid decrease of the glaciers' surface (up to -18%), the negative trend of b_{ia} reflects the ongoing climate change. Whereas b_m is the result of climate and the glacier's adaptation to changing climate conditions, b_{ia} provides a clearer information on climate variations. In Phase III rates of ice ablation were up to 30% higher than in Phase II and ice ablation starts 14 days earlier in average but there is no extension into the autumn. Air temperatures indicate increasing availability of energy mainly during May - July that is in good agreement with the earlier beginning of the ice ablation season.

50A010

The GLACIOCLIM-SAMBA transect

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In response to global warming, climate models predict that the largest change (increase) in surface mass balance on the Antarctic ice sheet will occur at the margins, in the coast to plateau transition region where the current accumulation is large. The GLACIOCLIM-SAMBA (<http://www-lgge.obs.ujf-grenoble.fr/~christo/glacioclim/samba>) transect was established to sample the spatial (~km scale) and temporal (interannual) structure of accumulation in the transition region of Adélie Land. The transect is currently ~150 km long, with 91 stakes and various meteorological instrumentation. It was progressively established since 2004 and first fully surveyed in early 2007. Spatial variability is large and appears at least partly stationary. Temporal variability is also very significant. The data are in good agreement with recent satellite-based maps of Antarctic accumulation (Vaughan et al. 1999; Arthern et al. 2006) except in the ~50 km closest to the coast where accumulation is highest. Because this is where slopes are strongest, this is also where climate models of the highest resolution show the best agreement with the observation and predict the largest future accumulation increase. In terms of surface mass balance and sensibility to climate change, the narrow coast to plateau transition slopes deserve more investigation than is currently being carried out.

50A011

South Cascade Glacier mass balance, 1935-2006

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A simple model uses daily observations of precipitation and temperature at a nearby weather station to estimate seasonal mass balance components at South Cascade Glacier back to 1935, which is 24 years before measurements began at the glacier. This is 13 years earlier than can be done with the NCEP-NCAR Reanalysis database, which begins 1 January 1948. Although the model's error in estimating winter balance b_w and summer balance b_s over 1959-2006 is greater than that of a model using the Reanalysis database, its error in estimating net balance b_n is comparable. The model uses an empirically determined precipitation ratio between the station and the glacier and a seasonally varying temperature lapse rate determined from nine years of measurements at the glacier. Temperature is used with a degree day formulation to estimate ablation and to partition precipitation between rain and snow for estimating accumulation. Both processes are assumed to exist through the year, with model results compared seasonally with adjusted observations of b_w and b_s .

The published mass balance series is adjusted to a constant-topography (1970) series, following the work of Daniel Ellsberg, in an attempt to remove the influence of changing topography on the glacier's response to climate. The reconstructed values prior to 1959 are also referred to the 1970 glacier topography. Because precipitation is measured at the weather station, rather than being inferred from other meteorological variables, it enables distinguishing more accurately between wet-day and dry-day conditions, including vertical lapse rates of temperature.

50A012 Best possible estimation of mass balance combining field data variance analysis and photogrammetry

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A variance analysis of the long time series of mass balance recorded at Sarennes glacier (45°07'N; 6°07'E, France) since 1949 shows that specific winter and annual balances deviates from their mean values over the period of record by an annual amount that is uniform all over the glacier. Regarding the annual mass balance data, this linear composition of the spatial and temporal variability's is only altered for a reduced number of years of strong negative budget at the lowest altitude measurement sites. Stake to stake annual balances are therefore highly correlated and sampling at a single site would be acceptable to record this annual deviation. The spatial variability of the data is found to be close to the natural overall spatial variability of the mass balance. However, a systematic error-free estimation of the glacier-wide balance seems to be preferably obtained from the volume changes measured by photogrammetry rather than with an integration of specific balances using the altitude area distribution.

50A013 Modelling the long term mass balance series of Storbreen, Norway, using an energy balance approach

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Storbreen is situated in the continental part of southern Norway and has one of the longest mass balance series in the world. Annual measurements of accumulation and ablation have been carried out since 1949, providing a total of 58 years of measurements. Generally, the summer balance values have a larger variability than the winter balance values. Except for a transient mass surplus in the period 1989-1995, the main trend has been mass deficit and the glacier had a total mass loss of -17 m w.e. for the period 1949-2006. Since 2001 an automatic weather station (AWS) has been operating in the ablation zone of Storbreen. Analyses of the data show that the mass balance of Storbreen is most sensitive to variation in temperature and albedo, and less to inter-annual variation in shortwave incoming radiation. The results from the AWS have been used to calibrate and validate a mass balance model for Storbreen based on energy balance principles. The mass balance model has been run for the period 1957 to 2006 using input data from meteorological stations outside the glacier. One of the major challenges was to deal with the lack of continuous series of meteorological input data in the vicinity of the glacier. Stations quite far from the glacier had to be used to model a long time series. In general, the mass balance model was able to capture the measured spatial and altitudinal variation in mass balance as well as the inter-annual variability. However, major discrepancies between modelled and observed balance occurred in several years.

50A014 Comparison of mass balances for Vernagtferner obtained from direct measurements and distributed modelling

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Distributed mass balance models have become a common tool to calculate a glacier's mass balance or its change due to a change in climate. While the processes determining glacier melt are well understood and the corresponding simulations often agree favourably with in-situ measurements of ablation or run-off, accumulation is treated in most models quite roughly or used as a tuning parameter. As a consequence, only few studies exist that compare modelled with measured mass balances over a full balance year. Now the question arises, whether models do provide a better estimate of the glacier mass balance than the interpolated measurements, given that the latter might be based on snow patterns or regression curves that have been obtained under different climatic conditions. In this study we present a detailed comparison of the mass balance from Vernagtferner, a long and well studied glacier in the Ötztal Alps (Austria), as obtained from direct measurements and a distributed mass balance model of intermediate complexity. Vernagtferner is particularly suited for such a study, as meteorological and run-off data from a nearby gauging station as well as winter and total mass balance data are available. The model is applied to the very different balance years 1997/98 (highly negative) and 1998/99 (near zero balance) and the comparison is performed for the mass balance in 50 m elevation bins, for individual stakes and pits, for the spatial pattern as well as ELA and AAR values. First results indicate that the mean balance values for the two different years are reproduced quite well by the model and that potential global radiation can explain a part of its observed spatial distribution. As expected, the overall pattern is better reproduced in the negative balance year where melt processes largely determine the balance. In the zero balance year, the influence of small scale processes (e.g. wind redistribution) that are not included by the model cause larger deviations. However, the mean values for 50 m elevation bins as well as ELA and AAR values agree fairly well. So we conclude, that the model allows to calculate the mass balance with the same accuracy as the measurements, but that local anomalies are better captured by human interpretation.

50A015

Mass Balances of Brewster Glacier, New Zealand, between 1978 and 2007

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The Brewster Glacier is a small retreating glacier that is situated on the Main Divide of the Southern Alps of New Zealand. Since 1978, a yearly end-of-summer snowline (EOSS) survey has been conducted by taking oblique photographs from a light aircraft. In the past, these records have been used as a proxy for the mass balance. In 2004, a field-based mass-balance programme was established on Brewster Glacier, and this provides an opportunity to compare direct mass balance measurements with the EOSS method. In this study, the mass balance is calculated for the last 30 years with an energy-balance model that is forced by nearby climate information. The mass balance model has been applied previously in the European Alps and this study provides a test of the model for the Southern Alps of New Zealand. The modelled mass balance is verified with the aerial photographs from the EOSS survey and the direct measurements. The model provides insight into melt processes on the glacier, for example it helps explain how the spatial pattern of melt is affected by nearby topography. Scenario based model predictions are used to estimate future melt for the investigated glacier. Past mass balances will be reconstructed and compared to the EOSS proxy mass balance. The modelled and validated mass balance data provides a good tool to evaluate the EOSS as mass balance proxy. There is a need for such investigations because results from the EOSS proxy method differ from the direct observations on the glacier, especially for the year 2006.

50A016 Measured and modelled sublimation as a key variable in the mass balance of tropical glaciers

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For glaciers in tropical climate regimes with distinct seasonality of humidity, sublimation plays an important role as an energy sink on the surface during the dry season. This energy-intensive process reduces the availability of energy for melting. As part of a field campaign in August 2005 sublimation was measured on the tongue of Glaciar Artesonraju (8° 58' S 77° 38' W) in the Cordillera Blanca (Peru). Cylindric pots were used as lysimeters and dug in the ice surface. Time series of sublimation for one 10-day and one 5-day period were obtained. Results show that there is a strong dependence on surface roughness. Daily sublimation sums therefore range from approx. 1-3 mm w.e. for smooth to 2-5 mm w.e. for rough conditions. The sublimation data were used to optimize a physically-based mass balance model. Input to the model was provided by an automatic weather station (AWS) placed on the glacier tongue. From the model output, the variable f (ratio of energy consumed by sublimation to the total energy available for ablation) was analyzed. Monthly means of f from April 2004 to December 2005 were computed using the AWS data; f shows a clear seasonality with 0.1-0.15 in the wet season and dominant peaks of 0.7 (2004) and 0.45 (2005) in the dry seasons. In a final step, the f -ratios computed from the physically-based model were compared to the lower-complexity ITGG mass balance model which parameterizes f simply as a function of monthly precipitation. This model was especially developed for tropical conditions and has the advantage of little input data requirement, but relies on a number of parameterizations that we want to test by more sophisticated methods. f in the ITGG-model is generally higher, especially during the wet season. Furthermore, the mentioned dominant peaks of f – on the basis of the measurements and physically-based model – stand in contrast to the constantly high values in the ITGG-model during the dry season.

50A017

Experiences gained and conclusions derived from the long-term mass balance measurements on the Stubacher Sonnblickkees

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On the Stubacher Sonnblickkees (SSK), situated in the Hohe Tauern, Eastern Alps, mass balance investigations have been carried out since 1963. From 1964 to 1980, the direct glaciological method was used to calculate the net balance each year. Since 1981 a semi-direct method has been used. In spite of the complex glacier topography, interesting empirical experiences were gained giving a better understanding concerning glacier type, mass balance and mass exchange. 17 years of direct mass balance measurements were used for a correlation between the net balance and the AAR, thus enabling an estimation of the yearly net balance in a semi-direct way. Using the mass balance figures of the SSK correlations, the relation between net balance, net accumulation and net ablation versus AAR could be derived. There are systematic relations which are typical for the glacier type represented by the SSK: the so called turnover 'curves' which indicate the relation between the net mass balance versus the specific accumulation and ablation (but defined as Bc/S and Ba/S). From the statistical point of view, they are logarithmic regression curves. There seems to be a topographical influence on the type of diagrams. Small glaciers without a distinct tongue show diagrams from the type SSK, alpine valley glaciers, like the Hintereisferner; belong to another type and the Vernagtferner lies in between. The Igan Glacier, for example, has similar curves to the SSK. Relatively early, after the first three years of mass balance studies (thesis H. SLUPETZKY, 1968), the idea of 'interim mass balances' was expressed. Meanwhile similar procedures were published (e.g. M.B. DYUGEROV, 1988). The goal was to prove systematic relations of the glacier type SSK with another glacier and to get basic information on snow depletion (temporary ELA), balance gradient and maximal balance variation range within a few years. On the Cathedral (Massif) Glacier, situated in the Atlin Region, B.C. Canada, data were recorded every 7 days in the summers of 1976/77 and 1977/78 to calculate the interim (temporary) mass balances. It was proved that interim balances could be used successfully to get basic information on the glacier system within a short time. The mass balance turnover diagram was used to calculate the net accumulation (bc) of the Storglaciären, Sweden, in selected years. On this glacier the winter/summer balance is measured to get the net balance and not by measuring the net accumulation (bc) and net ablation (ba) as in the Alps. For seven years the net ablation of ice (and firn) was calculated and the correlation between ba (Ba/S) and b was estimated. Then the net accumulation (ba) was calculated. It was found that the curves of SSK and Storglaciären are similar. The experiences gained from the long-term

50A018 Six decades of available glacier mass balance observations – a review of the worldwide monitoring network

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Glacier mass balance is the direct and undelayed signal to annual atmospheric conditions and, hence, among the essential variables required for global climate monitoring. The World Glacier Monitoring Service (WGMS; www.wgms.ch) collects and publishes glacier mass balance data from the direct glaciological and the geodetic methods as a contribution to the Global Terrestrial Network for Glaciers (GTN-G). Annual mass balance measurements with the direct glaciological method, based on an extensive net of ablation stakes and snow pits, were initiated in 1945 on Storglaciären, Sweden. Taking into account the one-year retention period for analysis and publication of the data by the investigator, 60 years of mass balance data is now readily available from the WGMS. This study provides a review of the present monitoring network, of the available data, of the glacier mass changes during the period 1946–2005, and of the current developments within mass balance monitoring. For the period 1946–2005, there are more than 3'000 annual mass balance results from 212 glaciers available through WGMS. 43% of the annual values are reported with winter and summer balances. The average length of the observation series is 16 years, with 38 glaciers having more than 30 years of data. However, there are only 30 glaciers with continuous mass balance measurements since 1976. Almost 90% of the mass balance series come from the Northern Hemisphere and 40% from Europe. At the beginning of the 21st century mass balance data is reported from 89 glaciers. The 30 glaciers with continuous measurements since 1976 show an average annual mass loss of 0.58 m water equivalent for the decade 1996–2005, which is more than twice the loss rate of the period 1986–1995 (0.25 m w.e.), and more than four times the rate of the period 1976–1985 (0.14 m w.e.). The results from these 30 continuous mass balance series correspond well to estimates based on all available annual observations, including short and discontinuous series. A step-change in climatic conditions would cause an initial mass balance change followed by a return towards zero values, due to the glacier's adaptation of its size (surface area) to the new climate. The observed trend of increasingly negative mass balances over reducing glacier surface areas thus leaves no doubt about the ongoing change in climatic forcing.

50A019 Challenges and strategies for worldwide monitoring of glacier mass balances and mass changes

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Annual mass balances and longer-term mass changes of glaciers and ice caps are key elements of glacier monitoring strategies within global climate-related observing systems. The accelerating changes in nature, technology and assessment philosophy, however, induce an urgent need to carefully consider new requirements and possibilities of future monitoring systems. The following thoughts should help stimulating a broad discussion about the necessary planning steps. Extensive mass balance observations for improving process understanding and for calibrating/validating numerical models as well as less sophisticated determinations of mass changes as regional climate signals are based on a limited number of small- to medium-size glaciers with surface areas typically a few km², and average thicknesses of a few tens of meters. With yearly thickness losses increasing from characteristic 20th-century values of a few tens of centimetres to now more than a meter, most of these glaciers are likely to disintegrate and/or completely vanish within the coming years to decades. In order to save the worldwide mass balance network through the near future and to guarantee continuity of the measured data, new and still larger glaciers must be envisaged as replacements. Corresponding activities have to start now or at least very soon, because an overlapping time period with parallel measurements on the previous as well as on the new glaciers must be foreseen. A strategy for assessing suitable new glaciers must be based on sensitivity and scenario analyses using numerical models. Digital terrain information greatly helps with this task and opens fascinating possibilities. In fact, differencing the SRTM model with regionally available DEMs from earlier aerial photography started to provide quantitative information on mass changes during the past decades for thousands of large and small glaciers and on their individual parts. For the first time, the representativeness of the few long-term in situ measurements and corresponding variability as a function of glacier geometry and microclimatic conditions can be investigated for entire mountain chains. This enables assessments of regional and global developments of glacier mass to become much safer. By comparing rates of change and remaining volumes (calculated using 3D-terrain information rather than area alone), extinction paths can be calculated for individual glaciers within drainage basins or mountain chains. This allows for improved impact assessments, which are especially needed with respect to regional runoff and water resources for lowlands surrounding glaciated mountain chains and for the contribution to sea level rise from glaciers and ice caps.

50A020 The state of glaciers of Tajikistan and adaptation of economic activities in conditions of global warming

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The main area of glaciations of the Republic of Tajikistan is in mountains of Northwest Pamir which its the center of which is Fedchenko glacier - the largest mountain glacier in the world. The length of a glacier is 77 km, average width is 2,5 km, the maximal width 5 km, thickness of ice reaches kilometer. From Fedchenko glacier begins Seldara - one of tributary of the Muksu river which, merging with Kizilsu gives rise Surkhob - to the right tributary of Vakhsh river. Thus, Fedchenko glacier can be found a source of Vakhsh River. By 1988 the glacier has receded more than on 500 m and has decreased on the area for four square kilometres. Average speed of step of Fedchenko glacier for the last century made 10-12 meters one year. Its lower part during nine kilometres settles was broken with numerous cracks. Thus Fedchenko glacier has lost almost all its right tributary- they became independent glaciers. Only for forty years from mountain ranges: Academy of Sciences, Zaallay and Kaindi have disappeared 14 not large glaciers with general area of 7,6 km². Average speed of movement of glacier in connection with loss of weight has decreased with 72 up to 69 sm daily. In total for 20-th century the glacier has lost about 12-15 km³ ice. Agency on hydrometeorology of the Republic of Tajikistan in September,2006 after a sixteen year has made survey of the Fedchenko glacier and a cross-section structure in area of Bivachni glacier. The glacier continues to recede with constant speed of 8-10 meters in one year, but irregularly. In the eightieth years of the last century the glacier receded 20 m in year. On a cross-section structure in seven kilometres the glacier is higher than tongue settles 1,5 meters annually though twenty years ago intensity of subsidence made 2,0 - 2,5 m in year. For irrigation and water-power engineering regulation of river flow are in an antiphase. The irrigation interested in demands of water in winter and the use of it in summer on the contrary to the water-power engineering - accumulation of water in the summer. The cardinal decision of these contradictions between irrigations and water-power engineering is the further development of the last by construction of many large Hydropower stations (HPS) with reservoirs. In this case the reservoirs located in downstream of the rivers will work in a power mode and reservoirs on the upstream rivers - in irrigational. Moreover, the possible changes of the river flow connected to change of the climate as show direct supervision, favourable to economic activities. The researches which have been carried

50A021 Calculation of sensible heat flux over a melting ice surface using data from automatic climate stations

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The calculation of sensible heat flux over a melting surface is obviously important for glacier-climate models. The most attractive approach is to use a bulk transfer coefficient where sensible heat flux is proportional to the product of wind speed and temperature measured at a single height, c. 2 metres above the melting glacier surface, by a recording climate station. The dimensionless transfer coefficient depends upon surface roughness and instrument height if one assumes the classic logarithmic wind profile but the latter need not be correct for aerodynamically stable conditions nor for the katabatic flows, that are common over glaciers. Other workers have extended the bulk transfer approach in a theoretical sense while I describe a more empirical approach. This is based on correlations between measured daily ablation, air temperature and wind speed data. I interpret the regression coefficient linking measured ablation to the product of wind speed and temperature as an estimate of the transfer coefficient. Data are available for hundreds of days of record at two sites in West Greenland (415 days at Nordboglletscher and 512 days at Qamanârssûp sermia) and for shorter periods in North Greenland (20 days in Kronprins Christian Land and 35 days at Hans Tausen Ice Cap). Average transfer coefficients for the four sites are in the range 0.003 to 0.005, which are in reasonable agreement with values reported elsewhere. I analyse the variability of the transfer coefficient in time, and under different weather conditions, using the long records from the West Greenland sites, and I describe the implications for estimating turbulent heat fluxes in energy balance models. The present study uses manually-observed estimates of daily melt rate but similar data could be collected with automatic climate stations using sonic ranging sensors.

50A022 Mass balance of Zongo glacier, Bolivia, between 1956 and 2006. Using glaciological, hydrological and volumetric methods

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Mass balances of tropical glaciers are recognized as good indicators of climatic change over the last decades in these high-elevation remote areas. Moreover, mass balance study is essential to estimate the water resources of some major cities in the highlands of Andean countries. Therefore the dramatic reduction of these glaciers reported in the last decades could directly affect the water supply in the dry season over these regions. Unfortunately, mass balance time-series are short. The longest continuous glaciological mass balance time-series in Bolivia started in 1991. On this glacier with 2.25 km² of area, mass balance measurements have been carried out only with 10 stakes in the ablation zone and 3 snow pits in the accumulation zone. Consequently, the uncertainty in the total mass balance is high, as many areas have not been sampled. Photogrammetric techniques offer a good way (i) to check the specific net balance over long periods, (ii) to extend the mass balance time-series to the past. Digital elevation models have been obtained using aerial photographs taken in 1956, 1963, 1975, 1983, 1997 and 2006. For this purpose, approximately 10000 points have been measured in irregular grids for each year on the whole area of the glacier (area average 2 km²). The measurement accuracy is 8.1µm for photograph coordinates and 0.65m for ground coordinates. From these measurements, volumetric mass balance has been calculated over the last fifty years. Furthermore, the hydrological budget has been calculated from discharge measurements in the river coming from the glacier and from precipitation measurements close to the catchment area. The purpose of this paper is to compare the glacier mass balance from the glaciological method (1991-2006), the hydrological method (1972-2006) and the volumetric method (1956-2006). The uncertainties of all methods have been assessed. With these new data, this time-series is the best-known mass balance time-series in this region.

50A023

Preliminary studies on the Mass Balance of Chotta Shigri Glacier India

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A synoptic survey has been carried out from 2002 to 2007 to study the mass balance on the Chhota Shigri glacier (32.2°N, 77.5°E; 15.7 km², 6263 to 4050 m a.s.l., 9 km long) located in Lahaul and Spiti valley, Himachal Pradesh, India. Chhota Shigri glacier lies in the monsoon-arid transition zone (western Himalaya) which is alternatively influenced by Asian monsoon in summer and the mid-latitude westerlies bringing precipitation in winter. The results of half decade of mass balance based on in-situ measurement using glaciological methods (using steam drill in Indian Himalaya and environmental friendly Bamboo stick) . The results shows that overall specific mass balances are mostly negative during the period studied and vary from a minimum value of -1.7 m water equivalent (w.e.) in 2005-2006 and 2006-2007. Equilibrium Line Altitude (ELA) also varies from a minimum value of 4855 m a.s.l. in 2005 to a maximum value of 5200 m a.s.l. in 2006. AAR (Accumulation Area Ratio) was maximum 74% in 2005 and minimum in 2006 less than 20%. Chhota Shigri glacier shows similarity to mid-latitude glaciers (like Alps. etc.) in term of ablation seasons which limited to summer month and a mean vertical gradient of mass balance 0.7m w.e. 100 m-1 in the ablation zone(similar to those reported in Alps). Mass balance is influenced by debris cover which efficiently protects the lowest part of the glacier from melting and incoming solar radiation which shows by exposure and shading effects of surrounding steep slopes. Our study indicate that melting is controlled by incoming solar radiation and surface albedo and suggest for regular and long term seasonal mass balance measurements and energy budget investigations in this important bench mark glacier of Himalayas.

50A024

Glacier velocity variability from repeat photography

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Automated repeat photography offers a means to observe outlet glacier dynamics at high spatial and temporal resolution, filling a gap in satellite or airborne remote sensing. This project is to determine surface velocity variations at key Greenland ice sheet outlet glaciers, both tidewater and land-terminating. The work explores a hypothesized link between surface climate, i.e., melting, and glacier dynamical variability, i.e., flow rates and ice berg calving.

50A025

Pattern of recent volume changes at Gran Campo Nevado ice cap: 2000-2007

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The Gran Campo Nevado Ice Cap (GCN), southernmost Chilean Patagonia, is located at one of the most pronounced climate divides of the entire earth. At around 53°S the Andean mountain range forms the only continental barrier for the southern hemispheric westerlies. This makes annual precipitation sums increase to more than 10,000 mm at the summit regions due to strong orographic effects. As a result of this very high precipitation sums the existence of an almost 200 km² large ice cap is permitted at comparably low altitudes below 1,700 m asl although mean annual air temperature at sea level is as high as +5.7°C. Influenced by this highly maritime climatic setting the GCN showed a remarkable pattern of changes in surface altitude during recent decades. Between 1984 and 2000 the ice cap showed a mean lowering of surface altitude of 0.4 m a⁻¹. However, this overall loss of ice masses features a strongly altitude dependent pattern of glacier change with a zone of zero altitude change at around 975 m asl. In accordance with the warming trend recently observed in southern Patagonia, the outlet glacier tongues showed a thinning of up to 3.2 m a⁻¹ at their lowermost ends. However, the uppermost parts of the ice cap showed a thickening of 0.7 m a⁻¹ that can be attributed to a strengthening of the westerlies represented in the observable positive trend of the Southern Hemisphere Annular Mode (SAM). This study shows that this remarkable pattern of glacier change so far continued until present. Two digital terrain models (DTM) were analysed to obtain changes in surface altitude and volume of GCN between 2000 and 2007. The surface topography at the beginning of this study period was taken from SRTM 3 data acquired in February 2000. For the surface altitudes representing the terrain situation in 2007 a DTM generated from ASTER data acquired in February 2007 was used. Based on the 2007 surface area of GCN of 189.4 km², the results indicate a significant mean surface lowering of 20.6 m. This thinning corresponds to a mean overall surface mass balance of -2.6±1.2 m w.e. a⁻¹ and to an estimated ice volume loss of 0.49 ± 0.23 km³ w.e. a⁻¹. As in the period 1984-2000 the observed glacier change in 2000-2007 is also characterised by a clearly altitude dependent pattern. For the lowermost regions of the outlet glaciers a strong thinning of up to 7.5 m a⁻¹ was obtained. However, for the interior areas of the ice cap the results yielded an ongoing thickening of up to 2.7 m a⁻¹ in the uppermost regions. For the period 2000-2007 a distinctly steeper gradient of surface altitude change and a pronounced uplift of the zone of zero altitude change to approximately 1,350 m a.s.l were derived. This reflects recent climate variability in southern South America. The extremely high precipitation sums form the basis of the ongoing glacier thickening in the summit regions, while the positive trend in air temperature causes an accelerated glacier thinning in the valley regions and thus an uplift of the zone of zero altitude change. Correspondingly, it could be concluded that in the near future the high precipitation sums might be insufficient to counteract the continuous expansion of the area of glacier thinning up to the uppermost parts of the ice cap.

50A026 Global glacier mass losses and mass balance sensitivities assessed from observations and gridded climate data

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Glaciers have generally experienced mass loss in the last couple of decades with strongly accelerated ice wastage during the last decade. We present a methodology for grid-based global assessment of mass loss of all glaciers and ice caps outside the ice sheets in Greenland and Antarctica, and their sea-level equivalent during the period 1961-2004. Regional and global estimates of glacier mass loss are computed from glacier area, mass balance sensitivities, and ERA-40 temperature and precipitation trends for each glacierized grid cell. Annual and seasonal mass balance sensitivities to temperature and precipitation changes are computed for a large number of glaciers based on calibration of a simple temperature-index regression model to observations of seasonal mass balances using ERA-40 re-analysis data as climate input. The mass balance sensitivities are then extrapolated to each glacierized grid cell by means of a continentality index and precipitation as derived for each grid cell of the ERA-40 grid. Results indicate that previous global assessments based on extrapolation of measured mass balances may have underestimated glacier mass loss during the last four decades due to underestimation of high mass balance sensitivities in areas where measurements are scarce.

50A027 Modelling the 20th century surface mass balance of Hardangerjøkulen, southern Norway

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A spatially distributed mass and energy balance model has been developed for Hardangerjøkulen, a small ice cap in southern Norway. The model has been used to study surface mass balance variations for the period 1905-2005. In addition, the spatial distributions of surface energy and mass balance have been investigated. Calculations were done on a 50 m rectangular grid to include topographic effects. Parameterizations were calibrated and validated with annual mass balances measured by the NVE, Oslo on one of the outlet glaciers of Hardangerjøkulen (1963-2005) and with measurements from an automatic weather station (AWS) operated by the IMAU, Utrecht University on another outlet glacier (2001-2005). Three different meteorological data sets were used as input to the model. Detailed records from synoptic weather stations in the vicinity of the glacier are available from 1958 onwards. Secondly, the model was driven with ECMWF re-analysis data (ERA40: 1959-2001) and operational data (2002-2005). Before 1958, data from Bergen were used. We derived parameterizations to simulate the local climate using the data from Bergen, by comparing the data from Bergen with data from stations near the glacier for the overlapping period (1958-1984). In this way we could reconstruct surface mass balances back to 1905. We find good agreement between modelled winter and summer mass balances and NVE measurements, although interannual variations are generally smaller in the model. In very wet years, the winter mass balance is underestimated with ERA40 input data. Modelling a realistic snow depth at the AWS location proves to be difficult as the snow distribution is only measured at one of the other outlet glaciers and is spatially highly variable. The model results show that net mass balance was strongly negative in the 1930's and 40's, then remained in approximate balance until the late 1980's. Around 1990, net mass balance was very positive, but since the year 2000, it has mainly been negative.

50A028

Surface mass balance changes of the Greenland Ice Sheet since 1866

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Mass loss from the Greenland Ice Sheet (GIS) over the past decade has caused the impression that the GIS has been behaving anomalously to the warming of the 1990s. We have reconstructed the recent (1866-2005) surface mass balance (SMB) history of the GIS on a 5 x 5 km grid using a runoff-retention model based on the positive degree-day method. We have extended this method further to account for the influence of year-on-year surface elevation changes on SMB estimates and have found this effect to be minor. The climatic input (precipitation and temperature) was assembled from ECMWF analyses for the period after 1958 and from a spatio-temporal correlation between coastal meteorological and ice core data and Polar MM5 output for the period prior to 1958. We compare SMB estimates from 1995-2005 to a similar period in the past (1923-1933) where SMB was comparable and conclude that the present-day changes are not exceptional within the last 140 years. Peripheral thinning has dominated the SMB response during the past decade, as in 1923-1933, but we also show that thinning was not restricted to the margins during this earlier period. Thinning in the ice sheet interior during 1923-1933 is the result of lower precipitation compared to the last decade.

50A029 Estimation of glacier mass balance in unsampled areas by means of topographic data

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Knowing the spatial distribution of the mass balance on glaciers is a key issue for climate sensitivity studies and hydrological modelling purposes. Detailed mass balance measurements are achievable by the direct glaciological method. However, for logistic and economic reasons, only a few representative glaciers are selected for direct mass balance measurements. Moreover, the selected benchmark glaciers rarely meet all the 'ideal glacier' requirements, and inaccessible areas are common in these glaciers. The aim of this work is to develop and test a simple method that allows to extrapolate direct mass balance measurements to unsampled areas of the benchmark glaciers or to nearby unsurveyed glaciers. The mass balance spatial distribution pattern on a glacier is quite similar from year to year and it is mainly controlled by the local topography, which affects both accumulation and ablation. The continuous observation and mapping of the snow cover, particularly during years characterized by extremely negative mass balances (e.g. 2003 in the European Alps), make it possible to improve the knowledge of the mass balance patterns both in the ablation and accumulation areas. We used the snow cover maps, (plotted every 2 weeks during the ablation season), to draw Equilibrium Line Altitudes and additional mass balance points in unsampled areas. These additional points are located along the snowlines mapped during the ablation season. The net ablation at each point is calculated, since the day of snow cover survey, by combining the mass balance data at the ablation stakes, the altitude and the cumulated clear sky radiation derived from DEM's by means of multiple regression. The extrapolation scheme was developed and tested on 4 mountain glaciers located in the upper sector of the Val de La Mare, (Trentino, Italy). This basin was selected for a study on climatic change effects on cryosphere and hydrology at high-altitude catchments. The 36.2 km² wide basin has an average altitude of 2906 m a.s.l.; presently, 25% of its surface is glacierized and the annual runoff regime is dominated by snow and ice melt. Direct mass balance measurements have been performed since 1967 on the Careser glacier (2.83 km²) and since 2003 on the La Mare glacier (3.97 km²), while on Vedretta Rossa (0.99 km²) and Vedretta Venezia (1.38 km²) no measurements exist. The accuracy of the extrapolated mass balances was assessed by comparing them with stake measurements and volume changes calculated by means of two LIDAR generated DEMs.

50A030

Air temperature and glacier melting in the outer-tropics

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The air temperature is a measure of the internal energy of the air under fixed conditions of pressure and humidity. It is no-linearly linked to most of the melting energy fluxes at a glacier surface. Numerous studies revealed a high correlation between ice or snow melt and air temperature. This relation explains the efficiency of degree-day models to forecast ice or snow melting in various climates. The degree-day model has been applied to investigate the sensitivity to climate change of glaciers throughout the world. However, rather few studies investigated the physical causes of the good correlation between air temperature and ice melting. The paradox is that radiation generally is the greater incoming energy flux, but is poorly correlated to the air temperature. In the Arctic Canada, Braithwaite [1981] showed that the high correlation between temperature and glacier melting is due to the sensible heat flux: although net radiation is the largest source of energy, the sensible heat flux is more variable than the radiation and better correlated with the temperature. Ohmura [2001] stressed the role of the atmospheric long-wave radiation. The sky long-wave irradiance usually is the largest incoming energy flux and comes from the near-surface layer of the atmosphere, whose temperature is well correlated to the temperature measured at screen level. These analyses may not be valid in all climates. Here, we analyze the relationship between the temperature and the melting energy fluxes on a tropical glacier to test these hypotheses in a low latitude climate. The case study is the tropical Zongo Glacier, Bolivia. We show that the sensible heat flux is less important on tropical glaciers than on mid-latitude glaciers because of smaller temperature gradients (low latitude) and smaller air density (very high altitude). Melting is controlled by the radiation fluxes. Solar radiation is positively correlated to the temperature, whereas long-wave radiation is negatively correlated to it. As a result, the melting of Zongo Glacier is poorly correlated to the air temperature at a daily time scale. This study suggests that the degree-day model may not be appropriate to forecast the melting of tropical glaciers at short time steps.

50A031 Ground based interferometric radar for velocity measurements of the calving front of Kronebreen, Svalbard

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The mass budget of tidewater glaciers consists of the calving-flux and the surface mass balance. The calving process is poorly understood due in part to difficulties with field measurements in the calving area. The velocity of the calving front is most often determined from satellite images with relatively poor temporal resolution. In this paper the flow velocity of the front of the tidewater glacier Kronebreen has been measured using high range resolution interferometric radar measurements at a high temporal rate (2 Hz). The radar was operating at 5.7 GHz at a distance of approximately 4 km from the calving front measuring an horizontal width of approximately 700 m of the front of the glacier. Video images were recorded to identify calving events and to aid in the interpretation of the radar data. The radar measurements were constantly being checked against a reference reflector standing between the radar and the glacier, in order to correct for variations in the refractive index. A total of 45 hours of measurements were completed. A velocity of 2.7 m d⁻¹ was measured at the front, decreasing up-glacier from the front. During the measurements a large calving event took place, and the variations in the glacier velocity were recorded. The velocity was linear and stable prior to the calving. Just before the calving event the velocity increased, and it continued to increase after the calving in the front part of the glacier. Further up-glacier, the velocity remained constant during the calving.

50A032 Analysis of the accumulation amounts of three neighbouring Oetzal glaciers based on measured and modelled mass balance data

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For three glaciers on the main alpine ridge, namely Hintereisferner (HEF), Kesselwandferner (KWF) and Vernagtferner (VF), long-term series of mass balance data exist, determined by the direct glaciological method. Since 1952/53 for HEF and 1964/65 for VF, winter and summer mass balances have been differentiated. The methods, however, differ: on VF, total winter mass balance as well as its altitudinal distribution is determined by measuring a large number of snow depths and digging a few snow pits to obtain density profiles; as to HEF, winter mass balance is determined as a residual of modelled summer mass balance and measured total balance. Since 1993, however, is the winter mass balance of HEF assessed with the direct glaciological method, thus delivering the altitudinal distribution of accumulation for HEF for these mass balance years. Additionally, the three glaciers are included in the modelling framework of the 'GLOWA-Danube' project, which covers the entire basin of the Inn River. By that, more information on the regional precipitation distribution is available. The cumulative mass balance series of the three glaciers show quite similar trends of mass gains and mass losses over the last four decades. This could be expected as a consequence of their rather similar climatic conditions. The absolute amounts, however, differ substantially. The influence of the area-altitude distribution and the exposition of the glaciers on accumulation in winter and on ablation in summer is rather well known and can be quantified by mass balance models. Other sub-scale processes like snow redistribution, ice flow and the influence of orography on precipitation are to a much lesser extent quantifiable, but they influence the winter mass balance considerably. In a first step, glaciologically determined winter mass balance data for HEF and VF are compared with respect to the different algorithms of handling the measured data for the period 1993 to 2005. Then, we analyse the influence of the above-mentioned processes on the winter mass balance of the glaciers and thus achieve a reliable data set, which provides a means for model validation.

50A033 Terrestrial photogrammetry for measurements of the calving rate of Kronebreen, Svalbard

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Calving is a large component in the mass budgets of tide water glaciers. Measurements of calving rates are essential for the determination of a calving law that can be used in a mass balance model of the glacier. Changes in climate may alter the ice dynamics and the melt water production, thus the calving rates may change rapidly. Despite their importance, calving processes are not well represented in numerical ice dynamic models, partially due to the difficulties and dangers of field data collection. Measurements of calving must be conducted in a safe distance to the calving front, and in this project we have applied terrestrial photogrammetry to the front of Kronebreen, Svalbard, in August-September 2007. Seven repeated stereo pairs were photographed from Nielsen-fjellet mountain side over a four-days period. Markers were placed on the strand and measured with GPS to georeference the images. The digital images are processed photogrammetrically for velocity measurements and volume estimates of the calving ice loss. The velocity data are compared to ground based interferometric radar measurements conducted in the same period, showing a velocity of 2.7 m.d-1.

50A034

The transfer of mass balance profiles $b(h)$ to unmeasured glaciers

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For the estimation of the mass balance of an unmeasured glacier its area distribution with altitude $s(h)$ generally is the only available quantitative information. The appropriate specific balance profile $b(h)$ needs to be transferred from a measured glacier, where transfer means modification and adaptation to the topographic and climatic situation of the unmeasured glacier, like altitude, exposition to sun and wind, or temperature. This study proposes the area median elevation M as a parameter of prime importance for the transfer. On the example of ten Alpine glaciers, including local clusters of three and four, the similarity of M and ELA is quantified and the effect of exposition and surrounding topography is qualitatively suggested. From a reference group with $M = 3070$ m the measured $b(h)$ is transferred to two groups with respective $\Delta M = -200$ m and $\Delta M = -400$ m, shifting $b(h)$ by equivalent amounts Δh . This yields fair agreement with the results of hydro-meteorological modelling. Further verification is presented by the transfer of the mean of $b(h)$ of 1969 to 1997 to these groups and comparison to the volume changes in the two Austrian glacier inventories 1969 and 1997.

50A035 On the application of distributed glacier mass balance models for the extrapolation of point measurements to the entire glacier surface

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Measuring mass balances is related to a considerable amount of fieldwork. Although several methods have been applied to reduce the number of direct measurements (e.g. statistical interpolation) or to determine mass balance from other data (e.g. remote sensing), the direct glaciological method remains essential for accurate mass balance data at a point. However, the reporting mode for mass balance is the mean specific value for the entire surface, which requires application of spatial interpolation to the point data. In general, the applied interpolation techniques are not reported and vary from precise manual interpretation with contour line drawing to simple regression techniques. In this study we propose a distributed glacier mass balance model as a tool for spatial extrapolation of direct measurements to the entire glacier surface. The method is based on the assumption that the main factors governing the spatial variability of ablation are well captured by such models. The approach is two-fold: In a first step the model is calibrated with a three year record of measurements on the adjacent glaciers Findel (area: 15.3 km², length: 7.2 km) and Adler (2.0 km², 3.1 km) as well as high-precision radiation data from a nearby station of the Alpine Solar Radiation Budget Network (ASRB). In the accumulation region, we use data acquired by helicopter-borne snow profiling along several transects to adjust snow distribution. The model reproduced mass balance at individual stakes in the ablation region very closely for the three years and the two glaciers. In particular, the variations for stakes at the same altitude but with a differing exposition are well captured. The mean mass balance values for discrete elevation intervals as computed by the model in the ablation region are thus regarded as very reliable. However, it was more difficult to calibrate the model in the accumulation region and a high uncertainty remains for the simulated spatial pattern. We thus conclude that a reduced number of stakes in the ablation region is sufficient for calibration of a distributed model, but more effort is needed to study the processes governing the spatial variability of accumulation. In a future step, we will normalize the modelled mass balance distribution in order to apply the spatial pattern obtained by the model independently from the climatic conditions.

50A036 Glacier facies transitions on Austfonna, Svalbard, derived from ground-penetrating radar

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We analyze ground-penetrating radar (GPR) data collected along several profile lines across Austfonna, Svalbard. Measurements were repeated during four consecutive spring seasons since 2004 and are supplemented by manual snow depth soundings and stratigraphic records from snow pits. The 800 MHz GPR returns provide information of the near-surface (~13m) snow/firn and ice. We mapped the winter snow cover by tracking the continuous internal reflection horizon arising from the density contrast at the last summer surface (LSS). Furthermore, the post-processed GPR data allow distinction between different glacier facies – firn, superimposed ice and pure glacier ice. In addition to the measurement of snow accumulation alone, this method provides also a measure of summer conditions. A comparison of the GPR-derived glacier facies with satellite SAR-data (Envisat) acquired in winter 2005/2006 and 2006/2007 yields good agreement. For each year, we mapped the extent of the various glacier facies and study their inter-annual fluctuations. Our analyses indicate that the mass balance in 2003/2004 was extremely negative, due to a combination of low winter accumulation and strong summer ablation, as indicated by a very small extent of the firn area. On the other hand, high winter accumulation in the mass balance years 2005/2006 and 2006/2007 coincides with a progressive increase of the firn area.

50A037 Assessment of precipitation in the Swiss Alps by adaptive tuning of a distributed glacier mass balance model

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In the past years several studies have calculated the mass balance of a glacier from distributed energy balance models and some general assumptions about the precipitation. While modelling of ablation-processes is well understood, large uncertainties remain for the accumulation as solid precipitation is difficult to measure and snow redistribution processes (wind, avalanches) are still incompletely understood. Hence, precipitation and its gradient are often used as tuning factors to fit the observations. In principle, we can benefit from this situation and use glaciers as precipitation gauges. If we assume that ablation can be modelled with sufficient accuracy, we can apply the precipitation tuning over large regions and for each glacier until the modelled mass balance fits the observations. This requires to focus on larger glaciers, where accumulation is not significantly modified by snow redistribution and ablation is restricted to direct ice melt (no extended debris cover or calving). Moreover, mass balance data must be available for all glaciers under consideration. In this study we assess the precipitation over glacierized areas in the Swiss Alps from a distributed mass balance model of intermediate complexity on a DEM with 100m resolution and adaptive precipitation tuning. We combined reanalysis data from an RCM at 18km spatial resolution, measurements from high mountain climate stations and distributed calculation of clear-sky global radiation to calculate gridded climatologies of air temperature, initial precipitation and global radiation for model input. Observed cumulative mass balance distribution 1985 – 2000 is obtained by DEM subtraction. Cumulative mass balances for the same time period are calculated by a simple numerical energy balance model. Precipitation is adjusted in an iterative way to match calculation and observation. The iteration is stopped when measured and modelled cumulative mass balance are within a certain threshold for all selected glaciers. As the suggested method of adaptive tuning has still many sources of uncertainty, we have only calculated the required relative precipitation changes. However, the model results clearly outline some regions along the northern slopes of the Alps (Glärnisch, Silvretta) with a considerable underestimation of precipitation in the initial climatology. On the other hand, in several regions the required corrections are not significant or show a high spatial variability that is difficult to generalize. The latter do also hint to glaciers, where additional and not included processes (e.g. snow redistribution) might have a considerable influence on the mass balance.

50A038 A 50 years accumulation history of Austfonna, Svalbard, derived from reanalysis data and field measurements

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There is considerable uncertainty about the current state of balance of Austfonna, the largest ice cap (~8200 km²) in Svalbard. Repeated airborne altimetry (1996-2002) indicated a marginal thinning concurrent to a thickening of the interior, a behaviour which may be associated to a change in the precipitation regime. On the other hand, field measurements on the ice cap suggested that Austfonna was in balance during the period 1986-1999 but recent in-situ data show negative surface mass balances since 2004. To provide a coherent accumulation history of Austfonna, we use atmospheric data from the ECMWF forecast model to drive a high resolution precipitation model and evaluate the obtained accumulation pattern to field data available for 1999, and 2004-2007. Having validated the method, it is applied to dynamically downscale the ERA40 precipitation to Austfonna. In doing so, we derive a 50 years accumulation history covering 1957 to 2007. The obtained fields are analyzed with respect to both, the total amount as well as the spatial pattern of snow accumulation.

50A039

Sensitivity of surface energy balance on Saint-Sorlin Glacier (French Alps) during summer 2006

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Meteorological and snow and ice ablation measurements were performed on Saint-Sorlin glacier (France) (3 km²; 45°N, 6°E) in July and August 2006 at 2750 m a.s.l, using a complete automatic weather station. This station included a sonic ranger for the snow and ice melt ablation. In addition to this experimentation, digital pictures of the glacier were taken 3 times a day (6.00 am, 12.00 am and 6.00 pm local time) and daily evolution of surface albedo around the automatic weather station was deduced from these pictures and from a digital model of the glacier. The local surface ablation was then computed with a complete surface energy balance method and with a degree day method. Results were compared to measured ablation. The objective of this work was to assess the sensitivity of the physical processes determining the melt during two very contrasted months. Firstly, albedo values deduced from digital pictures and from direct measurements (with pyranometers and pyrgeometers) were compared and the difficulty to model this key parameter was enhanced. Second, snow and ice melt sensitivity to various meteorological variables and especially albedo was then evaluated. It was shown that snow falls occurring during summer could strongly influence melt calculation, depending on the parameterization used for albedo. This study enabled to focus on the spatial distribution representativity of the different variables entering in the surface energy budget all over a glacier.

50A040 Growth and decay of Argentiere glacier (Mont-Blanc area, France) from mass-balance and ice-flow analysis over the last fifty years.

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Numerous glaciological data have been obtained from measurements carried out on the glacier of Argentiere (Mont Blanc area) since the beginning of the 20th century. As for thickness variations and volumetric mass balance since 1905, old maps and photogrammetric data have been used. Moreover, annual mass balance, ice-flow velocities, thickness variations and length fluctuations data have been obtained from yearly measurements performed since 1975. This data set gives a very good opportunity to analyze the relationships between surface mass balance and dynamic response of the glacier over two time periods which have undergone opposite trends. Indeed, these data reveal strong changes in mass balance and dynamics over the last fifty years: on the one hand, following a positive mass balance period between 1954 and 1981, the ablation zone experienced a large increase in thickness and ice-flow velocities. On the other hand, the strong negative mass-balance period since 1982 leads to strong thinning, deceleration and retreat of the tongue. The dynamic response of the glacier to surface mass-balance is analyzed from ice-flow calculations performed on transverse cross-sections. Over these same cross-sections, this analysis enables to compare the ice-flow obtained from surface mass-balance upstream with the ice-flow calculated from cross section thickness and ice-flow velocity data. Finally, this data set will be useful to constrain input data and check results from ice-flow numerical modelling experiences.

50A041 Modelling the energy balance of a tropical glacier in the Cordillera Blanca and the implications for regional water resources

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We apply an energy balance model to Glacier Artesonraju in the Cordillera Blanca, 9S, 78W, in the Andes of Peru. This is a distributed and multilayered physical model, fed with local meteorological measurements and physically plausible assumptions, aided by atmospheric profiles derived from general circulation models. The fitness of the model is assessed by photographic records of snow cover, ablation measurements on a limited number of ablation stakes and by measured volume changes in a lake draining the entire basin. After one year simulation, discrepancies are only a few mm water equivalent on the snow free areas of the glacier (exposed ice). We assess the effect of changing climatic parameters on the glacier from the historical record over the last 50 years (reanalysis data). From this assessment we found that temperature can explain only less than 50% of energy input variations, while cloud cover and humidity are responsible for most of the rest. Finally we elaborate on future implications and on the adequate measurements and modelling approaches to get a reliable estimation of water resources under changing climatic conditions.

50A042

Mass balance monitoring of glaciers in the arid Andes of Norte Chico, Chile

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The Norte Chico region of Chile extends south of the Atacama Desert to $\sim 32^\circ\text{S}$. At this latitude glaciers are generally small and limited to the high Andes. The climate is seasonal, with precipitation maxima, and temperature minima, occurring in winter months. Seven years of meteorological data at 4,930m.a.s.l. shows the monthly mean temperatures lie between -0.4°C in January and -11.0 in July. Wind speed in excess of 30 ms^{-1} occurs year round. River runoff data suggest a strongly nival runoff regime, with glaciers having a lesser impact on runoff. Nevertheless, glaciers are locally considered to be an important water resource, and there are concerns about evaluating the current and future water resource potential of glaciers in this region under the influence of a changing climate and anthropogenic activity in the high Andes. Norte Chico's glaciers are relatively unstudied and the detailed interaction between climate conditions and glacier mass balance is not well understood. The glaciers have been shown to respond to ENSO state, and although they have been retreating during the 20th century, the rate of observed recession decreased during the El Ni o years of the 1980's. Of particular interest is the fact that the glaciers of this region undergo strong sublimation in the summer months resulting in the formation of large penitentes. Significant sublimation and its resultant formations present an interesting challenge both for measuring and modelling mass balance parameters. Here we present an outline of our strategy for monitoring mass balance and runoff at 7 glaciers in 2 locations within the Norte Chico region, and present preliminary results of this monitoring program.

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The global mass-balance database is dominated by direct measurements, in which density and surface elevation change are measured directly at the surface of the glacier, but geodetic measurements, in which surface elevation is measured at two dates with respect to a fixed datum outside the glacier, are increasing in relative importance. Our confidence in regional and global balance estimates would be greater if it were possible to combine direct measurements, mostly annual, and geodetic measurements, mostly multi-annual, into a single database with improved temporal and spatial coverage. The aims of this paper are 1) to compare all available direct-geodetic and geodetic-geodetic measurement pairs so as to appraise random errors and possible biases affecting the two methods, and 2) to develop a statistical formalism within which balance measurements over different time spans can be reduced to common time spans. The comparison reveals no strong evidence that direct and geodetic measurements are biased with respect to one another, but random errors can be substantial and the compiled database contains a number of outliers. The statistical formalism can be understood by considering an n -year balance measurement, with n large. It can be seen as an average of the elements of a series of hypothetical 1-year measurements, but in fact it is also an estimate, with calculable uncertainty, of the average for any m -year period contained by the longer n -year span. For this claim to be valid it is necessary that the series of annual measurements be stationary and normally-distributed with independent elements. There is good evidence that these conditions hold. It is therefore possible to present an n -year measurement as a set of, for example, decadal ($m=10$) or pentadal ($m=5$) estimates. However the uncertainty of the latter can be determined only if we know the variance of the underlying annual series, which means that annual direct measurements from a nearby glacier, or equally reliable information about variability, are absolutely indispensable. Given this information, the new methodology promises to be a valuable practical tool for assimilating measurements with irregularly distributed start and end dates. Regional-scale examples are presented to illustrate the viability and usefulness of the methodology, and the complications which arise in the presence of a trend are discussed.

50A044

Glacier Inventory based on Remote Sensing Data in Pakistan

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The Upper Indus Basin (UIB) is home to three of the world's mightiest mountain ranges. The Karakoram and the Himalayan Mountain Ranges are in the north and northeast of Pakistan while the Hindukush Mountain Range guards the northwestern frontiers of the country. Most of the runoff generated in the Indus River comes from snow and ice melt. About 37% area in the Karakoram and 17% in the Himalayas is covered with glaciers (Tarar, 1982). Glacial melt is one of the major sources of inflow in the Upper Indus Basin. Most of the winter precipitation, which provides nourishment to the Indus glaciers, occurs at higher altitudes. The active hydrologic zone for the Indus River lies between the elevations of 3000 m a.s.l to 5500 m a.s.l. Unfortunately, all monitoring stations are located below the elevation of 3000 m a.s.l. The glaciers of Hindu Kush-Karakoram-Himalayan are retreating in the face of accelerating global warming and resulting in the formulation of glacial lakes. Rapid accumulation of water in some of lakes can lead to a sudden breach of their unstable moraine 'dams'. The resultant discharge of water and debris – a Glacial Lake Outburst Flood (GLOF) – often cause catastrophic effects downstream. Snow and glaciers melt in HKH region of Pakistan contributes more than 50% of the total flow of the Indus system. These valuable resources have never been systematically harnessed in the past. Knowledge of this resource seems to be an outstanding requirement for future planning of water resources and flood hazard monitoring in the country. An inventory of glaciers and glacial lakes of this part has been developed using satellite remote sensing and topographic data and a comprehensive database has been developed. This study also aimed at identification of the potentially dangerous lakes that needs to be monitored in future. Total geographic area of the Indus river basin studied is about 128,730.8 sq. km. Part of Upper Indus Basin in Pakistan has been divided into ten sub-basins in the three great mountain ranges. Altogether 5,218 glaciers are identified in the basin which covers about 11.7% of the total geographic area studied. The total ice reserves estimated in this region are about 2,738.5 km³. There are altogether 2,420 glacial lakes covering an area of 126 sq. km. Based on the detailed characteristics of each lake, 52 lakes are identified as potentially dangerous lakes which include Cirque (13), End Moraine dammed (31) and Valley lakes (8). The erosion lakes are generally stable and are therefore less susceptible to GLOF provided not associated with a large mother glacier. These results

50A045 Perspectives and limitations of laser scanning in glaciology – six years of experience in measuring volume changes of Hintereisferner

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Since 2001, Hintereisferner has been under regular observation by using laser scanning technique. Meanwhile 15 data acquisitions have been carried out allowing for annual and seasonal analyses of glacier volume changes in a very high spatial resolution [m^2] and vertical accuracy in the order of 10 cm. Besides the presentation of a time series, which includes a comparison of the extremely negative mass balance year 2002/2003 with five less negative mass balance years, the methodological potentials of the laser scanning technique will be discussed as a tool for glacier research and monitoring. Although laser scan DEMs/DSMs are based on single points or pulses, their high density allows to obtain an almost continuous representation of the surface. Laser scan data provide quantitative information on the topographical situation (x, y, z-coordinates) but also qualitative information about surface properties. Several mono-temporal approaches such as the analyses of manual optical, semi-automatic geometrical, and semi-automatic intensity signals offer a potential for the delineation of the glacier boundaries in very high detail. Furthermore, these methods provide an option to determine different phenomena at the glacier surface like crevasses, supra-glacial till cover, and melt-water channels. By use of the intensity signal, snow and ice properties at the glacier surface can be distinguished. Multi-temporal analysis of laser scan data are used to quantify volume changes and, with some limitations due to the lack of detailed snow density measurements, mass changes over the respective time periods. The tracking of detailed geometrical surface features provides surface velocity fields. Finally, present limitations and future potentials of the laser scan technique are addressed. Despite the fact that there are still many open questions (e.g. the vertical velocity component, material density), the technological progress (e.g. full wave signal) and new concepts of application may allow laser scanning technique to become a standard key method in glaciology.

50A046

Mass balance of Austfonna Ice Cap, Svalbard

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Austfonna (8200 km²) is the largest ice cap in the Svalbard archipelago. There is considerable uncertainty about its current state of balance and its possible response to climate change. The geometry changes of the ice cap have been measured using airborne laser and ground-based GPS profiling. Repeated airborne laser profiles carried out by NASA in 1996 and 2002 indicated a clear thickening of the upper central part of the ice cap with as much as up to 3.5 m over the six year period; a change of about 0.6 m a⁻¹, and a peripheral thinning. This indicated a positive mass balance of the ice cap. The net surface balance of the ice cap in the period 1986-1999 was previously estimated to be close to zero. This estimate was based on net balance gradients in the accumulation area of the ice cap derived from 19 shallow ice cores drilled in 1998 and 1999 where the depth down to the Chernobyl accident fallout in 1986 was found. Since 2004, we maintain a network of stakes distributed over the ice cap, from which we obtained the net surface mass balance at several points over the period autumn 2003-autumn 2006. The stake data was used to establish the net balance gradient in two basins covering together 4670 km² of the ice cap. The mean total net balance for the three year period was estimated at ~ -2 km³, yielding a specific net surface balance of -0.25 m water eq. per year. This indicates a change towards negative mass balance compared to the period 1986-1999. However, it is short series of only three years and the summer 2004 seems to have been an extreme warm summer which may have biased the results.

50A047 Glacier volume changes over the past 43 years at Urumqi River basin, eastern Tianshan, China

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Topographic measured data and satellite imagery have been largely used to measure glacier volume evolution by detecting change of geometric factors taken at different times. Located at the centre of the Eurasian continent, east Tianshan is surrounded by arid and semi-arid landscape. Glacial runoff is a major water supply for local economy and ecosystem. However, glacier change under the climate warming in this region is poorly documented. In this study, volume changes of 155 glaciers in the Urumqi River basin in eastern Tianshan between 1962 and 2005 are calculated. The geometric data in 1962 was created from aerial photographs with an approximate error of +/- 10 m. The geometric data in 2005 was created from Spot5 stereo images with an error of +/- 5m. By comparing the datasets, the changes in terminus positions and altitudes and areas of the glaciers are determined. The primary result indicates the shrinkage of the glaciers occurred significantly in this river basin. For a number of glaciers, the rate of shrinkage appears to have accelerated in last two decades. Small glaciers tend to have lower absolute change quantity and higher change rate. This is because small glaciers are considered to possess a larger energy exchange relative to their volume than the large ones. Several small glaciers were found disappeared during the 43 years. Based on the calculations of volume change, the contribution of glacier runoff during 1962-2005 was estimated.

50A048

Study on the mass balance of Urumqi glacier No.1, eastern Tianshan, China

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Glacier change in east Tianshan is poorly documented in literatures. The Glacier No. 1-oriented observations, implemented by Tianshan Glaciological Station (TGS) at the headwaters of Urumqi River in east Tianshan from 1958, promise the best datasets for glacier and climate changes in this region. Based on these observations, this paper summarizes and analyzes the spatial-temporal variations of the surface mass balance series beginning from 1958 at each measurement point on the glacier. In addition, attention has also been paid to variations in the glacier frontal position and the equilibrium line altitude and the relationship between mass balance and climatic factors. The result shows during the past 43 years, both air temperature and precipitation have demonstrated an overall increase, particularly after 1995. This area is currently experiencing the wettest and warmest period in recorded history. Under such a pattern of climate change, Urumqi Glacier No.1 has been in an intensive mass wastage, amounted to -9599mm during 1959 and 2002, which corresponding to the thickness thinning over 10m on the glacier. An accelerating trend of mass losing on Glacier No.1 was observed to be -739.6 mm annually during 1987-2002. Variation in mass balance of the glacier No.1 is primarily under control by air temperatures, a good negative relation exists between the mass balance and the summer means air temperature with the correlation coefficient of -0.72 at the 99% significance level. It was found that cold seasonal precipitations played a key role in the variation in winter balance. Affected by the accelerated mass wasting, the glacier No.1 has experienced an obvious retreat at the terminus part since the 1960s, and this was more evident at the end of west branch of Glacier No.1 during 2000 and 2007.

50A049

Spatio-temporal Variability of Snow Cover in Svalbard

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Evidence for ongoing large changes in the Arctic climate has been accumulating during the last decade, particularly with regards to sea ice, permafrost and glacier mass balance. Due to the effect of global warming dramatic changes in the Arctic snow and ice coverage are currently observed, expressed by a reduction of 10% over the last 30 years associated with an extended and longer lasting melting season. Previous studies have demonstrated the capacities of active microwave instruments for the detection of surface melt and freeze-up due to the high sensitivity of radar backscatter to snow wetness. Spaceborne scatterometers provide data at low spatial but high temporal resolution allowing consistent observations on a daily time scale. This study focuses on the Svalbard region characterized by a highly variable climate throughout the year due to its position within a zone that includes both the polar ocean and atmospheric fronts between the Arctic Ocean, Nordic Seas and Barents Sea. Nevertheless, over a long enough period of time we expect to see a general climatic trend by monitoring the spatio-temporal variability of snow distribution and melt all over Svalbard. For this we utilize microwave backscattering measurements continuously carried out by the Ku-band scatterometer QSCAT since fall 1999. Furthermore, we tested retrieval algorithms for the assessment of single snow fall events and the amount of snow accumulation during winter. A set of glaciological ground-truth data serves us for interpretation of the backscattering signatures, i.e. snow accumulation measurements by means of snow probing, snow pit sampling, drilling of shallow ice cores as well as ground penetrating radar measurements. In addition, meteorological data from weather stations around Svalbard are available to investigate links between atmospheric circulation, moisture transport, near surface air temperature and corresponding deposition and melting of snow, respectively. The analysis demonstrates that coarse resolution scatterometer data can be usefully applied to trace consequences of a warming climate in the Arctic.

50A050

Mass balance trends inferred from elevation changes in Northwest Svalbard

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Geodetic mass balance estimates provide an independent approach to traditional mass balance measurements for understanding glacier changes in relation to climate. Recently, the acquisition of elevation data of glaciers has become more efficient through digital photogrammetric techniques as well as increased use of differential GPS (dGPS) and laser altimetry. Elevation changes of four glaciers in Northwest Svalbard (Midtre Lovénbreen, Austre Lovénbreen, Uvarsbreen, Kongsvegen) is derived for 2 epochs. The first elevation change epoch is derived from DEM comparison (1936-1990) while the second epoch is derived from DEM comparison with differential GPS profiles (1990 – 2005). For all glaciers, the geodetic balances have become more negative since 1990. The annual geodetic balances for the two smaller glaciers (~4 km²) is twice as negative for the most recent epoch as compared to the first epoch. The larger glaciers (> 50 km²), however, experience a geodetic mass balance three times as negative for the most recent epoch.

50A051 Uncertainties in the present-day and future surface mass balance of the Greenland ice Sheet

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The surface mass balance of the Greenland ice sheet has, in the past, been determined most commonly with the aid of a positive degree day model (PDDM) to estimate ablation. This is a reduced form of an energy balance model (EBM) where temperature is the sole variable that determines melt. Less empirical EBMs exist that, for example, take account of radiative, turbulent and sensible heat fluxes explicitly but the data needed to drive them, until now, has been inadequate. Consistent global climate re-analysis data have recently been generated that show considerable skill in reproducing the observed temporal and spatial trends in key variables such as radiative fluxes and precipitation, and which are starting to be used to force EBMs of the ice sheet. EBMs and PDDMs have different sensitivities to climate forcings. For example, an EBM is sensitive to changes in cloud cover as this affects both long and shortwave radiative fluxes, while a PDDM is only indirectly affected through any changes in surface temperature that may result from the different cloud cover. To investigate these differences quantitatively for a future climate warming scenario we forced an EBM and PDDM for the Greenland ice sheet with the output of a coupled atmosphere-ocean GCM, HadCM3, which was run from the present-day forward in time for 110 years assuming a 4 x CO₂ forcing trend. The EBM comprises two components: one that determines the energy balance and a second snow diagenesis part that models the evolution of the snowpack and its thermal energy. The PDDM, by contrast, uses a simple parameterization for determining the proportion of melt that refreezes within the snowpack. The HadCM3 data were used to force the two models forward in time for 300 years with constant climate from year 110. As expected, the two models produced markedly different melt volumes (by up to a factor 2) but, more surprisingly, differences in the amount of refreezing were as large as differences in total melt. It is the case that there are tuneable parameters in both models and that some of the difference could be reduced by changing these values. However, here we used relatively 'standard' values for the PDDM and the EBM was tuned to provide agreement with in-situ observations of mass balance along the K-transect in southwest Greenland. There is, therefore, limited scope for tuning without moving one or other model away from observations. Our results highlight the large uncertainty in estimates of the future surface mass balance response of the ice sheet. They also highlight the importance of refreezing as well as the method for estimating the amount of melt. To date, most emphasis has perhaps been placed on the latter compared with the former possibly because of the difficulty in acquiring direct measurements of measurements of refreezing.

50A052 The influence of drainage boundaries on specific mass balance results, a case study of Engabreen, Norway

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Mass balance measurements in Norway have traditionally been related to the needs of hydropower development. The primary interest was the effect of glaciers on run-off in hydrological catchments. Hence, glacier boundaries were defined by their hydrological boundaries, i.e. where does the meltwater flow. The majority of glaciers measured are outlet glaciers from plateau glaciers (e.g. Nigardsbreen and Engabreen), where the boundary for an individual outlet is not always obvious. In order to calculate the specific mass balance the boundaries of the investigated glacier areas were set to be equivalent to catchments of downstream discharge stations. Where glacier thickness was mapped the hydrological drainage divides were mapped by calculating the hydraulic head. Recently, changes in glacier length and area as a response to climatic changes have been addressed more extensively. When the response of a glacier to climate change is modelled, the glaciological drainage divide is used. This is the glacier area feeding ice to the glacier terminus, and is not always coincident with the hydrological drainage divide. Here we investigate the influence on area-averaged mass balance results of different choices of glacier boundaries on Engabreen, an outlet from Svartisen ice cap in northern Norway. Mass balance has been measured on Engabreen since 1970 and the glacier shares a border with Storglombreen glacier to the east. The hydrological glacier boundary of Engabreen includes all glacier areas draining to the river discharge station Engabrevatn. Three areas within the hydrological boundaries do not contribute glaciologically to the main terminus of Engabreen. A small glacier outlet (Litlebreen) on the north-eastern side is separated from the main outlet by a rock hill. An area that terminates at the top of a cliff on the western side of the glacier contributes some ice mass through avalanching to the main glacier. From hydraulic head-calculations it is found that an eastern part of the accumulation area contributes hydrologically to the inflow to Engabrevatnet, while stake measurements of glacier velocity show that the glacier ice is draining towards Storglombreen. The area as defined by the glaciological drainage boundary (27.2 km²) is smaller than that defined by the hydrological drainage boundary (39.6 km²). The area reduction is largest for the altitudinal band between 1300 and 1400 m a.s.l. Generally, the 'glaciological' glacier is lower in mean altitude than the 'hydrological' glacier, and this affects the calculated specific mass balance. Using the glaciological boundary leads to a reduction in mean winter and summer balance (when the difference in spatial distribution is ignored) of ~ 0.12 m w.e. a⁻¹ and ~ 0.15 m w.e.a⁻¹, respectively. The resulting difference in cumulative net balance for the period 1970-2006 is ~ 10 m w.e. which amounts to about 50 % of the calculated mass surplus in this period.

50A053

Stratigraphic versus fixed date mass balance

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Mass balance terms may be evaluated at fixed dates, e.g. the hydrological year (Oct 1 - Sept 30) or according to the stratigraphic system. The stratigraphic net balance is the sum of accumulation and ablation between the absolute minima of glacier mass in two subsequent years, the stratigraphic winter balance is the absolute maximum of snow cover in the course of the year. % This definition implies averaging. Using a mass balance model with high temporal and spatial resolution daily mass balance components are calculated. This study investigates differences between the concept of the stratigraphic and the fixed date mass balance. We present a methodology to derive mean specific mass balance quantities (e.g. net, winter, summer balance) for variable periods based on comprehensive glacier monitoring data sets. For the period 1865-2007 a grid based temperature-index mass balance model is applied to four well investigated glaciers in Switzerland - Grosser Aletschgletscher, Rhonegletscher, Griesgletscher and Silvrettagletscher. The model is calibrated using ice volume changes derived from 5 to 9 digital elevation models of the glacier surface, large data sets of seasonal mass balance measured at stakes and discharge records. The field data cover the entire 20th century. We determine the timing of the absolute minimum and maximum of glacier mass for each year and evaluate stratigraphic and fixed date mean specific mass balance quantities. The mean absolute deviation of stratigraphic and fixed date net balances is 0.09 m water equivalent (four glacier average). The differences may reach 0.5 m w.e. in individual years. During the last century a significant trend (about 1 day per decade) towards a longer melting season is observed. The mean termination of the melting season has shifted from September 22 to October 4. The winter maximum of glacier mass is reached around the end of May. The evaluation of monthly values of mass balance for all glaciers shows that negative trends of -0.2 m w.e. per century occur during the summer months July and August. In May, however, our results reveal increasingly positive mass balances. We analyze mass balance time series in daily resolution based on extensive field data sets and use them to shed light on different concepts to evaluate mass balance and to discuss the impact of regional climate change on glacier mass.

50A055 A new early instrumental bias corrected temperature dataset for the European Alps

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Evidence from

Tree ring and ice core proxies, together with difficulties in mass balance modelling of the early 19th century glacier advances suggested to have a second closer look at possible systematic errors in early instrumental (EI) climate time series in the region of the European Alps. Although much work had been already invested in the creation, quality control and homogenisation of the HISTALP-dataset, relatively high warm-season temperatures in the decades near 1800 still caused serious difficulties in understanding, explaining and modelling the large glacier extensions of this period. Even the positive high precipitation anomalies before 1850 helped reducing the glacier-climate mismatch - but not enough to eliminate it. It was likely that the homogenisation so far applied could not successfully adjust for the effects of insufficient shading of the typical early historic measuring installations. Therefore we tried to use the unique occasion of a more than ten years comparative dataset at a completely preserved and documented historic site (at the monastery of Kremsmünster in Upper Austria) with a close by modern standard one to develop a correction model for typical early instrumental datasets. The multi annual hourly dataset of historic minus modern temperature differences then was extended to a simple model representative for three differently orientated typical historic EI-sites (NW, N and NE facing window-installations several meters above ground) and applicable for all different EI-means-calculation algorithms. In a second step we re-analysed in detail all available metadata information from the more than thirty EI-series in the region. For the majority of them the necessary information (shading device, orientation and means calculation mainly) is known now. Thus we could directly apply the EI-correction models on most of the EI-sites and adjust the remaining few to the new standard. The result is a new set of long-term temperature series (some back to 1760) showing now lower warm season temperatures in the early part. The removed EI-bias is of the order of 0.5°C in the most affected months of May, June and July and decreases to zero towards winter. This makes sense in terms of the physical reason of the bias - insufficient to non existent radiation screens. The fact that the correction was strictly based on instrumental information makes the new independent dataset applicable for respective comparative analysis with proxies. One of these fields is climate-glacier studies for which the reduced ablation-season temperatures promise better results now. Some preliminary respective results will be

50A056 Geodetic mass balance of Vestfonna, Austfonna and Kvitöyjökulen ice caps since 1983

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Vestfonna, Austfonna and Kvitöyjökulen, located in the north eastern part of the Svalbard archipelago, make up a combined glacier area of 11300 km² which corresponds to about 30% of the total glacier cover on Svalbard. Annual GPS/GPR surface profiles over Austfonna from 2004-2007 and ICESat laser altimetry of the three ice caps from 2003-2007 show large annual variations in snow accumulation and elevation change. Longer time series are needed in order to reveal mass balance trends. The most comprehensive elevation dataset, covering all three ice caps, is from a radio-echo sounding (RES) campaign in 1983. We use the RES and ICESat profiles to determine elevation change at crossover points over the last two decades. The geodetic mass balances are then estimated by spatial interpolation of the crossover elevation changes over the extent of the ice caps. Preliminary results of Austfonna indicate a pronounced interior thickening combined with marginal thinning, leading to an over all positive mass balance. The same trend was found from repeated airborne laser profiles in 1996 and 2002. Vestfonna remains closer to balance, while Kvitöyjökulen has thinned. Geodetic mass balances are also estimated for individual basins to gain insight into the spatial variability of the interaction between climatic effects (accumulation/ablation) and dynamic effects related to surge type basins.

**50A057 A COUPLED MASS-BALANCE AND ICE-FLOW MODEL FOR MIDTDALSMBREEN;
PROJECTION OF FURTHER GLACIER LENGTH BASED ON CLIMATE SCENARIOS
(CES)**

Kjetil Melvold, Tron Laumann

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At Midtdalsbreen, central southern Norway, glacier front variations are known at several times during the Holocene. Detailed knowledge about glacier geometry and ice flow exists for the present glacier. A coupled dynamic/mass balance model for Midtdalsbreen has been developed in order to estimate the response of the glaciers to past, present and future climate changes. The degree-day mass-balance model computes glacier mass balance as a function of altitude based on observations of temperature and precipitation at a meteorological station. The ice-flow model is forced by the output from the mass-balance model and computes the length and volume change of the glaciers with time. The model is calibrated for Midtdalsbreen for the present configuration. It is forced with climate scenarios defined in CES (Climate and Energy Systems project) that are under development for the Nordic countries for the purpose of outlining the hydrological consequences of further climate change. Simulations will focus on changes in the period 20–40 years from now (i.e. in the period ca. 2030–2050). Transient simulations will be carried out based on several alternative climate change scenarios spanning a range of possible future changes. The study shows clearly that unless a climate warming (or present climate) is accompanied by a dramatic increase in precipitation the glacier will lose considerable amount of mass during the next decades.

50A058 Geodetic mass balance of the western Svartisen ice cap in the periods 1968, 1985 and 2002

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The geodetic mass balances of the western Svartisen ice cap in Northern Norway are determined in this project from photogrammetry on vertical aerial photographs taken in 1968, 1985 and 2002. The existing 1968 digital terrain model (DTM) was generated using analytical photogrammetry, and the 1985 and 2002 DTMs are newly generated using digital photogrammetry. The DTMs are subtracted, and preliminary results show that the mass balance is close to zero for the whole of western Svartisen in the period 1968 to 2002. The errors of the DTMs and the geodetic mass balance are assessed. Firstly the contribution to the uncertainty comes from low contrast in the images. Homologous point coordinates of the stereo pair are identified using cross correlation calculations in digital photogrammetry. Areas with low correlation values due to poor contrast are thus mapped automatically. Cross correlation calculations are carried out on some of the 1968 stereo pairs to identify areas of low contrast. Low correlation values are found in areas with white snow and steep hillsides in shadow. Secondly, the accuracies of the DTMs are reduced due to poor quality of the ground control points. The orientations of the DTMs are adjusted according to relative elevation differences of the mountains to reduce the uncertainty in the geodetic mass balance from georeferencing.

50A059 Recent glacier volume change in the Chon-Kyzylsuu river basin, Teskey Ala-Too range, Tien Shan mountains, using airphotos, topographic maps, and ALOS PRISM satellite

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In order to clarify recent glacier volume changes in the Tien Shan mountains, Digital Elevation Models (DEMs) from different times are compared in this study. The study area is the Chon-Kyzyrsuu river basin, located the eastern part of the Teskey Ala-Too range in the northern Tien Shan of Kyrgyz Republic. In the study site, glacier area diminished by about 8% in the western Teskey Ala-Too range between 1971 and 2002 (Narama et al., 2006). For this study we produced DEMs from airphotos taken in 1976, topographic maps from 1985, and ALOS PRISM satellite stereo data from 2006. The ALOS PRISM sensor includes a nadir, a forward, and a backward sensor, generating a stereoscopic image data set of 35 km in width 35 km and with a spatial resolution of 2.5 m. The airphotos and the ALOS PRISM data were oriented using ground control points from the 1:50,000 topographic maps. A DEM from the topographic map was generated by digitizing and interpolating contour lines from the 1:50,000 topographic maps. The quality of the different DEMs was assessed for stable terrain outside the glaciers using data from kinematic-GPS field campaigns in 2007, the ASTER DEM, the SRTM DEM, and the 1:50,000 topographic maps. The resulting remotely-sensed glacier volume changes are compared to mass balance data from the Kara-Batkak glacier observed from 1972 onwards. Glacier area in the Chon-Kyzylsuu river basin shrank by 9% between Corona data from 1971 and ASTER data from 2004. Most glacier volume was lost in the period 1985-2006, and glacier termini of some glaciers lost up to 50 m in surface elevation.

50A060

MODIS albedo and regional mass balance of high Arctic glaciers

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MODIS albedo products are compared to glacier mass balance measured on eight glaciers in the high Arctic, in north-western Svalbard. The glaciers range in size from ca. 5-500 km². We use MODIS L3 albedo products (MOD43B3), which have a nominal resolution of 1 km, and for which data cover the spring to autumn months of 2000-2006. We compare the albedo data to four glaciers for which there are mass balance measurements in each of the years in the study period (Austre Bröggerbreen, Midtre Lovénbreen, Kongsvegen, and Waldemarbreen), as well as four glaciers with some years of mass balance measurements (Holtedahlfonna, Irenebreen, and Elisebreen). While six of the glaciers are only represented by a few MODIS pixels, there is still good correlation between parameters derived from annual albedo minima and the equilibrium line altitude (ELA) of the study glaciers. However, there is no simple threshold method which can be used to directly extract the ELA from the albedo data.

50A061 Ground based gravimetry and GPS for measuring small scale mass changes on glaciers

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Mass changes on a glacier result in corresponding changes in the Earth's gravity field. In the present analysis, we review the combined use of gravimeter and GPS observations to observe small scale mass changes on glaciers. Observed gravity change on a glacier surface is a composite of several effects, e.g. melting and accumulation of snow and ice, redistribution of mass with depth by refreezing of meltwater, and height change of the glacier surface. A gravimeter is an integrating sensor which observes the sum of all effects influencing the gravity. In order to isolate the contribution from one particular effect, it is essential to combine gravimetry with other measurements like probing, density observations, and height changes observed with GPS. Models and equations necessary to estimate the measured gravity change due to different effects are presented. We evaluate the propagation of observational errors. The proposed methodology calls for observations with accuracy close to the limit of the present technology. Theoretically the method may observe a mass change of minimum 0.6 m of ice, thus on many glaciers requiring repeated measurements over a time interval of some years. The potential for conducting estimates of the amount of refreezing of meltwater and generation of superimposed ice, when combined with additional measurements, and a sub-surface meltwater refreezing model is discussed. The paper also presents experiences with gravity and GPS measurements carried out on Hardangejökulen, Norway, and discusses improvements to achieve the required accuracy for measuring the mass changes.

50A062 A sensitivity study of mass balance monitoring networks of two glaciers in Hohe Tauern (Austria) - Can the influence of topography on the mass balance be used to design a monitoring network on the PC?

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Monitoring the mass balance with the direct glaciological method affords much work. For an optimization of mass balance monitoring – minimizing field work without losing accuracy – it is essential to select representative measuring points. In this study the influence of areas with poor mass balance information of the glaciers Pasterze and Goldbergkees on the mass balance accuracy has been investigated and compared. The Pasterze (17.7 km²) has a dense monitoring stake network at its large glacier tongue, but network coverage gets thinner in the upper parts where the glacier is more difficult and dangerous to access. The stake network has an averaged mesh size of 8 stakes/km² in the ablation area (7km²), mainly at the glacier tongue. The ablation in the upper part of the glacier needs to be interpolated of a few measurements. Especially the glacier part near the steep crevasse zone to the glacier tongue lacks more measuring points. The interpolation of different exposed areas, not considered in the measurement, weakens the mass balance result. A way to include these areas has been found using the potential short wave radiation for calibrating the adjacent measurements for the different topographic situations. Contrary on this a part of the stakes placed on the tongue proved to be redundant, because of its homogeneous topography. On the smaller Goldbergkees (1.4 km²) mass balance has been measured since 1987 with a meanwhile well developed monitoring network of the whole area. The dense stake network (14 stakes/km²) results from the high topographic variability of this glacier. Nevertheless we found small areas not investigated, with an exposition and slope angle not according to the adjacent measuring points. These small scale topographic differences can influence the mass balance of a small glacier like the Goldbergkees. For the mass balance of the Pasterze such small topographic variability's have no significant impact because of its greater area. The investigations showed that the measuring network needs to be denser, the higher the topographic variability and the smaller the glacier is. The dependency of the mass balance on the topography was deciding for an attempt of adjusting a mass balance network using a digital elevation model. With ArcGis a grid has been created where every pixel showed its significance for being a measuring point. This investigation could help to optimize field work.

50A063

Automatic mass balance observations in Greenland

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The importance of the Greenland ice sheet in the global climate system is commonly known. And, observations over the last decade reveal that the interior is almost in balance whereas the margin is thinning significantly. This thinning has been accelerating over the last years and is often confined to areas with large calving outlets. But, also land based margins have shown sign of thinning over this period. The traditional way of collecting mass balance data by use of ablation poles is safe and reliable method. However, frequent visits and maintaining the net by frequent re-drilling makes it a timely and costly method especially in remote regions such as the Greenland ice sheet. Therefore, any automatic mass balance data collection method is likely to improve our in situ observation from the ice sheet. Over the years a Danish version of an automatic mass balance station has been developed and deployed. This station consists of a 'classical' energy balance station with additional sensors to measure ablation and snow accumulation. A hydrological water level recorder has been modified to record melt and is currently in use. And, to install the sensor to 30 meters depth a new high pressure steam drill has been developed. Experience with this system will be presented at the conference.

50A064 Recent contribution of glacial meltwater in the Chon-Kyzylsuu river basin of Teskey Ala-Too range, Tien Shan mountains

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To reconstruct the changes in contribution of glacial meltwater to the river discharge under conditions of glacier mass and area loss, the amount of meltwater from glaciers was estimated over the period 2004-2007 for the Chon-Kyzylsuu river basin of the Teskey Ala-Too range, Kyrgyz Republic. The amount of glacial meltwater was calculated using the electric conductivity (EC) method and a heat-balance model based on data from an automatic weather station (AWS) at the Kara-Batkak glacier front. The EC was observed at a water discharge station 20 km downstream from the glacier termini. Glacial meltwater production derived by a heat-balance model, which confirmed glacial meltwater production derived from EC, and stake measurements on Kara-Batkak and Ayrapampa glaciers shows that the contribution of glacial meltwater from river discharge reached more than 20% during summer. The excess glacial meltwater in 2005 results from the negative glacier mass balance, and the discharge of rivers that have glaciers in their watershed depends on the net balance condition of glacier in each year.

50A065 After six decades of monitoring glacier mass balance we still need data but it should be richer data

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The longest continuous mass balance series now covers six decades and mass balance monitoring extends to most of the glacierized regions of the World. With the widespread perception of Global Warming, mass balance monitoring is needed more than ever. The paper will start with an up-to-date review of available measurements and will point out that many of the datasets amount to little more than estimates of net balance for a few years. The concept of rich mass balance data will be outlined with examples of how they may be used. Most obviously, mass balance studies acquire greater value when they include separate estimates of winter and summer balances as well as net balance. Mass balance amplitude, defined by winter and summer balances, is a good indicator of the climatic setting of a glacier, e.g. with low amplitude in dry-cold continental settings and high amplitude in wet-warm maritime settings. In areas where winter and summer balances are not well defined, e.g. on glaciers with a precipitation maximum in the summer, new methods of estimating annual accumulation and ablation should be found. In addition to publishing mean specific balances, workers should be encouraged to publish more tables of specific mass balance as a function of altitude as such data are invaluable for developing and testing mass balance models. Annual values of equilibrium line altitude (ELA) should also be determined and published as part of any mass balance study as many glaciers show a strong correlation between annual values of mass balance and ELA. The slope of this balance-ELA equation depends on the climatic setting of the glacier. Melt water in the accumulation area, is often refrozen within firm as a form of 'internal accumulation' that is difficult to detect in routine mass balance studies. Workers should be encouraged to monitor changes in firm temperature throughout the melt season in an attempt to evaluate refreezing. Lastly, with the increasing availability of lightweight recording stations, climatic variables should be increasingly monitored on the glacier itself, e.g. close to the ELA, in parallel with mass balance measurements. Richer mass balance data will at least help us to improve glacier-climate models and may help us to make better estimates of mass balance in areas where we presently have no measurements.

50A066

Uncertainty assessment in model-based predictions of surface mass balance

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The main sources of uncertainty in model-based predictions of the surface mass balance (SMB) of an ice mass include structural uncertainty (i.e. choice of processes to include and how to represent them), parametric uncertainty (i.e. uncertainty in values assigned to tuneable parameters), and uncertainty in the forcing data used to drive the model. It is known that, at least for future predictions, uncertainty due to forcing (as determined by climate models) is large, but hitherto the structural and parametric uncertainties in SMB models have not been quantified. Using techniques from the statistical field of Computer Experiments, we carry out a parametric uncertainty analysis of a state of the art energy balance and snowpack model which is being used to predict the SMB for the Greenland Ice Sheet. We run ensembles of 1D simulations of the model, driven by an idealised forcing representing a typical profile across the ablation zone. The ensembles are generated using an efficient sampling over parameter space, which is constrained as far as possible by relevant observations for each tuneable parameter. We also perform a regression based sensitivity analysis on these ensembles, to identify the parameters causing greatest uncertainty. Here, we discuss the implications of our results for the uncertainty in model based predictions of the current and future SMB of, specifically, the Greenland Ice Sheet and more generally.

50A067 Detection and adjustment of inhomogenities in mass balance series in the alps. Local and regional approach

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Winter and annual mass balance data of the 3 small glaciers Wurtenkees, Goldbergkees and Kleinfleisskees in Goldberggruppe (Hohe Tauern, Austria) obtained by the direct glaciological method go back to 1982. Observed inhomogenities and breaks in the 25-year time series can have various reasons. They are due to different measurement devices or techniques, unequal amounts of sample points from year to year, a different interpretation of areas with poor mass balance information, varying persons conducting the field measurements, different methods of mass balance calculation (interpolation by hand or in a GIS environment, different interpolation algorithms), not adjusted glacier areas, different methods in determining equilibrium line altitude, man-made influences on mass balance like snow production of ski resorts etc. In a first step - on the local scale - we tried to quantify the inhomogenities in the mass balance times series of Goldberggruppe, which have been measured at our institute, and produced more homogenous time series. This helps also to get a first estimation of the possible magnitudes of the various inhomogenities of mass balance data of other glaciers. In a second step - on the regional scale - we used relative homogeneity tests, a common method in climatology, to detect inhomogenities in mass balance time series of various alpine glaciers. The standard method at our institute is the HOCLIS-method, which we already had been applied on hundreds of time series of different climate parameters in the alpine region. Results show, that the mean occurrence of significant breaks in climatological time series is about 20 years. The success of this method in climatology and our theoretical and practical experience in break detection and adjustment motivated us to apply this method on glaciological time series.

50A068 Glacier Volume Changes 1871-1998 in Goldberggruppe (Hohe Tauern, Austria) extracted from historic contour maps and digital elevation models

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Contour maps of the three main glaciers of Goldberggruppe in Hohe Tauern (Austria), Goldbergkees, Kleinfleisskees and Wurtenkees have been produced in a different quality several times in the late 19th century and during the 20th century. For example the map of Goldbergkees of 1909 was the result of the first terrestrial photogrammetric survey carried out for glaciological purposes. Out of the historic contour maps and modern digital elevation models changes in glacier volume have been calculated using different geodetic methods. This study describes the different methods, the advantages and disadvantages of each method and the final results of the glacier volume changes in Goldberggruppe over the past century. As glacier bedrock was acquired by a ground penetrating radar survey (GPR) in 2003, the glacier volumes can be calculated in absolute values. Further we investigate how the volume changes correlate to accumulated mass balance data in the recent periods and how the information of the historic maps can be used as a validation for mass balance models. The accuracy of the historic maps mainly depends on the scale and quality of the photographs, surface conditions on the glacier and the quality of the geodetic network. Some inaccuracies arise from map compilation, paper shrinkage and drafting. The accuracy of a map can easily be checked by comparing the contour lines of these maps to modern high quality digital elevation models (DEM's) of the surrounding rock areas, which are assumed to be stable. This assumption is not valid in case of debris covered marginal parts of the glacier or in case of debris covered dead ice, which can be detected with this method. Within the digitalization of the historic glacier maps it resulted therefore necessary to reinterpret the debris covered areas in the maps after comparison of one map to another and perform a kind of homogenisation of glacier areas before using the maps for calculations of volume changes.

50A069

Reconstruction of the surface mass balance of Morteratschgletscher since 1865

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We reconstructed the surface mass balance of the Morteratschgletscher, Engadine, with a two-dimensional energy-balance model for the period between 1865 and 2005. The model considers a parameterisation for the surface energy fluxes, an albedo which decreases exponentially with snow depth as well as the shading effect of the surrounding mountains. The model was first calibrated with a 5-year record of surface mass balance measurements made at about 20 different sites on the glacier between 2001 and 2006 using meteorological data from surrounding synoptic stations. Only records of temperature and precipitation are used to drive the model as these are available from 1864 onwards from MeteoSwiss and from the HISTALP project. The model is able to reasonably well reproduce the observed mass balance (mean rms error of 0.74 m w.e. a-1) except for the lower part during the warmest years. Most crucial to the results are the altitudinal precipitation gradient and the timing of precipitation events, which variables are both hard to quantify from long mean monthly climate records from nearby valley stations. The simulation shows an almost continuous mass loss since 1865, with short interruptions around 1890, 1915, and 1980. A trend toward a more negative mass balance was observed since the beginning of the 1980s. The simulated cumulative mass balance for the whole period from 1865 to 2005 was found to be -48 m w.e.

50A070

A method to determine seasonal mass balances of Alpine glaciers since 1865

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Alpine glaciers have suffered major losses of ice in the last century. We compute spatially distributed seasonal mass balances of four glaciers in the Swiss Alps (Grosser Aletschgletscher, Rhonegletscher, Griesgletscher and Silvrettagletscher) for the period 1865 to 2006. The mass balance model is forced by daily air temperature and precipitation data compiled from various long-term data series. The model is calibrated using ice volume changes derived from five to nine high-resolution digital elevation models, annual discharge data and a newly compiled data set of more than 4000 in-situ measurements of mass balance covering different sub periods. The cumulative mass balances over the 142 year period vary between 35 and 97 m revealing a considerable mass loss. There is no significant trend in winter balances, whereas summer balances display important fluctuations. The rate of mass loss in the 1940s was higher than in the last decade. Our approach combines different types of field data with mass balance modelling to resolve decadal scale ice volume change observations to seasonal and spatially distributed mass balance series. The results contribute to a better understanding of the climatic forcing on Alpine glaciers in the last century.

50A071 On the importance of including the heat conduction into the snow and icepack in glacier energy-balance modelling

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The energy-balance at the glacier-atmosphere interface is the key control of the interaction between glaciers and climate and a key step to study the mass balance of glaciers. A component of the surface energy-balance that is often neglected in numerical studies is the heat conduction into the snow and icepack (also referred to as subsurface flux), which is commonly assumed to be small during the ablation season when melting is taking place. In these conditions, many models assume the snowpack to be at melting point (zero-degree assumption). This is not the case at night and for certain climatic conditions (i.e. strong radiative cooling as in the dry climatic settings of the dry Andes of Chile), and can lead to a significant overestimation of modelled ablation, since part of the energy that in reality goes into heating up the snowpack to melting point is used for melt. Several studies have used and validated energy-balance models that do not include the subsurface heat flux, showing that they can be successfully used for simulation of melt. Other works, on the other side, have demonstrated that neglecting internal heat conduction leads to a considerable overestimation of ablation. Evidence on the applicability of the zero-degree assumption and the magnitude of the fluxes is therefore not conclusive. This work intends to contribute to the ongoing debate. We use meteorological measurements from Automatic Weather Stations (AWS's) to test the zero-degree assumption, and to quantify the error that is made by neglecting subsurface fluxes. For this purpose, we run an energy-balance model with and without inclusion of the internal heat flux and test the model performance against measurements at both ablation stakes and Ultrasonic Depth Gauges (UDG's). The subsurface fluxes are computed using a two-layer model, assuming that 36 % of the total incoming shortwave radiation is absorbed by the surface layer and that the rest penetrates into the snowpack. We use meteorological data and ablation observations from Gornergletscher and Haut Glacier d'Arolla in the Swiss Alps collected over several ablation seasons, so that the zero-degree assumption is tested over seasons with different climatic conditions. Our study also includes data from Juncal Norte glacier in the dry Andes of central Chile, where climatic conditions favour strong radiative cooling at night and the related cooling of the snowpack. Under these conditions, the zero-degree assumption most likely does not hold.

50A072

HYDROLOGICAL MODELLING OF ZONGO GLACIER, BOLIVIA

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In the Andes several regions profit significantly from glacial melt water for drink water supply and electricity production. During the dry season, glacier melt is an important source of water in the semi-arid region of La Paz, Bolivia. The Andean glaciers are retreating and thus the water resource will decrease. This implicates serious environmental and socio-economical consequences. For an effective attenuation, it is crucial to furnish quantitative predictions of the glacier mass loss and its effects on the water resources in these regions. The mass balance of these tropical glaciers is controlled through the energy and mass fluxes at the ice or snow interface. Energy flux measurements on tropical glaciers [Hastenrath, 1978; Hardy et al., 1998; Mölg et al., 2003] showed that during periods of dry air and strong wind, the melting energy is considerably reduced by energy loss in ice sublimation. During the wet season the mass balance is often positive and melting is high, while during the dry season the melt is reduced. Sicart et al. [2005] have demonstrated that in the outer tropics, high-altitude glaciers are characterized by a marked long-wave radiation. The cloud emissions during the wet season in the outer tropics strongly enhance the normally rather low long-wave emittance of the thin atmosphere. The principle reason of reduced melt during the dry season is a deficit of long-wave radiation. This direct link between cloud-cover/humidity and the long-wave radiation make it a key variable for the energy balance of tropical glacier. Former works on tropical glacier have mainly concentrated on mass and energy balance studies. A distributed energy balance model based on the model of Hock (1998) is developed to model mass balance and melt induced discharge of tropical glaciers. The model has been adapted to the tropical high mountains. We want to predict the changes in glacier melt discharge for the region of La Paz, Bolivia and later regionalize the model to a larger area. The model is operating on daily steps and has a 20 m grid resolution. The Glaciar Zongo is a 1.8 km² glacier with a 63% glacierized catchment. Measurements are available on daily bases from 1991 onward. In the absence of long series of data without gaps we decided to calibrate the model with European Centre for Weather Forecast (ECMWF) ERA-40 data. Field measurements (humidity, wind speed, temperature, global radiation

50A073

Measuring the mass balance of mountain glaciers – an overview

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The presentation it thought to introduce to the workshop from the viewpoint of measuring the mass balance of mountain glaciers. A short historical overview will lead to the questions of why what was/is/will-be measured and how. Consequently, a definition of mass balance and related terms will follow, well knowing that glacier mass balance terminology has somehow become watered over the years. In a second part I will try to address the accuracies of mass balance measurements as required from different viewpoints. This is faced by error estimates for measurements and analysis procedures, our knowledge about and the respective gaps. The facts that traditional in situ mass balance measurements are cost and manpower intensive and that they cannot be applied on many potentially highly interesting glacier sites simply for logistic and for safety reasons (representative glaciers in the Himalaya and the Andes e.g.) demand for new measuring methods. I will concentrate on giving an overview on the present sate of the application of laser scan technology and will try to outline its potential and limitations.

50A074

Mass balance sensitivity of cirque glaciers in the northern U.S. Rocky Mountains, Montana, U.S.A.

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Glacier National Park, Montana, USA, contains 37 cirque glaciers, each less than 1 km² and together comprising about 17 km². These glaciers lie at relatively low elevation (2000 – 3000 m) and latitude (48° N) and are influenced by both maritime and continental air masses. The region has seen dramatic glacier retreat since the mid-nineteenth century, when an estimated 150 glaciers existed. Continuing volume losses and the disappearance of glaciers in recent decades are used as key indicators of regional warming. Here we investigate whether glacier changes in recent decades are responses to contemporary climate trends. Specifically, we examine the sensitivity of the mass balance of glaciers in the northern U.S. Rocky Mountains to regional climate factors that drive accumulation and ablation, and to local factors that enhance accumulation, such as wind drifting and avalanches. We analyze data from a long-term mass balance monitoring program initiated in 2005 on Sperry Glacier (48.6° N, 113.75° W), a 0.8 km² cirque glacier that has undergone an 80% reduction in size since the mid 1800s. We measured surface mass balance, meteorological variables, and ice velocity and calculated both winter and summer balances using standard glaciological field methods. We augmented the point measurements of snow accumulation and melt with data from meteorological stations on and adjacent to the glacier, data from a nearby automated snow pillow, and images from time lapse cameras. During three existing years of record, the net mass balance was negative (approximately -1 m w.e. a⁻¹). The winter balance showed marked spatial gradients (1 m w.e. in 100 m) across the glacier surface; these gradients are of greater magnitude than interannual precipitation variability and occur in spatial patterns that are consistent from year to year. Summer balance was relatively uniform across the glacier surface and showed little relationship with elevation. Locations with positive net mass balance are limited to small areas where wind redistribution and/or winter and spring-time avalanches and cornice falls augmented the seasonal snowpack by a factor of two or more. We use meteorological and snow pillow records in conjunction with the field mass balance measurements to extend a mass balance sensitivity analysis to the last three decades.

50A075 Estimations of glacier net balance from Synthetic aperture radar data over Svartisen, Norway

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Glacier mass balance is a standard measure of the 'health' of a glacier. Traditional methods of manual measurements are accurate but time consuming and expensive. Remote sensing methods for observing glacier change have typically employed proxies such as Equilibrium Line Altitude (ELA) mapping or transient snow line mapping to infer the net balance of a glacier. Synthetic Aperture Radar (SAR) estimations of net balance have been developed for the dry snow zones of the large ice sheets. In the dry snow zone the snow-firn volume is regarded as a layered medium with scattering at the interfaces between annual layers. In the percolation zone the 'mass balance signal' is partially masked by ice inclusions and spatial variations in firnification. Here we establish that there exists an inverse relationship between mass balance and SAR backscatter for an arctic icecap which experiences percolation. We show that SAR backscatter is anti-correlated with mass balance for the Engabreen outlet glacier of the of the West Svartisen icecap. Using backscatter modelling we explain the fundamental processes affecting backscatter and investigate backscatter variations in time and space. The SAR method enables us to extend estimations of mass balance from an outlet glacier to the entire icecap. The method is then further extended to investigate mass balance change of the neighbouring icecap East Svartisen. The application to East Svartisen is evaluated with reference to winter balance estimates derived from precipitation modelling. We show that SAR data can provide a valuable addition to in situ mass measurements and that in combination with modelling provides a powerful tool for the investigation spatial patterns of mass balance.

50A076

Regional differences in point observations of mass balance in Switzerland

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Seasonal components of the mass balance provide the best insights to analyze climate-glacier interactions. Point observations at fixed locations directly reflect climatic conditions and are not biased by interpolation effects or the dynamic behaviour of the glacier. In order to compare observations taken at different dates, mass balance quantities need to be homogenized to common periods. We present long-term time series of mass balance observations of Claridenfirn, Grosser Aletschgletscher and Silvrettagletscher. Using a mass balance model based on the temperature-index approach, direct field observations are corrected for varying dates and data gaps. The records are assessed for measurement and systematic errors. The resulting homogenized datasets cover most of the 20th century reaching back to 1920s. The records from the three glaciers located in different areas of the Swiss Alps enable to investigate regional variability. Differences in the seasonal components of mass balances are evaluated and interpreted in terms of temporal and regional variations. We discuss rates and trends in the context of climate change.

50A077 Modelling the 21st century mass balance of Svalbard glaciers using ERA-40 reanalysis and general circulation models

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Ice caps and glaciers of the Arctic Islands form about 45% of the land ice outside of the Greenland and Antarctic ice sheets and would raise global sea levels by ~0.5m if they were to melt entirely. The aim of this project is to develop a distributed mass balance model that can ultimately be used to investigate the climate sensitivity of large glaciated regions in the Arctic. The model will use an energy balance approach and will be driven by statistically downscaled data from the European Centre for Medium-range Weather Forecasting ERA-40 reanalysis. The response of Arctic ice masses to 21st century climate change scenarios will be investigated using an ensemble of downscaled simulations from 17 general circulation models. Initial results are presented for Midre Lovénbreen, a small valley glacier in the Kongsfjorden region of northwest Spitzbergen, Svalbard. The ERA-40 data used to drive the mass balance model are validated against observations from a surface weather station near the glacier. Future mass balance projections are then made by driving the model using statistically downscaled GCM simulations.

50A078

Ice volume change in Arctic Alaska, 1970-2007

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We measured ice volume change of 135 glaciers in Arctic Alaska through a combination of techniques and found that nearly all of these glaciers are losing mass at similar rates, and that these rates are increasing with time. In the central Brooks Range of Alaska, surface elevations of 123 of these glaciers was measured in 2001 using airborne synthetic aperture radar (SAR), with spatial resolution of 10 m and relative vertical accuracies between pixels of several centimetres. These maps were compared to topographic maps based on 1970 photogrammetry, using a variety of techniques (some novel) to assess errors. The majority of glaciers are losing mass at an aerielly-averaged rate of 0.3 m per year or higher. At a dozen glaciers in the eastern Brooks Range, airborne laser altimetry and GPS ski profiles along the same routes were measured over several intervals from 1993 to 2007, and these were compared to topographic maps based on 1956 photogrammetry. At each of these multi-interval time-series, the rate of change of volume loss was found to be increasing, with those glaciers with the lowest accumulation areas losing mass the fastest. These data form the spatial backdrop against which the theory of benchmark glaciers can be tested, using the long and intense record of McCall Glacier as a test case. A newly funded project will provide topographic maps for the remaining 542 glaciers in Arctic Alaska, such that we should be able to determine which, if any, of the glaciers here could serve as a suitable benchmark glacier, or whether several glaciers are needed to adequately predict the variance. The proximal cause of this volume loss is a steady increase in equilibrium line elevation. Because snow lines have often been above glacier elevation in recent years, internal accumulation of meltwater is likely the dominant form of accumulation and new field studies are planned to better measure and model this process.

50A079 GRACE and Aircraft Altimetry Estimates of Alaska Glacier Changes: Can Mass Balance Models Explain Recent Trends?

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Using a high-resolution technique for processing data from the Gravity Recovery and Climate Experiment (GRACE) satellites, we are producing time series of the regional trend and amplitude of Alaska glacier mass balances within 2 by 2 degree grid cells at a temporal resolution of 10 days. In an ongoing study we have validated GRACE estimates of glacier mass changes against 2003-2007 aircraft laser altimetry data in the St. Elias Mountains of Alaska, and we find that both estimates agree within the bounds of calculated errors. In this study we investigate regional mass balance simulation models in an effort to identify causes of recent mass changes of glaciers in the St. Elias. Our goal is to quantify the proportion of mass loss attributable to surface mass balance versus dynamic losses from tidewater and lacustrine glacier dynamics. In doing so we will improve understanding of the processes controlling mass variations in these regions and begin to build better models of future conditions. Two models will be used in these investigations: (1) a regional model of glacier mass balance using sensitivity parameters derived from comparisons of in situ temperature, precipitation and surface mass balance data; and (2) a degree-day mass balance model that accounts for elevation-dependent variations in surface air temperature and precipitation. Both models will be driven by output from the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis model and surface climate station data where available. Given the uncertainty in model parameters and in the quality of input meteorological data for these regions, our model experiments will be performed as a series of sensitivity tests over a range of reasonable parameter values. The output from these tests will be compared with regional mass change estimates from GRACE to assess the proportion of mass changes due to surface balance changes, with the residual changes attributed to dynamics thinning or thickening. Aircraft laser altimetry measurements of surface elevation changes will allow us to place some constraints on the magnitude of dynamic changes resulting from calving and non-steady flow behaviour. For example, thinning of tidewater glaciers at low elevations that exceeds the amount predicted by mass balance models will be attributed to dynamic thinning, and will help us quantify the proportion of tidewater mass changes resulting from calving.

50A080

Mass balance of Storglaciären, Sweden – Re-evaluation and error assessment

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Storglaciären, a small valley glacier (3 km²) in northern Sweden, has the longest detailed mass balance programme in the world starting in 1945/46. Measurement routines have varied with time, but since 1966 winter mass balance has been derived from snow probings in a 100 x 100 m regular grid and a few density pits and summer balance from roughly 50-80 ablation stakes across the glacier. We recalculated the entire mass balance series in a consistent manner, based on a newly digitized data set of all available snow probings, a new set of digital elevation models and glacier outlines and re-evaluation of all available density data. Results show that seasonal balances differ up to 0.4 m compared to previously published results indicating that even for a glacier where abundant data are available upon which mass balances are based uncertainties can be large. We also performed a number of sensitivity experiments to systematically evaluate the sensitivity of results to assumptions on factors, such as snow density, definition of glacier outlines, number of snow probings and ablation stakes, etc.. Mass balances turned out to be sensitive to some of these assumptions. Equilibrium line altitudes varied by more than 100 m depending on how they were derived. Our results emphasize the uncertainties associated to glacier mass balance data and the need to report details on the calculation procedures to allow such uncertainties to be evaluated.

50A081 Monitoring Glacier Hydrology and Mass Balance on a Small Temperate Glacier Using a Sensor Web

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As part of the Southeast Alaska Telecommunications and Monitoring for Science, Education and Research (SEAMONSTER) project we are establishing a sensor web to monitor the hydrology and mass balance of the 11 square km Lemon Glacier near Juneau, Alaska. To date, we have installed two climate stations, one on a ridge above the glacier and a second 3 km below the terminus. An in-situ water quality sonde measures water temperature, conductivity, turbidity, pH, and dissolved oxygen continuously in Lemon Creek, the proglacial stream draining the glacier. In addition, the U.S. Geological Survey maintains a stream gauging station at the location of the sonde. To monitor outburst flood events, we have installed a pressure transducer to monitor stage in a supra glacial lake that forms annually in the spring and early summer and drains in the late summer. We are currently developing a communication system that will allow data from all of these sensors to be transmitted to our lab at the University of Alaska Southeast in real-time. The data collected via the SEAMONSTER sensor web is being used for a variety of applications. Data from the climate stations is being used in conjunction with a temperature-index ice and snow melt model and a digital elevation model to model runoff from the Lemon Glacier and evaluate the glacial contribution to stream flow in the upper Lemon Creek watershed. Water quality data are being used to assess the impact of glacial runoff on the physiochemical quality of Lemon Creek across the glacial melt season. Stage data from the supra glacial lake are being used in conjunction with the modelled glacial runoff and water quality data to evaluate the magnitude of the annual glacial lake outburst flood and its impact on water quality in Lemon Creek. Public outreach is an integral component of our project and we are developing database access and visualization tools that will allow data to be displayed on the web in real-time. In particular, we have developed preliminary user interfaces that allow the data from the sensor web to be displayed in a virtual earth environment such as Google Earth.

50A082

Glacier surface melt modelling: inter-comparison of two energy-balance and one temperature-index approaches and their sensitivity to the input data quality

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This study addresses two questions relevant to modelling of ablation and consequently mass balance: 1) how robust are both energy-balance models of different complexity and an enhanced temperature-index melt approach to variations in the quality of input data, and 2) how the quality of snow depth and snow density measurements used for model validation affects conclusions about the model performance. Extrapolation of input data (such as meteorological measurements and glacier surface properties) used to force distributed ablation models is important because of availability of input data at the point scale at Automatic Weather Stations (AWS's). Approaches for the spatial distribution of input measurements vary widely in complexity from simple linear extrapolations to complex atmospheric boundary layer models, e.g. used to derive temperature gradients with elevation. Relatively simple extrapolation techniques are commonly used in current models. Here we investigate the influence of replacing on site measurements of meteorological variables with extrapolated measurements from stations outside and inside the glacier boundary layer on melt computation. We use two energy-balance models that differ for inclusion of the heat conduction into the snow pack, and an enhanced temperature index model incorporating the shortwave radiation flux. For the validation of the hourly melt rates simulations we use measurements of surface lowering at an Ultrasonic Depth Gauge (UDG) converted into water equivalent with density measurements. The effects of different assumptions about the density of old and new snow on the conversion of surface height variations into water equivalent are discussed. We show that small variations in snow density have a major influence on the validation of the model performance. This study is conducted on Haut Glacier d'Arolla, Swiss Alps, where AWS measurements are available for five locations on the glacier in the 2001 ablation season, and for one location outside the glacier. For the 2005 and 2006 ablation season measurements from the off-glacier AWS and from one glacier AWS are used.

50A083 Hydrological analyses supporting traditional mass balance studies on South Tyrolean glaciers

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The Ufficio Idrografico of the Autonomous Province of Bolzano, Italy, carries out mass balance studies on four glaciers in South Tyrol. The main working approach is given by the traditional direct glaciological method. On the Fontana Bianca - Weissbrunnferner glacier (I4L00110103) and on the Malavalle - Übeltalferner glacier (I4L00121108) the analyses are integrated by the hydrological data collected on two gauging stations positioned downstream the glaciers. Both glaciers are situated in the north-eastern part of Italy. The Fontana Bianca glacier is a small east-exposed glacier of the Ortles-Cevedale Group. It covers an area of 0.49 km², extends from 2890 m to 3340 m a.s.l. and has two short tongues. The Malavalle glacier is situated in the Stubaier Alps on the boarder to Austria, has an area of about 7.2 km², extends from 2590 m to 3470 m a.s.l. and has a composed basin structure with eastern main exposition. The discharge measurements are made both with propellers and salt dilution method and allow the construction of stage - discharge rating curves. Discharge data permit to estimate maximum ice melt rates of about 5-6 cm ice / day for whole glacier. On the catchment drained by the gauging station positioned downstream the Malavalle glacier even the GEOTRANS hydrological model is applied. This model uses morphological meteorological (temperature and rainfall) input data and reproduces the entire hydrological cycle at catchment scale: discharge, evapotranspiration, snow cover and snow melt. A simple ice melt routine, based on the degree - day algorithm, has been integrated in the model. The modelling results show a good fit between simulated and measured daily discharge oscillations.

**50A084 25 years of glacier mass balance monitoring in the Sonnblick region (Austrian Alps) –
overview and major outcomes**

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The mass balance of a glacier is known as both a key parameter for monitoring climate change in alpine regions as well as an important climate impact factor. Time series of glacier mass balances of the Alps are among the longest available and therefore an important data source for modelling and understanding the climate-glacier relation. From the different glacier monitoring programmes of the Alps the Sonnblick monitoring programme stands out because of its detailed measurements of both winter as well as summer mass balance for 3 small glaciers (Wurtenkees, Goldbergkees, Kleinfleißkees) capturing strong regional climate gradients (from the effect of Alpine main divide on weather patterns and consequently on climate), its long-term glacio-hydrological network back to 1928 as well as because of the extensive and long-term climate information from nearby Sonnblick Observatory (3105m.a.s.l.). Based on series of mass balances from geodetic method back to 1871 the mass balance monitoring for Sonnblick region by the glaciological method was started in 1982 at Wurtenkees and extended for Goldbergkees in 1987 and for Kleinfleißkees in 1999. Small and meso-scale precipitation and wind patterns during winter produce differences in winter mass balance of about 30% for the three immediately adjacent glaciers. Moreover, the winter mass balance data from Sonnblick region are very meaningful to better understand high Alpine precipitation patterns and precipitation quantities as measurements from meteorological networks fails at those high elevated sites. Monitoring of winter mass balance includes not only measurements of snow density and snow depth but also measurement of snow temperature and estimation of snow water content, snow hardness and snow crystal type. From this data set the influence of climate change on properties of winter snow cover and consequently winter mass balance can be quantified. Investigation of the sensitivity of the glaciers of Sonnblick region to climate shows that these glaciers are currently reacting to variability of climate conditions during summer and not during winter. However, in the much longer context of measurements of precipitation and snow height in the Sonnblick region it can be concluded that this relation is not stable in time. In fact temporal variability of precipitation and snow height had reduced significantly since the 1940s and therefore variability of summer climate overrules contribution from winter-accumulation today.

50A085 On the accuracy of winter mass balance data from different measurement approaches

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Winter mass balance measurement is conducted on a few glaciers in the Alps only, although such data are important to fully understand the climate-glacier relation. The lack of winter mass balance measurements certainly results from the quite laborious field works and from the higher level of alpine risk during winter season. In Sonnblick region (Austrian Alps) the winter mass balance is monitored since 1982 for 3 small glaciers (Wurtenkees since 1983, Goldbergkees since 1987 and Kleinfleißkees since 1999) in the vicinity of Sonnblick Observatory. The measurement accuracy of snow depth and snow density is crucial for estimating the SWE of snow cover and consequently the winter mass balance. For Sonnblick region this measurement accuracy is affected from large snow depths of up to 11m of snow. Different measurement approaches of snow density and snow depth were tested for the monitoring. Snow density was measured using 20cm (length) aluminium samplers, 40cm aluminium samplers and a 130cm aluminium sampler. For estimation of systematic biases between the ('standard') 20cm sampler and the 130cm sampler a detailed inter-comparison study was done using an additional maxi sampler with 70cm length and 65cm diameter. From the results of the inter-comparison together with some additional comparative measurements it can be concluded that the 130cm snow sampler works well under wet (high density) snow conditions but fails for snow covers with high depth-variability of snow density. Moreover our field measurements show very clear the high influence of maintenance of scales on the accuracy of snow density measurements. Snow depth was measured with avalanche probes and since the last few years with ground penetrating radar (GPR). Comparison between the 2 methods shows that snow probing can result in large measurement errors for large snow depths and weak solidified snow-horizon from previous year. In such cases GPR can significantly improve the accuracy of snow depth measurements. Finally our study discusses the difference of winter balance estimation between the fixed date system and the stratigraphic system.

50A086 Mass balance of McCall Glacier Alaska, 1956-2007, and relationship to recent and future climate change

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We assessed the mass balance of McCall Glacier, in arctic Alaska, from IGY to IPY using a combination of techniques and found it to be increasingly negative during this period, though with substantial year to year variation. Our methods include a traditional stratigraphic stake methods for about 18 of these years, geodetic map comparisons over the largest gaps, and a new method of spring and summer GPS profiles coincident with the stake measurements. Trends during this time began with net mass balances of about 0.2 m a⁻¹ w.e., increasing to over 0.8 m a⁻¹ w.e. in recent years. The average equilibrium line here has risen over 300 meters during this time, and more since the end of Little Ice Age conditions (about 1890AD). Air temperature trends from global reanalyses models indicate an increase over this time, with the rate increasing after the mid-1970s, which is also when the mass balance rates show an increase trend towards negativity; field measurements of air temperature show similar trends, though are not continuous in time. Field measurements indicate that even the largest winter mass balance on record cannot compete with a medium summer mass balance, and modelling confirms that annual mass balance is dominated by summer trends. As surface accumulation decreases, the relative importance of internal accumulation is increasing, and our measurements show that internal accumulation is occurring every year and that the amount is limited more by water than by firm temperature. Numerical flow modelling shows the dynamics of the glacier are sensitive to the rate of internal accumulation in this polythermal glacier. If recent conditions are maintained, modelling predicts that McCall Glacier will likely disappear in less than 200 years, and likely much sooner given if current climate trends are extrapolated. Given that McCall Glacier is one of the largest glaciers in arctic Alaska, it is therefore likely that most of the ice here will disappear in the next 100 years, and this is supported by the fact that many of the lower, non-north facing cirque glaciers have largely melted away since IGY based on photographic and map evidence.

50A087

Hydrologic and climatic balances for Gulkana and other glaciers

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It has been proposed that mass balance programs report both the conventional ('hydrologic') balance and the reference-surface ('climatic') balance. The former is more useful for water supply or sea level applications, but the latter is more useful for climate applications because the effects of glacier adjustment have been removed from the balance series. The difference between these two balances depends upon the forcing climate and the time scale for glacier response, which is thought to be several decades for typical valley glaciers. Since this time is comparable to the duration of many mass balance programs, a significant difference between the two balances has had time to develop. In addition to the issue of climate applications, it is important to understand the differences between these balances because failure to do so may lead to substantial systematic errors in the reported conventional balance, especially for programs with long records. The difference may be small for annual balances, but it is systematic and substantial differences may show up in the cumulative balances. These points are illustrated with data from the Gulkana and other glaciers. To obtain the glacier-wide balance for a given year, one essentially determines balance versus elevation and integrates it over elevation intervals read off a map. The current map for a given year must be used if hydrologic balance is to be calculated. If the map is never updated, the climatic balance series is determined automatically. Thus in a Gulkana-type program, at least, it tends to be easier to determine the climatic than the hydrologic balance because less mapping is required. If the map is not updated continually, but at erratic intervals, neither of the two balances is obtained, but instead something with no clear physical meaning. Gulkana Glacier is an interesting case. Prior to 2000 the map used to calculate annual balances was never updated. This meant that the balance series reported between 1966 and 1999 as the conventional hydrologic was actually the pure climatic balance series. Subsequently the hydrologic balance series was determined with the help of maps made from repeat aerial photography, and interpolation between them. Over this period the cumulative hydrologic balance is about

50A088

Modelling the Mass Balance Sensitivity to Climate Change of Three Glaciers in the Cascade Mountains, USA

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In order to evaluate the impact of potential climate change on glacier health in the Cascades of Oregon and Washington, a simple mass balance model is perturbed using multiple future climate projections. By utilizing the links between climate, mass balance, and erosion, the PTAA model reconstructs glacier mass balance using only Precipitation, Temperature, and the glacier Area Altitude distribution as inputs. Model simplicity, ease of data acquisition, and independence from direct measurements make the PTAA model extremely attractive. Utilizing the unique parameter optimization method, we are able to simulate the recent mass balance history of three glaciers that do not have direct mass balance measurements. Extrapolation of mass balance measurements from a single benchmark glacier to nearby glaciers or even to an entire region can be refined using simulations for local unmeasured glaciers. Long-term meteorological data were acquired from low altitude stations that are <50 km from the glacier. Although data acquired at the glacier are preferred, because such records do not exist for the study glaciers, we rely on proximal stations to recreate climate conditions at the glacier. The area altitude profiles were calculated from two different sources: United States Geological Survey (USGS) topographic maps and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) satellite imagery. Snow accumulation and snow and ice ablation are then simulated at regular altitude intervals using a series of algorithms with 15 optimized coefficients. The lengths of each model run depend solely on access to reliable meteorological observations and therefore, are variable for each glacier, ranging between 48 and 80 years. The mass balance sensitivity was calculated by perturbing the temperature observations from -1°C to +2°C at 0.5°C intervals and precipitation observations from -20% to +20% at 10% intervals. The sensitivity of Tahoma Glacier, WA to a +1°C temperature change and a +10% precipitation change was determined at -0.92 m w.e. a-1 and +0.25 m w.e. a-1 respectively (m w.e.: meters water equivalent). Sensitivity runs for White River Glacier and Jefferson Park Glacier, OR yielded similar results. As might be expected, these maritime glaciers have a high sensitivity to temperature changes and a more subdued relationship with precipitation fluctuations.

Massive Pliocene moraines in the McMurdo Dry Valleys, Antarctica indicate greatly expanded alpine glaciers in the region during this epoch. In contrast, modern glaciers in these valleys have limited extents, are cold-based and produce narrow ice-marginal moraines, suggesting significant climatic differences between the Pliocene and the present. To quantify this difference in glacier-climate regimes, we evaluated key climate controls on the modern equilibrium line altitude (ELA), reconstructed early Pliocene ELA, and estimated the ELA change. Modern ELA's were calculated for six Wright Valley glaciers using mass balance data from 1972-83. Stake readings and maps were digitized into a GIS and interpolated with a Triangulated Irregular Network method. The ELA's were determined by interpolation of the 50-m elevation intervals where the net mass balance was zero. Mass balance and accumulation area distribution indicate that wind-controlled snow dispersal plays a major role in determining both accumulation and sublimation processes. The Wright Valley ELA's, ranging between 795-1500 m a.s.l., constrain a steep ocean-inland mass balance gradient of 24 m/km. The average modern accumulation area ratio and terminus-head altitude ratio were both 0.61 and the balance ratio was 1.1. This balance ratio gave the best estimate of present-day ELA in a test re-calculating the ELA's, and was used to estimate modern ELA values for Hart Glacier (Wright Valley) and for Sollas and Stocking Glaciers (Taylor Valley). Pliocene glacier margins and hypsometry were reconstructed for Hart and Meserve (Wright Valley) and Sollas and Stocking (Taylor Valley) Glaciers, using aerial photographs in combination with data from LIDAR DEM and established radiometric dates of ice-marginal moraines. Pliocene ELA's were estimated by various mass balance methods. Reconstructed Pliocene ELA's for the four alpine glaciers range from 1105-1315 m a.s.l. Assuming 150-500 m uplift since the early Pliocene, this implies ELA's 535-1165 m above the early Pliocene sea level. The Pliocene mass balance gradient, based only on the four reconstructed glaciers, was ~20 m/km, only slightly lower than the present. The early Pliocene glaciers were 35-100% larger than modern Dry Valleys glaciers, and Pliocene ELA's were ~300-600 m lower; indicative of a significantly different Pliocene glacier regime. With more open water in the McMurdo Sound maintained by warmer Pliocene temperatures, more moisture was available to enter the Dry Valleys than presently. We therefore suggest that Pliocene precipitation, accumulation, and ablation were higher, and that the glaciers had a higher mass-turnover rate, explaining larger-than-present ice-marginal moraines

50A090

Analysis of snow cover by Ground Penetrating Radar (-GPR)

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Determination of spatial distribution of snow cover thickness and snow cover stratigraphy is extensive work, but in case of for example mass balance or hydrological discharge modelling of a glacier absolutely required. Analyzing the snow cover by GPR in a 'Constant Offset' - arrangement is a possibility to get continuous profiles and hence continuous information about the estimated thickness and a rough stratigraphy of the snow cover. The area of investigation is the accumulation area of the 'Pasterze' glacier, at the foot of the 'Großglockner' (3798m), the highest mountain of Austria. In the framework of snow accumulation measurements for mass balance calculation of the 'Pasterze' glacier in summer 2006, also GPR investigations of the snow cover were performed. The main frequency used in this survey was 500 MHz. The collected data show snow and firn layers of several years reaching an exploration depth of estimated 10m. One eye-catching firn layer in an estimated depth of ~4m can be detected after due stratigraphically considerations as the firn layer of the year 2003. To estimate the thickness and absolute depth of a snow layer the propagation velocity of the GPR signal has to be well known. Since there exists a correlation between the propagation velocity of electromagnetic signals and the density of snow, one can estimate the propagation velocity out of measured snow densities from a snow pit. The GPR data and the snow pit data will be compared to estimate the accuracy for this GPR survey. Based on this dataset different layered snow/firn cover models are generated and synthetic GPR data are computed. After the inversion the accuracy of the synthetic GPR data can be determined. The aim of this project is to get continuous information of snow cover thickness, stratigraphy and density along a profile by objective GPR data. Especially in accumulation areas with an existing firn horizon it is nearly impossible to palpate exactly the snow/firn-border by manual snow probing. The glaciological field technique of snow probing can be a very subjective method and digging a snow pit is extensive work. Therefore, especially for larger survey areas, GPR gives a good option in addition to the classic glaciological investigation methods.

50A091 Change detection on Drangajökull, Iceland, from ICESat profiles and ground GPS survey data

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Located on the Vestfirðir (Northwest Fjords), Drangajökull is the northernmost ice cap in Iceland. Ice caps in the North Atlantic region, such as this one in Iceland, are sensitive to climate variability because small increases in summer temperature can cause significant changes in the extent of the ice cap's ablation area and the ice cap's year-to-year mass balance. Currently, the ice cap exceeds 900 m in elevation at its summit, and has a total area of 146 km². The ice cap has decreased in area from about 160 km² a few decades ago and has been losing mass since the early 1900s. Drangajökull's size and relative accessibility for GPS surveys as well as the availability of repeat satellite altimetry profiles make it an excellent target for mass-balance/change-detection analysis. The ice cap was surveyed by GPS units mounted on snowmobiles in April 2005 and has been profiled in two places by ICESat (Ice, Cloud, and land Elevation Satellite) 'repeat tracks' twelve times from late 2003 to late 2007. Cloud conditions have hampered acquisition of the laser altimetry data and may also reduce accuracy. Mean differences between the temporally-closest ICESat profile elevations and the digital-elevation model (DEM) derived from the ground-based GPS surveys (ICESat - DEM) range from -0.79 to +0.35 m (ICESat 3C data Release 428) and have standard deviations of 2 to 4 m. This suggests that uncertainties remain in the ICESat-derived elevation data; therefore, mass balance assessments using these data will have substantial uncertainties as well. Finally, the latitude (~66.2°N) and topography are similar to nearby coastal regions of Greenland, thus the elevation uncertainties across Drangajökull may also be present in repeat profile studies of similar ice topography along the nearby margin of the Greenland ice sheet.

50A092

Glacier Mass Balance; Results from Direct Observations

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Glacier changes are having impacts on processes of global importance such as sea-level rise, hydrology of mountain-fed rivers, freshwater balance of oceans, and even the shape and rotation of the Earth. Glaciers and ice caps, all perennial ice masses other than the Greenland and Antarctic ice sheets (GRIS and AIS) have contributed 60% to the eustatic component of sea level rise mostly due to negative surface mass balance, leaving to GRIS and AIS 30% and 10%, correspondingly (IPCC-2007). Faster decrease the surface area of glaciers in 21 century has occurred in mostly maritime regions, and may be compensated by increase area of local glaciers around GRIS and AIS due to disintegration of ice in the coastal areas. Here I will present the results of glacier mass balance reanalysis of glaciers and ice caps. The results of reanalysis will include glacier area and area change by regions since 1950s, observational results of seasonal mass balance components and annual mass balance rate, equilibrium line altitude and accumulation area ratio. I will focus on problems with glacier mass balance extrapolations from individual glaciers to the regions and global scales, and major uncertainties in the knowledge of glacier mass balance, such as internal accumulation, iceberg calving fast decrease in accumulation area.

50A093 Glacier Inventory and Change in the American West and Directions for the Future

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We have identified over 8300 glaciers and permanent ice/snow features in the western USA exclusive of Alaska. We gathered the data from digital representations of snow and ice features identified on topographic maps. To identify 'glaciers' specifically we filtered the data using slope and thickness estimates to calculate basal shear stress. For those features whose basal shear stress exceeds 105 Pa we classified them as 'glaciers'. This is a more robust definition rather than using an arbitrary size threshold. For a subset of glaciers we compiled changes in glacier area since the Little Ice Age, largely based on historic maps and photographs. Results show that all glaciers have receded but the rate and magnitude of recession is far greater in some regions compared to others. Differences in the magnitude appear to be related to differences in regional climate and differences in area-altitude distribution of the glaciers. Furthermore, some glaciers appear to become less climatically sensitive with time as they shrink into small and steep cirque basins, which reduces incoming solar radiation due to topographic shadowing and alters snow accumulation through avalanching and snow wind drift. While these processes were always active at these sites, the fraction of glacier area influenced increases with time as glacier area decreases and the altitude distribution increases.

Volume changes are estimated from area-volume scaling relations. While this method is inaccurate for individual glaciers compensating errors across a large sample of glaciers improves the accuracy. Such estimates complement measurements made at individual 'benchmark' glaciers and provide an approach for estimating mass change over regions. This approach will be contrasted with traditional and other methods to synthesize a direction for the future of glacier monitoring in the face of climate change.

50A094

The Utility of the Benchmark Glacier Concept

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The benchmark glacier concept was developed during the International Hydrology Decade of the 1960s. In essence, a glacier was selected in each glaciated region and intensively studied to identify the important mass balance processes and their linkage to climate variations and to patterns of water runoff. This 'benchmark' glacier concept was predicated on the idea that the important glacier processes and the response of a benchmark glacier to climate variations was representative of the glaciers in that region. When selecting a benchmark glacier, the selection was based, understandably, on more practical criteria, such as access to the glacier, ease of travel over the glacier, and so on. These practical considerations often resulted in the selection of a glacier that differs in many ways from the 'typical' glacier of that region. The benchmark glacier concept is an important issue because many of the estimates of the contribution of alpine glacier shrinkage to sea level rise are based, in one way or another, on this idea. We investigate the application of South Cascade Glacier, in the north-western part of the continental US, as a benchmark glacier for the western US. The topographic characteristics of South Cascade differ greatly from those in the region and include a glacier area that is two orders of magnitude larger and an average slope that is much less. The glacier has been losing mass much more rapidly than those in the region but the temporal trend in shrinkage is representative except for some of the most distant glaciers. Therefore if the mass loss of South Cascade Glacier is used to infer the rate of loss in the surrounding region then the results are over estimated. However, if the temporal pattern of loss at South Cascade is used to infer when the temporal pattern of change in the region, then the results should be fairly accurate. To properly infer the relation between benchmark glacier changes and those in the region, a regional analysis must be performed and not assumed. That relation is probably individual to each benchmark glacier depending on how it's topographic characteristics differ from the other glaciers in the region and how those characteristics interact with the regional climate.

50A095

Do long term mass balance series need homogenization?

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Mass balance measurements are performed to investigate the relationship between climate and glacier. Over decades, glaciers can significantly change as a reaction to a changing climate. This has an effect on the mass balance, so that the mass balance reflects not only the reason for a glacier fluctuation, but also its results. How significant is the impact of these glacier changes on mass balance, and can the effects be separated from climate signal a posteriori? For Hintereisferner and Kesselwandferner, two glaciers of different types in Öztal Alps located near each other with a size of several km², these effects and the resulting effect on the mass balance is investigated. Examples for glacier changes are the separation of glacier tributaries, area changes, albedo changes, changing runoff, changes in size and location of crevasse zones, changes of surface runoff. In addition to these changes in glacier physics, in most if not all long term mass balance series, methods are not the same over decades. A suggestion for a possible homogenization of long term mass balance series is made.

50A096 Investigating the sensitivity of glacier mass balance to changing meteorological conditions and surface energy balance on Djankuat Glacier, Northern Caucasus, Russia

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Variations in surface energy balance provide a physical link between glacier ablation and climatic variability. Ablation records from Djankuat Glacier (northern Caucasus, Russia) dating back to 1967 are often used as an indicator of climate change in the high-altitude regions. These records show that the cumulative mass balance of the glacier has been in pronounced decline during the first decade of the 21st century due to a considerable increase in ablation. The ablation season of 2007 was particularly warm enhancing glacier melt to the record level in 40 years of observations. Ablation exceeded the long-term average of 2580 mm water equivalent (mm w.e.) by 50% surpassing the previous maximum recorded in 2000 by 300 mm w.e. To date, however, little information has been available about the surface energy balance and meteorological regimes of Djankuat Glacier making it difficult to evaluate the physical mechanisms of climatic forcing of glacier recession. This study investigates climatic controls of glacier ablation using a two-year data set from automatic meteorological station, which operated in the ablation zone of Djankuat Glacier between June and October in 2006 and 2007. Inter-seasonal variability in meteorological parameters, components of net radiation (measured directly) and turbulent heat fluxes (estimated using bulk method) and their links with daily ablation rates are analysed showing the predominant importance of solar radiation and sensible heat flux for glacier melt. Climatic variables and processes driving glacier ablation during a very warm ablation season of 2006 and a uniquely warm season of 2007 are identified providing quantitative data for a wider discussion of glacier retreat in the Caucasus Mountains.

50A097 Assessment of Mass Changes in the Azarova Glacier (the Kodar Mountains, Eastern Siberia) Using Cartographic Method

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The Kodar Mountains in eastern Siberia accommodate 30 glaciers with a combined surface area of approximately 19 km². The glaciers are positioned approximately 1200-1400 m below the climatic snowline and are preserved in the shadowed, deeply cut, and narrow canyon-like valleys. These are cold glaciers, growing primarily through the superimposed ice formation, with a very brief ablation season in July-August. A basic assessment of the extent of the Kodar glaciers and ablation rates were conducted in the 1970s – early 1980s. However, very little is known about changes in the state and mass balance of the Kodar glaciers in the last 30 years. In the summer of 2007, measurements of ablation, ice flow velocities, glacier discharge, as well as meteorological measurements were conducted on the Azarova Glacier (118 E, 57 N) and the glacier was mapped. Ablation rates were compared to those observed in the early 1980s. Glacier mass balance for the period between 1979 (when the glacier was first mapped) and 2007 was calculated through a superimposition of the two maps of the glacier. This assessment has revealed a comparatively low loss of ice mass pointing at a slow response of the glacier to the warming climate. Although the glacier has retreated since the end of the Little Ice Age, this retreat was slower than in most other glaciated regions.

50A098 Preliminary analysis of the mass balance of Hurd Peninsula glaciers, Livingston Island, Antarctica

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Hurd Peninsula, located in Livingston Island, South Shetland Islands (SSI), Antarctica, is covered by two main glaciers, Johnsons –tidewater– and Hurd –with landed terminus–, extending over an area of about 10 km². The location of the Spanish Station Juan Carlos I in the vicinity of these glaciers has allowed to carry out mass balance measurements. However, very limited results have been published so far, and all of them refer to mass balances at specific points not providing an overall representation of the global mass balance of these glaciers. The purpose of this paper is to review the main mass balance estimates referred to data taken up to 2000, to present some preliminary mass balance data taken thereafter, and to compare them with those from other SSI locations and with the regional meteorological records. During the austral summer 1994-1995, 10 shallow (0.5-16 m) ice cores were drilled to identify both the 137Cs 1965 layer stemming from thermonuclear tests and the 1970 tephra layer stemming from the eruption at the neighbouring Deception Island, in order to estimate the average mass balance for the periods 1965-1993 and 1970-1993. In summer 1999-2000, 3 intermediate (22-35 m) additional cores were drilled in Johnsons glacier with a similar aim, but in this case looking for markers from earlier volcanic eruptions. The measurement of a net of 17 stakes on Johnsons glacier during the austral summer campaigns 1994-1995 to 1999-2000 allowed the estimation of the yearly mass balances along this period. Seven of such stakes were approximately located along a flowline covering most of the altitudinal range of the glacier. However, such flowline, by itself, is not representative of the overall characteristics of Johnsons glacier, and most of the remaining stakes were located at the ablation area, resulting in an undersampling of the accumulation area. Finally, the comparison of digital elevation models for the glacier surface constructed from 1956 British aerial photographs and from our geodetic measurements in 1999-2001, allowed us to estimate the ice volume changes during 1956-2000, which represent a ca. 10% decrease from the 1956 volume and are equivalent to an average annual mass balance of -0.23 ± 0.10 m in water equivalent during such period. The new mass balance data correspond to the extension in 2001 of Johnsons' net of stakes, to provide a more homogeneous sampling of the glacier, and the deployment of a new net of stakes on Hurd glacier, making a total of about 50 stakes.

50A099 Reconstructing glacier volume change through modelling with trial and error proxies

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The response of glaciers to climate change is a highly relevant issue in climate research and can be modelled by both static and dynamic means. Critical is the climatic forcing with which the model is forced: with future scenarios the, unknown, extent of glaciers is modelled with a fixed climate scenario at hand, whereas for paleovariations, extents are known but past climates may be less well constrained. We apply both a traditional 1-D and a new 2-D flow model to study how temporally variable summer temperatures and winter precipitation compare with known glacier variations in the past 500 years. The climatic variables forcing the models are obtained from proxy data as well as from synthetic data to yield a probability envelope for reasonable model outputs which fit observations. The two models perform well within the calibration period of simultaneously measured mass balance and glacier extent change. The 2-D model has the benefit of being insensitive to estimating where the flow line constituting the 1-D model needs to be placed in the glacier catchment. The results provide insights into what climate forcing has provided the observed glacier variations in northern Scandinavia over the past 500 years. By better improving the glacier model performance, using observed past climate variability, we can improve the capability of modelling future scenarios.

50A100

Uncertainty in the glacier mass balance measurement

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Mass balance measurements constitute a fundamental measure for estimates of effects of global warming on sea level change. A problem plaguing mass balance measurements is the absence of error estimates, which makes it impossible to assess the accuracy of the calculated effects from mass balance changes on a larger scale. Without defining the uncertainty in glacier mass balance measurements we have no understanding of the reliability of the results. All too often authors ignore the uncertainty in mass balance results. One of the important issues is that as glaciers approach equilibrium with the environment, the errors overwhelm the magnitude of the balance and even the sign of the balance can be unclear. Even worse, glaciers with small annual budgets, continental type glaciers, will always have net balances that are close to measurements errors, whereas maritime type glaciers due to their large mass fluxes yield more reliable results. We investigate the uncertainties by examining each of the components of the continuity equation, the foundation for any mass balance study: Surface height change, internal mass flow (flux) and the external mass flux (accumulation/ablation).