ABSTRACTS

(Rev. 4)
A distributed energy balance snowmelt model as a component of a flood forecasting system for the Inn river

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Snowmelt is an important contribution to Alpine runoff and to the generation of floods in Alpine rivers. Thus, a snow (and glacier) melt model has been developed as a component of an operational flood forecasting system which is under development for the Inn river in Tyrol. The model is based on a fully distributed energy balance approach, and internal processes are parameterized. Because radiation energy input is the most important factor for snowmelt in Alpine regions special attention is paid to the temporal variability of albedo during snow melt. In contrast to many snowmelt models, the decrease of albedo during melt is not modelled as a function of time with the well known aging curve approach of the US Army Corps of Engineers (1956) but as a function of the total energy input the snowpack has received since the last snowfall. This approach seems to meet the physical background of the process better than the aging curve: Alpine skiers know that on the same day snow conditions (e.g. density or albedo) can be totally different on north or south facing slopes, respectively. This difference can be traced back to the different energy consumed by the snow on the two slopes.

The point snowmelt model was calibrated and checked against data collected at the research plot of the Commission for Glaciology of the Bavarian Academy of Sciences and Humanities near the Vernagtferner (Ötztal, Tyrol). The model is then applied for fully distributed snowmelt simulations in the headwater reaches of the great southern tributaries of the Inn river. A distributed model needs to be calibrated and evaluated with distributed data. Distributed measurements of data suitable for verifying such a model type, e.g. continuous measurements of snow water equivalent or of snowpack outflow, usually do not exist. The only distributed information on melt is the existence or non existence of snowcover on the ground. This information can be derived from a series of photographs taken from a definite point in the catchment and rectifying them to a map scale. These depletion patterns can then be compared to the results of the depletion simulations performed by the model. This procedure could be performed making use of photos taken from the Schwarzkögele above the Vernagtferner. They were rectified, and the depletion patterns were identified manually, which was complicated due to the fact that snow and firn had to be distinguished. Corresponding to the observations the model was upgraded to simulate the water balance of the firm as well. At the present state, the model is driven with parameters calibrated and evaluated with photos of the Vernagtferner and applied to other headwater catchments in the Ötztal region where no photos but runoff measurements of the streams exist. These runoff observations can be seen as an overall performance check of the melt model. On the whole, the model shows reasonable results. For better simulations of the runoff dynamics, however, it was necessary to implement routing algorithms based on cascades of linear reservoirs that allow the routing of meltwater trough the snowpack and along the river reaches to the gauging stations.

Coupling the snow and glacier melt model with a soil moisture accounting hydrological model is on the way.
Provision of snow information from satellite data within PolarView and application example for the a mesoscale Alpine catchment using PROMET

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Information on snow cover, snow line and occurrence of snow melt is operationally provided using multisensoral satellite data in the frame of PolarView. PolarView is an international consortium with a mandate to make Earth Observation services more accessible to stakeholders interested in Polar Regions. PolarView is supported by the European Space Agency and the European Commission within the Global Monitoring of Environment and Security (GMES) programme that emphasises on operational services. Although PolarView has a focus on the Artic and Antarctic regions with services ranging from the monitoring of sea ice, icebergs, ice edge, and ice drift, also outside the Polar Regions snow and ice products are provided by the team. The snow services cover Northern and Central Europe with the Alps being one central area of interest. Within PolarView VISTA is in charge of Central Europe and provides snow cover maps for the Alpine Region and Southern Germany with spatial resolutions of 1 km. The temporal frequency of data provision is irregular, but during the winter season 2005/2006 more than 20 meaningful products could be provided.

Optical AVHRR sensors of the NOAA satellite are used for snow mapping and snow line delineation. Although these acquisitions are available several times per day, cloud cover hinders frequent updates of snow cover maps. As an additional remote sensing data source microwave data from ASAR on ENVISAT is used. The wide swath mode of ASAR is selected as input data source that provides a medium spatial (150 m) and also good temporal coverage. Since C-band SAR sensors are only sensitive to snow with a high content of liquid water, the application of ASAR is limited to the melting periods. However under these conditions the developed procedure allows not only to delineate the snow cover in a comparable way as from optical data, also the additional information where the snow is melting is provided. Data processing is performed fully automatically with direct data reception of the optical data at the University of Munich and near real time provision of ASAR data by ESA within a couple of hours after data take via FTP.

Users of this data service are two flood forecast centres in Germany, responsible for the runoff and flood forecast for the Neckar, Upper Rhine, and Mosel. Also the German Weather service (DWD) use these maps in order to optimise their snow water equivalent model results provided with SNOW-D. The user base can be extended to further interest users.

In order to demonstrate how the remote sensing products can be used for improved water balance modelling, an application example for the watershed of the Upper Danube will be presented. This test-site is the research area of the integrative research project GLOWA-DANUBE that is conducted by the University of Munich. Model results using the PROMET-model of snow distributions with and without data assimilation of the remote sensing products will be given. Different data assimilation concepts will be presented. Through data assimilation, the modelled snow cover agrees better with the mapped snow cover information from satellite. The optimised model provides maps of snow water equivalent, that can not directed by assessed by remote sensing. The water storage in the snow cover and its later release during snow melt is essential for runoff formation. The impact of data assimilation on the modelled runoff will thus further be analysed.
Modelling snow transport processes in a high alpine area (Berchtesgaden National Park, Germany) using SnowTran3D

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Wind-induced snow transport processes lead to a significant variability of the snow cover. Knowledge about this variability is important for e.g. determining the temporal dynamics of the snowmelt runoff, the spatial variability of the snow cover and for the prediction of the energy balance of the surface. The rates of transported snow are especially high in alpine terrain which is due to strong winds and the existence of massive snow packs. Unfortunately the generation of appropriate wind fields is very complicated in such areas. In consequence we used a modified version of the PSU/NCAR Mesoscale Model MM5 to derive wind fields for a 24 x 19 km area at a target resolution of 200 m. To ensure sufficient computational performance of the coupled models, it was not suitable to integrate MM5 as an operational routine. Therefore, we separated the wind field and the snow transport modelling by computing the wind fields in advance. The wind fields were then integrated as a library of look-up fields that could be called by the snow transport model. The extraction of a given wind field from this library during a snow transport simulation was based on spatially averaged 700hPa-level German Weather Service (DWD) Lokalmodell (LM) wind fields. These were compared with corresponding MM5 data, which allowed extraction of the appropriate MM5 wind field from the library for any given hour of a snow-transport simulation. For the snow transport simulation itself we used SnowTran3D. The results were validated at two test sites within the Berchtesgaden National Park via field campaign data. Both of the observed sites dispose over fully automatic meteorological stations which hold interpolation errors of meteorological variables low. In consequence we assume that we can investigate the effects of blowing snow events very well at these sites. The results will be presented in this paper.
Snow variability and change in Romania

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In this study, we investigated the observed variability and trends in snow depths at 93 Romanian stations, from which 18 are located in the Carpathian Mountains. The analyzed interval is 1961-2000. A statistically significant signal of reducing winter snow depths (December to February) was identified in the Western Carpathians and in the north-eastern part of the Romanian territory. Consistent upward trends in local temperature and downward trend in local precipitation are associated with this signal. A canonical correlation analysis statistically linking snow depth data and geopotential heights at the level 500 hPa over the Northern Hemisphere shows that the local snow signal and the related large scale changes in atmospheric circulation are partially due to the upward trend in the North Atlantic Oscillation. However, large scale atmospheric circulation seems to be less successful in explaining snow variability in other Romanian regions.
An investigation of the impacts of different snow process algorithms in terms of catchment streamflow simulation

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Conceptual hydrologic models are frequently used to simulate streamflow in alpine watersheds to understand a variety of different water resource and environmental issues. The complexity of the snow accumulation and melt processes varies considerably among the many different conceptual hydrologic models available throughout the USA and Europe. The degree to which the snow process dynamics must be represented within conceptual hydrologic modes in order to accurately simulate streamflow at the catchment scale is not clear in many cases due to differences in specific model input, application, process interactions, and output constraints. In this study, snow model components have been extracted from a set of hydrological models and separately coupled to a previously applied and calibrated hydrological model to simulate streamflow resulting from input data sets for snow driven catchments in the USA and Germany. The simulated streamflow from each of the coupled hydrologic models are compared among each other for the purpose of gaining an understanding of the similarities and differences related to each snow model component in terms of several important hydrograph characteristics (e.g., volume, peak, rising limb, falling limb, etc.).
Snow Cover Variability in Bulgarian Mountainous Regions, 1931-2000

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Principal component analysis (PCA) was carried out on annual snow cover series from 15 mountain climate stations in Bulgaria to characterize the spatial and temporal variability in snow cover over the 1931-2000 period. The PC analysis revealed three distinct snow cover response regions: (1) high elevation sites above 1500 m; (2) low elevation sites below 1000 m in the eastern Rodope and southern Pirin Mountains and (3) a mid-mountain zone covering stations in the 1000-1500 m elevation band. Over the 1931-2000 period snow cover exhibited evidence of decadal-scale variability but no evidence of long-term trends linked to climate warming. Over the more recent 1971-2000 period stations in the 1000-1500 elevation band have exhibited more coherent temporal variability in maximum snow accumulation and a trend toward a later start to the snow cover season.

Composite analysis of high and low snow accumulation winters revealed that high accumulation years tended to be associated with a negative North Atlantic Oscillation (NAO)-like atmospheric circulation pattern that favored increased winter precipitation over the Mediterranean and Balkans, and an anomalously easterly flow across the Black Sea into Bulgaria. In contrast, low snow accumulation years were associated with positive modes of the Scandinavian (SCA) pattern that generated fall warming and a delay to the start of the snow cover season. This pattern was responsible for an extended period of low snow conditions during the late-1950s and early 1960s.

The North Sea-Caspian pattern (NCP) was found to exert important controls on winter precipitation and air temperature over the Balkans, however, it had a limited influence on snow cover as the temperature and precipitation anomalies were offsetting. Correlation between major PCs and leading modes of atmospheric circulation did not generate any robust relationships, and only spring snow cover at the higher elevation sites was found to be significantly correlated with climate variability over the Balkan region. The results reflect the complex climate regime of Bulgaria, which is located at the crossroads of Mediterranean and Continental climate influences, and on the periphery of the main nodes of influence associated with NH circulation patterns that play important roles in Eurasian snow cover variability.
Evaluation of snowmelt from MODIS images

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The snowmelt is the main process affecting the river discharge for those mountain watershed characterized by high altitudes. In fact, during the snowmelt season, the discharge observed in a river is a direct consequence not only of the rainfall inside the basin, but above all of the snow melting. Simulate river discharge represents a basic step for a correct use of the available water and to forecast the maximum discharge and consequently to prevent risks. The purpose of this work is the simulation of the snowmelt in an Alpine watershed and the modelling discharge in a certain section of the river. For evaluating snowmelt at a regional scale, ground data collected by weather stations are not sufficient and must be integrated with remotely sensed data. Remote sensing, in fact, allows the monitoring of the whole Earth surface and provides spatial information that can be validated with the ground truth. Snowmelt Runoff Model (SRM), developed by Rango and Martinec (1985), has been selected for the analysis. This model estimates the snow melting by a simple degree-day approach, in which air temperature is considered the only variables affecting the process. Then, in order to spatialize the analysis, SRM requires estimation of snow covered area of the basin during the whole snowmelt season as input. For this specific goal, polar satellite images have been considered the most useful, since they provide daily information about a certain area. For evaluating the snow coverage MODIS (Moderate Resolution Imaging Spectroradiometer) sensor onboard EOS TERRA platforms has been selected. The choice of this sensor, among the available coarse/medium satellite, has been a direct consequence of the high radiometric resolution and the suitable spatial resolution (variable between 250 meters and 1 kilometer according to the different bands). In particular, the availability of two bands (visible: 0,620–0,670 μm and near infrared: 0,841-0,876 μm) at 250 m spatial resolution together with an unmixing classification technique (fuzzy) allows the retrieving of information about snow coverage with high detail. For evaluating the other model inputs (variables and parameters), ground data collected by snow gauges, flow gauges, rain gauges and thermometers have been processed. The analysis has been carried out in the upper-Adda sub basin, in the Italian Alps, characterized by high altitudes and consequently great snow coverage. The activity has been performed in the framework of AWARE project (a tool for monitoring and forecasting Available WAter REsource in mountain environment), in Sixth Framework Programme of the European Commission.
Comparison of modelled and measured ablation and runoff generation for different data set inputs

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Runoff from snow and ice melt is the main water resource in many mountain regions, yet an accurate estimation of runoff generation is hindered by a general lack of meteorological data in these environments. As an alternative, an approximate data set could be derived from general circulation models.

Here we present a comparative study modelling the ablation and runoff on a small, glaciated catchment in the Alps with data from direct measurement on the site, data from a network of meteorological stations in the vicinity and data derived from GCM. The GCM data comes from reanalysis and from high-resolution analysis. They have been input both directly and pre-processed after downscaling or bias correction. The application of this approach to other ungauged basins is addressed, as well as its limitations, shortcomings and possible improvements.
Meteorological measurements at Haut Glacier D’Arolla from 2001–2006 and mass balance estimation for this period using DEM’s

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Our goal is to assess the impact of future climate scenarios on water availability in glaciated basins. We are accomplishing this by implementing a combined field observation and distributed modelling approach. Accurate estimation of water stored within the snow and ice cover of these basins requires knowledge of the distributed snow and ice mass balance throughout the year.

Here, we are presenting the continuous meteorological record at the Haut Glacier d’Arolla since 2001. The measurements include meteorological data from weather stations outside and inside the glacier. Measurements from neighbouring Meteo Swiss network ANETZ stations can be used to supplement our data. These meteorological data is employed to assess the observed change on the glacier, which is derived from a continuous monitoring of runoff and mass balance. The mass balance is evaluated through ablation/accumulation stakes, snow depth measurements, modeling techniques and the comparison of two recent DEM’s.

The DEM’s of the Haut Glacier d’Arolla are derived by digital photogrammetry using high resolution areal photographs from September 1999 and 2005. Their grid size is 10 m and the absolute accuracy in both horizontal and vertical direction is 0.6 to 0.7 m.
Retrieval of snow covered areas at the sub-pixel size and surface snow grain size in alpine regions from Spot-Vegetation data

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Estimation of the Snow Covered Area (SCA) is an important issue for meteorological application and hydrological modelling of runoff. Snow Grain Size (SGS) has an important effect on the snow albedo and is, therefore, an important parameter for any study which needs energy balance at the surface. With spectral bands in the visible, near and middle infrared, the SPOT-4 and -5 VEGETATION optical sensor (VGT) can be used to detect snow cover because of large differences between reflectance from snow covered and snow free surfaces. At the same time, it allows separation between snow and clouds. Because the depth of penetration of near- and middle-infrared wavelengths in the snowpack is very small, only the surface grain size can be studied. As other optical sensors, the VGT instrument provides a daily coverage of large areas, but the SPOT-4 and –5 platforms present a simultaneous validation capability at the local scale with the high resolution instrument (HRVIR). The objective of this study is to use the high resolution mode HRVIR to validate the enhanced SCA and SGS products from VGT. With a pixel size of 1km x 1km, a VGT pixel may be partially covered by snow, particularly in Alpine areas, where snow may not be present in valleys lying at lower altitudes. Also, variation of reflectance due to differential sunlit effects as a function of slope and aspect, as well as bidirectional effects may be present in images. For our study, more than 20 relatively cloud free VEGETATION images were available from the 1999-2000 winter. For SCA mapping, the methodology consist to compare after atmospheric correction each VGT image with a full snow cover (Ris) and a snow free (Rif) references in order to determine the percentage of snow cover at the sub-pixel level (F index). The validation is provided by HRVIR data selected for key days over the same area. This method is presented for the French Alps (N 45°.20’ / E 6°.15”) with corrections for sunlit effects using 1000-m (VGT) and 20-m (HRVIR) DEMs. For SGS mapping, the grain size radii (μm) of each VGT image are derived from the Stamnes model and normalised reflectance ratios using the near- and middle infrared channels. The retrieved values of the grain size are compared with the data given by a physically-based numerical model from Météo-France (Crocus) dedicated to snow metamorphism (avalanches forecast). The SCA results are focused on the melting season (March to June). For groups of 2x2 and 5x5 pixels, the agreement between VGT and HRVIR goes respectively from 74% to 96% for a ± 10% difference between estimations and from 95% to 100% for a ± 25% difference. One the other hand, preliminary SGS classification results are in accordance with the Crocus data mainly for small and medium grains (> 400 μm) for different ranges of elevation. Those results can be considered as quite satisfactory, given the problems encountered in high mountainous areas.
Snow cover is an important parameter for the natural environment (hydrology, vegetation) in alpine regions. Earlier snow melt and an elongation and/or shift of the snow-free period - correlated to increasing summer temperatures observed since the 90’s – can impact on various facets of alpine ecology. The objective is here to expand an existing snow model, PREVAH from Zappa and Gurtz (WSL, Switzerland), in a GIS-oriented mode (ARC-Info GRID files) over an Austrian alpine site. This spatially-explicit model will generate various snow cover maps that will then be tested as predictor variables in predictive models of alpine species’ distribution. In the following, the focus is mainly given to the first step, i.e. on issues pertaining to the development of the snow cover model. A meteorological data set from the Austrian meteorological service (ZAMG) since 1981 and from the University of Natural and Applied Life Sciences, Vienna (collected since 1993/94) are used, providing daily means values (temperature, precipitation, humidity, wind speed). Complementary data during the snow-free season are also available: topographical wetness and erosion indices (Gallant & Wilson model), topographically modified solar-radiation income (Solarflux model) and water balance calculation (Turc formula). Then, a fine digital elevation model (DEM) is used to spatialise all these data. The study area is located in the North-eastern Calcareous Alps (NCA) of Austria (47°30' to 47°50 N and 15° to 16° E) comprising four different mountain ranges (Mt. Hochschwab, Mt. Rax, Mt. Schneealpe, Mt. Schneeberg) with an overall area of 150 km². The issue will be primarily to expand and adjust the Swiss model to predict mean annual snow cover duration and mean Julian day of snowmelt in a spatially explicit way. The results should serve as a basis for analysing and predicting the consequences of current and potentially changing future snow cover patterns on the dynamics of plant species confined to habitats characterised by long-lasting snow-cover (“snowbeds”). The PREVAH model is used to obtain a physically-based predictor for snow cover duration, information primarily relevant to mountain plant distribution. The different steps to expand this model on snowbeds-related plants dynamics will be (i) to modify the model in a way that takes different climate change scenarios into account: e.g. temperature increases, precipitation change, different distribution of solar radiation across the year and their impact on evapo-transpiration. The main parameter analysed will be the timing and duration of the snow-free period. This would allow for tracking spatial patterns of snowbed habitats, or analysing if emerging gaps or corridors would prohibit, respectively facilitate adaptive migration of plants. (ii) Secondly, to refine the model in the sense that it delivers the average date of snowmelt per year rather than the cumulative duration of snowmelt over the last 20 years and to see if these two variables are related or not. The methodology and the problems related to topography will be presented; e.g. the necessity to interpolate temperatures and precipitations from valley stations to higher elevation sites taking in account local facets. Also for each particular grid cell, how to provide interpolated local snow parameters (depth, duration), given the problems encountered in high mountainous areas.
Snow cover modelling for alpine plants dynamics (Austria)

Project OSS – ‘Observing Snow Avalanches at Svalbard’: Establishing long term monitoring of snow avalanches in a High Arctic wilderness at Central Spitsbergen, Svalbard

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At Svalbard in the High Arctic Norway, Central Spitsbergen has a high intensity of winter sport activities and a fast growing infrastructure – yet human settlements have existed for only 100 years and no long term avalanche observations exist. In autumn 2005 the project ‘OSS’ was launched: A system of long term monitoring of snow avalanches at Svalbard was initiated by the local university UNIS and the local Red Cross rescue centre. The aim is to create the basis of applied avalanche research and a user defined avalanche service at Svalbard. So far avalanches have been registered through one season and a website has been launched. Temporary results will be outlined. Topographic, climatic, cultural and infrastructural conditions are very different from temperate and more densely populated mountain terrain, and the challenges we are facing on that basis will be described. The current project is partly based on a smaller avalanche survey at Central Spitsbergen which was carried out in 2002 and is described in Ellehauge, Humlum and Christiansen (in writing): Avalanches were recorded regularly in April, May and June in a field area in and around Longyearbyen on central Spitsbergen. Avalanche observations were compared with meteorological data, ground surface temperatures, automatic daily photos and historical data. The investigation indicates that topography and wind are the most important controlling factors on avalanche activity. Loose snow and cornice fall avalanches become more frequent towards spring. Slab avalanches are rare and depend more on the possible development of weak layers in the snow. Weak layers may occur, but are less likely to develop here than under temperate conditions, since the presence of permafrost does not facilitate depth hoar creation and persistent strong winds prevent undisturbed surface hoar and loose snow from being buried.
Modelling subalpine forest snow processes

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Snow and forests have strong influences on the microclimate, hydrology, ecology, stability and aesthetics of slopes below the treeline in subalpine regions. Snow falling on a forest canopy is partitioned into interception by the canopy and throughfall to the ground. Intercepted snow may sublimate, unload or melt within the canopy. Snow on the ground is sheltered from wind and solar radiation by the canopy but subjected to increased thermal radiation and may melt at a significantly different time from snow in adjacent meadows. The accumulation and ablation of snow in forests are thus determined by many complex and interacting processes. Models with a wide range of complexities have been developed to represent forest snow processes for meteorological and hydrological applications, and we are undertaking an intercomparison project to evaluate the performance of these models. An overview of the project will be given, and preliminary results will be presented for a subalpine site included in the intercomparison (Alptal, Switzerland). Evaluation data include measured radiative fluxes beneath the forest canopy and snow water equivalent at forest and meadow sites.
Two important episodes of heavy snowfalls and avalanche activity over the Catalan Pyrenees are analyzed using synoptic circulation data, high elevation meteorological observations, and the corresponding avalanche data collected. Discussion about the mechanisms related with heavy precipitations over our mountain area and their relation with avalanche release is made. The first episode, occurred on 30 January of 2003, shows a northerly advection bringing humidity from the Atlantic Ocean joined with very cold air from high latitudes. Strong winds were observed and precipitations much over the average were accumulated; the location of the jet-stream over the Pyrenees looks as the main reason for the important amount of snow in few hours. Major avalanches were produced on the northern side of the Catalan Pyrenees and closer areas, isolating the Val d’Aran, the most populated area of the range The second example occurred on 28 January 2006 and is related with a Mediterranean low pressure pumping humid air from the Mediterranean. Important amounts of precipitation and, specially, fast changes on the snow level are the most relevant elements of this situation. In this case, major avalanches were produced in general over all the treated area, including exceptional avalanches exceeding the maximums run out zones collected in the official database. In this case, was the first time with maximum hazard level over all the areas of the Catalan Pyrenees since the beginning of the avalanche warnings (1989).
Operational snow depth mapping in the Swiss Alps using synergy of satellite and in situ observation

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The Swiss Federal Institute for Snow and Avalanche Research in Davos (SLF) provides snow depth maps on a spatial resolution of 1x1 km for Switzerland. These snow depth maps are derived from snow station measurements using a spatial interpolation method based on the dependency of snow depth and altitude. During a winter season the number of operating snow stations varies and the area-wide snow depth interpolation becomes increasingly difficult in spring.

The objective of this paper is to develop an operational and near-real time method to calculate snow depth maps using a combination of in situ snow depth measurements and the snow cover extent provided from space borne observations. The operational daily sub-pixel snow cover product obtained from the polar-orbiting NOAA AVHRR satellite is used to gain an additional set of virtual snow stations to densify the in situ measurements for an improved spatial interpolation. This method is demonstrated on several days during winter 2005. Cross-validation tests are conducted to examine the quantitative accuracy of the synergetic interpolation method. The error estimators (mean absolute error, RMSE) show a clear improvement in accuracy comparing the conventional method using in situ observations only with the new synergetic interpolation approach. The distinct error estimators demonstrate the potential of the virtual snow station technique mainly at the snow-no snow borderline where melt processes during spring are intense over large areas.

In the future, an alpine-wide snow depth map would be of great interest. In situ observations from station networks supported by other countries within the European Alps could be considered to generate such an alpine-wide snow depth map based on homogeneous data sets, the NOAA AVHRR snow product and the interpolation method, we presented here. An adaptation and comparison to other mountain regions in the world might be of relevance.
The goal of this presentation is to identify the nivometeorological conditions releasing major avalanches in the Catalan Pyrenees. One of the main points on the study is dating and reconstructing of major avalanches occurred before the avalanche warning system was started on 1989. In this way, dendrochronology information on major avalanches activity is added to the usual sources of information in avalanche research such as historical documents, population inquiry and intensive, local avalanche observations. After identifying and dating major avalanches, weather and snowpack conditions releasing these events have been reconstructed and analysed. The results show a great variety of different nivometeorological patterns comparing to areas with similar extension over the Alps. The singular geographical factors of the Catalan Pyrenees as proximity to Mediterranean Sea and Atlantic Ocean, zonal disposition of the axial range, and relatively low latitude of the massif, determine the complexity of the Catalan Pyrenees climate. On the other hand, comparisons with previously established circulation patterns for heavy snowfalls at synoptic scale over the study area highlight the robustness of the results. Due to not all major avalanches are linked to heavy snowfalls, these major avalanche events have been also related with low frequency patterns as NAOi (North Atlantic Oscillation index) and WeMoi (Western Mediterranean Oscillation index), showing consistent results. Looking to the results obtained, we can conclude that both the identification of several weather and snow conditions patterns releasing major avalanches and the relationship with low frequency atmospheric circulation patterns will clearly contribute to improve short and mid term forecasting of major avalanche events over the Catalan Pyrenees.
Mathematical modelling snow-cover and frozen soil metamorphic structural evolution under various meteorological conditions

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We propose the current mathematical model using meteorological data to simulate the snow-cover and soil characteristics for the purpose of clarifying the structural and physical-mechanical properties changes in the stratified snow-cover under changing weather conditions. The mathematical description of the internal snow structure evolution and the layer's texture is needed for the study of the quantification of the texture related parameters. Snow structure, texture and thermo-mechanical properties are a key of avalanche forecasting. This mathematical formalisation gives possibility to differ between depth-hoar, faceted crystals, skeletal, dendritic and overriming crystals, rounded (fine and coarse) crystals and to calculate its changes due to metamorphism (fresh deposited and old snow). The snow layers have different structural parameters: average grain radius, shape grain surface, bonds with radius and diameter, grain number; different temperature, density, water vapour pressure and mechanical properties. Mathematical nonlinear model include the heat balance equation, diffusion equation (water vapour migration), densification, structural and strength relations in snow cover and layer of soil. It was used common equation for water vapour migration in snow cover and for water vapour migration in soil. Some numerical experiments were done using the complete model (inside snow cover) and real data. Monitoring of the snow properties using the present mathematical model can be an important part of the avalanche warning service which requires the snow-cover mathematical modelling based on the detailed structural approach.
On the parameterization of the snow detection algorithm from multi-temporal synthetic aperture radar – A case study

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The Scandinavian Snow Monitoring Service applies a snow cover area processing line for ASAR and MODIS imagery. The SAR part of the system is based on the Nagler & Rott (NR) algorithm (2000) using wide-swath ASAR data. Wet snow is mapped by detecting a backscatter decrease in comparison with a dry-snow or snow-free reference images. The retrieval and validation of reference SAR scenes have been a continuous ongoing activity in the development of the SAR based snow-monitoring service. Many problems arise when wide swath imagery are being used as reference scene since the whole 500 km swath seldom is entirely covered by dry snow or bare soil. After four years in orbit, however, Envisat provides several images for each individual satellite track in order to construct averaged mosaic of reference images. Hydropower companies are interested in the total snow cover fraction inside a drainage basin. To derive the total snow cover from the wet snow detections, we use interpolated surface temperature maps and consider any region above a certain wet snow altitude as dry snow if the temperature is below 0°C. The lower altitude limit of dry snow is set to the average wet snow altitude minus its standard deviation. In this paper we study the sensitivity of the snow cover against different parameterization of the snow detection algorithm. We study a limited area around the hydropower catchment Altevatn. We consider especially the influence of the threshold of the backscatter decrease varying between 0 dB and -3 dB on the snow cover as well as using a sigmoid function to retrieve snow fractions. The window size for the calculation on the average wet snow altitude is also a crucial parameter. One specific difficulty in northern Norway is that the temperature gradient from the Atlantic Coast towards the inland can be very strong in winter varying between +5°C and -30°C. Year-long time series of the wet, dry and total snow cover around Altevatn will be presented for the different parameterizations and compared to optical observations from the MODerate resolution Imaging Spectroradiometer (MODIS).
The effects of snow relocation in the altitudinal and polar treeline ecotone

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In the treeline ecotone, fragmentary tree-stands, interspersed with open patches of subalpine and alpine vegetation strongly influence the relocation of blowing snow. The extent and manner of this relocation is determined by size, coverage, structure and morphological characteristics of the fragmentary stands. Once relocated, the snow deposits may override the effects of regional thermal conditions in the treeline ecotone. Changing distribution pattern, geometry and density of the tree-stands also modify the influence of snow relocation compared to warmer environments make it difficult to establish any predictions with regard to the relationships between spatial and temporal structures and micro-climate in the treeline ecotone. In the early stage of treeline advance in Alpine or tundra environments, open tree-stands are likely to cause higher snowpack than in previously treeless areas. However, the local and microscale effects may even prevent an advance on a closed front of the subalpine or northern forests to greater altitude or more northern positions.
Comparison of index based snowmelt models for different temporal and spatial scales

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In the frame of an ongoing research project the authors developed and tested different types of index based snowmelt models. Temperature index, radiation index and mixed type models were compared and validated at two basins. The first basin is the Obersulzbachtal with an area of approx. 80 km² and mean elevation of 2300 m.a.s.l. The second one is the Upper Salzach basin with 580 km² and a mean elevation of 1800 m.a.s.l.. The modelling period included 5 years (2001 – 2005). The spatial resolution of the snowmelt model was by means of 100-Meter elevation bands. The snowmelt performance was tested against discharge observations with hourly time resolution. The runoff formation is considered by a lumped conceptual rainfall runoff model. Quick runoff components are described by a saturation runoff excess concept and by soil water release (interflow). Delayed runoff (base flow) is transformed by a linear storage approach.

The main questions addressed in the presentation are
(1) Can the snow melt parameter from an intensively monitored remote basin be transformed to the two basins of interest?
(2) Do the snowmelt model performances of the different approaches rely on the temporal scale (hourly, daily, weekly time scale)?
(3) How sensitive are the model results due to the spacing interval of the elevation bands?
(4) How important is the assumption of seasonal varying indices and the use of albedo models in terms of models performance?

In addition some remarks on deficits and shortcomings of the available programs are given. They address the lack of cold content assumptions in the initial phase of snow melting as well as the limitation of the saturation runoff excess approach for the description of runoff peaks.

The transformation of model parameters (1) worked reasonably for the smaller basins, as it is quite comparable in terms of elevation and glacierized areas to the experimental basin. For the description of subdiurnal time scale the integration of radiation indices is required to perform the diurnal variation of the discharge (2). For the spacing of the elevation zones the standard 100 meter discretisation was approved to be reliable. Exceeding approx 250 meters the results showed a significant time shift of the temporal snowmelt pattern (3). The conclusions (4) are under preparation and will be presented during the conference presentation.
Measuring air temperatures over snow: the relevance of probe ventilation for the performance of snow hydrological models

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The Swiss Federal Institute for Snow and Avalanche Research (SLF) runs a monitoring network for automatic measurements of meteorological parameters to provide the avalanche forecast service with appropriate input data. These data could potentially be used as input for snow hydrological catchment models as well. However, the stations were not equipped with ventilated air temperature probes due to considerations concerning power supply and availability of service. Recent tests with air temperature probes and different ventilation strategies revealed that in certain situations the unventilated probes overestimate true air temperatures by up to 10 K. Especially problematic are daytime situations with intense solar radiation, low winds, and snow featuring a high albedo. In the Alps, these situations may be typical mid to later winter during the melt-out. As this time is especially important for snow hydrological models, it seemed important to understand whether the output of a snow hydrological model would be sensitive to the characteristic differences of ventilated / unventilated air temperature measurements. We modelled snowcover and runoff for one winter in the Dischma valley of Davos. Using the ALPINE 3D model, two runs were stipulated: One run was based upon a data set originally measured using unventilated air temperature probes. The other run was based on data artificially altered according to the measured offsets of unventilated probes depending on wind speed and solar radiation. We discuss the differences of the output by the two runs as well as the match to measured runoff data.
Comparative analysis of different snow process algorithms and concepts found in various conceptual hydrological models

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Hydrological process dynamics are often a key component in environmental model applications. There are a large number of conceptual hydrological models available to simulate the entire range of natural processes to reproduce the hydrological dynamics. In higher elevation catchments, snow processes are often a significant source of the variability of runoff dynamics during winter and spring. Most hydrological models consider the influence of snow accumulation and snow melt in their concept, however the implementation of the snow process dynamics vary considerably among the different approaches in terms of complexity. The degree of complexity ranges from models with simple black-box approaches which consider the temporal snow dynamics only in terms of accumulation and melt (models primarily driven by temperature and precipitation) to models with very complex process description which consider the various state variables of the snow pack (e.g. liquid and dry snow water equivalent, depth and density of the snow pack, cold-content, albedo) as well as the thermo-dynamic and mechanical processes like phase changes, energy input from various sources as well as snow compaction and metamorphosis by mass changes, melt and rain. The aim of this study is to identify and evaluate the capabilities of the different snow process algorithms found in a set of hydrological models popular in the US and Germany. Within the study, the snow model algorithms were extracted and applied isolated from the original model environment with driving data sets from the US and Germany to compare their capability for simulating snow dynamics for a period of ten years. In addition, an assessment of uncertainty introduced by the input data, the process description, as well as of the sensitivity of the algorithm’s calibration parameters on the response will be presented. Finally, a comparison of the simulated state variables in terms of their conceptual meaning and representation of the natural system will be shown.
Physically based model of snow accumulation and melt in a forest

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A physically based model of snow accumulation and melt accounting influence of forest canopy on snow processes has been developed. The model describes temporal change of snow depth and density including processes of metamorphism as well as influence of forest vegetation on energy and mass balance at the upper boundary of snow cover. The radiation components are calculated by the Kuzmin formulas. The turbulent fluxes of sensible and latent heat are determined on the basis of the bulk formulas approach. To estimate the snow interception and evaporation of intercepted snow, empirical formulas taking into account leaf area index, height of trees and albedo of the canopy were used. The model was tested using the long series of data obtained for two small watersheds at Valdai experimental station (the central Russia region). Comparisons of calculated and observed snow water equivalents were shown that the developed model gives the satisfactory results without calibration both for the open and forested areas. The model was used for estimating the role of snow interception and evaporation of intercepted snow in variations of differences of snow characteristics in the open and forested watersheds.
Distributed model of snowmelt runoff generation for a mountainous river basin

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The distributed physically based model of snowmelt runoff generation for a mountainous river basin has been developed. The model is based on a finite-element schematization of the river and includes the description of formation of snow and ice cover, snow and ice melt, evaporation and infiltration, overland and subsurface flow, water movement in the river network. The input data (the air temperature, precipitation, air humidity, wind speed and cloudiness) are calculated using available observations, interpolation and extrapolation procedures taking into account elevation, vegetation and exposition. The case-study was carried out for the upper part of the Kuban River basin (the North Caucasus region). The catchment covers an area of 16,900 km2 with altitudes from 300 to 4500 m. To construct and to test the model, the data of observations for 10 years (1971-1980) were used. The model was used for comparison of the heat balance and degree-day methods for calculating the snow and ice melt and for investigation of the relative contributions of different runoff components.
Alpine3D, a model of alpine surface processes and its application to the radiation balance over snow in a forest gap

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The snow cover in complex alpine terrain has a high spatial variability caused by blowing and drifting snow and local differences in the surface energy balance. The variability has a large influence on the formation of avalanches, on local plant and animal life and on mountain hydrology. We present Alpine3D, a model that treats the surface processes with enough detail to describe the variations of snow cover depth and snow microstructure. The model is driven by flow and meteo fields from measurement stations or from an atmospheric model and calculates then blowing and drifting snow in saltation and suspension, the terrain influence on the radiation fluxes and the snow cover development. For snow transport calculations, a time-dependent and three-dimensional flow field is determined from the mesoscale atmospheric model ARPS. Using a physical saltation model and a streamline upwind Petrov-Galerkin method to solve the 3D advection diffusion equation, local erosion and deposition of snow mass can be predicted. As an example, the snow transport calculation for a snow storm over a steep alpine ridge is presented. In complex alpine terrain, radiation (short- and longwave) is influenced by smallscale topographic effects such as shading, multiple scattering and emission of long wave radiation from the surroundings. A large number of field measurements would be needed in order to cover the large spatial and temporal variability of these fluxes. Due to this fact a modelling approach to obtain information about the energy fluxes in complex terrain is very reasonable. We present modelled radiation fluxes and compare them with selected measurements at various locations. The study site is located in the Eastern Swiss Alps close to the village of Davos. The forest gap, which was chosen for investigation, is part of a skislope in the Parsenn skiing area at an elevation of approximately 1900 m. The time periods studied are 47 days in the winter of 2004/05. Meteorological verification data was obtained by a mobile station equipped with devices to measure radiation (shortwave and longwave), humidity and temperature. Input data was taken from a station at the study site located close to the Weissfluhjoch at an elevation of 2540 m. Measurements showed that within small distances large differences in snow surface temperatures could be measured, caused by shadowing, varying emission of longwave radiation and (multiple)-reflected radiation from the surrounding terrain. Within a typical measurement setup we observed that the reflected shortwave radiation from the snow-surface exceeded over several time periods the incoming shortwave radiation over several time periods. This can be explained by an additional radiation input that is received at a certain point on the snow-surface from surrounding terrain. In the model these effects are accounted for by the implementation of a so-called view factor concept that “scans” the surroundings regarding its distance from the observer and its surface properties. Measured characteristics could be reasonably well explained with the modelling approach and give a clear idea of the importance of different small-scale effects for various applications.
How can we link large-scale atmospheric and climate features with small-scale alpine snow processes?

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Understanding Earth-system climate variability and change requires solving the challenge of representing relatively fine-scale terrestrial processes (less than 100-m) within coarse-scale (2-km to 300-km grid increment) atmospheric models. An additional problem involves defining how changes in large-scale climate processes affect local terrestrial processes. Because many hydrologic and ecologic processes occur at spatial scales that are 2- to 3-orders-of-magnitude smaller than global climate models, methods are needed to translate global atmospheric features to the local scales pertinent to terrestrial processes. This need is particularly relevant in snow-covered alpine regions where key snow-related processes occur at very fine spatial scales.

One way to accomplish this linkage is through a nested-grid modelling system (Figure 1) that unites a collection of models and datasets, each operating at spatial and temporal scales relevant to the governing processes simulated by the model. This presentation discusses these linkages and the associated models, with a specific emphasis on the higher-resolution models such as MicroMet and SnowModel (which includes the latest version of SnowTran-3D) that have direct application to the high-resolution processes that dominate snow-covered alpine environments.

Figure 1. Schematic illustrating a nested-grid modelling system capable of accounting for the interactions among larger-scale weather and climate features, and the relatively smaller-scale snow-related alpine features (the grids are not drawn to scale). Also shown are images of progressively smaller-scale components of the snow-land-atmosphere system.
Nordic large-scale medium resolution multisensor snow cover area monitoring

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A service for near real time snow monitoring has been established for the Nordic peninsula. An area covering Norway, Sweden and parts of Finland will be monitored daily at 250 m spatial resolution using the Terra MODIS and the Envisat ASAR sensors, to provide optimal snow cover classification in a challenging climatic region where clouds are frequent. The service aims at serving hydrologic users as well as hydropower companies, and will be operated in near-real time in the melting period 1.april-31.july.

The multisensor and multi temporal snow cover maps are based on single sensor snow maps from SAR and optical sensors. Each data acquisition over the area are classified into snow maps and projected on a common grid. A confidence raster is also produced where the accuracy of the classification of each pixel in the snow map is represented as a confidence value between 0 and 100\% depending on incidence angle, probability of clouds, air temperature (if available) and on the type of snow (wet/dry). Each single sensor product is fused to the latest multisensor product with its associated confidence image to produce an updated snow map.
Long-term Variability and Trends of Snow Cover in the Swiss Alps

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Monitoring of snow is an essential task for countries like Switzerland, where snow is an important natural resource. Data of 140 snow observation stations between 200 and 3000 m a.s.l. throughout the Swiss Alps were investigated towards natural variability and possible trends. The results demonstrate that the snow cover is varying substantially on interannual to decadal time scales. The mean snow depth, the duration of continuous snow cover and number of snowfall days all show very similar trends during the last 70 years: A gradual increase until the early 1980s (with insignificant interruptions during the late 1950s and early 1970s) followed by a decrease towards the end of the century. High altitude stations show no or only slight changes, whereas the decreasing trends become statistically significant at stations below 1300 m a.s.l.. Results suggest that the recent decrease in low altitude snow cover can mainly be attributed to an increase in temperature.
Comparison between several sets of modelled and analysed precipitation fields over French Alps. Impact of different spatial resolution

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Since the nineties, Météo-France has developed a software named SAFRAN in order to produce relevant parameters for a snow cover evolution model, named CROCUS. SAFRAN could be described like an objective downscaling operator from meteorological model information (data and model outputs) to massif scale. These massifs are considered as homogeneous in terms of daily precipitations. Every massif represent an area in average about four hundred square kilometres and a vertical extension between two or three thousands meters. The elevation range is divided by step of three hundred meters in French Alps and Pyrenees. Another vertical step can be chosen. The current vertical step has been defined to avoid under-determination in the analysis scheme.

The analysis version of SAFRAN merges meteorological model outputs and observations (ground, radio-sounding, …) while the forecast version of SAFRAN runs like a downscaling operator, and uses statistical methods in order to calculate unbiased daily precipitations and also to reduce the main standard deviation errors.

In this paper, we present some comparisons over French Alps divided into twenty three massifs. This work focuses on daily precipitations, and mainly two meteorological output sets are used:
- The first one provided by ARPEGE.
- The second one by ALADIN.

For ALADIN, two spatial definitions are extracted from archives, a coarse one similar as ARPEGE extraction with a latitude, longitude grid mesh around seven kilometres and a fine one twice more precise in the two directions.

The daily data set of ARPEGE and ALADIN (“coarse extraction”) is composed of about two thousand days and starts the 27th December 2000.

The daily data set with ALADIN (“fine extraction”) starts the 18th march 2004 and so we have about eight hundred days for comparisons in terms of spatial input definition.

Firstly, using some basic statistical criteria, both temporal and spatial forecast errors are discussed. The errors are in this section defined as differences between forecast and analysis. Then, the spatial structure of errors is focused. Some possible statistical improvements are presented in order to have more accurate forecast especially when the precipitation are heavy.

In a second part, the analysed version is compared to ALADIN forecast or ARPEGE forecast. Some relevant criteria and methods are discussed in this part.

Finally, some concluding remarks and some improvements about rules and statistics used by massif are proposed.
Snowmelt runoff forecasting using satellite data

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Applications of satellite images from optical and SAR sensors for forecasting the daily runoff in alpine basins are presented. In mountainous terrain topographically induced variability of meteorological parameters and of the snow pack is complex and makes spatially distributed estimates an essential requirement for alpine runoff modelling and forecasting. Therefore, the Hydrological Modelling Platform (HMP) was developed by ENVEO to take into account the temporal and spatial assimilation of various data types required as input for semi-distributed hydrological runoff models. A modified version of the Snowmelt Runoff Model (SRM) from Martinec and Rango is applied, using meteorological station data, numerical weather forecast data and spatially detailed snow information as input. The snow information is retrieved from satellite data of optical sensors and Synthetic Aperture Radars. The raster snow maps are spatially aggregated to the scale of hydrological response units used by the hydrological model. On days without satellite data a physical snow model is applied to interpolate between the snow observations of two satellite acquisitions or, if running in forecasting mode, to predict the snow extent using numerical meteorological forecasts of temperature and precipitation. A statistical approach is used to correct for sensor specific differences in the obtained snow information. This is particularly relevant for matching optical and SAR snow maps. We report on the results of real time forecasts of daily runoff of up to 7 days in advance for the Ötztal and Zillertal region in the melting periods 2005 and 2006. The Ötztal and Zillertal basins are located in the Western Austrian Alps and cover an elevation range from about 800 m to 3700 m. The Moin watersheds were divided into several sub-basins according to the availability of real-time runoff gauges. Runoff forecasting was carried out for each sub-basin separately, water routing of the upstream basins takes into account the time lags determined by runoff simulations of previous years. Near real-time snow cover information was derived from MODIS Data and ENVISAT ASAR Wide Swath data, received within 24 hours after image acquisition. A data link was established to receive meteorological measurements from stations and products from the ECMWF numerical weather models. ECMWF deterministic forecast were used, as well as the ECMWF Ensemble Prediction System (EPS), which consists of 51 of meteorological forecasts for each time step enabling to take into account the uncertainty of meteorological forecasts for runoff prediction. The Ensemble Runoff forecasts were statistically evaluated providing the median, the 25% and 75% quartiles and the minimum and maximum values out of the 51 single runoff forecasting runs. Examples of the runoff forecasts and evaluations of the quality are presented.
Mapping Temperature-Sensitive Snowpacks and the Frequency of Warm Winters in the Coterminous United States

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One of the most visible and widely felt impacts of climate warming is the change (mostly loss) of low elevation snow cover in the mid-latitudes. Snow cover that accumulates at temperatures close to the ice-water phase transition is at greater risk to climate warming than cold climate snowpacks because it affects both precipitation phase and ablation rates. This study maps areas in the coterminous United States that are potentially at-risk of converting from a snow-dominated to a rain-dominated winter precipitation regime, under a climate warming scenario. We use a data-driven, climatological approach of snow cover classification to reveal these “at-risk” snow zones and also to examine the relative frequency of warm winters for the region. Using 4-km resolution temperature and precipitation data, Nolin and Daly (2006) have shown that the Pacific Northwest snowpacks are particularly vulnerable to climate warming with approximately 9200 km² of the normally snow-covered area converting to a rain-dominated regime by mid-century. Furthermore, the frequency of warm winters is projected to increase although the changes are non-uniformly distributed with largest projected impacts at lower elevations in the mountain regions. This extended work maps those portions of the California Sierra Nevada that have “at-risk” snowpacks as well as some smaller regions in the eastern United States. A number of lower elevation ski areas could experience negative impacts because of the shift from winter snows to winter rains. The results of this study point to the potential for using existing data sets to better understand the potential impacts of climate warming.
Although important properties of snow such as the elastic modulus, optical reflectivity and thermal conductivity depend on the microstructure, a sound method for parameterizing these properties in terms of microstructure does not exist. We can produce complete three-dimensional reconstructions of snow samples with x-ray computer tomography or serial sectioning. However, these techniques render geometrical information and not a parameterization of the physical properties. Density, specific surface area (SSA), and curvature, either alone or in combination, have been found useful parameters to correlate to physical properties. However, it turns out that snow density alone often is not sufficient to directly correlate to physical properties such as thermal conductivity. SSA is a key parameter for snow chemistry and is also used to characterize snow metamorphism; the methods to determine SSA include processing of CT images, stereology on vertical sections, gas adsorption, and, indirectly, nearinfrared photography. We use data from experiments and simulations from a three-dimensional model to investigate if an unambiguous correlation exists between density, specific surface area and other physical properties. We are especially interested in how the bonds between ice partials, which are highly relevant for thermal and mechanical properties, are represented by these parameters.
Controls on Radiative and Turbulent Transfer to Snow: New Theoretical Considerations and Comparison to Observations

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Snowmelt is largely driven by inputs of energy from radiation and turbulent transfer from the atmosphere. Radiation transfer estimation is still subject to uncertainty because of difficulties in calculating the radiative surface temperature of the snowpack. It is shown that the surface (‘skin’) temperature of the snowpack is largely insensitive to internal energetics and to shortwave radiation. A new model, the longwave-psychrometric model, presumes thermodynamic equilibrium at the surface, insignificant heat transfer from the surface to the snowpack and insignificant shortwave absorption at the surface. It calculates the radiative temperature of snow, solely as a function of longwave irradiance, wind speed, air temperature and relative humidity. The model is further bounded by consideration of the surface energy that can potentially be supplied by atmospheric heat. The potential use of this model in both calculating outgoing longwave radiation from the snowpack and in partitioning the available energy between sublimation and that available for internal energy change and/or snowmelt is presented and evaluated. Melt and internal energy are derived from the sum of the surface energy that is excess to sublimation requirements and the energy provided by shortwave penetration into the snowpack, precipitation and ground heat flux. This technique is applied to sites in the mountains of Alberta and Yukon, Canada, prairie in Saskatchewan, Canada and high elevation glacier snow in Bolivia and is compared to calculations from observations using surface lysimeters, longwave radiometers and eddy covariance systems.
Nine years of snow- and ice-melt of the Adamello Glacier: observations and modelling

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The Adamello Glacier with its 18 km2 size is the largest in the Southern Alps, and its retreat since the end of the Little Ice Age was monitored starting with the surveys of Julius Payer in 1864 and published in 1865. To assess the yearly mass balance of this area an energy-balance modelling has been attempted, supported by snowpack, meteorological, runoff and satellite measurements. The seasonal snowpack model is a distributed two-layer model which was previously tested at the point scale with in situ snow measurements of snow depth, density, grain size and liquid water content and, during two experiments conducted in a test-site in the Dolomites, microwave radiometry. The model was adapted to simulate also ice-melt using a different formulation of albedo, turbulent fluxes and conductive heat in the energy balance at the surface. The accuracy of the model in simulating the retreat of the snow covered areas during the melt season at the large scale is verified using the snow cover monitored by two 15 m resolution ASTER images at the beginning and during the 2003 melt season. One of these two satellite images was also used to estimate distributed values of snow and ice albedo. Point measurements of snow reflectivity at the 3020 altitude of the Passo della Lobbia meteorological station and at several points were also used to verify the simulated albedo on a continuous time basis. The simulated hourly values of runoff produced at the scale of a 78.4 km2 basin, mainly due to snow- and ice-melt, were compared with stream gauge data over a nine year period. The resulting value of the yearly mass balance results in an average net loss of 2100 mm a⁻¹.
Snow cover area (SCA) estimation and analysis in the alpine range using moderate resolution satellites

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In the recent years, a generalized global warming and a continue glacier retreat on the Earth surfaces increase community attention on water availability problems. The environmental importance of medium and high latitudes snow cover is well established. As well as its role in albedo feedback it is an indicator of the global climate, though a complex one since a warming climate can have both positive effect through increased precipitation and a negative effect through increased melting. Snow melt dynamics generate a complex set of interactions, which dictates a need for long-term monitoring of snow cover in conjunction with other climatological variables. Excluding the great ice sheets of Antarctica and Greenland, snow cover is primarily a phenomenon of the northern hemisphere and the mountainous ranges. So, snow coverage analysis all over the mountainous ranges and the cold regions is a key aspect in this climate research challenge that involves all the world populations and countries. Estimate with a global coverage the processes of snow melting will be more and more fundamental for the management of water resource of the globe. There is considerable interest in monitoring their long-term variations and linking these to climate change. Suitable data can be derived from satellite observations. Moderate satellite sensors help in the survey of the variations of snow coverages because they provide synoptic information over large territories, have low costs and adequate spectral resolution, even if the low spatial resolution it is still a problem. Previous works have been focused on the monitoring of American northern regions and the procedures involved have been tuned to large areas. In particular NASA mission on Moderate Resolution Imaging Spectroradiometer (MODIS) have been tailored to monitor spatial phenomena all over large areas. The activity here presented has been performed in the framework of AWARE project (a tool for monitoring and forecasting Available WAter REsource in mountain environment), in the Sixth program of the EC. This is a Research Project that aims at providing innovative tools for monitoring and predicting water availability and distribution in snowmelt regime Alpine catchments. Different hydrological models will be applied to basins situated all over the Alps to estimate the amount of water availability from snow variations in the melting season (April – July). Among the available sensor, MODIS has been chosen as the most suitable for producing the required parameters, according to factors identified in the analysis of requirements, such as temporal coverage and resolution, spectral and spatial resolution. Alpine basins considered have a dimension that not allows the application of NASA MODIS mission elaboration methodology. A new approach tailored on Alpine basins has been settled. Due to the high number of images to be processed (for the high temporal resolution required by the hydrological models) some procedures have been set up and implemented to automatically identify, download, geocode and calibrate images as well as to extract snow parameters. As the main information used by all project models is the snow covered area (SCA), different images classification procedures for producing snow cover maps have been compared in order to identify the most suitable for the purpose taking into account the need for repeatability and automation. The comparison resulted in a modification of the Normalised Difference Snow Index (NDSI) in order to customize it on the Alpine characteristics. While basins requiring a more detailed spatial resolution and fractional cover information (Switzerland and Austrian ones), a set of classified images has also be planned by using the fuzzy statistical classifier useful (Wang).
ESCIMO – a physically based model for the simulation of accumulation and ablation of snow

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The one-layer snow model ESCIMO (Energy Balance Snow Cover Integrated MOdel) is designed as a physically based model for the hourly simulation of the energy balance, the water equivalent and the melt rate of a snow cover. For the simulation of the energy balance the short- and longwave radiation, the sensible and latent heat fluxes, the energy conducted by solid or liquid precipitation as well as condensation/sublimation and a constant soil heat flux are taken into account. The snow albedo is modelled using a function considering the age and the surface temperature of the snow pack. For each time step the following scheme is followed: first, it is distinguished between melting conditions (air temperature ≥ 273.16 K) and no melt (air temperature < 273.16 K). In the first case, the computations include: (a) calculation of the energy balance, (b) decision whether eventual precipitation is solid or liquid (if not measured), (c) calculation of the water mass and energy budget based on the hypothesis of no snowmelt at the current time step, (d) comparison of the total available energy with that sustained as snow by the total available mass of the snow pack at 273.16 K, (e) calculation of the snowmelt produced by the available excess energy and (f) update of the mass and energy budgets. In the other case (air temperature < 273.16 K), an iterative procedure for adopting the snow surface temperature and for closing the energy balance (with re-calculation of the energy balance in each loop) is applied. Recently, the model was extended with algorithms for the simulation of the forest snow processes interception, sublimation and melt/fall down from the trees of a canopy. In our paper we present the validation of the model on the point scale, and its distributed application in various alpine regions.
CoreH2O - A dual-frequency SAR mission for snow and ice research

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Scientific and technical details for the satellite mission COld REgions Hydrology Highresolution Observatory (Core-H2O) were worked out by an international team of 35 scientist in cooperation with EADS Astrium GmbH. The mission was submitted to the 2005 Call for Ideas for Earth Explorer Core Missions and recently selected by ESA for further studies. The mission focus is on spatially detailed observations of snow, ice, and other parameters of the water cycle that are required for understanding and modelling hydrological and glaciological processes on land surfaces and oceans, including surface/atmosphere interactions. Snow and ice play a major role in the water and energy cycles of high latitudes and in many mountain areas. CoreH2O aims at filling major gaps in observations of snow and ice masses in order to improve the characterization of cyrospheric processes and feedbacks. The mission will provide detailed information on important snow and ice parameters that are needed to initialize, run and validate hydrological, weather, and climate models for research and operational applications. Key parameters to be measured include extent, water equivalent and melting of the seasonal snow cover, glacier facies and snow accumulation, properties of sea ice with emphasis on ice formation and snow burden, and extent and physical properties of permafrost. Theory and experimental data show that backscatter at X- and Ku-band frequencies is very sensitive to physical properties of snow and ice. The proposed sensor is a dual frequency SAR, operating at 17 GHz and 9.6 GHz, co- and cross-polarizations. Ku-band is sensitive also to shallow snow, whereas X-band provides greater penetration for deeper snow. Co- and cross-polarized channels are useful for separating surface and volume scattering contributions, so that the combination of the four channels can significantly improve the accuracy of snow retrievals. The technical realization of the mission applies a cost–efficient concept with innovative reflector antenna technology operating in ScanSAR mode. The satellite operation concept plans for two sequential mission phases: 3-day repeat observations during the first two years focussing at well equipped test sites and some other key regions for advancing snow and ice process models and for validating the satellite products, followed by full coverage of the global cryosphere in 15-day repeat cycle.
Influence of seasonal snowpacks on near-surface ice temperature profiles in a temperate Alpine glacier

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Seasonal variations in thickness and density of supraglacial snowpacks buffer energy exchanges between the glacial surface and the boundary layer atmosphere over annual cycles. Atmospheric energy exchange affects the temperature of near-surface ice and, consequently, the ice mass balance, rheology and flow velocities. However, the influence of supraglacial snowpacks, and especially the seasonally variable ability to buffer thermal energy transfer to and from surface ice, is poorly documented. In this study we compare in situ snowpack and meteorological observations with high resolution vertical temperature profiles from the surface to the bed of a temperate valley glacier (Glacier de Tsanfleuron, Canton Valais, Switzerland). Vertical temperature profiles of near-surface ice (top 10 m) show the penetration of a cold wave from around the onset of snow accumulation, which continues throughout the winter. As the snowpack begins to ablate, ice temperatures warm progressively from the surface, downwards into the ice. Snowpack-atmosphere energy exchanges and internal snowpack processes are modelled and compared with snowpit measurements to discuss the thermal buffering capacity of supraglacial snowpacks and their potential influences on ice mass balance and near-surface ice velocities.
The Dilemma of Resolution and Seasonality of Snow Cover in Alpine Environments

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In alpine environments spatio-temporal patterns of snow accumulation and snowmelt are mainly influenced by topography. Despite interannual variation of weather conditions, seasonal snow patterns remain relatively stable over the years. Such long-term patterns substantially control vegetation and permafrost distribution, as well as hydrology. For quantitative analyses of snow cover distribution, data with high spatial and temporal resolution are required. Conventional approaches of seasonal snow cover monitoring are based on remote sensing techniques. Satellite images with coarse spatial and high temporal resolution (MODIS with a spatial resolution of 463 m and a repetition rate of 1 d) cannot detect fine-scaled objects. Vice versa, satellite images with high spatial resolution have a low repetition rate, which can be reduced by clouds (LANDSAT TM with spatial resolution of 30 m and a repetition rate of 16 d). Thus snow melt patterns are not detectable. In our investigation we used two digital cameras (MetSupport©) that monitored daily variation of snow distribution on northwest and southeast-facing slopes in the valley Lötschental (Switzerland). Using a spatial resolution of 10 m and a temporal resolution of 5 days, classified and georeferenced terrestrial images enabled statistical analyses of the impact of topography on snow coverage depletion. An automatic image processing technique calculated orientation parameters for each image and assured high position accuracy. A comparison of different models with variable cell size showed the importance of approaches with high spatial and temporal resolution for analysing interactions of snow, permafrost, and vegetation. The approach presented here, the use of terrestrial images, will help solve the dilemma of resolution and seasonality of snow cover in alpine environments.
CFD Simulation of Snow Drift in Alpine Environments for Operational Avalanche Warning

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Due to increasing development of Alpine environments by transport and tourism the forecasting of avalanche danger becomes more and more important. The protection of civil facilities and human lives is one major aim of avalanche forecasting. The snow depth at mountainsides and the dead load of snow slabs are important factors which contribute to avalanche danger. In addition to fresh fallen snow, snow drift contributes a lot to the amount of snow at mountainsides. Mainly leeward the snow depth is determined by the strength of drifting snow. Cornices and snowbanks are primarily formed by snow drift. If the boundary shear stress acting on the snow cover, which is induced by the wind, exceeds a certain threshold, snow will be entrained. On the contrary, if the flow does not exert enough shear stress, snow is deposited. Hence, erosion and deposition zones are built, whereby the geometry of the snow pack changes. These deformations of the shape of the snow pack couple to the wind field and thus the flow is changed by the new geometry. This coupling creates time dependent erosion and deposition zones. The amount of snow grains, which can be transported by the flow, contributes additionally to snow drift occurrences. An increasing wind speed raises the amount of drifting snow. If a fence slows down, the flow snow will be deposited by a decreasing amount of drifting snow. The numerical simulation of complex snow drift processes has to challenge with time dependent geometries of the snow cover and particle transport phenomena. Furthermore, snow erosion and accumulation are determined by boundary shear stress criteria leading to a deformation of the snow cover. In this work a numerical snow drift model based on a mixture model approach will be presented.
Changing Impact of Weather Types on the Snowcover of the German Low Mountain Ranges

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The poster will present a study which investigates the impact of general weather situations (according to the definition from Hess and Brezowsky) on the snow cover of the German low mountain ranges. Special focus has been put to the identification of how much the influence of general weather situations on the snow cover has changed during the past decades.

The study is based on datasets covering air temperature, precipitation and height of snow cover of several meteorological stations as well as the “Großwetterlagen Europas” dataset; both provided by the DWD (German meteorological survey).

A selection of general weather situations commonly occurring during wintertime was tested on their influence on the snow cover of low mountain ranges.

The poster shows for example that the impact on the snow cover of the most common general weather situation ‘WZ’ (cyclonic west) has significantly changed during the last two decades. By comparing the mean air temperatures occurring together with the ‘WZ’ during the 1980s and the 1990s a significant warming can be observed. The influence on the snow cover of the ‘WZ’ changed from about neutral until the 1970s to snow melting during the 1980s and even more pronounced during the 1990s, a development which was probably mainly triggered by the changing air temperatures.
Two Different Approaches on Snow (cover / parameter) Monitoring in the Black Forest Region

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This poster will present two different methodical approaches from two different research projects at the Department of Physical Geography which address snow cover related topics in the Black Forest region.

As a top down approach remote sensing data are analysed in order to optimise two dimensional data extraction; as bottom up approach local data is correlated with atmospherically circulation patterns.

The first project tends obtaining terrestrial longwave emission and visible reflectance and their interactions with landcover changes over snow covered terrain from satellite data of different spatial and temporal resolutions. Therefore special emphasis is put on the following topics:

To what extend is it possible to obtain, interpret and model complex radiant fluxes, especially thermal, from satellite data resolving different spatial and temporal scales at day and night time? How do landcover types affect the terrestrial longwave emission over snow covered and non snow covered terrain? Which role do relief and snow pack properties play for analysis and modelling from satellite data? Can the above-mentioned interactions be parameterised? Can climatic processes on local scales (e.g. inversion) be associated with the identified interactions between the different factors?

The second project detects hemispheric circulation patterns which have influence on local winter climate beyond the North Atlantic Oscillation pattern.

The basis is formed by multi layer NCEP-NCAR reanalysis data provided by the NOAA Climate Diagnosis Center as well as local atmospheric and snow cover data provided by the German weather survey (DWD) covering the past 35 years on a daily basis. After detrending, seasonal compensation and aggregation of both datasets, the local data has been correlated with the gridded NCEP-data with a time shift of up to 36 month. Results are currently being examined and evaluated.

Recent findings are presented.
Snow Water Equivalence Retrieval Using X and Ku band Dual-Polarization Radar

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The study of snow has become an important area of research in the natural sciences, particularly in hydrology and climatology. Snow water equivalence is the most important parameter. Active microwave sensors are highly sensitive to the most snowpack parameters interested by hydrologists. However, the studies have found, in general, that the sensitivities of radar measurements to dry snow water equivalence are very weak at C-band. The higher-frequency radar is needed to provide the reliable measurements for quantitative retrieval of snow water equivalence.

In this study, we evaluated the feasibility of using the dual frequency (X-band 9.6 GHz and Ku-band 17GHz) and dual polarization (VV and VH) radar to estimate snow water equivalence. The components in this study include:

1. Using model to establish a database for algorithm development: The simulation model is a second-order radiative transfer model where 1) the surface scattering components s are simulated by AIEM model for the co-polarized signals and the semi-empirical model of VH/VV for the cross-polarization signals, 2) the volume scattering component are calculated by the dense medium model with ellipsoid grain shape in order to simulate the cross-polarization signals, and 3) the bi-static IEM model is used for the boundary condition so that the interaction components between snow volume scattering and the surface scatterings can be correctly simulated.

2. Decomposition technique: we found that the depolarization factor VH/VV is proportional to the volume scattering and surface-volume scattering contributions and inversely relates the surface scattering contribution. Using this phenomenon, we developed a technique the estimate the snow volume and the ground surface scattering components.

3. Estimation of SWE using the volume scattering components: We found that the ratio of the volume scattering components from two frequencies can be written as a function of snow optical thickness at corresponding frequencies. In this way, the effects of snow volume scattering albedo can be minimized so that the optical thickness of snow pack at each frequency can be estimated. Then, the albedo and SWE can be estimated.

4. Estimation of the snowpack optical thickness using the ground surface scattering components, it is found that the surface scattering components of VV polarization at two Ku-band can be also used to estimate the snowpack optical thickness. This is due to the surface backscattering at snow-ground interface is almost identical since the surface is rough at 9.6 and 17 GHz. The difference in the surface scattering components (after passing snowpack) results from the difference in optical thickness of snowpack at these two frequencies. However, the other snow extinction properties are still required for estimation of SWE.

It is found that the both the volume and surface scattering components are required for SWE estimation in order to cover a wide range snow properties.
Distributed modelling of snow processes in the Berchtesgaden National Park
(Germany)

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In the Berchtesgaden National Park an automatic network of meteorological stations belonging to the Bavarian avalanche warning service and other institutions has been assembled. From these stations, continuous records of 10 minute to half-hourly measurements are collected via wireless GSM transmission and stored in a central database, starting in August 1998. The spatial arrangement of the stations, their range in altitude between 617 and 2445 m a.s.l. and the temporal duration of the measurements generated a unique data set enabling a continuous, distributed and physically based modelling of a wide range of environmental processes. This paper describes the application of a spatially distributed snow processes model which includes (a) spatial interpolation of the meteorological variables considering topography, (b) a sophisticated scheme to compute short- and longwave radiative fluxes and shadows, (c) derivation of cloudiness from records of global radiation, (d) parameterization of snow albedo based on its age and temperature and (e) simulation of the snow surface energy balance by iteratively adopting its temperature. Finally, snow interception, sublimation and melt unload in forest canopies are simulated with a physically based scheme considering effective leaf area index and tree height for the prevailing mixed forest, larche, spruce and mountain pine stands in National Park area. The simulation results for the ground snow cover are compared to point measurements. This modelling system represents the basis for including further distributed eco-physical models, e.g. for the simulation of hydrological, climatological or biological processes.
Repeated Snow Distribution Patterns—Are We Ignoring a Useful Aspect of Snow?

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Topography and vegetation can be thought of as “fixed” controls on snow distribution because they change on time scales that are long compared to the seasonal cycle of snow. These landscape controls interact with wind and snowfall to produce drift features and snow distribution patterns that are often visually quite similar from one year to the next. Geography (the distribution of mountain ranges, valleys, and water bodies) is a similarly slow-changing control that interacts with storm patterns to produce orographic and aspect-controlled patterns of snow distribution. These larger-scale patterns also tend to repeat from year-to-year, but with more apparent variability than topography/vegetation driven patterns. Using data from both arctic and alpine environments, I examine the temporal repeatability of snow patterns at scales ranging from local (ϑ ≈ 100 m) to landscape (ϑ ≈ 1000 m) to geographic (ϑ ≈ 10000 m). Visually similar patterns at landscape scale in some cases prove to contain more variability than expected, while some geographic scale patterns exhibit surprisingly greater similarity than anticipated. These annual snow distribution patterns are potentially useful attributes of snow that could be used for snow mapping, but rarely are. Ways to use the patterns are suggested.
Climate change and the competition among ski areas for day tourists

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We analyze the competition dynamics of ski resorts for day tourists when exposed to climate change. To this aim, we develop a new model for day tourism and apply it to the hydrological catchment of the Upper Danube with 237 ski areas. Climate change is expected to play a major role in the adaptation process of ski resorts. According to earlier studies the altitude of snowreliability will increase from 1200 masl to 1800 masl. Technical adaptation can be used, but has its limitations, too. We model the decision making of ski tourists by a discrete choice model similar to the multinomial logit model. In our model the preference of ski tourists to visit one of the ski areas depends on the attractiveness of the ski area, which is a function of the capacity and the maximum altitude of the ski resort, and the travel times between the residence of day tourists and the ski areas. The use of realistic travel times is important for the discrete choice model. To show this we compared the results from the model for two different setups. Whereas the first setup uses Euclidean distances to determine the travel times, the second setup is based on travel times determined by the traffic model DaTraM and relies on the road network of the Upper Danube catchment. The standard deviation of the difference between the two setups amounts to about 10% in the number of day tourists for all ski areas, with maximum values up to 40%. Moreover, we observe a systematic trend. For ski resorts located at high altitudes the number of day tourists is systematically overestimated with Euclidean distances. This can be explained by the reduced density of the road network in mountain regions and the necessity to adapt the road network to the topography. As the consequence of climate change, the level of snow reliability will move to higher altitudes. A global temperature increase by 1 °C is estimated to shift the level of snow-reliability about 150 m upwards. We systematically studied the competition dynamics of the ski areas in our model by gradually moving the line of snow-reliability to higher altitudes. As a consequence, ski resorts located at lower altitudes will drop out of the competition due to snow deficiency. The movement of the level of snow-reliability to 1500 masl causes 32% of the ski resorts to close, for a shift to 1800 masl and 2100 masl the values are 54.4% and 71.7%, respectively. Whereas in the long run only the ski resorts located high enough are expected to survive, ski resorts at medium altitudes may also profit in the nearer future due to a redistribution of the day tourists.
Climatic and environmental information about snow, firn and firn ice in high mountains of South-Eastern Europe

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High mountains of South-Eastern Europe are located in the transition zone from temperate to mediterranean climate. They are of great importance to the water balance in their neighbouring, semi-humid landscapes, for delivering and storing water. In terms of reconstructing and monitoring current and historical climatic and environmental changes there is a wide spectrum of archives: e.g. artefacts of soil genesis, sediment and peat layers from silting areas of glacial lakes, ecotones of the timberline or geomorphological forms (moraines). But glaciological archives react more sensitively to the current climatic changes. As a consequence they indicate changes much earlier then realised in general. Because of the low altidude the most of south eastern mountains are not recently glaciated areas. Only the residuals of former glaciers and snow patches could be conserved and grown in climaticly appropriate locations. Whether there are adequate objects to observe and reconstruct climatic and environmental changes are unknown since they have been rarely investigated. So far only information about the Pirin Mountains of Bulgaria, the Tatra Mountains of Slovakia and the Triglav National Park of Slovenia are available. This research includes:

• the logging of climatic time series,
• assessment of the combination of the geoeological factors, which are essential for the presence of perennial snow patches and glacierets, which could describe their morphological activity,
• the monitoring of the surface and volume changes since the beginning and middle of the 20th century by surveying and photogrammetry and
• vertical firn archive sampling of chemical and physical parameters (trace elements, density, conductivity and other; the analysis of stable isotopes/ isotope ratio is projected 2005 and 2006).

The results show that snow patches and glacierets have a sensitive reaction to climatic and environmental impacts. Since the beginning and middle of the 20th century a significant decrease of surfaces and volume can be observed from a maximum in 1850. The decrease is connected directly to the global warming (and indicates the increase of aridness in this region?). This trend is modified by the local situation/ characteristic of the mountain cirques (e.g. shadow by cirque walls, the low albedo of limestone, the rapid and subsequent drainage of melting water in karst regions and the high snow avalanche supply). Snow, firn and firn ice have high potential for conserving atmospherically transferred trace elements and stable isotopes which are recorded exemplary but have not been sufficiently investigated. In terms of the derivation of climatic and environmental information, from the snow and firn of recently unglaciated mountains, there are a lot of methodical problems for measurement, sample analysis and statistical analysis, which have to be further investigated. Previous research shows that any kind of measurement approach has to deal with large error margins (photogrammetric methods, analysis of chemical and physical parameters). In case of a lack of melted yearly firn layers, the chronological dating of the glacial-morphological recordings could be complicated. Furthermore the environmental and climatical information of firn ice could be falsified by leaching rainwater, which causes an interference of summerly and winterly signals from year to year.
The temperature of a melting surface of snow or ice should never exceed 0°C even if the layer of air above is much warmer. Hence the thermal layering mostly is characterized by a stable state. Normally under such condition exchange of heat and moisture are severely limited because of depauperate turbulence. During a clear day between 80 to 90 percent of the energy available for melt is delivered by the radiation budget. Nearly the complete residual of the surface energy balance is distributed on the turbulent fluxes of sensible and latent heat. Over a period of time with overcast and windy weather the relevance of the turbulent fluxes may rise from 10 to 30 percent and more. Thus the accurate calculation of the turbulent heat fluxes is very important for melt water production modelling. To parameterize turbulent transport processes within the stable stratified surface layer using the MO-Theory is inaccurate in contrast to unstable conditions. Catabatic flows be generated at inclined slopes may raising the efficiency of mixing by forcing mechanical turbulence. Under such conditions e.g. the prerequisite of the fluxes invariance with height is definitely violated and therefore the common known scheme in inapplicable. The analysis of data from Eddy-Correlation-measurements over an inclined surface shows an insight to the structure of turbulence within the surface layer. The results show that the integral to the cospectra and thus the cinematic fluxes can be well calculated using the so called “flux-variance relationship”. Therefore an approach like a bulk formula can be proved as the best fit as a parameterization. The amazing analogy of the turbulent structure of the enthalpy distribution in contrast to that of moisture suggests, that the latent heat flux can be calculated using a similar algorithm. This contribution shows a workable bulk parameterization scheme to calculate the turbulent fluxes in the case of a stable stratified surface layer.