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International Conference on

Snow Hydrology

The Integration of Physical, Chemical, and Biological Systems

Janet Hardy, Mary Albert, and Philip Marsh, Editors

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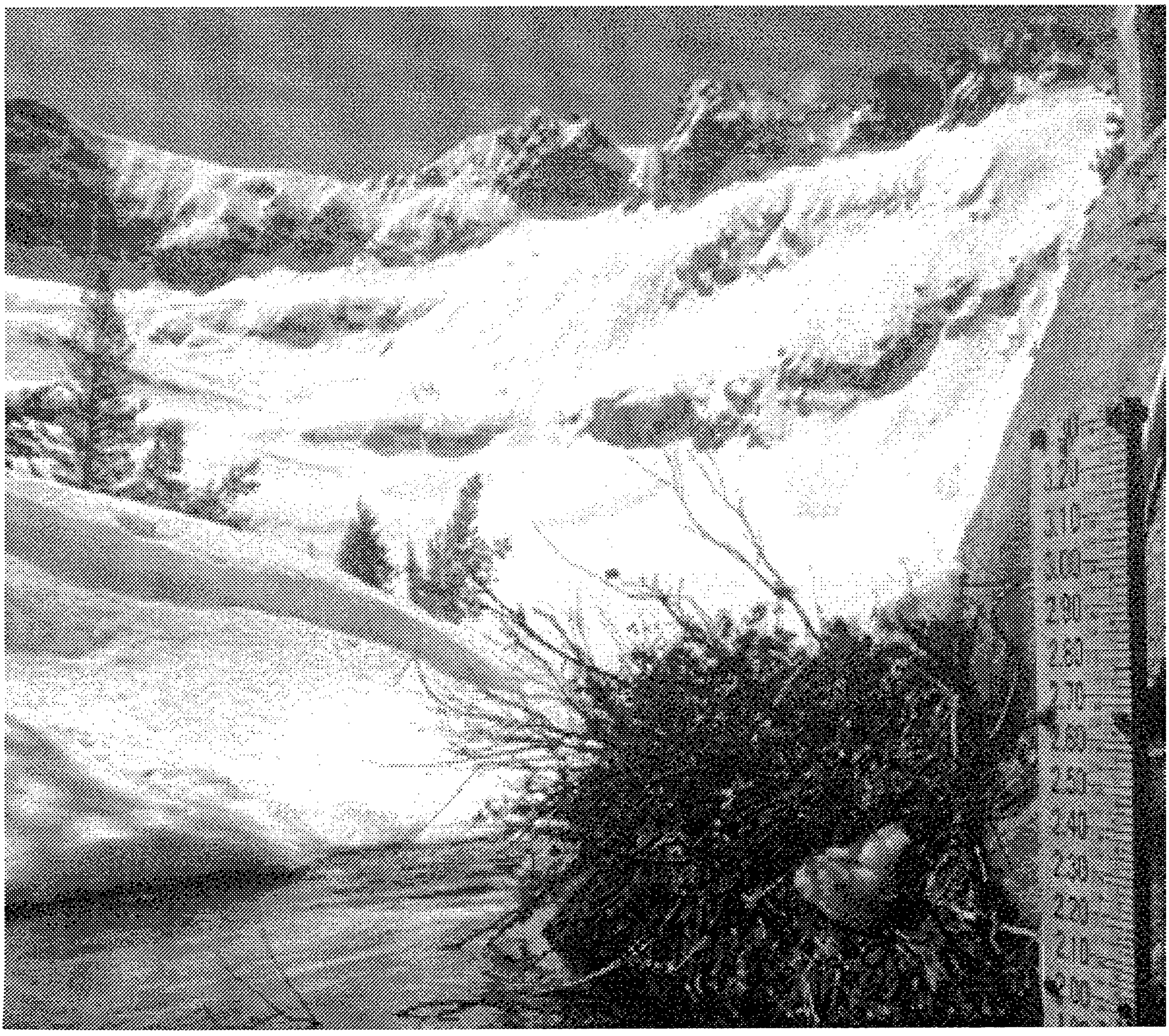

Cover: Emerald Lake Basin, Sierra Nevada, California, USA. (Photo credit Richard Kattelmann.)

Abstracts from the

International Conference on

Snow Hydrology
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Janet Hardy, Mary Albert, and Philip Marsh, Editors

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PREFACE

This report comprises the abstracts of all papers presented at a special four-day conference on snow hydrology held at Ascutney Mountain Resort in Brownsville, Vermont, USA, 6–9 October 1998. The purpose of this conference was to provide a forum for sharing new knowledge on snow-cover properties and processes, chemical processes in the seasonal snow cover, biotic interactions with the seasonal snow cover, distributed snowmelt models, and scaling problems in snow hydrology. To encourage exchange between disciplines, we sought papers that addressed the relation between processes—physical, chemical, and biological—and the integration and distribution of these processes over different spatial and temporal scales. This conference brought together approximately 20 nations, with 44 papers presented orally and more than 60 poster presentations.

This report contains one-page abstracts of all papers presented at the conference. Approximately 75 full manuscripts were submitted for peer review and publication in the international journal *Hydrological Processes*. Additionally, papers most pertinent to the conference objective will appear in the book series *Advances in Hydrological Processes*, titled *Snow Hydrology: The Integration of Physical, Chemical, and Biological Systems*, edited by Janet Hardy, Mary Albert, and Philip Marsh.

The co-sponsors of this conference are:

U.S. Army Cold Regions Research and Engineering Laboratory (CRREL)
Montana State University
International Glaciological Society
Eastern Snow Conference
IAHS–International Commission on Snow and Ice
U.S. Army Research Office
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The assistance provided by the U.S. Army Cold Regions Research and Engineering Laboratory and the U.S. Army Research Office is gratefully acknowledged. Thanks are also extended to the many individuals who contributed to the success of the conference, including Tom Vaughan, Marilyn Aber, Chad Adams, Jane Mason, Bruce Ashley, David Cate, Jack Rouillard, Gioia Cattabriga, and Donna Valliere of CRREL; Doug Hardy of the University of Massachusetts; Russell Harmon of the U.S. Army Research Office; and Malcolm Anderson of the University of Bristol.

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Scaling Problems in Snow Hydrology

Snow-Cover Properties and Processes

Philip Marsh[1]

During the last 20 years, considerable progress has been made in our understanding of the properties of seasonal snow covers and the physical processes controlling changes to these properties. An improved understanding of these provides the basis required for a better understanding and ability to predict the complex role snow plays in northern environments. These include, for example, streamflow, climate, fluxes of nutrients through the snowpack, and subnivean ecology. An improved predictive ability also provides the ability to better alleviate a variety of environmental issues, including the rapid release of pollutants from snow-covered landscapes, as well as a variety of climate-change-related issues.

This paper will outline recent progress made in understanding the following properties and processes, and attempt to provide a synthesis of the current state of our understanding and critical areas for future research. Issues to be considered include regional variations in snow-cover properties, and processes controlling grain size, layering, ice layers, surface energy fluxes, blowing snow, forest canopy interception, energy fluxes within the snow cover, meltwater flux through the snow cover, runoff, and frozen soil infiltration, for example.

One of the major features of recent research into these snow properties and processes is the ongoing recognition of the importance of the heterogeneous nature of the snow cover at all scales, and attempts to properly consider this spatial variability. Although earlier work recognized the great spatial variability of snow cover, limited theoretical understanding and/or computational power resulted in most studies considering the snow cover as being spatially homogeneous. With increasing theoretical understanding and computational power, researchers have increasingly attempted to incorporate spatial variability. This has included, for example, the role of patchy snow cover in controlling surface energy fluxes, flow fingering during vertical water percolation, the fractal nature of snow patches, and the layered nature of snowpacks. A major focus of this paper will be on reviewing our progress to date on such factors.

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Unsaturated Water Flow in Snow: Experiment and Simulation

Martin Schneebeli[1]

Unsaturated water flow in snow is an important factor for wet snow avalanche formation and transport of nutrients stored in the snowpack. The formation of the often strongly preferential flow patterns is not completely clear. Different mechanisms seem to be responsible for the initiation of preferential flow patterns: (i) freezing of the infiltrating water due to subzero temperatures of the snow, (ii) impermeable or partially impermeable ice layers, and (iii) capillary barriers, i.e., a layer with smaller grains above a layer with coarser grains. The snowpack in the Alps shows rarely the strong subzero temperatures typical for subarctic and arctic snowpacks; however, water flow seems to be preferential in most cases, even in an isothermal snowpack. The flow pattern was investigated using dye tracers. Special attention was given to a minimal depression of the freezing point of the tracers, because this can cause substantially different flow patterns. Two main experiments have been run: (i) a rainfall in a slightly subfreezing snowpack, and (ii) a designed experiment with artificial infiltration and subsequent application of three different dye tracers. The flow pattern was detected by excavating long profiles. The snowpack was characterized using surface sections and conventional snow profiles, as well as water content measurements. The simulation of unsaturated water flow was done with the two-dimensional finite element code SWMS_2D (U.S. Salinity Laboratory) improved to take account of the changing hydraulic characteristics during infiltration. Spatial heterogeneity of the hydraulic properties was simulated assuming Miller similarity. The experiments showed that capillary barriers seem to be very important for the initial formation of preferential flow paths in a climate typical for the Alps while ice layer interfaces seem to be less important. However, it could be observed that capillary barriers often form at the location of melt–freeze crusts. Melt–freeze crusts are often very coarse grained. It is supposed that melt–freeze crusts have often been interpreted as impermeable ice layers instead of as a capillary barrier. The preferential flow paths visualized by the different tracers have not been stable over one day, but took different routes. It is not clear if this is caused by the not completely steady-state infiltration rate or by changing hydraulic properties due to wet snow metamorphism. The preliminary results of the simulations showed a similar development of flow patterns as observed in the field. The simulation of water flow in snow based on standard snow profiles will remain a very difficult task. Much more experimental data is needed to improve the relations between saturated and unsaturated hydraulic conductivity and the sorption desorption curves. There is also a severe lack in understanding and experimental data of wet snow metamorphism in partially saturated conditions. However, the experiments undertaken show that the first occurrence of two hydraulically differing layers is extremely important to the onset of preferential flow. This is of great importance to avalanche forecasting, because at the first interface nearly saturated conditions appear in a continuous thin layer, conducive to mechanical failure.

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Correlation Lengths of Vertical Flowpaths in Melting Snowpacks, Colorado Front Range, USA

Mark W. Williams[1], Richard Sommerfeld[2], Sam Massman[1], and Mark Rikkers[1]

The melting of snow is known to be an inhomogeneous process. The spatial distribution of meltwater flowing from the bottom of melting snowpacks is the result of horizontal and vertical flowpaths within the snowpack. The ability to characterize the spatial distribution of these meltwater flowpaths would be useful in developing snowmelt runoff models that could better characterize snowmelt hydrographs. Near-infrared aerial photos of melting snow have been analyzed using a moving window analysis that can characterize correlation lengths in the reflectance of the snow surface. Near-infrared is sensitive to snow grain size, which indicates the concentration of meltwater; the grains grow faster if the liquid water content is higher. The probability of finding such correlation lengths was about 0.22 in May 1997, when the melt had just started, and rose to 0.68 by June when the melt was well established. Correlation lengths for all sampling dates ranged from 5 to 7 m. Liquid water content at the snow surface was sampled with a dielectric sensor at 0.5-m intervals on two 100-m^2 grids. Semi-variograms showed a sill at 5 to 6 meters. The liquid water measurements at the snow surface suggest that the correlation lengths derived from the infrared aerial photos represent surface expressions of vertical flowpaths through the melting snowpack. A circular array of 16 snowmelt lysimeters, each with areas of 0.2 m^2, was operated for two years at Niwot Ridge in the Colorado Front Range. Variograms indicated that flows were correlated over a distance of 5 to 7 m. These three independent methods all suggest a correlation length of 5–7 m for vertical flowpaths draining ripe snowpacks in the Rocky Mountains.

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Impact of Ice Layers on Storage Characteristics of a Snowpack

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For various countries of the world, streamflow generated from the melting of seasonal snow cover is an important source of water for irrigation, hydropower, water supply, and various other applications. Accurate information on both timing of seasonal rise in snowmelt runoff and volume of snowmelt runoff is important for the management of water resources. There are several factors affecting the initial time of runoff generated as a result of melting of snowpack. The timing of initial rise in streamflow depends on a variety of processes that control the release of meltwater to streams. Energy balance on snow surface, snow depth, cold content of snowpack and underlying soil surface, internal accumulation of meltwater, topography of underlying surface, and clogging of channels are the important factors influencing the release of meltwater from snowpack. This combination of processes can prevent the small quantities of initial snowmelt runoff from flowing downstream, thereby adding a delay to the lags caused by the snowpack. For example, in the Alaska range of North America, internal accumulation alone can delay release of water for two to four weeks at an average melt rate of 10 mm/day. Obviously, a knowledge of the impact of physical characteristics of snowpack on the onset of snowmelt runoff is needed to model snowmelt runoff.

In the present study, the impact of the existence of ice layers in the snowpack on the release of meltwater has been investigated. Artificial rain was simulated over a snow block of known dimensions (2.30 m ¥ 1.30 m ¥ 1.08 m) prepared in the Glatzbach basin in the Austrian Alps, very near to the Grossglockner, the highest peak in Austria. The experiment was made in the month of May at an altitude of 2640 m just before onset of snowmelt runoff from the snowpack at that altitude. Stratigraphic studies were made before and after the experiment. The snowpack contained five ice layers ranging from about 2 to 8 mm in thickness and was in an isothermal state before the experiment. The average liquid water content of the snow plot was observed to be about 4% by volume. It was found that an amount equivalent to 103 mm was absorbed by the snow block before appearance of runoff from the block. Results indicate that storage capacity of a snowpack is enhanced to more than double because of the presence of ice layers in the snowpack. Keeping in view the energy patterns of that region, it is estimated that ice layers may delay the generation of runoff for several days.

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On Dielectric Properties of Dry and Wet Snow

Anatoly D. Frolov[1] and Yury Ya. Macheret[2]

Density and moisture content in snow cover are the important parameters for snow hydrology as they determine practically all physical and mechanical properties of this medium. One of the most sensitive properties relative to these parameters is a complex dielectric permittivity of snow, which is indispensable for interpretation of high-frequency electromagnetic remote-sensing data. There are many experimental data on real and imaginary parts of complex dielectric permittivity at high (from 1 MHz to 10 GHz) frequency, but the results obtained by different authors are not in good quantitative agreement. There are no convincing reasons to prefer something from them. Therefore we decided to consider in detail all available data in order to find their satisfactory approximation appropriate for practical aims.

In literature there are many attempts to model the snow dielectric properties (especially for wet snow) by various mixture formulae, but the authors frequently did not take into account that this is physically justified only at small concentrations of inclusions in a matrix medium. Usually this is not the case for snow. Because of this we used the statistical approach for experimental data approximations, applying the structure-independent mixture formulae only as a version of describing the resulting correlations. It is commonly supposed that a real part of dielectric permittivity of wet snow may be expressed by linear relation [$\varepsilon_w = \varepsilon_d + \Delta\,\varepsilon_w$], which was taken by us, too.

Firstly, we defined more precisely approximation for dry snow matrix dielectric permittivity as the function of density in the state near melting point: [$\varepsilon_d = (1 + 0.857\,\rho)^2$]. Secondly, the expression for incremental dielectric permittivity due to water content [$\Delta\,\varepsilon_w$] was found by statistical averaging of published experimental data in the form of the following regression expression: [$\Delta\,\varepsilon = 16.7\,W + 42.5\,W^2$] ($R = 0.915$). The comparison with statistical mixture formulae has shown that it is quite possible to use Looenga's formula for description of the above-mentioned dependencies with the deviations about 2%. Corresponding forms of this formula for [ε_d] and [$\Delta\,\varepsilon_w$] are presented and discussed in this paper. All obtained relations reflect well enough the main available experimental data and are quite useable for practical implementation in snow hydrology and radio-echo sounding data interpretation concerning the moisture content and hydrothermal regime of snow cover.

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Estimating Snowmelt Infiltration into Frozen Soils

Litong Zhao[1] and D.M. Gray[2]

In most northern regions, melting of the seasonal snowcover is one of the most important events of the water year. Snowmelt water recharges soil moisture and groundwater storage, and supplies reservoirs, lakes, and rivers. Reliable methods for partitioning the amount of meltwater released during snow ablation to infiltration and runoff are requisite for efficient management of this natural resource for agricultural, domestic ecological and other purposes, and for estimating the moisture and energy transfers occurring at the land surface/atmosphere interface in investigations concerned with global climatic change.

This paper describes the derivation and testing of a general parametric correlation for estimating snowmelt infiltration into frozen soils. The correlation is developed using the results from a numerical model, HAWTS. This model includes a set of partial differential equations that describe water and heat transport with phase changes in frozen soils. The model was run for soils with average textures ranging from sandy loam to clay.

The proposed relationship relates infiltration to the total soil moisture saturation (water + ice) and temperature at the start of snow ablation, the soil surface saturation during melting, and the infiltration opportunity time—the time that meltwater is available at the soil surface for infiltration. The expression is calibrated to predict snowmelt infiltration in boreal forest and prairie soils. Comparisons of estimates of infiltration calculated by the equations against corresponding measured amounts for these environments agreed with a standard deviation among differences of 10 mm.

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Surface Energy Exchange over an Arctic Snowpack: Comparison of Two Snow Models

H. Koivusalo[1] and M. Heikinheimo[2]

The objective was to simulate energy exchange, skin temperature, and albedo at the snow surface using standard meteorological data. Snow and micrometeorological measurements were taken at a site located 100 km north of the Arctic Circle in Finland. The site was an opening within a sparse coniferous stand. Point measurements of vertical snow temperature and density profiles, snow surface skin temperature, net radiation, and albedo had been taken during March–May 1997. Standard three-hour meteorological measurements were available near the snow site at the Sodankyla Meteorological Observatory. The study period included two weeks of measurements of turbulent heat fluxes with the eddy correlation method above snow as a part of the NOPEX-WINTEX project, "Land-surface-atmosphere interactions in a wintertime boreal landscape." Two joint models with different snow process representations were tested to assess the necessary level of complexity to compute radiative and turbulent energy fluxes at the snow surface. UEB (Tarboton and Luce 1996) was chosen as a simple modeling approach, which derived the relevant energy fluxes at the snow/air interface but treated the snowpack as one layer. SNTHERM (Jordan 1991) represented a sophisticated model to simulate mass and energy transfer in detail at the snowpack boundaries and within the snow cover. The performance of the UEB was checked against both the measurements and the results of the SNTHERM, which was also tested using the information on internal snow-cover properties. The measurements on the turbulent energy transfer were used to check the modeled fluxes and the assumed logarithmic profile of vertical wind distribution. The UEB showed reasonable performance for the overall mass and energy balance during spring 1997 after the parameters of the albedo procedure were adjusted for snowmelt conditions. The latent heat flux calculated by the UEB was close to the measured flux and the SNTHERM results. The modeled sensible heat fluxes deviated slightly from each other and from the measurements, which presumably included contribution from the coniferous stand acting as an additional heat sink/source.

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Energy Balance and Climate of a Snow-Covered Frozen Lake in the Boreal Forest

R.J. Harding[1], C.M. Taylor[1], and J. Pomeroy[2]

Lakes make up nearly 20% of the Canadian boreal forest region. The contrast between the surface characteristics of coniferous forest and snow-covered lakes is probably the largest that can be found naturally anywhere. This contrast leads to fluxes of differing sign over the forest and the lake and a likely advection of heat from the forest to the lake, providing the energy for snowmelt on the lake. The paper describes measurements of turbulent fluxes and climate made above a snow-covered lake in the springs of 1994 and 1996, taken as part of the BOREAS experiment. The measurements show albedos in excess of 85%, decreasing following melt to less than 70%. The roughness lengths are highly variable, with mean values ranging from 0.01 to 10 mm, with a hint that the roughness length for heat and water vapor are less than that for momentum. There is a strong diurnal variation of wind and air temperature on the lake. Air crossing the lake is observed to speed up and cool; this may result in the melt on the lakes being dependent on their size. These patterns of surface meteorology are a product of interactions with the surrounding forest and enhance the turbulent fluxes into the snow cover during the daytime and may have important consequences to the onset of melt on the lake.

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Physical and Optical Properties of Snow Covering Arctic Tundra on Svalbard and Its Impact on Biota

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Snow thickness, duration of snow coverage, and amount of soil covering ice are crucial for the development of biota in the Arctic tundra environment. The snow thickness and optical properties control the amount of Photosynthetic Active Radiation (PAR) that is available for vegetation. A late snow cover may prevent birds from nesting on the ground. Furthermore, ice at the snow/soil interface can be an obstacle for grazing of Svalbard reindeer and affect the microfauna population.

Snow and ice thickness, physical and optical properties of snow covering Arctic tundra were measured near Ny-Ålesund in the Kongsfjord area on the Brøgger peninsula on Svalbard in spring 1997. Ny-Ålesund is located at 79°N latitude; however, due to the North Atlantic Current, the regional climate is relatively mild. The initial maximum thickness of snow in the observed areas varied from 0.4 to 0.9 m. The snow around Ny-Ålesund began to disappear by the beginning of June, with the entire snowpack melting within 2–3 weeks. At the bottom of the snowpack, we found a 5- to 10-cm-thick ice layer covering the soil. Radiation and reflectance parameters (spectral albedo, attenuation of PAR, and global radiation) were obtained as well as physical properties of snow (e.g., temperature and density) over six weeks from early May to late June. Electrolytic conductivity measurements on melted snow samples from snow pits showed different conductivity for different stratigraphic sections of the snowpack in early June. Later on, these contrasts disappeared as internal ice layers melted and the snowpack underwent percolation. The albedo maximum before melt onset exceeded 0.9 (visible wavelength range), whereas in the later phase of melting, snow surfaces exhibited significantly lower albedo due to metamorphosis, thinning, and blackening by soil-particle contamination. However, even an apparently "clean" snow surface had about 30% lower albedo in mid-June than in mid-May. We measured furthermore that PAR radiation penetrates deeper into the snowpack after the onset of snowmelt than before. Consequently, the radiation available for warming of the deeper part of the snowpack and for vegetation at the soil surface increases with time and the melting process might be accelerated.

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Controls on Meltwater Production and Lake Level Rise in the McMurdo Dry Valley

Andrew G. Fountain[1], Karen J. Lewis[1], and Peter Doran[1]

Glacial meltwater is the only important source of water to the ephemeral streams and perennially ice-covered lakes in the McMurdo Dry Valleys. The ecosystems that inhabit the streams and lakes depend on this water for their habitat and for the distribution of nutrients. Lake levels have been rising since 1905, indicating that the hydrology of the valleys is not in equilibrium. The cause of the lake level rise is glacial melt and suggests that the climate of the valleys is changing. Large volumes of meltwater are generated in the valleys when air temperatures are well above freezing. Meltwater is also generated when air temperatures are just below freezing because solar radiation penetrates the glacier surface, raising ice temperatures to the freezing point. During the past few years, typical summer air temperatures have been below freezing and the flux of meltwater small. In response, lake levels have been steady or slightly declining. One major factor in the meltwater flux is the effect of snow. Under current summer conditions, a thin layer of snow (cm) covering the ice can persist for much of the season and is sufficient to eliminate meltwater production by increasing the surface albedo. To investigate the effect of snow on ice for meltwater flow, a simple energy balance model was developed. The model is used to examine the range of atmospheric and surface conditions that enhance or diminish meltwater production. Implications of the results for climatic conditions that create rising lake levels are explored and the relevance to the formation of paleo-Lake Washburn (13,000 years ago) are discussed.

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Simulating Arctic Alaska Snowdrifts Using a Numerical Snow-Transport Model

Glen E. Liston[1] and Matthew Sturm[2]

A physically based, three-dimensional numerical snow-transport model (SnowTran-3D) is used to simulate the snow-depth evolution over complex terrain in arctic Alaska. Included in the domain are gently rolling topographic features, as well as several relatively sharp ridges that produce large snow-accumulation traps. The model includes snow transport resulting from saltation and suspension, snow accumulation and erosion, and sublimation of the blowing and drifting snow. It is driven by a wind model that computes the flow field over the complex topography. The snow-transport model requires static inputs of vegetation type and topography, and temporally evolving atmospheric forcings of air temperature, humidity, precipitation, and wind speed and direction. The vegetation type is used to define a vegetation snow-holding capacity that determines the snow depth that must be exceeded before any additional snow is available to be transported by the wind. Model outputs include the spatial and temporal evolution of snow depth resulting from spatial and temporal variations in precipitation, saltation and suspension transport, and sublimation. In these simulations the model is driven using a one-day time step, and covers a two- by three-kilometer domain using a grid increment of twenty meters.

Using four years of meteorological and snow-depth-distribution observations from Imnavait Creek Basin in the foothills north of the Brooks Range in arctic Alaska, the model is found to closely simulate the observed snow-depth distribution and the interannual variability. In addition to successfully simulating the snow distribution over the gently rolling topography, the model also reproduces the cross-sectional profiles of the large drift traps within the domain. Because the snowcover evolves as the winter progresses, the model methodology allows identification and analyses of the individual precipitation and wind events that produce the snow distributions. Thus, the model simulations, in conjunction with the observations, can be used to quantify the snow transport occurring as part of each storm event leading to the end-of-winter drift profiles and the storm-event stratigraphy.

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Validation of 1-D Snow-Cover Simulations by the CLASS Land Surface Scheme for GCMs

Ross Brown[1]

The Canadian Land Surface Scheme for GCMs (CLASS; Verseghy 1991) employs a simplified one-layer treatment of the snowpack. It has been stated (Loth et al. 1993, Lynch-Stieglitz 1994) that multilayer models are required to resolve the characteristic steep near-surface temperature and vapor gradients in a snowpack in order to successfully model snowpack processes. This paper compared CLASS snowpack simulations with those of a detailed multilayer model (CROCUS; Brun et al. 1992) with meteorological and snow data from measurement sites in different snow climate zones. The one-layer model was observed to exhibit a consistent cold bias in snow surface temperature and underestimated the aging of snow during the snow season. In spite of these problems, the one-layer model was able to provide realistic simulations of interannual and seasonal variation in important snowpack properties (albedo, snow cover, snow depth, SWE, and runoff).

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Chemical Processes in Seasonal Snowpacks

Martyn Tranter[1] and H. Gerry Jones[2]

We review the processes that may modify the chemical composition of both dry and wet snow cover, covering processes at the snow/air and snow/ground interfaces and within-pack processes.

The chemical composition of dry snowpacks may be modified by dry deposition, photochemical processes, sublimation of organic material, and by wind pumping, which may exacerbate the effects of dry deposition and sublimation. In addition, gases may be added to the snowpack by diffusion from the underlying soil. Wind transport both adds or removes chemicals from surface snow, depending on whether or not chemicals are lost from or scavenged by airborne snow crystals. Whether or not solute is gained or lost from ice crystals during dry snow metamorphism is currently an area of contention. Finally, rain falling on cold snow adds as a solute source if total freezing occurs within the pack.

Ripe snowpacks contain liquid water, which enhances the rate of dry deposition at the surface and allows microbial activity and dissolution/ion exchange reactions to modify the chemical composition of wet snow. These latter reactions serve to partially neutralize acidic snows in some locales. Wet snow metamorphism is believed to relocate solute into the adjacent liquid water, so allowing percolating melt to efficiently scavenge solute from the pack. The micro- and macro-distribution of solute throughout the pack, the flowpaths in operation, the depth of snow, and the rate of melting all have an influence on the scavenging efficiency.

To date, attempts to model the variable chemical content of snow cover and snowmelt have been rather limited, due to the physical and chemical variability in snowcover at both local and catchment-wide scales. Efforts are now underway to incorporate chemical leaching parameters into distributed snowmelt models, to improve on the prediction of snowmelt quality at catchment scales.

Traditionally, the chemical composition of snowcover has been the domain of environmental pollution, since dry snow cover potentially acts as a passive record of atmospheric deposition and serves as a store of overwinter atmospheric pollutants. Increasingly, the modern trend is to challenge the notion of snowcover as a passive reservoir of chemical signatures. This being the case, there is a note of caution for the uncritical acceptance of the chemical signatures frozen into ice cores. Finally, the chemical composition of snow and snowmelt on glaciers and ice sheets is receiving attention, since these may have an impact on the amount of chemical weathering that may occur in subglacial environments.

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Modeling Studies of the Fate of Nonpolar Organic Chemicals during Snowfall and Snowpack Metamorphosis

Frank Wania[1], Ray G. Semkin[2], John T. Hoff[3], and D. Mackay[4]

Recent advances in the understanding of the interactions between nonpolar organic chemicals and frozen water have revealed the immense importance of the ice–air interface and the possibility of quantitatively treating the adsorption process on the ice surface in terms of chemical-specific interfacial partition coefficients and the snow-specific surface area. As a result, it is now feasible to be quantitative about many of the snow- and ice-related processes experienced by nonpolar organic chemicals in cold environments. A series of simple fugacity-based chemical fate calculations that aim to describe quantitatively nonpolar organic chemical behavior during snow scavenging, and snowpack settling and melting, will be presented.

These model calculations are evaluated and calibrated as part of the Canadian Federal Government's Northern Contaminants Program using available field data on snowpack, firn, and meltwater concentrations and snow scavenging efficiencies of organic contaminants such as organochlorine pesticides (OCPs), polychlorinated biphenyls (PCBs), and polycyclic aromatic hydrocarbons (PAHs) measured in the environment, primarily in the Canadian Arctic. Specifically, the following field measurements were sought to be reproduced in model simulations: 1) the change of concentrations of several PCBs and OCPs in a shallow Arctic snowpack during a one-month period prior to melting, 2) the change of runoff concentrations of PCBs and OCPs in a small Arctic creek during a one-month melting period, and 3) snow scavenging ratios of PCBs and PAHs measured during several snowfall events in mid-latitudes.

The model calculations indicate that the specific surface area of ice crystals and the air–ice partition coefficient of these chemicals are the two key parameters governing these processes, and it is the uncertainty in these parameters that presently limits the capabilities of the models to simulate and ultimately predict the effect of snow and ice on the behavior of nonpolar organic chemicals. Recent advances in developing methods for measuring surface area make it possible to better characterize the sorptive capacities of various types of snow and ice. If progress can also be made in measuring reliably the partitioning coefficients of less volatile, nonpolar organic chemicals onto the ice surface, a more rigorous evaluation of chemical snowpack models will become feasible.

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The Impact of Early-Season Acidic Snowmelt on the Magnitude of Chemical Erosion in a Glacierized Alpine Catchment

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Two major types of chemical weathering reaction control base cation acquisition by meltwaters beneath alpine glaciers, namely simple dissolution and acid hydrolysis. Protons to fuel acid hydrolysis reactions are primarily derived from two main sources: the oxidation of sulfide minerals such as pyrite, and the dissolution and dissociation of atmospheric CO_2. In addition, acidity to perform chemical erosion may also be derived from the dissolution of acids (e.g., H_2SO_4 and HNO_3) in the seasonal snowpack, and significant contributions of H^+ from this source have been shown to be limited to the early melt season.

The average measured NO_3^- and SO_4^{2-} concentrations in the 1990 snowpack overlying Haut Glacier d'Arolla, Switzerland, were 3.52 and 3.74 (eq l-1 respectively, which inputs 545 and 449 kg of NO_3^- and SO_4^{2-}, respectively, when the supraglacial snowpack is eradicated between 2560 and 3100 m). If 100% eradication of the supraglacial snowcover is invoked, these fluxes increase to 1097 and 905 kg, respectively. However, snowpack fluxes of NO_3^- and SO_4^{2-} are considerably lower than those presented in the literature, which may suggest significant snowpack-derived solute contributions from above 3100 m on the glacier surface, extraglacial snowmelt inputs to the hydroglacial system, or interseasonal storage of snowmelt-derived ions in the subglacial hydrological system.

Assuming eradication of the supraglacial snowcover between 2560 and 3100 m, snowpack-derived acidity liberates 0.23 and 0.31% of the total 1990 lithogenic Ca_2^+ and Mg^{2+} fluxes when atmospheric H^+ is attributed solely to carbonate weathering. These carbonate-derived fluxes of Ca^{2+} and Mg^{2+} are reduced to 0.12 and 0.26% when atmospherically derived H^+ is also apportioned to the weathering of silicates, which contribute 0.04 and 0.39% of the total Ca^{2+} and Mg^{2+} fluxes, and 0.64 and 0.30% of the seasonal Na^+ and K^+ fluxes. More significant contributions of lithogenic solute liberated by snowpack acidity are only possible if the maximum recorded snowpack NO^{3-} and SO_4^{2-} concentrations are used in the calculations, and 100% eradication of the supraglacial snowcover is invoked.

These estimates of crustal weathering associated with neutralization of snowpack-derived acidity suggest that actively glaciated Alpine headwater catchments are more than capable of neutralizing atmospherically derived acidity, due to the abundant supply of freshly ground, geochemically reactive lithogenic material.

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The Use of Mass Flux or Concentration for Sensitivity Analysis of the Alpine Hydrochemical Model

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Sensitivity analysis for hydrochemical models requires consideration of the multivariate nature of watershed response. A robust, multiobjective, generalized sensitivity analysis (MOGSA) algorithm, recently developed at the University of Arizona, was used to fully investigate the parameter sensitivity of the Alpine Hydrochemical Model (AHM). In this paper, we discuss differences in parameter sensitivity that result from using mass flux objective functions as opposed to concentration objective functions. A total of 20,000 simulations for the 1986 and 1987 water years (water year day 1 = October 1st) were conducted for the Emerald Lake watershed in Sequoia National Park, California (36°35'N, 118°40'W). A total of 21 objective functions, discharge and both concen–tration and mass flux for 10 chemical species, were evaluated for each simulation.

The MOGSA algorithm determined that only 2000 simulations were necessary to determine parameter sensitivity for the 24 model parameters used in these simulations. We found significant differences in parameter sensitivity for concentration and mass flux objective functions. For example, the snowpack elution parameter and a number of hydrologic parameters were sensitive for Cl^- concentration, while only the snowpack elution parameter was sensitive for Cl^- mass flux. For Ca_2^+ and the other cations, fewer hydrologic and mineral weathering parameters were sensitive, but soil exchange parameters were more sensitive for mass flux objective functions.

Our results indicated differences in hydrologic parameter sensitivity between the soil and talus subunits of the AHM. Flow rate parameters were more sensitive on the soil subunit, while volume parameters were more important for the talus subunit. These results indicate that future field efforts need to emphasize improved measurement of the effective reaction volume of talus slopes in alpine watersheds.

The differences in parameter sensitivity between the mass flux and concentration objective functions are due to the pronounced seasonality of discharge in alpine basins and the varied influence of different hydrologic and chemical processes across the seasons. Mass flux calculations emphasize the spring snowmelt and peak discharge events of the early summer, while concentration objective functions equally weight the entire year. Our results indicate that using mass instead of concentration permits better identification of the model parameters that most affect stream conditions during peak springtime flows and that some combination of mass flux and concentration objectives should be used in evaluating model performance.

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Comparison of Rainfall Season and Snowmelt Season in Relation to Carbon Discharge in a Small Steep Forested Watershed in Hokkaido, Northern Japan

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We measured carbon discharge from a small steep forested watershed and discussed differences between rainfall floods and during snowmelt. The water samples were passed once through the 0.106-mm mesh screen and filtered through 0.001-mm glass fiber filters. The filters were dried and the residual matter was weighed and then ignited. The further weight loss due to combustion of the organic matter was measured. Particulate Organic Carbon (POC) was estimated as 50% of the further loss weight. Dissolved Organic Carbon (DOC) and Dissolved Inorganic Carbon (DIC) concentrations in the filtrate were analyzed using a total organic carbon analyzer.

POC was around 5 mg/L and increased in floods. Its maximum exceeded 80 mg/L in rainfall floods, but did not exceed 20 mg/L in snowmelt, during which water discharges were more. DIC and DOC fluctuated seasonally and temporarily in floods. The maximum DOC was 5.2 mg/L in snowmelt and 15.4 mg/L in rainfall season. DIC decreased from 4.0 mg/L to 1.4 mg/L while snowmelt progressed. After that, it increased progressively to 7 mg/L in August and September, and decreased gradually. DOC increased rapidly from 2 mg/L to 4 mg/L in the beginning of snowmelt and plunged to 2 mg/L when snow disappeared. It increased gradually to exceed 5 mg/L from July to October and decreased gradually.

DIC and DOC were not synchronized with daily fluctuation of water discharge during snowmelt. DIC decreased in rising limb and increased in falling limb in rainfall floods. DOC increased in rising limb and decreased in rainfall floods. In November, however, DOC fluctuated like DIC. The annual discharges of water, POC, DIC, and DOC were 925 mm, 21 kg/ha, 19 kg/ha, and 33 kg/ha, respectively.

Annual organic carbon discharge was 2.7–3.6% of carbon quantity of litters produced by the forest. Sixty nine percent, 54%, 58% and 65% of the annual discharge of water, POC, DIC, and DOC respectively, flowed out in snowmelt (62 days). In the rain season, carbon discharge was extremely concentrated in flood events.

These results indicated the following: 1) There were relationships between DIC and base flows, and between DOC and direct flows; 2) DIC originated from carbon dioxide with respiration of plant roots and microorganism; and 3) DOC corresponded to resolution of organic matters in the soil.

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Effect of Subalpine Canopy Removal on Snowpack, Soil Solution, and Nutrient Export, Fraser Experimental Forest, Colorado

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Long-term research on the effects of vegetation manipulation on snowpack, soil water, and streamwater chemistry and flux is a major objective at the alpine/subalpine Fraser Experimental Forest (FEF), Colorado. In Rocky Mountain subalpine ecosystems, revegetation following disturbance is slow. There is particular interest in the fate of increasing atmospheric inorganic nitrogen (N) inputs, and the interaction between canopy removal and ecosystem N loss. Greater than 95% of FEF snowmelt passes through the watersheds as subsurface flow, and soil processes significantly alter meltwater chemistry. To better understand the mechanisms accounting for annual variation in watershed streamwater ion concentration and flux with snowmelt, we studied subsur-face water flow, its ion concentration, and flux in conterminous forested and clear-cut plots. Re-sults were compared to streamwater ion flux and concentration from an adjacent watershed. The plots were established in 1978 and 1979 and monitored in an undisturbed state until 1984 when one was clear-cut. The effect of clear-cutting was then studied for a decade. Repetitive patterns in subsurface flow and chemistry were apparent. Control plot subsurface flow chemistry had the high-est ion concentrations in late winter and fall. When shallow subsurface flow occurred, its Ca^{2+}, SO_4^{2-}, and HCO_3^- concentrations were lower and K^+ higher than deep flow. The percentage of Ca^{2+}, NO_3^-, SO_4^{2-}, and HCO_3^- flux in shallow depths was less and K^+ slightly greater than the percent-age of total flow. Canopy removal increased precipitation reaching the forest floor by about 40%, increased snowpack peak water equivalent (PWE) >35%, increased average snowpack CA^{2+}, NO_3^-, and NH_4^+ content, reduced snowpack K^+ content, and increased runoff fourfold. Clear-cutting doubled the percentage of subsurface flow at shallow depths, and increased K^+ concentration in shallow subsurface flow and NO_3^- concentrations in both shallow and deep flow. The percentage of total Ca^{2+}, SO_4^{2-}, and HCO_3^- flux in shallow depths was less than the percentage of shallow sub-surface flow, but K^+ and NO_3^- flux were greater. Relative to the control, canopy removal increased the percentage of total Ca^{2+} flux at shallow depths from 5% to 12%, SO_4^{2-} 5.4 to 12%, HCO_3^- from 5.6 to 8.7%, K^+ from 6 to 35%, and NO_3^- from 2.7 to 17%. The increases in CA^{2+} and SO_4^{2-} flux were proportional to the increase in water flux, HCO_3^- flux was less, and NO_3^- and K^+ greater. Increased subsurface flow accounted for most of the increase in nonlimiting nutrient loss. For limiting nutrients, loss of plant uptake and increased shallow subsurface flow accounted for the greater loss. The increase in NO_3^- flux from the clear-cut (net N loss 6 kg N ha^{-1} yr^{-1}) was the most pronounced response. After a decade of study, NO_3^- concentrations in subsurface flow from the clear-cut remained above the control plot (mean of 49 versus 2 μeq L^{-1}). Streamwater and control plot NO_3^- concentrations and variation were identical during the 10-year study. Patterns of seasonal ion concentration in subalpine streamwater and plot subsurface flow were similar, indi-cating that processes defined in the plot study may regulate seasonal change in streamwater chemistry.

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Application of Natural Process of Snow Metamorphism for Concentration and Purification of Fluid Wastes

Jeffrey A. White[1] and Janusz A. Szpaczynski[1]

Snow as a thermodynamically unstable material has the ability to change its physical characteristic even at very low temperatures. Although the natural snowflakes are quite different from manmade snow crystals, the metamorphism takes place with both types of snow. Based on the phenomenon of snow metamorphosis and the elution of ions from the snowpack during the melting season, it has been hypothesized that conversion of fluid wastes into snow and its subsequent metamorphism can concentrate the contaminants within the first 20–30% of runoff. The remainder of the meltwater having low concentrations of contaminants can then be discharged or reused. The process of waste-water atomization in cold atmosphere as well as the crushing of ice cubes was applied to convert different industrial fluid wastes into ice crystals. The experiment was performed both in the laboratory-scale and in the pilot-scale operation. Different distribution of ice crystal size was applied. An elution of anion and cation during the "ionic pulse" was monitored. As was expected, a high concentration of contaminants was reported in the first 20% of meltwater. The results of concentration of heavy metals, chlorides, sulfates, and suspended solids for different fluid wastes and selected environmental conditions are shown. The mathematical model of concentration efficiency is also presented. It was concluded that the Atomizing Freeze Crystallization process can be successfully apply for concentration of selected industrial fluid wastes.

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Snowpack Controls on Nitrogen Cycling and Export in Seasonally Snow-Covered Catchments

Paul D. Brooks[1] and Mark W. Williams[2]

Here we provide an overview of current research activities on nitrogen (N) cycling in high-elevation catchments of the Colorado Front Range. We then use this information to develop a conceptual model of how snow cover controls subnivial (below snowpack) microbial processes and N leachate from the snow/soil interface to surface waters. The duration of snow cover is divided into four snowpack regimes: zone I is characterized by shallow short-duration snowpacks; zone II is characterized by high interannual variability in snow depth and duration; zone III is characterized by early developing, continuous snow cover; and zone IV is characterized by deep, long-duration snow cover verging on perennial snowpacks. In zone I, soils remain frozen and there is little microbial activity and N leachate is high. In zone II, total microbial activity is highly variable and the amount of N leachate is highly variable. In zone III, total microbial activity is high and there is little N leachate. In zone IV, microbial activity is reduced because of carbon limitation and N leachate is high.

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Biotic Interactions with the Seasonal Snow Cover

The Role of Snow in the Ecology of Seasonally Snow-Covered Ecosystems: A Review

H. Gerry Jones[1]

Snow ecology has a long history of studies on the mechanisms by which metabolic change and specific snow–organism interaction can lead to adaptation to the cold and over-winter survival of many plants and animals. However, the role of snow in the global nutrient dynamics and biological productivity of terrestrial ecosystems has not, until recently, received the same degree of attention. In this paper we will present an overall review of progress in the field by drawing on a variety of recent studies that describe the physical, chemical, and microbiological characteristics of snowpacks that allow essential processes of nutrient flow and change to continue in, and under, seasonal snow covers. Particular attention will be paid to snow as a mediator of energy exchange between the atmosphere, vegetative cover, and the subnivean environment and as a hydrologic and nutrient reservoir of importance to both snow biology and to growth in the snow-free growing seasons. The microbiological activity of snow-covered soils will be reviewed with particular reference to soil respiration and the emissions of gases produced during the wintertime dynamics of nitrogen—the overall limiting factor to terrestrial productivity. In addition, the life cycles of some true nival organisms will be discussed and some possible food webs based on both these true snow organisms and other active supra- and subnivean species will be presented in the light of recent work.

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Measuring Branch Deflection and Calculating the Intercepted Snow Mass on Spruce Branches

Michael Bruendl [1]

Snow interception plays an important role in the hydrological cycle of mountain forests because it determines water supply for discharge in spring. A common way to measure the intercepted snow mass on trees is to put a cut tree on a scale. This method yields accurate results with a high temporal resolution but it destroys the natural system of tree, snowpack, and soil. Hence, it does not work when water transport processes between the tree, the snowpack, and the soil are investigated. We developed a nondestructive method to continuously observe and measure snow load on spruce branches during a winter.

Throughout a winter season we continuously observed a spruce with a video camera. To quantify the motion of branches during the snow interception process we suspended small illuminated balls on branches at different distances from the trunk. The position of the balls at a certain time could be analyzed by image analysis of the video image. The calculation of the position of the balls could be partly done automatically. Images recorded at nighttime could be automatically analyzed, while for daytime images the contrast between the balls and the background was too low. In this case we had to extract the position of the balls by hand. The result of this analysis is a time series of branch motion during an interception event.

Given the measured deflections, the intercepted mass on branches was calculated. The deformation of branches under certain branch temperatures was calibrated with known weights. By using a finite element model, the calibrations were used to calculate the linear relation between the branch temperature and the Young's modulus. The calculations indicated that the mechanical properties of a living branch can vary over the length of the branch. The relation between Young's modulus and the branch temperature was used as input into a finite element model, allowing calculation of the intercepted mass. For a fully snow-capped spruce branch, we found an intercepted snow mass of 4.7 kg. The calculated snow mass was compared with snow storage measurements at a spruce that was put on a balance. The results show that it is possible to estimate the intercepted snow mass on a spruce by knowing the snow mass intercepted on a single branch.

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Differences in the Characteristics of the Heat Balance above the Canopies of Evergreen Forest and Deciduous Forest while Snow Covered

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Heat and water exchanges in forest areas constitute one of the most important hydrometeorological systems. A lot of investigations about the heat and water exchanges were carried out on the snow-free forest canopy compared with on the snow-covered canopy. Unfortunately, therefore, little is known about the characteristics of energy balances in forest areas when covered by snow.

In the present study, the energy balances above three forests located in northern Japan were measured when the land surface was covered with snow. Two were evergreen conifer forests and the third was deciduous. The characteristics of the heat balance are investigated above each forest canopy during the snow-covered season, and the properties of the aerodynamic parameters are discussed in this paper.

From this study we obtained the following new interpretations: There was no significant distinction between the magnitudes of net radiation and sensible heat, and the ratio of sensible heat to net radiation among the three experimental forests, despite the major differences in canopy conditions. Net short-wave radiation was larger above the evergreen forests than above the deciduous forest. However, for net long-wave radiation, the converse was true; this may be due to the difference in the upward long-wave radiation. Consequently, there was no clear distinction between the net all-wave radiation above the two types of canopy. Canopy conditions caused major differences in roughness length and zero plan displacement. In the deciduous forest, the zero plan displacement was small and roughness length was large, while in the evergreen forest the opposite was true. In the deciduous forest, the area in contact with the atmosphere increased because of the low position of the "active surface," and roughness length was also high. Consequently, sensible heat from the deciduous forest did not differ from that of the evergreen forests.

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An Effect of Canopy Snow on Energy Balance above a Coniferous Forest

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To evaluate an interactive effect of snow with forest on energy exchange between forest surface and atmosphere, the energy balance above a forest was measured continuously between midwinter and snowmelt season of the winter 1996–97 in Sapporo, northern Japan.

The forest was a dense, 23-year-old, coniferous plantation. The trees were two species of spruce and a fir species, all 23 years old with an average height of 6.4 m, a mean trunk diameter of 0.09 m, and a density of 0.24 stems m-2. The leaf area index was estimated to be 6.0 m^2 m-2. The total stand area of 46,000 m^2 was bordered by deciduous forests extending over an area of 1,300,000 m^2. The study site had frequent snowfalls and the canopy was frequently covered with snow.

Snowcover on the canopy was daily monitored using a photo camera above the canopy, and a ratio of the snowcover to the total area of the canopy was determined as an index for the canopy snow. Turbulent fluxes above the canopy were measured using eddy and band-pass covariance method. The effect of the canopy snow on turbulent energy exchange was examined using an expression of the evaporative efficiency for the canopy layer in a double-source model that combined the energy balance and the bulk turbulent transfer both for the canopy and for the forest floor.

The diurnal courses of the measurement showed that turbulent fluxes were sensitive with the snowcover on canopy. This means that latent heat fluxes dominated above the snow-covered canopy and that sensible heat flux prevailed above the snow-free and dry canopy. The evaporative efficiency for the canopy layer changed dynamically with the canopy-snow condition even during a short term and could be positively related to the extension of the snow-covered canopy. A relationship was empirically determined between the evaporative efficiency and the fraction of the canopy-snow area. The snowcover season can be typified into the following two types of energy balance: (1) latent heat flux from the canopy dominated and the Bowen ratio was positive but low for midwinter under the snow-covered canopy; (2) for the snowmelt season, sensible heat flux from the dry canopy prevailed and the Bowen ratio was much larger than for midwinter.

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Transformations of Snow Chemistry in the Boreal Forest: Accumulation and Volatilization

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This paper examines the processes and dynamics of inorganic chemical accumulation and loss in boreal forest snow during the cold winter period. Field observations from Inuvik, NWT, and Waskesiu, Saskatchewan, and process-based modeling are used to link chemical transformations and physical processes in boreal forest snow. Through dry deposition and episodic wet deposition, inorganic N and S are incorporated in intercepted snow and surface snow over the winter season. Dry deposition rates of N increase by an order of magnitude when the snow surface temperature approaches the melting point. However, N is not well conserved by snow over the winter. N is lost from snow that has been physically transformed through sublimation (intercepted snow) and kinetic metamorphism (surface snow). The loss of N during these processes is roughly proportional to the loss of SWE from surface or intercepted snow. Measured and modeled estimates of snow loss from intercepted snow sublimation and strong kinetic metamorphism suggest a subsequent enrichment of S but not N, a result matched by field data.

Climate, canopy, and snow structure therefore strongly affect most of the factors important to over-winter snow chemical fluxes. In warmer zones of the southern boreal forest, N losses due to intercepted snow sublimation and N + S gains due to dry deposition to wet snow are important, but N losses due to metamorphism are not, a situation reversed in the northern zones near the subarctic. Besides a marked climate sensitivity, the sensitivity to structure of the forest canopy means that alteration of the native forest through burning, harvesting, and replanting will have strong consequences for winter chemical fluxes.

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Natural Variability in Nitrogen Export from Headwater Catchments: Snow-Cover Controls on Ecosystem Nitrogen Retention

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The growth of urban communities in the western United States has resulted in an increase in atmospheric N deposition to adjacent headwater catchments. Before the effects of this N deposition can be evaluated, the causes of natural variability in catchment scale N export need to be understood and quantified. Previous research has demonstrated that as much as 80% of the annual water input and 50% or more annual N deposition is stored in the snowpack and released to the catchment during snowmelt. The majority of this N enters an actively cycling soil N pool, and the snowmelt flush of both soil and snowpack N is responsible for the increase in the concentration of both N and other solutes during the first portion of snowmelt. The snowmelt period accounts for 60% to 90% of annual N export, but exhibits significant interannual variability suggesting that changes in N source/sink relationships in soil during melt have a large impact on N export. This study evaluates controls on the strength of the N sink and the size of the leachable N pool concurrent with the spring hydrologic flush that is responsible for the transport of N to surface water.

Controls on the variable source/sink relationship for N during the snowmelt period were evaluated in alpine meadow, subalpine meadow, and subalpine forest ecosystems in four catchments in Colorado. The study sites included Loch Vale in Rocky Mountain National Park (RMNP), Niwot Ridge/ Green Lakes Valley in the Front Range, and the Snake River and Deer Creek catchments in Summit County. At all sites and in all vegetation types measurements of N leachate during melt were inversely related ($r^2 > 0.9$) to over-winter heterotrophic activity measured as CO_2 flux, consistent with previous work that identified soil microbial biomass as the primary sink for N during melt. Because over-winter soil heterotrophic activity and microbial biomass are inversely related to snow depth, catchment-scale N export should be higher in low snow years if these plot-scale results are important to catchment N export. This hypothesis was evaluated using a long-term record of winter precipitation, N deposition, and N export from Loch Vale in RMNP. Data from a nine-year record identified a strong, linear relationship ($r^2 = 0.68$) between catchment-scale N retention and winter snow cover, consistent with the subnivean, soil-based controls on the mobile N pool identified at the plot scale. These results indicate that while spring snowmelt is the major control on the timing of hydrologic N export, the size of the mobile soil N pool during melt is controlled by the timing and depth of winter snowfall. This natural variability in N export controlled by winter snow cover needs to be considered when evaluating the potential effects of increased N deposition on either terrestrial or aquatic ecosystems in seasonally snow-covered watersheds. For management purposes, the effects of increased N deposition are likely to appear in the aquatic ecosystem during low snow years before the terrestrial vegetation is affected.

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Snow Depth, Soil Frost, and Nutrient Loss in a Northern Hardwood Forest

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A lack of snow cover results in colder soil temperatures, more extensive soil freezing, and an increase in freeze/thaw cycles. Previous studies have suggested (but not verified) that these stresses result in root and microbial mortality, releasing labile organic carbon and nitrogen to soil (via root and microbial death) and increasing soil moisture and available N (via reduced uptake by trees and microbes). These changes lead to increases in net mineralization and nitrification rates, nitrate (NO_3^-) and cation leaching losses and acidification of drainage waters. Over the long-term, we believe that differential resistance to freezing stress will be a key regulator of species composition in northern forests under a warmer climate condition.

We have initiated a long-term experiment to examine the consequences of decreases in snowpack accumulation at the Hubbard Brook Experimental Forest (HBEF), a northern-hardwood-dominated forest located in the White Mountains of New Hampshire. We are quantifying the effects of decreases in snowpack accumulation on root dynamics of two key tree species in this forest (sugar maple, yellow birch), microbial biomass and activity, NO_3^- and cation loss, the acid-base chemistry of drainage water, and soil- atmosphere trace gas fluxes. We are calibrating an existing model (SNTHERM) that depicts snow depth and soil frost dynamics given past or future climate scenarios for our site.

In this paper, we describe the methods we are using for the manipulation studies that began in the winter of 1997/1998 and present preliminary results from pilot studies conducted during the winter of 1996/1997. Results from the pilot studies show that the SNTHERM model is capable of depicting snow depth and soil temperatures in our plots and that a six-week midwinter snow removal treatment led to significant increases in early spring soil inorganic N levels. In a more practical sense, results from the pilot studies suggest that it is quite feasible to keep plots snow free by shoveling, without disturbing the forest floor. The pilot studies results also show that snow removal will induce soil freezing and effects on soil N dynamics, even if air temperatures are not extremely low.

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Long-Term Experimental Manipulation of Winter Snow Regime and Summer Temperature in Arctic and Alpine Tundra: An Integrated Ecosystem Approach

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Three 60-m-long, 2.8-m-high snowfences have been erected to study long-term effects of changing winter snow conditions on arctic alpine tundra. This paper describes the experimental design and short-term effects of the manipulations. One fence has been placed at Niwot Ridge, Colorado, a temperate high-altitude site in the Colorado Rockies (40°03′N, 105°36′W; 4085 masl), and two have been placed at Toolik Lake, Alaska, a high-latitude site (68°37′N, 149°32′W; 700 masl). The fences result in a drift that is about 3 m at its deepest and which tapers to low snow conditions at about 65 m from the fences. Open-top fiberglass warming chambers are placed along the experimental snow gradients and in control areas outside the fences; each warming plot is paired with an unwarmed plot.

The purpose of the experiment is to examine short- and long-term changes in the integrated physical-biological systems under simultaneous changes of winter snow regime and summer temperature. The studies are part of the Long-Term Ecological Research network and the International Tundra Experiment. Initial results indicate that although experimental designs are essentially identical at the arctic and alpine sites, experimental effects are different. The drift at Niwot Ridge lasts much longer than do the Toolik Lake drifts, so that the Niwot Ridge fence affects both summer and winter conditions, whereas the Toolik Kale fence affects primarily winter conditions. The temperature experiment also differs between the sites. Although the average temperature increase at the two sites is very similar, at Toolik Lake there is only minor diurnal variation, whereas at Niwot Ridge the daytime increases are extreme on sunny days (as much as 7–10°C), and minimum nighttime temperatures in the chambers are often slightly cooler than ambient. The experimental drifts resulted in wintertime changes in temperature and CO_2 flux. Temperatures under the deep drifts were much more consistent and warmer than in control areas, and at Niwot Ridge remained very close to 0°C all winter. These increased temperatures were likely responsible for observed increases in system carbon loss.

Initial changes to the aboveground biotic system included in increase in growth in response to both snow and warming, despite a reduced growing season. This is expected to be a transient response that will eventually be replaced by reduced growth. At least one species, *Kobresia myosuroides*, had almost completely died at Niwot Ridge 3 years after fence construction, whereas other species were increasing. We expect in both the short and long term to see the strongest effects of snow at the Niwot Ridge site, and stronger effects of temperature at Toolik Lake.

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A Review of Spatially Distributed Modeling of Snow

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Spatially distributed modeling of snow has a wide variety of applications, from providing lower boundary conditions and elementary hydrology for atmospheric circulation models operating at coarse spatial scales, to providing details on snow processes, and fluxes of meltwater and chemical species for biological studies at fine spatial scales. Research and operational efforts to implement spatially distributed models of snow have some common interrelated issues. These include 1) the tradeoff between model complexity and computational expense; 2) the estimation of error due to forcing variables (i.e., surface meteorology) and due to model performance; 3) the approach to segment landscape and terrain data at suitable scales in relation to surface heterogeneity; and 4) the challenge of validating and/or updating model predictions over large areas.

Model complexity controls the type of measurements that can be used to validate model predictions. For example, simple bucket-type approaches, once common among land surface calculations in general circulation models, may only allow testing the presence or absence of snow and water equivalents within a cell, polygon, or patch. As models become increasingly complex in process detail, one has the opportunity to use a variety of measurements for model testing. The separation between error due to incorrect meteorological variables and due to model performance has usually been addressed by testing at snow plots. Validation efforts at the study-plot, or local-area scale using manual measurements, have become the standard approach to building model credibility. However, this type of validation becomes increasingly cost prohibitive when testing snow model predictions over larger and larger areas. Many tests of snow model predictions distributed over large areas have suffered from the difficulty in quantitative evaluation due to variability in snow extent patterns and snow physical properties. Recent modeling approaches parameterize the effects of land cover and terrain heterogeneity on surface energy and mass fluxes. The effort is important whether or not the data are segmented into regular or irregular areas and may help address what can be accomplished with point measurements of snow properties through geostatistical stratification of sampling procedures. Recent distributed model implementations have also parameterized the relationship between snow extent and mean snow water equivalents. The albedo of areas that have incomplete snow cover is thus estimated from predictions of water equivalents, coupling the snow model back to the atmosphere model. This approach assumes that depth information is contained in snow extent, which has not been tested over a wide variety of land cover, terrain types, or spatial scales. Finally, recent advances in remote sensing have demonstrated construction of images of grain size, wetness, and water equivalents. These methods offer the potential to test distributed models at compatible resolutions, comparing spatial data with spatial predictions.

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Investigations on a High Alpine Catchment: The Sarennes Basin (France)

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The snow cover plays an important role in determining the discharge of mountainous rivers in temperate regions. During spring, high amounts of water are released, so that river discharges are very sensitive to heavy rain. On the contrary, the snow cover can limit flow hazard if precipitation is (at least partly) stored as snow in the upper part of the basin. Investigations on a high alpine catchment are currently under process to quantify the role of the snow cover in river flows during extreme events. The Sarennes basin (28 km, outlet 1435 m) covers a wide range of elevations (up to 3300 m) and a small glacier is situated in the upper basin. The CIG distributed hydrological model is used. The meteorological and snow input are provided by the meteorological analysis system SAFRAN coupled with the snow model CROCUS. Eighty meteorological zones are defined and are characterized by elevation, orientation, and slope. Glacier mass-balance data and additional measurements were used to validate the snow-cover simulation.

Despite the absence of meteorological measurements in the basin, the meteorological data analyzed by SAFRAN appeared to be of good quality, except for some storm events. Detailed investigations of flood episodes showed that they are mostly due to intense snowmelt or rain-on-snow events. During these episodes a significant part of the basin is covered by snow. Floods due to precipitation only are extremely rare. A 10-year simulation of discharge showed that the main statistical characteristics of the discharge are well reproduced. Sensitivity analyses, including the simulation of a rain-only scenario, highlighted the role of snow as a moderator of floods in autumn and winter.

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Snowmelt and Runoff Modeling for a Test Basin in West Greenland

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Simulations using different types of hydrological models have been carried out for a test basin in West Greenland. The results show that presently the conceptual modeling system named HBV performs best. This model is widely applied in both Greenland and most of the arctic regions of Scandinavia. However, a general wish to use models not only for water resource applications, but also as a tool for improving data collection and gaining insight into the hydrological processes, has promoted a general interest for using more physically based models. Therefore, the study also included the Danish version of the physically based SHE hydrological modeling system (MIKE SHE).

Despite the physical basis of MIKE SHE, it treats snowmelt in a conceptual way (as in HBV). This has motivated us to develop a horizontally distributed energy balance snowmelt model (APUT) for this study. Parameterizations were needed in APUT, both for coupling with MIKE SHE and to overcome the general lack of field data in Greenland. The key parameterizations in APUT constitutes albedo parameterizations based on the age of the snow, as well as the transformation from grid into sub-catchment distribution of meltwater runoff.

As stated, the HBV model presently performs the best simulation of discharge. However, the combination of MIKE SHE and APUT, i.e., a physically based modeling system, shows promising results by improving the timing of the spring peak flood. The performance of the combination of MIKE SHE and APUT is likely to reach the level of HBV if processes of water storage and flow in snow are incorporated in this modeling system.

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Estimation and Evaluation of Spatially Distributed Snowmelt Model Parameters Using the Modular Modeling System (MMS)

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The U.S. Geological Survey (USGS) Modular Modeling System (MMS) is an integrated system of computer software developed to provide a framework for the development, integration, application, and analysis of hydrologic and ecosystem models. MMS uses a library of compatible modules and models for simulating a variety of hydrologic and ecosystem processes. A geographic information system (GIS) interface, the GIS Weasel, has been developed to support MMS in model development, application, and analysis. The GIS Weasel permits application of a variety of GIS tools to delineate, characterize, and parameterize the topographic, hydrologic, and biologic features of a physical system for use in a variety of lumped- and distributed-parameter modeling approaches.

A major difficulty in the application of distributed-parameter models has been the general lack of objective methods for parameter estimation. To address this problem, a number of parameter-estimation methods are being developed and evaluated using available digital databases, MMS, and the GIS Weasel. Databases used in this study were USGS 3-arc second digital elevation models, State Soils Geographic (STATSGO) 1-km gridded soils data, and Forest Service 1-km gridded vegetation type and density data.

Initial research is being conducted using the distributed snowmelt-model component of the USGS Precipitation-Runoff Modeling System (PRMS). PRMS uses an energy-balance approach to simulate the initiation, accumulation, and melt processes of a snowpack. Distributed PRMS parameters estimated using the digital databases include slope, aspect, elevation, soil type, available water-holding capacity of the soil, vegetation type, vegetation cover density, solar radiation transmission coefficient, and interception-storage capacity for each hydrologic response unit (HRU) delineated. Precipitation distribution was computed using selected precipitation-elevation distribution methodologies coupled with MMS.

Evaluation of estimated parameters on four basins in the Rocky, Sierra-Nevada, and Cascade mountain ranges showed reasonable simulations of snow accumulation and melt, and of streamflow timing and volume. Robustness of parameter estimates and the accuracy of simulation results were a function of database accuracy, resolution, and scale, as well as the uncertainties associated with precipitation distribution and basic model conceptualization. While initial evaluation efforts are being focused on PRMS applications in the United States, the tools provided by MMS and the GIS Weasel are generic and are applicable to a wide variety of distributed-parameter snowmelt models and geographic regions. Additional models and regional data sets will be added to the analysis in the next phase of this investigation.

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Remote Sensing of the Alpine Snow Cover: A Review of Techniques and Accomplishments from the Visible Wavelengths through the Microwave

Jeff Dozier [1]

In regions where snow accumulation and ablation vary spatially, distributed snowmelt models are a promising approach to improving runoff analysis and forecasts. Employment of distributed models requires spatially distributed input data, hence the desire to remotely sense snow properties. Alpine regions pose particular challenges for remote sensing. There is usually considerable variability in snow depth and other properties at a fine spatial scale, and analysis of the remotely sensed signal must account for geometric effects that the sloping terrain and range of elevations cause. In some areas, persistent cloud cover hampers regular acquisition of data.

Many snow properties might be obtainable from remote sensing. Rather than try to cover all plausible variables, I concentrate on three.

The most elementary snow property is the presence or absence of a snow cover, so we must distinguish snow from other types of surfaces and from clouds. For snow mapping in the absence of cloud cover, a combination of visible and near-infrared wavelengths gives excellent results. With rich spectral data from multispectral or especially hyperspectral sensors that operate in the visible and near-infrared parts of the electromagnetic spectrum, we can estimate the snow-covered portion of a pixel and the snow's spectral albedo. In cloudy conditions, we can map snow with the microwave part of the spectrum, using either active or passive sensors. The active microwave (radar) has a finer spatial resolution that is necessary in mountainous areas.

The most essential property for hydrologic analysis is usually the snow water equivalence. For deep mountain snowpacks, the active microwave is the spectral region where we might directly estimate the water equivalence. The presence of liquid water in the snow makes the analysis of such data difficult because water and ice have such different dielectric properties in the microwave. Topographic variability also complicates the analysis, because the signal is sensitive to the incidence angle. Moreover, the models often incorporate snow properties that are difficult to measure, and they are analytically formidable and difficult to invert.

Finally, while the effect of liquid water on the microwave signal hinders the retrieval of snow water equivalence, it does allow estimation of the liquid water content in the near-surface layer to an accuracy of about 2%.

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Integration of Remote Sensing Techniques into the Snowmelt Component of Hydrological Models

Owen Turpin[1], Rob Ferguson[1], and Barbro Johansson[2]

Models of daily runoff from seasonal snowpacks and glaciers require knowledge or assumptions about the decline in the snow-covered area (SCA). Some semi-distributed models (e.g., SRM) rely on satellite data as an input in addition to meteorological data, but general-purpose hydrological models with a snow component (e.g., HBV) do not normally use earth observation (EO) data. EO data have the potential to verify or update SCA predictions generated by these models. Integration of EO data into general-purpose hydrological models poses an initial problem, though, as they tend to assume that energy input reduces the snow–water equivalent (SWE), but that the SCA remains equal to that of the sub-area until snowmelt within the sub-area is complete. Two possible solutions are either to allow a stepped SWE distribution within a sub-area, or to assume uniform melt over a nonuniform snowpack within a sub-area. In both approaches melt is then converted into a reduction in SCA as well as SWE, thereby allowing snowpack depletion to be compared directly with EO data.

Two examples are given in which the gradual reduction of SCA is verified using EO data. The HBV model is applied to a basin in arctic Sweden and a recently developed glacier runoff model is applied to a basin in the Swiss Alps. Landsat TM data of both basins revealed considerably less snow than that predicted by the models. TM data for the Swedish basin show that only glaciated zones were 100% snow covered. Despite over-predicting the SCA, both models achieved very good observed discharge fits. It is argued that runoff models should correctly simulate the hydrological system if they are to be transferred to different environments or new climate scenarios with confi-dence, and that EO data can play a valuable role in this.

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Distributed Snowpack Simulation Using Weather Radar with Hydrologic and Land Surface Models

Steven R. Fassnacht[1], E.D. Soulis[1], and N. Kouwen[1]

Hydrologic modeling to estimate peak spring snowmelt flows relies on an adequate representation of the melt and runoff processes, as well as a satisfactory approximation of the quantity and condition of the snowpack prior to or at the beginning of melt. For most modeling efforts, adequate assessment of the state of the snowpack at the onset of melt has become the limiting factor in reliable snowmelt hydrograph estimation. To address this, the snowpack is modeled continuously throughout the winter, from accumulation to melt, using weather radar as the precipitation input.

The radar imagery that is used to approximate the accumulation of snow over the winter season is adjusted for scaling errors, and variation in hydrometeor characteristics with temperature. The hydrologic modeling is accomplished using a coupling of WATFLOOD, a distributed hydrologic model developed at the University of Waterloo, and CLASS, the Canadian Land Surface Scheme developed by Environment Canada. Both models use the Grouped Response Unit, or mosaic approach, that considers land cover heterogeneity within computational units.

The results are the integration of four different datasets, namely, weather radar precipitation estimates, measured and simulated meteorological parameters, field snowcourse data, and streamflow hydrographs. The radar snowfall estimation is shown to be very similar to Nipher-shielded Belfort precipitation gauge collection, after adjustment. Simulated snow depth and snow water equivalence are shown to be quite comparable to observed values measured at snowcourses at most locations and times. The modeling is validated by a good match between the computed hydrographs and the observed hydrographs for 1993 at various streamflow gauge sites in central southern Ontario.

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Spatially Distributed, Physically Based Assimilation of Satellite, Airborne, Surface, and Atmospheric Model Data to Estimate Snow Water Equivalence over Large Regions

Don Cline[1] and Tom Carroll[1]

To support routine streamflow forecasting in seasonally snow-covered regions, estimates of the areal extent of snow cover (AESC) and snow water equivalence (SWE) must be provided to regional forecasters in a timely manner. Historically, these estimates have been made by classifying remotely sensed data into maps of snow cover, and by interpolating, using various methods, satellite-, airborne- and surface-based observations of snow water equivalence. These methods cannot readily utilize other snowpack observations, such as snow depth, which is routinely observed at a large number of sites, or snow albedo, which can be observed from remote sensing, or other hydrometeorological observations that indirectly provide information relevant to snowpack conditions. A comprehensive mechanism is needed to translate available, diverse observations that are irregularly distributed in time into routine, timely estimates of SWE and AESC. To address this problem, the National Operational Hydrologic Remote Sensing Center is currently developing an operational data assimilation framework for spatially distributed, physically based snow modeling to take maximum advantage of available operational satellite, airborne, surface, and atmospheric model data over large regions. The system consists of four major components: 1) data ingestion, quality control, and management, 2) a physical snow modeling basis for data assimilation, 3) data assimilation procedures and decision criteria, and 4) on-line validation. We will first provide an overview of our approach to developing this snow information assimilation system. We will then discuss in detail the data used in the assimilation scheme and describe several of the problems associated with using these data.

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Scaling Problems in Snow Hydrology

Günter Blöschl [1] and Kelly Elder [2]

The concept of scale can be used to quantify three different things, (a) a natural process (such as the correlation length of the spatial SWE variability); (b) a measurement (such as the size of a snow density sample or the footprint of the satellite sensor), and (c) a model (such as the DEM grid size). We denote the different types of scale as process scale, measurement scale, and model scale, respectively. Scaling problems arise because measurements never capture all the detail of the natural variability and because model scales are generally different from the measurement scales. Hence some sort of interpolation, extrapolation, aggregation, or disaggregation of the data is needed. We will discuss three alternative genres of methods for interpolation, extrapolation, aggregation, or disaggregation. In all three genres we view the effects of measurement scales and model scales as a filter where the ratios of measurement scale on process scale, and model scale on process scale are the driving parameters. Methods of the first genre are based on the spatial correlation structure of, say, SWE or snow cover. Based on the variogram we demonstrate that (i) aggregation always reduces variance, (ii) large footprints of satellite images will bias the spatial variance, (iii) that these and other biases introduced by the measurement scale and the model scale can be estimated and corrected by regularization methods. Methods of the second genre consist of running physically based distributed models. The main advantage over the first method is that here we can represent nonlinear snow processes, and that we can explicitly account for process controls such as solar radiation and terrain effects. However, there are a number of fundamental scaling problems with distributed models, some of which are related to the incompatibility of the process scale and the model scale of the computational grid. We will discuss grid resolution effects on model performance and whether there exists an optimum grid size. We will give methods for estimating subgrid variability and point to potential avenues for parameterising subgrid variability. Methods of the third genre attempt to combine the advantages of the other two. They are sophisticated enough to retain the important processes controls, but parsimonious enough to avoid some of the scale issue of methods of the second type and to capitalize on some of the analytical results of methods of the first type. As an example we will discuss the SWETREE model, which uses binary decision trees (regression trees) to estimate the spatial distribution of SWE. This models uses physically based independent variables (net solar radiation, topography, soil and vegetation cover type) and SWE measured at individual points as inputs. While most of the presentation will focus on physical snow processes, similar conclusions apply and similar methods are applicable to chemical and biological processes.

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Spatial Properties of Snow in an Alpine Basin, Colorado Front Range

Kelly Elder[1] and Don Cline[2]

Mountain snowpacks are spatially heterogeneous, reflecting the influences of rugged topography on precipitation, wind redistribution of snow, and surface energy fluxes during the accumulation and ablation season. No widely suitable method yet exists to directly measure the spatial distribution of SWE in rugged mountain regions. The problem of determining the volume and distribution of snowpack water storage within mountain basins remains acute. The test basin used in this study was the Green Lakes Valley (8 km^2), which lies in Colorado's Front Range, just west of the city of Boulder. Intensive snow surveys were carried out in GLV on two dates near maximum snow accumulation of the 1996 water year. More than 550 depth measurements were taken and 17 snow pits were excavated for density during the two field sessions. Snow depths were measured using aluminum sounding probes. Snow density was measured in snow pits. Data from intensive field surveys are statistically analyzed to determine inherent spatial properties. We quantify the relationship between spatial variability of SWE and variability in the controlling physical factors, such as topography and net solar radiation, which have correlated with SWE distribution. Classic spatial statistical methods are employed to determine spatial characteristics and uncertainty in estimations of SWE distribution. The data set is used to further test scale effects on a model (SWETREE) developed for distributing SWE in complex terrain. SWETREE uses binary decision trees (regression trees) to determine the spatial distribution of SWE by relating physically based independent variables (net solar radiation, topography, soil and vegetation cover type) to measured SWE to estimate SWE over a gridded domain. This research improves our understanding of spatial scaling properties of snow water equivalence from point to basin scales.

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Blowing Snow Fluxes over Complex Terrain

Richard Essery[1], Long Li[1], and John Pomeroy[2]

Significant amounts of sublimation can occur from blowing snow in open, windswept environments, and redistribution of snow by wind leads to variations in depth that influence the depletion of snow during melt. Transport and sublimation rates increase rapidly with increasing wind speed and so are highly sensitive to wind speed variations. Wind speed, in turn, is strongly influenced by variations in topography and surface roughness. In this study, a distributed model is used to investigate the scaling of blowing snow fluxes over complex terrain.

The distributed model is derived from a physically based model of blowing snow over homogeneous terrain. To allow the model to be run with high spatial and temporal resolution (40-meter and 30-minute), a simplified version is introduced which, while lacking a physical basis, can reproduce the blowing snow model results closely with much greater computational efficiency. Wind speed maps are produced for an area using a terrain windflow model. Inputs required are digital elevation and vegetation maps and time series of temperature, humidity, and wind speed.

The model has been run using data from an arctic tundra basin. Area-average sublimation is found to be only slightly increased over that predicted by the blowing snow model for uniform terrain, but the cumulative influences of transport generate large variations in snow depth. This redistribution is sensitive to the ad hoc representation used for the response of transport to changes in wind speed; further work is required on this problem.

Distributed models are unsuitable for large-scale applications, and scaling methods have to be used. From the equations used by the windflow model, approximate relationships are developed between topography and the distribution of wind speeds over an area. These relationships are used to model the statistical and fractal properties of redistributed snow covers.

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Subgrid Parameterization of Snow Distribution for an Energy and Mass Balance Snow-Cover Model

Charles H. Luce[1], David G. Tarboton[2], and Keith R. Cooley[3]

The spatial variability of snowpack accumulation and ablation processes can cause point-scale physically based snowmelt models to give poor estimates of average snowmelt over a small area or basin. Distributed snowpack modeling is a popular tool to handle spatial variability in snowpack accumulation and ablation across watersheds. Because of the high computational burden and the cost and uncertainty of input data associated with fine grids, elements of distributed models may be made large relative to the assumptions of uniformity of snowpack conditions within a model element. Approaches are needed to describe a model element as a heterogeneous unit within a physically based modeling framework.

Our approach uses a parameterization of snow-covered area as a function of area-averaged snow water equivalence. This parameterization is linked to a physically based snowmelt model describing the lumped energy and mass balance of the snowpack. For each time step, the energy and mass balance are calculated for the snow-covered area. The snow-covered area is updated according to the basin-averaged snow–water equivalence. The dimensionless relationship between snow-covered area and averaged snow–water equivalence (area-equivalence curve) can be derived from the spatial probability density function of snow–water equivalence at peak accumulation.

Outputs of the lumped model derived from this reasoning were compared to outputs from a distributed snowmelt model and to distributed data in the 26-ha Upper Sheep Creek sub-basin of Reynolds Creek Experimental Watershed in Southwest Idaho. The snow-water equivalence observations were taken on a 30.3-m grid with 255 cells over the basin, and the distributed model was run on the same grid.

Comparisons of the lumped model outputs to distributed model outputs show good agreement. Both models showed reasonable agreement to the observations. Comparison of the area-equivalence curve derived from the probability density function of snow water equivalence at peak accumulation to one derived from a series of measurements across the basin and another based on outputs of the distributed model also showed good agreement.

This parameterization and the method to obtain area-equivalence curves provide a practical method for scaling-up point-scale energy and mass balance models to cover a small basin with accuracy comparable to a distributed model. The method may be particularly useful in hydrologic models that may use large (relative to assumptions of snowpack homogeneity) elements, such as land-surface submodels of climate models or models of large river basins.

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Scaling Up from Point Scale to Small Catchment Scale Using a Quasi-Physical Approach

Narendra Kumar Tuteja[1] and Conleth Cunnane[2]

Runoff forecasting in the case of seasonally snow-covered small catchments with shallow snowpack requires application of a quasi-physical approach wherein the dominant snow accumulation and melting processes are accounted for by an intensive physically based modeling approach, and transformation of the snowmelt and the rainfall to streamflow is accounted for by a conceptual modeling approach. In the case of shallow snowpacks both high and low water saturation can occur more frequently and therefore the physically based distributed (in depth) snowmelt model must account for capillary pressure gradients as well as gravity drainage. One such physically based snowmelt model, entitled UCGVDSM, which accounts for coupled transport of mass and energy into the snowpack, developed from the Eulerian principles, is first validated on point snowmelt data of station K¸htai located in Austria. UCGVDSM is then applied to the Tich·Orlice catchment (96.8 km^2) located in the Czech Republic. It is shown how the constraints of data availability for application of the physically based snowmelt model can be handled to reproduce accurately the three state variables, namely, the snow water equivalent (SWE), the depth of snowpack (H), and the meltwater flux (qmelt). The snowmelt rates thus obtained for the snowcover periods are then incorporated along with the rainfall and the evapotranspiration data into the Soil Moisture Accounting and Routing model (SMAR), a conceptual rainfall runoff model. It is shown that incorporating a number of curve fitting techniques into the SMAR model have no effect on improving the model performance, while accounting for physical processes improves the model performance. An updating component is finally incorporated into the SMAR model to set up the small catchment scale hydrological forecasting model.

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Wintertime Surface Heat Exchange in a Boreal Forest: From the Plot to the Stand

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The present study aims to quantify the heat exchange for a 10-km^2 boreal forest in the north of Sweden (64° N latitude) during wintertime. The forest is a composite of old spruce stands, heath, and pine stands; it includes different soil types and open clearings. A GIS-database with extended information on vegetation, soil type, and topography is available. Detailed physical measurements have been conducted continuously at single selected points during the last three winters, and a spatial snow and soil frost monitoring program within the different stands ran last winter. All these data are used for the parameterization and validation of a numerical model (WINSOIL) to quantify the heat balance. The model is one-dimensional with a single snow layer and a sophisticated description of the soil frost. Our simulation strategy is to conduct multi-run simulations where some governing parameters vary randomly within an (observed or estimated) reasonable interval. The results are presented as means and standard deviations of a large number of simulated outputs, such as frost depth or temperatures. This gives us an idea of the spatial variability within the forest investigated. The first multi-run simulations confirm the considerable variability of surface temperature and frost depth measured at different locations both within the stands and between different stands. A model validation with ground measurements demands an enormous amount of work for such an extended area. A direct validation of the simulated turbulent heat fluxes with eddy correlation systems is planned for the coming winter. Finally, we will be discussing how the multi-run method could be used to improve the parameterization of GCM models with a grid size of some km^2 applied to northern Scandinavian winter conditions.

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Representativeness of Local Snow Data for Large-Scale Hydrologic Investigations

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Arctic snow cover usually attains maximum values at the end of winter and such information is important for hydrological investigations because most floods are associated with spring snow–melt. Snow data obtained from weather stations or collected at some local sites are often extrapolated to large areas, but without verifying that the upscaling procedure yields correct results. This study compares maximum snow cover data gathered over two large target areas (170 to 300 km^2) with weather station snow course measurements to determine the representativeness of local-scale data for areas typically occupied by large grid cells of macro-hydrological models. The field snow survey results confirmed the controlling role of terrain on snow distribution in the High Arctic. The variability of area mean snow water equivalence for a grid cell (with dimensions of 1×1 km^2 to 13×13 km^2) increases with terrain complexity but decreases with grid size. Although point data do not represent the snow cover over an area, an attempt was made to upscale the weather station data to the target areas using an index method. Test results show that this index approach works well in the area with a shallow snow cover, but the error increases for an area with relatively deep snow. More effort is need to refine this method, perhaps in conjunction with remote sensing, so that point data can be upscaled to yield snow information suitable for large-scale hydrological models or land surface schemes.

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Simulation of Snow Mass and Extent in Global Climate Models

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An evaluation of the Biosphere-Atmosphere Transfer Scheme (BATS) snow sub-model was done, both in a stand-alone mode and within the National Center for Atmospheric Research (NCAR) Community Climate Model (CCM). We have evaluated, in the stand-alone mode, the performance of BATS parameterizations at local scales using ground-based observations from the former Soviet Union and from Mammoth Mountain, California. The BATS snow scheme reproduces the seasonal evolution of snow water equivalent in both sites, and the results compare well with those from a more complex, physically based model (SNTHERM). In the coupled mode, we have evaluated the modeled precipitation, temperature, and snow cover extent from BATS as linked to the NCAR CCM using available observations. The coupled models capture the broad pattern of seasonal and geographical distribution of snow cover, with better performance in the Eurasian than in the North American continent. The poor simulations of snow variables coincide with poor simulations of surface air temperature and precipitation, primarily due to lack of realism in the model topography. Because of the importance of snow for correct climate simulations, it is necessary to determine what level of complexity of snow models is adequate for general circulation models (GCMs) and what snow properties need to be simulated. Several features of process-level snowmelt models could be used to help capture sub-grid scale variability and improve snowmelt simulations.

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Posters:

Snow-Cover Properties and Processes

Capillary Rise in Snow

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Snow is a complex porous medium where liquid water may rise to several centimeters high due to capillary rise.

Previous experimental measurements in a cold laboratory on wet snow samples allowed us to relate the capillary rise level with snow characteristics (porosity, grain size).

In this study, a network model was adapted to snow to simulate this phenomenon. The pore texture of a wet snow block is simulated by a cubic lattice of cylindrical bonds. Bond lengths are the same, equal to the mesh size of the lattice. Their circular sections vary with the two-dimensional pore size distribution, computed from image analysis of thin sections. At a given height, a bond contains water if the two following conditions are fulfilled: first, it should be thin enough in radius so that capillary pressure balances hydrostatic pressure at this level; second, there exists a continuous path of such bonds that connects the bottom of the lattice.

Simulations were systematically compared to observations of the maximum level of capillary rise for ten different snow samples. Simulated and experimental results varied in the same direction. Difference between simulation and measurement varied from 0.5 to 2.8 cm when the height of capillary rise varied from 1 to 10 cm. We could infer from previous results that the ratio of the mean convex radius of curvature to density contained relevant information on pore size. Simulated profiles of liquid water content were compared to vertical thin sections of three refrozen samples of saturated snow. They decreased too slowly above the fully saturated layer.

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Snowpack Depth and Density Changes during Rain on Snow Events at Mount Hood, Oregon

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The U.S. Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) operates a near-real-time remote snow-measuring system called SNOTEL in the Western United States. The SNOTEL system has been in full operation since 1980 and currently has 693 stations across the West. Each station collects snow water equivalent, precipitation, and temperature. Additional sensors can be installed at the remote sites to measure other types of data that are of interest to cooperators. One of the additional sensors is an ultrasonic snow-depth sensor, which was field tested at several SNOTEL sites beginning in the fall of 1996. This study focuses on the results of the first year of operation of the snow-depth sensors installed at three stations on the slopes of Mount Hood in the Cascade Mountains located east of Portland, Oregon. These sensors were installed to add to the snowpack information already collected at each site. This additional information has improved our knowledge on how the snowpack reacts during melt events.

Rain-on-snow events can occur at any time during the winter, but are more prevalent during November through February on the west slopes of the Cascades. During rain-on-snow events in the 1997 water year, snow depth, snow water equivalent, precipitation, and temperature readings were taken on an hourly basis. Data indicate that the snowpack reacted differently in each location. The amount of reaction to the rain-on-snow was very much dependent on the depth of the snowpack, and was most volatile during early season snowpack accumulation when large and rapid changes in density were observed. During rain-on-snow events, the density of the snowpack usually increased to 45 to 50 percent, but did not always produce a loss of snow water equivalent at the site. Conversely, in some rain-on-snow events, the snowpack with a lower density of 35 to 38 percent density did produce snowmelt runoff from the site. While the relationship of streamflow runoff to snowpack density is a complex issue, the additional snow depth data is a valuable tool for snowpack analysis and early warning of a major runoff from mountain snowpacks. These real-time data are easily accessible and analyzed by cooperators and can be used in preparation for rain-on-snow induced flooding in the Pacific Northwest and elsewhere.

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Incorporation of Spectral and Directional Radiative Transfer in a Snow Model

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Present radiative transfer methods in physically based energy budget models of snow do not include adequate spectral or directional resolution to deal with the scattering of solar radiation. This paper reports on results from an advanced physically based snow energy budget model (SNTHERM) linked with a discrete ordinate radiative transfer model (DISORT) at nine wavelengths assuming spherical snow grains. Scattering properties were averaged over a small range of grain sizes (as seen in real snow) to eliminate interference-induced fluctuations.

A method was derived to split a single measurement of spectrally integrated solar radiation into its direct and diffuse components at nine wavelengths. The split of radiation is required as input to the radiative transfer model, and is produced as a weighted average from days of total cloud cover and days of clear skies (from the 6S atmospheric radiative transfer model).

The fully linked model was tested on a data set from a field campaign on the Uranus Glacier, Antarctica, December 1994–February 1995. An automatic weather station provided meteorological inputs, with additional measurements made of solar radiation. A vertical array of thermistors made continuous measurements of snowpack temperature in the top meter of snow, though solar heating and melting contaminated those thermistors near the surface. Snow pit data were used to initialize the model.

The combined model was tested against simpler radiative transfer parameterizations, such as the method of Marks and fixed albedo and extinction techniques. Albedo predictions from the discrete ordinate radiative transfer model show large variations in albedo with solar zenith angle and the diffuse and direct spectral radiative split, though unfortunately no albedo measurements were available for direct comparisons. RMS deviations in measured and modeled temperatures at a depth of 70 cm were found to be 1.2 in. for the optimum fixed albedo (0.8) and extinction (50 m^{-1}), 2.0 in. for the Marks method, and 0.6°C for the DISORT method. The use of a spectral method was thus seen to provide markedly superior results for snowpack temperatures over the test period.

The measurement period was of limited duration at a single location. Further testing is recommended to demonstrate the benefits over longer time periods and at other test sites, where the snow grains may be less rounded.

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The Effect of Ground Frost on Snowmelt Runoff at Sleepers River, Vermont

James B. Shanley[1] and Ann Chalmers[1]

Ground frost has been monitored at the Sleepers River Research Watershed in northeastern Vermont since 1984. Frost develops every winter, particularly in open fields, but its depth varies greatly from year to year in inverse relation to snow depth. During the 15 years of record at a benchmark mid-elevation open site, the seasonal frost depth maximum varied from 7 cm to 39 cm. At the outlet of the 111-km^2 watershed, the runoff/(rain + snowmelt) ratio was positively correlated ($p < 0.05$) to the maximum seasonal frost depth for the period leading up to peak flow, and negatively correlated ($p < 0.05$) to the maximum seasonal frost depth for the period from peak flow to the return of base flow. These same runoff-frost relations appeared to be even stronger for 6 years of flow and frost depth measured at a small agricultural catchment within the Sleepers River watershed. The runoff-frost relations can be explained by the greater tendency of snowmelt or rainfall runoff to flow overland to the stream channel when ground frost is present. In the absence of ground frost, snowmelt and rain more readily infiltrate and recharge groundwater. Ground frost thus tends to shift runoff toward an earlier date by increasing surface runoff in early spring and limiting the recharge that normally sustains high base flows in mid- to late-spring.

Based on analysis of six events, the presence of frost appeared to promote a larger and somewhat quicker response to rainfall relative to the no-frost case, although snow cover caused a much greater time-to-peak regardless of frost status. The role of frozen ground in increasing early spring runoff is important both from a water supply standpoint (less recharge) and a water quality standpoint (erosion and rapid transport of surface contaminants to channels).

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Snow Cover and Snowmelt Floods in Belarus

Boris Fashchevsky[1] and Alexander Pachomov[2]

This report focuses on assessment of peculiarities of snow cover forming in Belarus both in time and spatial aspects. Frequency curves are carried out at the main point observations (over 100) for a long-term period of snow-cover characteristics: maximum height and maximum reserve of water equivalent of snow cover. The maps of maximum height and maximum water equivalent of snow cover are compiled in the years of 95, 50, 25, 5, and 1% frequency. Moreover, the computations of spatial variation of maximum height and maximum reserve snow cover are made on selected directions. The mean (50% frequency) maximum height of snow cover changes from 7–10 cm in river basins of the Zap, Bug, and the Prypyat to 25–30 cm in headwaters of the Dnieper and the Zap Dvina. The mean (50% frequency) maximum of reserve of water equivalent of snow cover on the open field plots changes from 30 to 110 mm, increasing to the northeast. The snow-cover height and reserve of water equivalent can be much higher in forests, bushes, and relief reduction. A lot of snow accumulates, especially in deciduous forests and at the forest glades, where reserve of water composes 120–150% of the reserve of water in field plots at the beginning of snowmelt. A forecast statistical model of volume and maximum level of snowmelt flood is elaborated on an example of the Prypyat river. This model takes into consideration the peculiarities of snow-cover formation in different years (frozen crust of snow, antecedent soil moistening, and so on). For this model, elaboration of snow cover as well as flow headwaters and the right tributaries data of the Prypyat river in the Ukraine were attracted. Computations made using this model gave good results.

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Sublimation from a Seasonal Snowpack at a Continental, Mid-Latitude Alpine Site

Eran W. Hood[1], Mark W. Williams[1], and Don Cline[2]

Sublimation from the seasonal snowpack was calculated using the aerodynamic profile method at Niwot Ridge in the Colorado Front Range. Past studies of sublimation from snow have been inconclusive in determining both the rate and timing of the transfer of water between the snowpack and the atmosphere, primarily because they relied on one-dimensional measurements of turbulent fluxes or short-term data sets. We calculated latent heat fluxes at ten-minute intervals based on measurements of temperature, relative humidity, and wind speed at heights of 0.5 m, 1.0 m, and 2.0 m above the snowpack for nine months during the 1994–95 snow season. The meteorological instruments were raised or lowered daily to maintain a constant height above the snow surface. At each ten-minute time step, the latent heat fluxes were converted directly into millimeters of sublimation or condensation. Total net sublimation for the snow season was 195 mm of water equivalent, or 15% of maximum snow accumulation at the study site. The majority of this sublimation occurred during the snow accumulation season. Monthly losses to sublimation during the fall and winter ranged from 27 to 54 mm of water equivalent. The snowmelt season from May through mid-July showed net condensation to the snowpack ranging from 5 to 16 mm of water equivalent. Sublimation was sometimes episodic in nature, but often showed a diurnal periodicity with higher rates of sublimation during the day.

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Estimating the Amount of Snowmelt Based on Viscous Compression Model of Snow

Yuji Kominami[1], Yasoichi Endo [2], and Shoji Niwano [2]

This study proposes a method to estimate the amount of snowmelt, using hourly data of total snow depth and precipitation. First, a snow cover is divided into a large number of thin snow layers named t_i-layer (i=1,2,...,n), which was deposited for one hour to time t_i. Assuming that a change in thickness of t_i-layer by snow melting from time t_{n-1} to t_n is resulted after deformation of t_i-layer by viscous compression, let $h'_i(t_n)$ and $h_i(t_n)$ be respectively the thickness of t_i-layer at time t_n deformed by viscous compression and resulted from both compression and melting. Then, thickness $D(t_n)$ of snow deposited or melted on the snow surface for one hour from time t_{n-1} up to t_n is given by

$$D(t) = H(t) - \sum_{i-1}^{tn-1} h'_i(t_a) ,$$

where $H(t_n)$ is total snow depth lying at time tn. Assuming that a relation between compressive viscosity η and dry density ρdry of snow is expressed by $\eta = C(\rho_{dry})^n$ with constants of C and a, we derived theoretically an equation giving thickness $h'_i(t_n)$ of t_i-layer from weight $w_j(t_{n-1})$ (ji) of each snow layer lying at time t_{n-1} on t_i-layer and hourly precipitation at time t_n, and computed $h'_i(t_n)$ of every t_i-layer to obtain the index $D(t_n)$. In a case of $D(t_n)0$, the value is considered to indicate a thickness $h_n(t_n)$ of t_n-layer deposited newly on the snow surface, and a weight $w_n(t_n)$ of t_n-layer at time t_n is given by hourly precipitation $p(t_n)$ at time t_n. In the other case of $D(t_n) < 0$, thickness $h_i(t_n)$ and weight $w_i(t_n)$ of snow layers lying to the depth of $-D(t_n)$ from the surface come to zero, because the value shows a thickness of snow melted on the surface. Supposing that hourly precipitation in the case of $D(t_n) < 0$ is supplied as rain, which is distributed with melt water downward according to such a simple tank model that water percolates into lower snow layer only in a case that water content $\alpha_i(t_n)$ of a snow layer exceed 15% by weight, we computed water content $\alpha_i(t_n)$ and weight $w_i(t_n)$ of each t_i-layer. Computing in order from time t1 by such a procedure, we can obtain thickness $h_i(t_n)$, weight $w_i(t_n)$, and water content $a_i(t_n)$ of each t_i-layer at time t_n from hourly total snow depth and precipitation. So depth of snowmelt was estimated by subtracting measured thickness of snow depth reduction and estimated thickness of snow compaction. The amount of snowmelt was estimated as the estimated dry weight of these snow layers, which was lost by snowmelt. The approximated results were found to be in good agreement with estimated results by the other methods in Tohkamachi in 1994/95.

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Characteristics, Development, Year-to-Year Variability, and Environmental Impact of a Large Arctic Alaska Snowdrift

Matthew Sturm[1], Glen E. Liston[2], and Jon Holmgren[1]

Arctic tundra snow cover comprises two diametrical components called the veneer and drift facies. Veneer facies is thin (<0.7 m), wind-blown, and consists of alternating layers of wind slab and depth hoar. Drift facies is denser, thicker (often in excess of 2 m), and generally consists entirely of wind slabs. It forms in the lee of bluffs, in gullies, or downwind of isolated shrub stands. Though occupying less than 5% of the landscape, it plays an important role in the hydrologic cycle because it continues to release meltwater long after the veneer facies is gone in the spring.

The volume, profile, and basal temperature of a typical large drift located in the foothills north of the Brooks Range, Alaska, was measured 25 times since 1985, with multiple measurements made during the winters of 1989 to 1993. Comparison of these measurements to total winter precipitation and wind speed show a complicated relationship, with both maximum and minimum drift sizes occurring during years of near-normal precipitation and wind. The results suggest that the largest drifts form when infrequent optimal conditions (significant snowfall immediately followed by strong wind) occur. Stratigraphic cross sections through the drift show that 90% of the total drift volume is often found in fewer than 4 layers of snow (i.e., fewer than 4 transport events). Continuous wind and snow surface elevation measurements obtained during the winters of 1994, 1995, and 1996 confirm that an appreciable thickening of the drift takes place only during a few events.

Observations and simulations using a melt model confirm that drifts can persist up to 50 days longer than the veneer snow. Meltwater derived from the drifts nourish snow bank and small riparian vegetation communities. Observations indicate that the under-snow temperatures beneath drifts are elevated, and suggest that migration of groundwater takes place long after the active layer is frozen in other locations. These factors, in addition to prolonged release of meltwater, may contribute to favoring the growth of these plant communities.

Both the poor correlation between drift size and winter precipitation, and the limited stratigraphic layering support the hypothesis that the timing of winter wind storms with respect to recent precipitation is the most important factor in drift formation. This finding suggests that prediction of the hydrologic response of the Arctic to changing climate must include consideration of changes in wind as well as precipitation, plus their combined timing.

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One-Dimensional Snow Water and Energy Balance Model for Vegetated Surfaces

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A number of point snow models have long been referenced in the literature. These models assume that the snow cover overlies a homogeneous surface; therefore, a one-dimensional (vertical) snow model at one location can represent the whole snow cover. To represent snow cover on more realistic areas with heterogeneous surfaces, work is needed to extend these point models. We have developed a three-layer snow model (coupled with a new version of the Biosphere-Atmosphere Transfer Scheme [BATS] of Dickinson et al. [1997]), which is a simplification of the complex one-dimensional snow property and process model (SNTHERM) of Jordan (1991). This point snow model has been tested in a bare soil case against the field data. The results are in good agreement with the observations and with Jordan's model (Jin et al. 1998). Because this snow model is developed for use in Global Climate Models (GCMs), it needs to be extended to an area where patches of snow, soil, and vegetation exist. We related this one-dimensional model to the heterogeneous surface by parameterizing the snow, soil, and vegetation patches into a mixture with varying fractional coverage for each surface type, then calculating the dynamic properties and states for each surface type through energy and mass balance under the grid-uniform atmospheric and radiative forcing. We tested this areal snow model using the field data from France (grass) and BOREAS (forest) to see the performance of this model in these two different land covers.

In conclusion, the agreement of the modeled snow depth with the field observations using the three-layer snow model is consistent with the results from the multi-layer SNTHERM model. Because of the substantial reduction of the computational requirement of the model compared to SNTHERM, it is applicable for use in GCMs. The model adds physical details of snow, such as melting–thawing cycles and vertical and diurnal variability, to the current GCM snow models. Introducing parameterization of subgrid heterogeneity into the snow model is a way of extending the point model to areas. The good matches of modeled and observed skin temperature and albedo and the reasonable explanation for the complicated responses of surface fluxes indicate that this approach captured the essentials of subgrid heterogeneity, and its formulations and parameter values are representative.

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Sensitivity of Soil Frost Models to Snow Cover and Density

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Frozen soils have important implications for the social well-being of those who live in cold regions. Loss of sediment and nutrients from landscapes during snowmelt, for example, depend upon the occurrence and depth of soil freezing. Soil frost models, therefore, may be useful in assessing the impact of land management on soil erosion and water quality in cold regions. There are, however, few independent evaluations of soil frost models. Four soil frost models were examined for their ability to simulate snow cover, water content, and frost depth of agricultural soils. Snow cover, soil water content, and frost depth were measured in plots varying in corn residue cover and height over two winters in west central Minnesota. These measurements were compared to those simulated by the SHAW, SOIL, Benoit, and Gusev models. The SHAW and SOIL models use finite difference equations to predict temperature and water profiles in the soil. The Benoit and Gusev models estimate soil frost depth by balancing heat flow through the snow-residue-soil system.

Snow cover is simulated by the SHAW, SOIL, and Benoit models and only the Benoit model mimics snowdrift. The SHAW and SOIL models performed better at simulating snow dynamics than the other two models. The SHAW model was more accurate in estimating soil frost depth than the SOIL model, partly due to a better simulation of snow cover. The SOIL model, however, mimicked changes in surface soil water content better than the SHAW model. The Benoit model performed poorly in estimating snow cover due largely to a rapid snowmelt. The Benoit model, using measured and not simulated snow depths, performed better than the Gusev model in estimating the depth of soil freezing, but was more sensitive to changes in snow density. An increase in snow density from 250 to 350 kg m^{-3} in the Benoit model caused a 150% deeper penetration of soil frost whereas this same increase in the Gusev model resulted in a 20% deeper penetration of frost. This study suggests that accurately simulating snow cover in soil frost models is critical to their performance in the field.

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Air Permeability and Capillary Rise as Measures of the Pore Structure of Snow: An Experimental and Theoretical Study

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Air permeability and capillary tension are macroscopic snow properties that are influenced by the pore structure of the snow cover. Formulas for predicting fluid transport, species elution, and acoustic wave propagation require parameterization of one or both of these properties. We report paired measurements of permeability K and capillary rise h from snow samples at field sites in Hanover, New Hampshire, and Sleepers River, Vermont. We augment these data with laboratory tests on sieved snow and glass beads. Our measurements demonstrate a linear relationship between K and Φ/h^2, which we corroborate theoretically using a simple conduit model of the pore space, where Φ is the snow porosity. We propose that scatter in the data results, in part, from the effect of crystal shape on air flow and imbibition contact angle. We also show that grain size D can be estimated from capillary rise, through inversion of Shimizu's equation.

Since the early measurements and classification schemes of Bader in 1939, many investigators have expanded the permeability database to include observations of a wide range of snow types. We summarize these data and report our own recent observations from the New England sites and from an additional site in Manitoba, Canada. We note that filter velocities are high in the CRREL permeameters and are likely beyond the range of Darcy's Law when they exceed $1.3\times10^{-4}(1-\phi)/D$ m s^{-1}. In this case, data can be corrected either with the Ergun equation or with a multiple regression of the pressure gradient on velocity and velocity-squared. Our measurements are in the high range of reported values. However, after normalizing our data by the square of grain size, they follow the empirical function of Shimizu fairly closely. This agreement supports our measurements, and demonstrates the usefulness of Shimizu's function for snow types other than the relatively dense, fine-grained snow used in his analysis.

Our normalized permeability data for low-density snow, as well as the Shimizu function, are below Happel and Brenner's (1965) cell model predictions for suspensions of spheres and infinite cylinders. By extending their cell model to oblate spheroids and discs, we estimate permeability that is in closer agreement with our data. Theoretically determined K from these models is reduced mainly because of the higher surface-to-volume ratio of more asymmetric particles. We suggest that a decrease in surface-to-volume ratio as snow ages accounts for a relative increase in normalized permeability.

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Spatial Variations in Finnish Seasonal Snow Cover

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The climate of Finland changes from the ephemeral (in south) to the subarctic taiga (in north) within just 1000 km. Snow season varies from 100 to 260 days and the amount of snowfall from the yearly precipitation varies from 30% to 50% on the way from south to north. Thereby observing the snow stratification, physical and chemical properties of snow across the Finnish nature will give us a lot of useful information about the effects of climate to the snow conditions. This is the first time that the seasonal snow cover will be mapped in Finland. The research will be based on the small-scale structures of snow, such as crystal sizes and types. The fieldwork, consisting of 18 measuring points across Finland, was done in January and March of 1998. The results from over 100 snow pits were added to a database, which already included weather data and temperature gradients (air/soil) from each point.

As a result, a map based on snow classification and physical properties of seasonal snow cover was drawn. The boundaries between different classes remain still difficult to determine because they correlate a lot with the winter weather pattern type (mild/severe). The database can also be a great help for people dealing with the remote sensing problems considering physical characteristics of snow. Results from this study can also be used as a database when running models predicting the global warming and its effects in the snow stratification.

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Physical and Microwave Modeling of Electromagnetic Fields within a Granular Snow Layer

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A fundamental component of monitoring snow characteristics from the air or from space is to understand and model the interaction of electromagnetic fields within the layer itself. For this purpose, a combination of empirical, numerical, and theoretical models are implemented to achieve a degree of mathematical simplicity in conjunction with flexibility for addressing a variety of real-world situations.

From a remote sensing point of view, the most important parameter for characterizing a generalized snow layer is to estimate its complex permittivity. Knowledge of this basic parameter is directly equivalent to having knowledge of the layer's emissivity, extinction coefficient, and propagation constant—critical components for modeling remote sensing observations using both radiometry and radar.

Depending on the observing frequency, models of the snow layer may take on one of three forms: i) a uniform dielectric slab (low-frequency), ii) a dielectric half space (high-frequency), or iii) a granular medium whose components strongly interact with the ambient field (mid-frequency). Because of the complex, dense-medium scattering interactions involved in the granular medium case, it is particularly problematic for developing reliable and consistent models. Current state of the art techniques involve coherently modeling the interaction of electromagnetic fields with the pseudo-crystalline structure of the snow layer via a theoretical approach called the quasi-crystalline approximation (QCA).

Because of the coherent field approach employed by this technique it is necessary to statistically describe the position of scatterers within the medium so that electromagnetic interactions between these particles may be accounted for. To achieve this end, a number of physical models for the arrangement of particles within the snow layer have been proposed. This paper will present one of those models (a deposition model) as well as demonstrate its application to a full three-dimensional determination of effective permittivity for the medium using both a numerical approach and the theoretical approach of QCA. Our long-term goals are to utilize the packing algorithm presented in this paper in conjunction with snow section data to firstly refine the model for crystal positions within the snow layer and secondly to develop a robust method for estimating effective permittivity without the requirement of in-situ measurements.

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Thresholds for Ice Lens Development in Glacier Snow and Firnpack

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On the Juneau Icefield, Alaska, ice lenses and ice layers make up 5–15% of the entire annual accumulation layer volume in midsummer. In contrast, on North Cascade, Washington glaciers in midsummer, ice lenses make up less than 0.1% of the entire annual accumulation layer volume.

The presence of ice lenses that can develop within glacier snowpacks have several important ramifications: 1) slowing the percolation of meltwater downward through the snowpack, allowing deeper areas to remain below freezing for longer; 2) retarding meltwater movement through, and consequent meltwater release from, the glacier system, and 3) refreezing of meltwater, which in turn is now internal accumulation and can be an important aspect of glacier mass balance. If climate warming prevented this internal accumulation from occurring, than this meltwater would be lost and the entire glacier would have a more significantly negative mass balance.

Ice lens formation requires the presence of cold-dry snow at the beginning of the melt seasons. Late winter snowpack temperatures in the North Cascades range from 0 to –1°C, versus –3 to –7°C in southern Alaska. The threshold snowpack temperature for ice lens formation is then below –2°C. Winter air temperatures at three stations in the North Cascades adjacent to glaciers indicate mean winter temperatures of –3 to –6°C. In southern Alaska mean winter temperatures have been noted on several glaciers to be –8 to –11°C. Another important factor reflected in the temperature record is the frequency and intensity of melting events. From 1 December to 1 March the number of melt event days (temperature maximum above 3°C) at glaciated levels in the North Cascades averaged 12 days. These events provide critical meltwater that is either refrozen as ice lenses if the snowpack is cold enough, or warm up the snowpack to 0°C via release of latent heat and percolation. On Lemon Creek Glacier, Alaska, the mean number of winter melting days is 3.

Ice lens development thresholds in the maritime snowpack are minimal melt events in the winter, air temperatures below –8°C, and snowpack temperatures below –2 or –3°C. The transition from cold-dry snowpack to 0°C snowpack that does not allow ice lens development is identifiable using SAR imagery. Thus, areas of internal accumulation and retarded meltwater release can be identified readily. This also provides an important climate marker for mean winter temperature conditions.

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Thermal and Physical Properties of Snow
during the Night Outcooling

Aleksey Isaev[1]

For the calculation of the snow parameters by the model of the snow cover it is necessary to know a number of the thermal and physical properties of snow. The evaluation of quantities comprising the equation of the common heat transfer in snow cover was made for the dry snow in the condition of the night outcooling.

It was shown that the nighttime outcooling of the dry snow at any depth is to be provided with two components: the ice skeleton conductive one and the thermal radiation. It is obvious that the integral heat losses along the whole snow cover depth in this period are to be supplied with the conductive heat exchange on the snow–air interface and with the thermal radiation of the snow cover with the subtraction of the value of the geothermal heat inflow from the soil.

The calculations based on the actual data of observations of the temperature regime of the snow–pack show that the inflow of the geothermal heat is much lesser than the heat losses in the snow–pack. The thermal radiation plays the major role in the nighttime outcooling. This is proved by the fact that the snow cover surface is cooled during the nighttime more strongly than the surface air layer.

The formula has been derived for the distribution of the snow temperature by the depth in the conditions of the sudden nighttime outcooling. It was shown that the relationship between the thermal conductivity of the dry snow and its density is presented in the same form as the temperature conductivity. The conclusion has been drawn about the possibility of the application of Fourie thermal conductivity equation for the estimation of the coefficient of the dry snow thermal conductivity by the data of 8 times thermogradient observations of the snow cover. The formula is presented for the relationship between the temperature conductivity and the snow density by the observational data obtained at Dukant station in the Western Tien Shan.

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About the Possibility of Layer Density and Wetness Determination in the Snow Cover by Reflectometry

E.V. Vasilenko[1], Leonid Kanaev[2], and V.P. Smirnov[3]

A system including the measuring line, automatic impulse reflectometer of picosecond range and PC/AT, connected to the reflectometer with COM-port, is presented in this article. A system ensures registration of the profile of the reflection factor along the measuring line depending on the snow physical parameters in which the line is set; inversion of the reflection profile to the profiles of the components of the complex permittivity $e' + je''$; calculation of the profiles of the snow volume wetness $w(e'')$ and snow dry density $p(e', w)$. At the frequency of 100 KHz, the measuring line is sounded at $t = 0$ by the voltage unit step at the wave front of the picosecond length. Reflections in the beginning of the line ($x = 0$) at the different moments $t > 0$ are the result of the line heterogeneities at some distance $x > 0$ and can be measured with the stroboscopic method. Observations at the discrete moments $t_i > 0$, $i = 1, 2...1024$ correspond to discretization of the measuring line along axis X to 341 layers with three sublayers in the layer. Reflection signals for 1024 two-byte values are being converted into binary code and recorded in RAM to its address. On PC/AT inquiry, the reflectometer outputs into communication channel 1024 two-byte values of the reflection signals. This file of values is used in PC/AT together with the stored files of the reflection signal values for the empty line to calculate the wave parameters Sk, Dk, Zk for all layers having numbers of $k = 1, 2...341$. The developed program of the Sk, Dk, Zk sublayer calculations supplies the method of the solution of the direct and inverse problems of scattering in the heterogeneous media by algebrazation of the non-line wave equations (method has been proposed by C.Q. Lee in 1982).

The same method (in sublayers) is used to calculate the values e'_k and e''_k and values $Wk\,(e''_k)$, $\rho\,(e'_k, w_k)$. While testing meter at the multi-layer snow density at the total depth of 120 cm, and as the density changes from 0.4 to 0.08 g/cm^3 and layer depth from 6 to 40 cm, we can identify the layers with the minimum density difference (about 0.02 g/cm^3) and distinguish with confidence the border between air and fresh fallen snow at a density of about 0.08 g/cm^3.

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FMCW Radar Applications for Snow-Cover Studies

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The use of radars for snow-cover studies has great potential. Radars are nondestructive and can cover large areas of snow-covered terrain, making them ideal for investigating the temporal and spatial variability of snow-cover properties and processes. The most promising radar technique for snow research is the frequency modulated continuous wave (FMCW) radar. FMCW radars are inexpensive, simple to build and operate, and compact enough for field-portable applications. A modular PC-based FMCW radar system developed at CRREL has been used for a wide range of applications. These applications include 1) detection of flow channels in a snowpack, 2) snow-cover effect on radar detection of buried land mines, 3) spatial variability of polar firn stratigraphy, 4) radar–snowpack interaction as a function of radar bandwidth, 5) depth profile of tundra snow, and 6) clutter statistics of snow cover. A brief review of these applications is presented to demonstrate the versatility of FMCW radars for snow-cover studies.

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Some Results of the Investigations of the Physical Properties of Snow in the Mountain Regions

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Investigations of the physical properties of snow cover began at the end of the 1950s, and now vast amounts of information presenting a definite interest have been compiled. A great part of these investigations is devoted to the determination of the snow strength characteristics in the prospecting pits. These observations were being conducted on the stationary platforms (in the snow avalanche stations) and were used for determination of the snow cover stability while determining avalanche vanishing time.

During the first years of these observations, analyzing such parameters as temporary shear and rupture strength was revealed that made the use of the obtained data in the analysis difficult. Accordingly, apart from the differential estimates of the snow bed stability, experiments on the study of snow acoustic characteristics and their correlations with bed strength on the mountainside have been carried out during some winter seasons. The results of these experiments raised our hopes, giving the integral of the snow cover stability on a great part of the area. It was established that, depending on snow stressed state, intensity of snow acoustic emission can define a decrease rate of snow cover stability that is illustrated by reduction rate of snow depth strength as a rule on its weaker level. Besides the given estimates during some winter seasons, the experimental data of the snow sliding and sedimentation have been obtained. The snow cover temperature observations form a large scope of the work; more informative are the observations conducted by the thermostationary plants. These observations have made it possible to draw a number of the important conclusions, the most considerable of which are the following:

1. Temperature measurement in the beds is good to work on by means of the multidimensional statistic analysis using density, depth of the thermometer setting, and so on.

2. Temperature investigations allow a conclusion about the predominant type of the snow metamorphism (recrystalization) in the conditions of Uzbekistan. Sedimentation is a type of metamorphism. Constructive metamorphism snows only in definite years (on the average once in 8–12 years) and to a great extent has a local character.

The information gained from studying such snow properties as sedimentation and sliding makes it possible to solve the different problems, not only in the regional aspect, but also generalizing the results of the studying of snow physical properties.

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The Basic Regularities of Acoustic and Elastic Property Changes during Snow Densification

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The structure-texture transformations that occur during dry snow densification and diagenesis cause changes in acoustic, elastic, strength, thermal, and other properties. The direct experimental study of these transformations is rather difficult. The acoustic and elastic parameters of snow are very sensitive to structural organization of porous media and can serve as the instrument of their investigation. In this paper the result of analysis of experimental data on acoustic parameters and dynamic elastic moduli of dry coherent snow-ice formations in the their whole density range and obtained basic regularities of its changes during densification are presented and discussed.

As the base of analysis we used the published data of different authors (density of snow from 350 kg/m^3 up to massive ice, 917 kg/m^3) as well as our own (snow density from 50 kg/m^3 to 500 kg/m^3) on the elastic wave velocities from ultrasonic and seismic field experiments. The tentative analysis of these data has led us to conclude that snow–ice formation acoustic property changes in their whole density range cannot be described satisfactorily by certain smooth functions of porosity (or density), including a polynomial of reasonable degree (up to fifth). Our work conception implies first that during snow densification and metamorphism the changes of it acoustic properties should not be monotonous in the wide density range. This circumstance reflects the peculiarities of snow medium structure reorganization. Secondly, that the structure of snow in passing from one transitive state to another should have one more perfect state with statistically dominant coordination number of medium grain packing corresponding to new space order. We also established that better comparative parameter, which enables more precisely approximates the laws of acoustic and elastic property changes, is porosity factor K_p, which we use in our further analysis.

The detailed analysis of experimental data permits us to reveal that there is a set of critical densities: 150, 340, 550, (~710), and 830 kg/m^3, at which there are sufficiently abrupt changes of laws of variations of acoustic parameters and elastic moduli of snow. These critical densities, corresponding to their porosities, limit the subranges in which a medium structure reorganization is conditioned by different dominant mechanisms. As obtained by us from analytical modeling, these densities correspond to different values of prevailing coordination numbers of snow-ice medium grain packing: 3, 4, 6, [8)], and 10–12, respectively). The empirical equations describing the dependencies of elastic wave propagation velocities (V_p and V_s), acoustic resistivities, and elastic moduli changes as the functions of porosity factor are obtained for five corresponding subranges in the density range from light snow to massive ice. The conception of transitive states and the data on critical densities are useful for comprehension of the correct route to study and examination of various snow physical properties that are necessary to solve some problems of snow hydrology, snow cover dynamics, melting, etc.

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Operational Use of the New Swiss SNOWPACK Model: A Method for Improved Winter Precipitation Estimates at High Alpine Sites

Michael Lehning[1] and Perry Bartelt[1]

The new SNOWPACK model developed at the Swiss Federal Institute for Snow and Avalanche Research is a 1D momentum, mass, and energy balance model. Its current version includes important features such as a numerical solution of the instationary heat transfer and creep/ settlement equations, a complete surface energy balance, phase changes, water transport, and snow microstructure development (metamorphism). The microstructural parameters are linked to the thermal conductivity and the snow viscosity. The Lagrangian finite element solution allows for a realistic representation of the layered snowcover structure.

The model is already in operational use. It calculates the local snowcover characteristics for approximately 40 automatic Swiss high alpine snow and weather stations located at altitudes between 2000 and 3000 m a.s.l. The stations provide the necessary model input air temperature, humidity, wind speed, surface temperature, reflected short wave radiation, and total snow height. These remote stations operate autonomously on solar energy. The main purpose of the stations and the associated model calculations is to provide weather and snowcover information to the avalanche warning service. One of the key parameters for avalanche warning as well as hydrology is the amount of new snow deposited during a certain time interval. Because only the total snow height is measured and no direct precipitation measurements are possible (no external power supply), the precipitation rate is calculated from the increase in the snowcover height, taking into account the modeled settlement rates of the snowpack. This requires a sophisticated data control routine because the snow height measurements are often erroneous. In addition, a model for the estimation of the new snow density is necessary. The method has been implemented into the SNOWPACK model and evaluated against measurements at the Weissfluhjoch experimental site.

The evaluation has been carried out for the winter seasons 96/97 and 97/98. The estimated amounts of new snow from the model as well as the modeled total water equivalent have been compared against manual measurements of new snow amounts (daily) and total water equivalent (twice per month) and against the automatic measurements from the standard precipitation gauge as used by the Swiss Weather Service. The gauges are especially equipped for high alpine snow precipitation. Without any parameter fitting, the agreement between the model estimates and the manual measurements is very good, while the automatic precipitation measurements typically underestimate the precipitation by 30%. We conclude that our method to combine controlled measured snowpack heights with our density estimation plus the modeled snowpack settling gives reliable winter snow precipitation rates with a high temporal (30 minutes) and spatial resolution at high alpine sites. Such information is desperately needed by hydrologists, meteorologists, and avalanche specialists, but could not be obtained with conventional methods until now.

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Posters:

Chemical Processes in the Seasonal Snow Cover

Nitrogen Dynamics in Paired High Elevation Catchments during Spring Snowmelt 1996, Rocky Mountains, Colorado

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Alteration of the nitrogen (N) cycle is a concern in high elevation ecosystems of the western United States due to the potential adverse effects of atmospheric N deposition on aquatic and terrestrial resources. Surface waters in the Rocky Mountains are especially sensitive to small changes in N deposition, most of which is deposited in seasonal snowpacks. Isotopic analyses have shown that the majority of N in the snowpack enters soil inorganic N pools during spring snowmelt before being transported to the stream. It has been suggested that the export of N in streamwater is regulated by microbial transformations of N throughout the winter in thawed soils beneath the snowpack. The objective of this study is to evaluate the spatial and temporal variability in N sources, sinks, and streamwater N export during spring snowmelt in two high elevation catchments. Snowpack, soil, soil leachate, and streamwater samples were analyzed for inorganic N in Snake River and Deer Creek catchments during snowmelt 1996. Both catchments are located in Summit County, Colorado, and range in elevation from 3350 to 4120 m.

Soil pools and atmospheric inputs from a melting snowpack are two possible contributors to N in streamwater during the initial phase of spring snowmelt. Soil N pools in Deer Creek and Snake River, 1868 and 1252 mg N m^{-2}, respectively, were two orders of magnitude greater than N inputs from snow, 88 mg N m^{-2}, indicating that soil N is a potentially larger source of N in surface water. Consequently, small changes in the fate of this pool may have a much larger impact on N export than changes in N inputs from snow. The potential for soils to be N sources during spring snowmelt was evaluated by the leaching of nitrate (NO_3^-). Nitrate leachate from Deer Creek alpine soils, 684 mg N m^{-2}, was significantly greater than from forest and meadow soils ($p < 0.001$). Leachate from Deer Creek forest soils was calculated at –44 mg N m^{-2}, indicating net N immobilization. This pattern of NO_3^- leachate from soils was consistent with patterns of streamwater NO_3^- concentrations along an elevational gradient. Concentrations in the alpine were highest, 0.22 mg N L^{-1}, and decreased to 0.13 mg N L^{-1} further downstream.

Patterns in streamwater N in both catchments were consistent with patterns in soil leachate, indicating that soil processes, in addition to hydrological processes, are important in controlling N export from these high elevation catchments. Soils function as both sources and sinks of N during spring snowmelt; alpine soils were a significant source of N to the stream, while forest soils were N sinks. Greatest variability in soil processes occurs in the alpine of these catchments, which until recently were also the least studied. To better understand N dynamics in these high elevation catchments, further research should be directed towards understanding variable soil processes in the alpine and their effects on N source/sink relationships during the snow-covered season.

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Variation Features of Chemical Composition in Snow Cover in the Western Part of the Tianshan Mountains, China

Wei Wenshou[1], Jiang Fengqing[1], Li Weihong[1], and Liu Mingzhe[1]

Seasonal snow cover is thick in the western part of the Tianshan Mountains, China. Its maximum depth can be up to 150 cm, and its multiyear average maximum depth is 86 cm. Because snow cover plays a unique role in monitoring environmental pollution, the western part of the Tianshan Mountains, China, is selected as the study area of the variation of chemical composition in polluted snow cover. The analysis of snow samples shows that the mean values of the main anions and cations in seasonal snow cover are 0.62–15.8 Mg/L. Generally, the ionic concentration of fresh snow is higher than that of whole snow cover (excluding Mg^{2+} and Ci^{-}). The concentration of $K^{+} + Na^{+}$ is relatively high in cations; their average values occupy 60% and 38% of the average ionic value, respectively. In anions, the content of SO_4^{2-} is obviously higher than that of other anions, which is about 60% of the total. The pH value of snow cover is about 6.5. Correlative analysis results show that snow pollution is mainly affected by continental sulfate and heavy carbonate. The analysis results of the spatial variation of anions and cations show that the ionic concentration of SO_4^{2-} and $K^{+} + Na^{+}$ has a lowering tendency with of elevation. However, it has an obvious high value in the areas where human activities are frequent. Therefore, one of the main factors causing a spatial variation of SO_4^{2-} and Na^{+} is local human activity.

The analysis results of temporal variation of anions and cations show that the variation of ionic concentration of Mg^{+} is small, and that of $K^{+} + Na^{+}$ and Ca_2^{+} is obvious. The variation tendency has a positive correlation with air temperature. This variation tendency is mainly caused by increase or decrease of dust amounts in air because most of the land surface in the study area and the Middle Asia is covered by snow during the snow-cover period. The snow reduces the amount of dust going into air while the amount of dust going into air increases along with the exposing of land surface in snow-melting season under the effect of wind, human activities, and animal movement. Except for the uncovered land surface, dried lake basins and deserts eroded by wind in the Middle Asia are the material sources of sulfates in pollutants of snow cover in the western part of the Tianshan Mountains. The variation of chemical composition in the polluted snow cover is also strongly influenced by human activities. The spatial distribution of $K^{+} + Na^{+}$, SO_4^{2-}, Ca_2^{+}, and HCO_3^{-} varies obviously in anions and cations in both fresh snow and old snow cover; the regional features are basically the same. Therefore, except for the change of natural environment, human activities are the main factors causing a high ionic concentration. Temporal variation of anions and cations in fresh snow is mainly influenced by scope, depth, and duration of snow cover, and is controlled by regional atmospheric circulation and temperature. Therefore, with a deep snow cover with an extensive distribution in midwinter, correspondingly, ionic concentration of pollutants is low.

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Using Tracers to Investigate Seasonal Variation of Flow Components in the Canadian Rocky Mountains

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The research presented is concerned with determining the usefulness of stable isotopic data for the purpose of ascertaining contributions of glacier ice melt to river flow in the Bow Valley in the Canadian Rockies. Using $\delta^{18}O$ as a tracer and simple mixing models, an attempt has been made to better understand groundwater and baseflow interactions with surface inputs of snow and rainfall and surface outputs to the river channel. The ultimate aim of this research, although not this presentation, is to produce a model of groundwater surface water interaction based largely on the hydrogeochemical data collected.

From May 1996 to November 1997, approximately 180 water samples were collected from various locations in the Bow Basin above Banff (2230 km^2). Samples of rain, snow, ice, groundwater (in the form of baseflow, springs, and from wells), lake inflows and outflows, river tributaries, and the Bow River itself have all been collected. An attempt has been made to isotopically characterize the major flow component sources of snow, ice, and rain and then both temporal and spatial patterns within groundwater and river flow samples have been investigated. It is found that increasing snow fall proportions at higher elevations lead to lighter $\delta^{18}O$ groundwater signatures. Melting of the snowpack also continues to lighten groundwater flowing from springs and extracted from deep wells into late summer. This suggests a lag time of perhaps several months for much of the snowmelt to transcend groundwater aquifers in this region. Only relatively small proportions of rainfall are found in these groundwater sources because a substantial amount is thought to be lost to evaporation and also surface runoff when the water table is relatively high.

$\delta^{18}O$ signatures of water draining both Peyto and Bow Lakes in the headwater regions display little seasonal variability, possibly suggesting a relatively high level of mixing compared to the more "piston-like" dynamics of localized groundwater. This low variability in output signature might mean that lakes display the amalgamation of all flow components all year round, i.e., they may provide an isotopic "overview" of hydrological processes upstream.

The seasonal $\delta^{18}O$ signature for the Bow River at Banff reflects the changing dominance from winter baseflow to spring melt to summer rainfall. However, near-baseflow values during the mid to late summer period of substantial rainfall has led to the hypothesis that icemelt in the headwaters during this time is buffering the rainfall signature further downstream. The results presented have provided some insight into groundwater/surface runoff processes following spring snowmelt and during summer glacial melt in a mountainous basin, but few conclusions can be drawn at this stage. It is felt that using isotopic and ionic tracers combined with other hydrometeorological mass balance techniques for the goal of accomplishing a reasonable separation of seasonal flow components, in order to quantify the relative glacial contribution, can be attained. To this end, further field work is currently being implemented to study geochemical tracers and their relation to hydrological processes in two headwater basins in the Bow Valley; one heavily glacierised and one nonglacierised.

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Hydrochemical Processes and Hydrological Separation in Headwater Basins of the Urumqi River, Tien Shan, China

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China's cultural practices and heavy reliance on coal burning have resulted in high concentrations of SO_4^{2-}, NO_3^- and H+ in precipitation both within major industrial cities and in atmospheric deposition to high-elevation areas where annual precipitation is dominated by snowfall. In other areas of the world, significant and severe ecological changes have occurred in terrestrial and aquatic ecosystems where levels of sulfur- and nitrogen-containing compounds are less than those currently existing in China. As part of ongoing efforts to fully understand the susceptibility of seasonally snow-covered alpine basins to deposition of atmospheric pollutants, the purpose of this study was to better understand the processes that control the hydrochemistry of high-elevation headwater basins within China during snowmelt runoff.

The Urumqi River Basin is located in the Tien Shan mountain range that extends from north-western China more than 2000 km westward into the republics of Kirgzhia. The research area was the headwaters of the Urumqi River, with an area of 29 km^2 above the Total Control (TC) gauging station. More intensive studies focused on two headwater basins, each about 2 km^2 in area: the glacierized Glacier No. 1 (G1) and the Dry Cirque (DC), a south-facing and ice-free cirque. Daily samples of stream water were continuously collected for solute analysis from April 30 to June 8, 1997, at TC, G1, and DC gauging stations. Snow pits were excavated and core samples were collected on June 8 at G1.

A parametric analysis for mutual regression shows that the solutes of streamflow were inversely correlated with discharge (e.g., < –0.66 for most solutes at G1) and correlated with Si (e.g., > 0.80 for most solutes at G1) within a basin, suggesting that the streamflow had strong signatures of soil-contacted water. Hydrological separations using Si as a tracer demonstrated that the soil-contacted water represented 40% of discharge at G1, 70% of discharge at DC, and 77% of that at TC. However, the release of solutes from storage in the seasonal snowpack in the form of an ionic pulse appeared to be an important process at times. For example, at G1 on May 6, 16, and 24, SO_4^{2-} concentrations were 4.65, 5.97, and 3.91 times the SO_4^{2-} concentrations at the onset of snowmelt on May 2. Similarly, NO_3^- concentrations in streamflow were as high as 3.75, 4.99, and 4.85 times the initial concentrations. Also, the ionic pulse occurred at DC, with significant peaks of Cl^-, NO_3^-, and Na+. It is suggested that both the ionic pulse and contributions of soil-contacted water are important in regulating the solute contents of the streamflow during the snowmelt season at headwater basins of the Urumqi River. At present, the resulting streamflow is not sensitive to the acidification.

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The Seasonal Snow Cover in a Small Alpine Catchment (Austria)

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From December 1996 to June 1997 the snow cover in the catchment of a small high mountain lake in the Austrian Alps was intensively investigated. Concentration and load of atmospheric trace substances in the snowpack, their temporal variability in the course of a winter, and local differences in snow and substance deposition within the watershed were the main topics of interest. The study was related to the EU project MOLAR, which investigates the dynamic response of remote mountain lake ecosystems to environmental change, and in the framework of which the input of atmospheric trace substances to the catchment (0.2-km^2 size) of Lake Gossenkölle should be determined.

Measurements were performed weekly at three selected sites between 2420 and 2510 m a.s.l. A detailed recording of snow stratigraphy, density, and temperature accomplished the snow sampling program. Snow was collected along vertical profiles at increments of 10 cm from the top of the snowpack down to the rocky bottom of the catchment. Chemical analysis comprised the determination of major ions by ion exchange chromatography, pH, conductivity, and alkalinity by Gran's titration.

Although only at horizontal distances of some 200 m, the snowpack at the three sites differed considerably in water equivalent, stratigraphy, and ion concentrations. Local differences of the water equivalent up to a factor of three by the end of the accumulation period were influenced by varying wind drift and aspect rather than by the effect of altitude. Due to the enhanced vertical mixing of the atmosphere, mean ion concentrations were about three times higher in spring than in midwinter. Peak values in April ranged from 5 to 7 µeq/L for sulfate, 11 to 17 µeq/L for nitrate, and 6 to 9 µeq/L for ammonium. However, considerably higher concentrations were found in distinct layers of March and April snow.

The poster will focus on the seasonal development of the snow cover at three sites of the catchment. It will show vertical profiles of snow temperature and ion concentrations covering both the accumulation and melting period. Effects of snowmelt on small brooks and on the lake water chemistry are considered, revealing a temporary dilution of most ions in brook and lake water. The investigation also clearly demonstrated that the selection of both date and site of sampling may strongly influence the result in respect to the measured input of atmospheric trace substances into a catchment.

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Processes of Flow and Transport in a Seasonal Snowpack and the Underlying Seasonally Frozen Soil

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The problem of contaminant movement in snowpacks and underlying seasonally frozen soils has become a relevant research topic within the last two decades. While some field studies have led to a better understanding of the complexity of flow processes in snow, for example preferential or fingered flow (Marsh 1991 and Bales 1997), the scarcity of field data limits further scientific developments related to flow and transport processes in snowpacks and frozen soils. To add to the store of available data, we performed two dye tracing experiments in the winter of 1998, one experiment on a small plot and the other on a small watershed.

On the small plot, three distinct dyes were used to trace the movement of the meltwater. The experiment was performed during the last snowmelt event of the winter, occurring in February. It was found that the transport time of dyes from the top of the snowpack to the bottom of the slope was found to range between 16 minutes for an average travel distance of 1.5 meters (the dye on the lowest portion of the plot) to 55 minutes for an average travel distance of 7.5 meters (the dye on the uppermost part of the plot). The water balance showed that the meltwater partially infiltrated the frozen soil. There is no direct relation between the recovered dye mass from the plot and the amount of water that infiltrated with the observed concentration. Possible explanations for this result are 1) the dye was adsorbed on the soil surface; 2) the dye infiltrated the soil at a higher concentration than that observed at the outlet; and 3) some of the dye never left the top of the snowpack during the snowmelt event. A simple reservoir model of the transport processes was developed and model parameters optimized to produce a good comparison between model predictions and experimental observations.

For the small watershed study, Uranine dye was applied over a 10-m^2 area at a location 200 meters upgradient of the flow measurement weir. During the final snowmelt of the winter the first evidence of the dye was found at the weir in the surface runoff at 9 days following the application of the dye. Only a fraction of the dye applied was recovered in the surface runoff. The water balance at the small watershed indicates that, like the small plot study, much of the meltwater infiltrated the underlying partially frozen soil. We are continuing to collect spring flow data at the watershed and expect that at some time the dye that infiltrated the water will eventually reach the weir.

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CO_2 and CH_4 Fluxes and Profile Concentrations in a Boreal Peatland under Varying Snowpack Conditions during the Spring Thaw, Manitoba, Canada

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Carbon dioxide (CO_2) and methane (CH_4) fluxes and profile concentrations were measured through the snowpack during the spring thaw from early April until June 1996, in a diverse peatland complex in northern Canada. The research was conducted in the Northern Study Area of the Boreal Ecosystem Atmosphere Study (BOREAS) near Thompson, Manitoba. The peatland included the full range of hydrologic, chemical, and plant community gradients typical of northern bogs and fens. CO_2 and CH_4 fluxes were extremely variable both spatially and temporally during this period. CO_2 fluxes ranging from 0 to 5 g CO_2–C m^{-2} d^{-1} were observed through the snowpack and were associated with presence or absence of ice lenses. CH_4 fluxes as high as 200 mg CH_4 m^{-2} d^{-1} were measured at the snow surface at flooded sites as the basal ice was melting. In drier hummock areas, CH_4 fluxes remained low throughout the melt period.

Profile concentrations of CO_2 and CH_4 generally increased with depth from the snow surface to the bottom of the snowpack, with the highest basal concentrations associated with the deeper snow pack. Mean snowpack densities ranged from 300 to 400 kg m^{-3} in well-developed faceted particles and cup-shaped crystals. We estimated snow permeabilities using Shimizu's (1970) empirical relationship and found that permeabilities were on the order of 400×10^{-10} m^2 and generally increased with depth. Occasionally, higher gas concentrations near the surface were found beneath less permeable ice lenses in the snow. CO_2 concentrations as high as 900 ppm were measured in the snow profile at the rich fen sites (pH 7.0) and up to 500 ppm at the bog sites (pH 3.9), indicating differences in substrate quality and decomposition potential.

Differential rates of snowmelt in microtopographic hummocks and hollows resulted in some areas of the peatland becoming a net sink of CO_2 as the higher peat surfaces were exposed and plants began to photosynthesize, while lower snow and ice-covered areas remained a source of CO_2 to the atmosphere. These highly variable carbon fluxes suggest that the quality of the snowpack, spatially variable rates of snowmelt, and timing of surface peat thaw are important to the seasonal patterns of carbon uptake and release in northern peatlands.

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Trends in Precipitation, Snowpack, Snowmelt, Soil, and Streamwater Chemistry in a Northern Michigan Watershed

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The Lake Superior Basin receives moderate atmospheric inputs of H^+, NH_4^+, NO_3^-, and SO_4^{2-}. The snowpack can temporarily store up to 50% of annual precipitation. In snow-dominated ecosystems, establishing the cause of season change in streamwater chemistry is not simple. A major source of variation is the degree to which snowmelt enters the soil. We have studied weekly precipitation, snowpack, snowmelt, forest floor percolate, soil water, and streamwater chemistry throughout winter for over a decade in the small (176 ha) northern Michigan Calumet watershed vegetated by 60- to 80-year-old northern hardwoods. In this paper, we examine physical, chemical, and biological processes responsible for observed seasonal change in streamwater chemistry based upon intensive study in water year 1997. Soils were unfrozen beneath the snowpack. Small, but steady, snowmelt occurred throughout winter. Uniform cool snowpack temperatures, and late winter increases in precipitation Ca^{2+}, NH_4^+, NO_3^-, and SO_4^{2-} concentrations and snowpack water equivalent (SWE) resulted in a high snowpack ion content late in the season followed by rapid snowmelt. Cumulative precipitation ion inputs exceeded peak snowpack content except for Ca^{2+} and Cl^-. The increased late winter snowpack Ca^{2+} and Cl^- content likely reflects increased regional use of road salt. Snowmelt ion concentrations were twice snowpack levels. Most snowmelt (90%) entered the forest floor and surface soil. During snowmelt, soil water levels rose rapidly to the surface, concentrations of base cations (C_B) declined, and NO_3^-, NH_4^++, SO_4^{2-}, and DOC increased. Soil lysimeter C_B concentrations increased with depth, but H^+, NH_4^+, and NO_3^- concentrations were <10% snowmelt levels. Linkages between soil water and streamwater ion concentrations were apparent. In shallow soils, rapid lateral movement of meltwater coupled with lesser amounts of readily weathered C_B material reduces soil water and streamwater C_B and HCO_3^- concentrations. At peak streamflow, dilution accounted for >90% of the decline in acid neutralization capacity. Increases in streamwater NO_3^- concentration before peak snowmelt and in shallow soil water during snowmelt indicate significant over-winter N mineralization and rapid NO_3^- mobilization by melt-water. The increased DOC concentrations in shallow soil water and streamwater at maximum discharge are additional indicators of high over-winter forest floor and surface soil organic minerali-zation. Streamwater $SO_4{}^{2-}$ concentration declined <10% during snowmelt. Soil desorption is the only process with the capacity to quickly provide enough $SO_4{}^{2-}$ to offset a large streamwater con-centration decline from dilute snowmelt. The watershed retained >99% of snowmelt H^+ by soil exchange, and >99% of NH_4^+ and >90% of NO_3^- by soil microbial and above-ground uptake while SO_4^{2-} output exceeded input. Mass balance analyses suggest little relationship of streamwater ion concentration and flux to precipitation or snowmelt inputs. Seasonal change in streamwater chem-istry primarily reflected hydrology, over-winter organic mineralization products, snowmelt/soil water movement of readily flushed ions and DOC from shallow soils, and mineral soil weathering when soil water was deep.

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Laboratory Studies of Snowmelt Using Stable Isotopes and Rare Earth Element Tracers

Susan Taylor[1,2], Xiahong Feng[2], and Carl Renshaw[2]

Given a snowpack of known isotopic composition, can we predict the isotopic composition of the meltwater as a function of time? Conversely, does the isotopic composition of meltwater reflect the dynamics of snowpack melting? To address these questions we are conducting laboratory experiments similar to those described by Herrmann et al. (1981); they found that the isotopic composition of the meltwater varies significantly depending upon melting conditions such as variations in heat flux. We seek to extend these results to include additional factors affecting the isotopic distribution, such as particle size distribution in a snow column.

Natural and laboratory-made snow of known isotopic composition is sieved into insulated columns and melted under controlled heat flux and temperature. To track the proportion of water originating from different layers within the column we use chemical tracers (rare earth elements) at different depths in the snow column. The concentration of the rare earth element tracers is set such that the freezing point depression is below 0.005YC. An ICP-MS is used to analyze the meltwater for the rare earth elements. Results of the laboratory measurements on the tracers will be presented.

These laboratory data will be used to interpret isotopic compositions and tracer concentrations in meltwater from lysimeters at Sleepers River watershed in Vermont and Central Sierra Snow Laboratory in California. At both sites rare earth element tracers were sprayed on the snow surface following large snowstorms.

Herrmann A., M. Lehrer, and W. Stichler (1981) Isotope input into runoff systems from melting snow covers, *Nordic Hydrology*, **12**: 309–318.

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Posters:

Biotic Interactions with the Seasonal Snow Cover

Site-Scale Ecosystem Carbon Balance Significance of Space-Based Radar Observations of Terrestrial Ecosystem Freeze–Thaw Dynamics

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Recent results from the BOREAS program indicate that mature boreal forest stands have a near-zero annual carbon flux, i.e., carbon uptake through photosynthesis nearly balances carbon release through respiration. Simulation and observation indicate significant interannual variability in carbon balance at a site. Much of this variability may be due to changes in growing season length, for which an important control is the timing of spring snowmelt and ecosystem thaw. An important step in assessing year-to-year changes in the boreal net carbon flux is to determine a method for accurately monitoring the interannual variation in growing season length. We report on initial analysis of space-borne active microwave observations, coupled with in-situ temperature and snow depth observations and ecosystem model simulations. We analyzed NASA Scatterometer (NSCAT) backscatter cross sections from 9/96 through 6/97 for three sites in the BOREAS Study Area in central Canada. The scatterometer operated at a frequency of 13.995 GHz (Ku band, 2.1-cm wavelength). The NSCAT data had 25-km spatial resolution and twice-daily temporal coverage. Our objective is to assess the utility of using radar-derived ecosystem freeze–thaw state to determine growing season length.

At the northern site the NSCAT signal showed a strong seasonality, with winter backscatter cross sections of –8 dB, versus –12 dB in early summer and fall. The southern BOREAS sites had less seasonality (–10 dB in winter, –11 dB in early summer and fall). At all three sites there was a strong shift in backscatter during spring snow melt (4–6 dB). At the southern site with the greatest fraction of deciduous cover, the NSCAT backscatter rose steadily from –11 to –9.2 dB during the spring leafout (June 1997); the more coniferous sites showed little rise during this period. All sites showed shifts in backscatter of 1 to 2 dB that were coincident with snowfall, periods of extreme cold weather ($T_{max} < -25°C$), or brief midwinter thaws. Previously developed radar freeze–thaw transition detection algorithms based on shifts in backscatter from mean summer or winter values gave reasonable results for the northern site but were not successful at the two southern sites.

NSCAT's strong spring snowmelt signal (at the beginning of snowmelt) coincided with the end of the ecosystem's steady winter respiration period; net carbon uptake by the forest ecosystem began when the snow had completed melting about 30 days later. The end of the growing season occurred in late September 1996 in both model simulations, when diurnal minimum air temperatures were consistently below 0°C. The NSCAT backscatter cross section dropped by about 1 dB at this time, but this was very near the beginning of the record. Shifts in NSCAT backscatter during the winter did not correspond to major shifts in NEE as the soils were cold and the ground snow covered all winter long.

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Seasonal Variations of Heat Balance Components over a Japanese Red Pine Forest in Snowy Northern Japan

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We observed meteorological elements and heat fluxes over a red pine forest for more than one-and-a-half years. There was significant seasonal variation in the global solar radiation, air temperature, and albedo above the forest canopy. During the spring thaw, the albedo above the forest decreased and reached a minimum value after the snow disappeared. Due to seasonal variation in the canopy structure, the ratios of insolation and wind speed at the forest floor compared to those above the forest canopy also varied. Under dry canopy conditions, the peaks of each heat balance component occurred at different times. The net radiation peaked in June, the latent heat flux peaked in July, and the sensible heat flux peaked in May. When the forest floor was snow covered, the Bowen ratio was more than 1.0 and the latent heat flux was virtually constant. The maximum ratio of sensible heat flux to net radiation also occurred during this period. This showed that the dry forest canopy was a significant heat source for the surrounding atmosphere. Potential evaporation from the forest canopy (E_p) was estimated by the Penman-Monteith method assuming a canopy resistance of zero. The ratio of total evaporation from the dry canopy (E) to E_p is the evaporation efficiency. The seasonal change in evaporation efficiency was similar to that in the air temperature above the canopy. When the daily air temperature was above 10°C, the evaporation efficiency and saturation deficit were negatively correlated. However, below 10°C this relationship disappeared. Snow cover also affected the relationships between evaporation efficiency and meteorological conditions. With snow cover, the evaporation efficiency increased as the air temperature decreased or the wind speed increased. In non-snow-cover conditions, however, evaporation efficiency decreased as the air temperature decreased or the wind speed increased. This was caused by properties of the snow cover. Furthermore, the relationship between the evaporation efficiency and the global solar radiation depended on the air temperature. If the air temperature was below 10°C, the global solar radiation increased the evaporation efficiency.

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Snow Accumulation and Ablation on Boards of Different Sizes and Shapes

Rolf Pfister[1] and Martin Schneebeli[1]

Snow accumulation and ablation on trees play a major role for the structure of the snow cover in snow hydrology and for protective effects of boreal and subalpine forests against avalanches. To better estimate this impact we examined the processes of snow accumulation and ablation on boards of different sizes and shapes. Boards were selected because real branches are too difficult to measure and model the complicated processes of interception. For this purpose we exposed the boards to natural and manmade snowfalls. After each snowfall, we measured the accumulated snow water equivalent on the boards as well as different snow characteristics and meteorological conditions. To investigate the ablation processes, we exposed the boards in an environmental chamber that allowed us to control the temperature and the short- and longwave radiation.

The observed snow interception efficiency increased with board width for snowfalls at a mean air temperature below –3°C. This is explained by the decreasing rebound of the snow crystals near the border. At temperatures above –3°C the snow interception efficiency was independent of the board width. The bridging of the snow between boards increased strongly for snowfalls at higher temperatures close to the melting point. For wet snowfalls bridging occurred even at distances of 10 cm between boards. The inclination and the shapes of the boards had a significant influence on the amount of accumulated snow. Based on the measured accumulation and meteorological data, we derived statistical models for the accumulation of snow. In addition to precipitation, the maximal wind speed exerts a significant influence on the snow accumulation.

In the environmental chamber we determined the sublimation rate in relation to different temperature and radiation regimes. We calculated sublimation with a physical model based on the sublimation rate of a single ice sphere and a model of the exposed numbers of ice crystals. Under action of a light source that emits short-wave radiation similar to the sun, we observed an increased sublimation rate compared to the model. The shortwave radiation transmitted through the snow and the subsequent absorption by the boards caused a substantial heating of them and accelerated the sublimation rate.

Our investigations showed that size and shape of branches are essential for snow interception, especially for snowfalls at cold air temperatures. The next step will be to transfer the accumulation models to real branches and trees, considering the particularities of bending branches and the wind influence. The incident solar radiation is an important energy source of ablation processes and consequently has an important influence for the snowpack and hydrology in forested areas.

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Snow Algae and Air Pollution in the Krkonoe Mountains

Milena Kocianova[1] and Helena Tursova[1]

The Krkonoe Mountains represent the Hercynian middle mountains of central Europe with a unique landscape system of arctic-alpine tundra displaying affinities to both subarctic and high mountain regions.

Although the intensive natural-historical explorations of this area have been carried out for nearly 200 years, the occurrence of snow algae was reported in 1976 for the first time. Since 1986 the presence of snow alga *Chlamydomonas nivalis* has been validated on the polluted thawing margins of the spring firn snow fields on open areas every year. The green, ochre, or pink spots (alga sp. *Chloromonas pichinchae*) on the spring firn snow patches contaminated by dust and needles of *Picea abies* appear rarely, while the colorless cryophilic fungus *Chionaster nivalis* is frequent.

The striking repeated occurrence of snow algae on the snow field margins contaminated by dust pollutants (accumulated by meltwater) and severe increase of air pollutants since the late 1970s suggest a possible interdependence of both these phenomena. The fir analysis demonstrates that Ca^{2+}, Mg^{2+}, Cu^{2+}, Fe, and SO_4^{2-} are the most abundant elements of the snow with alga *Chlamydomonas nivalis.*

The contents of the pollutants in snow cover depend on the kind of precipitation and interaction of precipitation with the tissue of trees. Two to four times higher concentration of pollutants in horizontal precipitation (rime, icing) has been detected than in the snow profile. This phenomenon could affect the occurrence of alga *Chlamydomonas nivalis* in the alpine area. The interaction of precipitation with the tissue of trees (needles, wood) evokes different contents of chemical substances in snow cover in a woody area compared to a free area and could affect the occurrence of alga *Chloromonas pichinchae*.

Theoretical dependence of occurrence of snow algae on the pollutants can be proven or refuted only by direct monitoring in coming years.

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The Influence of Snow Cover on Soil Solution Chemistry: Preliminary Results of the Soil Freezing Experiment at the Hubbard Brook Experimental Forest, New Hampshire

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Snow depth strongly influences soil temperature, root and microbial dynamics, soil solution and stream water chemistry, as well as soil–atmosphere trace gas fluxes. A lack of snow cover is hypothesized to cause the following: 1) colder soil temperatures, 2) an increase in the severity and vertical extent of soil freezing, and 3) increased occurrences of freeze–thaw cycles. Previous studies have suggested that soil freezing can result in root and microbial mortality, which releases labile N and C to soil, resulting in increased rates of net mineralization and nitrification. Soil freezing can therefore accelerate the input of nitrate and dissolved organic carbon to soil solutions, causing mobilization of cations and drainage water acidification. The soil freezing experiment at the Hubbard Brook Experimental Forest examines the role of snow cover in fine root dynamics, microbial C and N dynamics, soil solution chemistry, and soil–atmosphere trace gas fluxes. This role is elucidated by comparisons between reference (no snow removal) and treatment (snow removal throughout winter) plots. The soil freezing experiment therefore integrates physical, chemical, and biological processes. This report from the soil freezing experiment focuses on the influence of snow cover on soil solution chemistry and incorporates lysimeter data from the first winter of the experiment (1997–1998). We hypothesize that soil freezing will result in greater nitrate, dissolved organic carbon, calcium, potassium, hydrogen ion, and inorganic monomeric aluminum concentrations and lower acid neutralizing capacity in soil solutions of treatment plots as compared with reference plots.

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Posters:

Distributed Snowmelt Models

The ABCs of Snowmelt: A Topographically Factorized
Energy Component Snowmelt Model

Kevin S. Williams[1] and David G. Tarboton[2]

Because of the crucial role snowmelt plays in many watersheds around the world, it is important to understand and accurately quantify the melt process. As such, numerous mathematical models attempting to describe and predict snowmelt have arisen. There are two main categories of models: conceptual index models and more intricate energy balance models. The index models, like the degree-day or radiation index models, are practical enough for use in large basins for operational purposes; the energy balance models, though they are complicated and require large amounts of data, can represent the physics behind melt and give more accurate representations of the spatial distribution of melt within small research basins. The ABC model presented here attempts to bridge the gap between these two extremes by providing a simple yet physically justifiable method that uses elevation and radiation indices together with some measurements to distribute melt over a watershed. This new model separates the energy that causes snowmelt into three components: a spatially uniform component, a component that is proportional to elevation, and one that is proportional to solar illumination (which is determined by topography). Measurements of snowmelt at several topographically unique points in a watershed are related to elevation and solar illumination through regression in order to factor the melt energy into the three separate components at each time step. Then the spatial patterns of solar illumination and elevation are used together with these regressions to determine the spatial distribution of melt over the whole watershed. Field data supplemented with synthetically generated data are used to test the model.

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Terrain Characteristics and Snow Cover Variability in Mountain Areas: An Example from the Spanish Pyrenees

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An evaluation of the spatial variability of snow water equivalent (SWE) in a small headwater basin in the Spanish Central Pyrenees is presented here. This work constitutes the first stage of a project whose overall objectives are to assess the causes of spatial variability in snow processes in mountainous environments, and to parameterize this variability into hydrological models in a physically based manner in order to assess its hydrological effects.

Continuous monitoring of meteorological and flow data has been carried out at the experimental site since 1984. In addition, intensive field campaigns took place during the 1997 and 1998 melt seasons, involving approximately weekly sampling of snow depth and density at a large number of points throughout the basin.

As a preliminary exploration of the causes of the observed spatial variability in SWE within the basin, the strength of relationships between observed SWE and a number of terrain characteristics was evaluated. These terrain characteristics, elevation, slope gradient, aspect and curvature, and deviation of pixel elevation from a neighborhood mean elevation, were derived from a 1-m resolution basin DEM. A simple terrain-based model of potential direct solar radiation input, taking into account slope gradient aspect and topographic shading, was also constructed. It was found that characteristics describing slope form (slope curvature, and deviation of pixel elevation from neighborhood mean) exhibited the strongest relationship with the spatial distribution of SWE, suggesting a topographic control on snow accumulation and redistribution. SWE distribution also displayed a secondary, but nonetheless significant, correlation with potential direct solar radiation input, demonstrating a topographic control on energy inputs during the melt season.

Scale effects were also evident, with stronger relationships between observed SWE and areal averages of the key terrain characteristics described above than for raw pixel values. This would seem physically reasonable, because snow accumulation tends to smooth out small-scale terrain variability. In addition, snow cover, by virtue of its high albedo, also promotes reflection of radiation from adjacent terrain, thereby reducing small-scale variability in solar radiation flux density.

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Modeling the Spatial Distribution of Snow Water Equivalence and Snowmelt in Mountain Basins

Don Cline[1] and Kelly Elder[2]

Two models based on very different methodologies are used to investigate the spatial distribution of snow water equivalence (SWE) in two mountain basins. The first model (SWETREE) uses binary decision trees (regression trees) to relate physically based independent variables (net solar radiation, topography, soil and vegetation cover types) to ground measurements of SWE in order to interpolate SWE across a gridded domain. The second model (SNODIS) estimates the spatial and temporal distributions of both SWE and snowmelt *post facto* at the end of the snowmelt season using a coupled remote sensing/spatial energy balance approach. Gridded fields of meteorological variables needed to compute the snow surface energy balance are estimated from micrometeorological data collected within each basin, and time series of remotely sensed snow cover are used to determine how long snow remains on each grid cell through the melt season. In this study, the two models are applied in the Green Lakes Valley and the Loch Vale Watershed, both located in the Colorado Front Range of the Rocky Mountains. Extensive field observations of SWE in these basins are used to evaluate the model-estimated SWE distributions. The SWE results from the two models are compared to help understand relative strengths and weaknesses of these different approaches to estimating SWE, and to identify how the two models could potentially be used in combination for operational forecasting purposes.

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Methods for Developing Time-Series Climate Surfaces to Drive Topographically Distributed Snowmelt Models

David Susong[1], Danny Marks[2], Tim Link[3], and David Garen[4]

Topographically distributed snowmelt models can accurately simulate both the development and melting of a seasonal snowcover in mountain basins. To do this they require time-series climate surfaces of air temperature, humidity, wind, precipitation, and solar and thermal radiation. If data are available, these parameters can be adequately estimated at time steps of 1–3 hours. Unfortunately, climate monitoring in mountain basins is very limited, and the full range of elevations and exposures that effect climate conditions, snow deposition, and melt is seldom sampled. Detailed time-series climate surfaces have been successfully developed using limited data and relatively simple methods. We present a synopsis of the tools and methods used to combine limited data with simple corrections for the topographic controls to generate high temporal resolution time-series images of these climate parameters. Methods used include simulations, elevational gradients, and detrended kriging. The generated climate surfaces are evaluated at points and spatially to determine if they are reasonable approximations of actual conditions. Future methods development is discussed in light of increasingly complex methods of parameter estimation. Recommendations are made for the addition of critical parameters and measurement sites into routine monitoring systems in mountain basins.

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Statistical Analysis of Sierra Nevada Snowpack Accumulation Trends

Tammy Johnson[1], Jeff Dozier[2], Joel Michaelsen[3], and Peter Fohl[4]

Most of California's water resources accumulate within the snowpack on mountains until it melts, usually in the spring. Several investigations on the subsequent streamflows indicate that the amount and timing of this fresh water supply is changing. This study uses a statistical model that links snow water equivalent (SWE) measurements over a 60-year time-series to clarify the spatial characteristics of snow accumulation trends in the Sierra Nevada.

Data difficulties include inconsistent monthly sampling, added and removed stations, and possibly a few moved or otherwise altered snow courses. To determine the effects of a monthly and irregular sampling schedule, we analyzed daily snow sensor data spanning 28 years. Furthermore, we employed a statistical test to check for possibly discontinuous snow course stations.

Results are presented for seasonal maximum and monthly changes by river basin groupings and range-wide elevation bins. Time-series regressions on station data from individual river basins below 2400 meters consistently indicate less maximum SWE or no change. Basins above 2400 meters indicate greater variability, with most showing increasing maximum SWE trends and earlier melt. Snowmelt timing changes were more obvious in the lower elevations. All 15 river basins below 2400 meters estimated earlier maximum SWE timing, with 9 trends supported by 95% confidence.

We found a strong linear elevational component to monthly SWE accumulation trends. Below 2400 meters, a range-wide average indicates that 14% less SWE is accumulating and it is melting a week earlier per 50 years. Five of the 10 lowest elevation bins' trends are supported with 95% statistical confidence. Higher elevations exhibit greater variability, with stations averaging 8% more SWE per 50 years, while snowmelt timing tends to occur earlier.

Monthly analyses show that higher elevation changes are due to 18% increased snow accumulation in February, as measured on March 1. This extra SWE persists through the April 1 measurements but by May 1 higher elevation SWE levels are decreasing by 13% per 50 years. Lower elevation SWE levels are decreasing each month: down 7% on February 1, 11% on March 1, 19% on April 1, and by 33% on May 1 per 50 years. This could be the result of warmer air masses having higher moisture contents. These observations support doubled-CO_2 model predictions for precipitation and temperature patterns in the Sierra Nevada.

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An Elevation-Dependent Snowmelt Model for Upland Britain

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An elevation-dependent snowmelt forecasting model, combining a rainfall–runoff model with a snowmelt module, is investigated for use in upland Britain. Here, the dynamic nature of snow cover, and the occurrence of heavy rain along with melt, can exert a considerable influence on major floods. The model comprises the PACK snowmelt model linked to a lumped conceptual rainfall–runoff model, the PDM (Probability Distributed Moisture) model. The PACK snowmelt module conceptualizes the lying snow as being made up of dry snow that has yet to melt and wet snow that has melted but is still held in the snowpack. When the temperature is above the melt threshold the dry snow melts at a rate proportional to the temperature excess above the threshold and contributes to the wet snow store. Water is released from the wet snow store at a rate dependent on the proportion of the pack that is melted snow, and is transformed into flow at the basin outlet by the rainfall–runoff model.

The variation of temperature in a catchment with elevation and its effect on melt can be incorporated into the model by partitioning the catchment into a finite number of elevation zones. Model performance is generally improved through the use of more zones. This result prompted the development of a snowmelt model that can use either a near-continuous distribution or a finite number of elevation zones derived from a digital terrain model (DTM). The new formulation allows the evolution of the snow line over time to be determined along with the water equivalent of the pack and the discharge at the basin outlet.

The new snowmelt model is tested on two upland catchments, Monachyle Burn in Scotland (11.4 km^2) and Trout Beck in Northern England (7.7 km^2). Excellent predictions of flow are obtained for both catchments with R^2 values of circa 0.9. A sensitivity study of the accuracy of flow simulations to the number of elevation zones employed suggests using a 30-m elevation range for a zone as a conservative choice. Observations of the position of the snow line in the Monachyle compare very well with model predictions (R^2 values of 0.74 and 0.66 for two snowmelt periods). An assessment is made of the use of daily snow survey and hourly snow pillow measurements for updating the Trout Beck model. The results suggest that the pillow data, if used with care, can provide as good if not better flow predictions. However, there is a tendency for snow to melt preferentially from the pillow compared to the surrounding vegetation.

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SNOWTOOLS—A European Project for Research and Development of Remote Sensing Methods for Snow Hydrology

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SNOWTOOLS is a European Commission Environment & Climate Program research and development project. The main objective is to develop methods for the extraction of snow parameters from optical and microwave remote sensing data. Based on interviews of various user groups, ranging from hydropower industry and water management to climatology, a set of snow products has been defined. The products include snow-cover area, snow water equivalent, albedo, snow wetness, snow surface temperature, and snow depth. The spatial resolution of the products is 250 and 500 m, and the required delivery time is between 2 and 24 hours for most products. The product specification is used as a "driving force" for development of algorithms.

A comparison between the products defined and the state of the art of snow mapping has resulted in recommendations for further research. For optical remote sensing of snow, research is mainly recommended for subpixel classification of SCA; modeling and compensation for temporal, topographic, and anisotropic reflectance effects; and compensation for vegetation/forest. For SAR, more research is needed on capability to measure snow-covered ground and melting snow, effects of vegetation, use of polarimetry, combined use of various frequencies, and use of SAR interferometry. Similarly, for PMR: Algorithms for multitemporal and low and high frequency data; effects of mixed signatures, vegetation, atmosphere and rugged terrain; investigation of error sources; development of new algorithms for the water equivalent retrieval; and assessment of interpolation techniques.

Two dedicated remote sensing experiments, one for mountainous basins and one for boreal basins, are carried out for both the development and validation. The mountain basin field campaigns in 1997 and 1998 have established a multitemporal/multisensor data set for algorithm development, including ERS, RADARSAT, Landsat TM, and DAIS airborne spectrometer data.

SAR data from the EMAC '95 campaign is also analyzed in the project. Three combined remote sensing and ground data acquisition campaigns were conducted in March, May, and July 1995. Several ERS-1 and EMISAR C- and L-band full polarimetric scenes were obtained from the test site. The extent of a wet snow cover observed by EMISAR C-VV corresponds to optical airborne measurements. Results show that C-band polarimetric data from March, when the content of free water in the snow was in the range 1–3%, are affected by the underlying vegetation. Discrimination between bare ground and snow is exceptionally good for wet snow.

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Distributed Mapping of Snow and Glaciers for Improved Runoff Modeling

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Runoff in glacierized alpine basins results largely from glacier ice and from seasonal snowcover. In general, snowmelt starts with melting the upper snow layers; the main runoff does not results until the whole snowpack is saturated with moisture. Glacier ice shows a completely different behavior: as soon as bare ice becomes exposed, runoff results. Considering time and behavior of melting, we aim at a separate simulation of snowmelt and glaciermelt runoff.

The condition in our approach for distributed runoff calculation is a distributed mapping of snow- and ice-covered areas. Due to high resolution satellite sensors, it was possible to map snow-covered and ice-covered areas in the basin of Massa-Blatten, 196 km (1447–4191 m a.s.l.). Depletion curves of snow-covered areas were derived in six elevation zones. In addition, the date was determined when the glaciers' ice became exposed. Melt depths were computed separately based on experimental measurements with regard to snow and ice.

With the use of the snowmelt runoff model SRM-ETH, the following input components to runoff were determined: seasonal snow cover, including new snow falling on the snow-covered areas, new snow falling on the hitherto snow-free area, rain, and glacier ice. In order to evaluate the effect of the refined snow and glacier mapping on detailed melt computations, the runoff was computed resulting from i) the conventional runoff simulation based on integral snow and glacier areas and from ii) an advanced simulation taking into account the individual contributions from snow cover and glacier melt. A significant improvement of the accuracy of the runoff simulation was achieved.

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Ten Years of Monitoring Areal Snowpack Using NOAA-AVHRR Radiometry and Ground Measurements in the Southern Alps

Roberto Ranzi[1], Giovanna Grossi[1], and Baldassare Bacchi[1]

Cost-efficiency and fine temporal resolution of images from the satellite-borne NOAA-AVHRR sensor indicate this source of information as a suitable candidate for monitoring snow cover in alpine areas. This is important for the estimation of the water storage at the beginning of the snowmelt season especially in view of irrigation, hydropower production, and water supply. The information can also be used for the "internal" validation of snowmelt models. As a result of a long-term study, ten years of snow cover area depletion curves have been estimated using remote sensing in seven watersheds of size larger than some hundreds of square kilometres in the Southern Alps.

Coupling of satellite imagery with detailed topographic data and some ground measurements of snowpack depth and density is shown to provide reliable regional estimates of snow water equivalent in the Southern Alps. The study area (15809 km^2) includes the major left-side tributaries to the Po river, from the Sarca to the Ticino river, thus covering part of the Trentino-Alto Adige, Lombardia, and Piemonte Regions in Italy and Switzerland. NOAA-AVHRR images are used for estimating the extension of snow cover, and cloud cover is filtered out by using the relationship between snow cover and topography. For the purpose, we used automated topographic data retrieved from a Digital Elevation Model (DEM) with space gridding of about 230×230 m^2 and resampled with a 250- $\times$ 250-m^2 grid spacing.

The validation of the distributed technique is carried out by comparing the basin estimates it provides with those obtained from the lumped water balance equation in some of the selected watersheds, computed for different snowmelt seasons. The satellite-based procedure is shown to result in a slight underestimation of the water balance-based estimate of the water equivalent.

In spite of many uncertainties and open problems, remotely sensed data seem to provide realistic estimates of snow water equivalent on alpine watersheds when ground measurements are available, and topographic effects are properly accounted for. The long-term statistics of the presence of snow in different altitude and aspect zones that can be derived using the proposed technique might provide useful information for the management of water resources and also for studying physical, chemical, and biological processes in mountain areas.

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A Simple, Computationally Efficient Distributed Snowmelt Runoff Model for Use on Large Basins

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There is a strong trend toward development of physically based, fine-grid distributed models for estimates of snowmelt runoff under varying hydrological conditions. The physical basis of these models is an improvement over simple degree-day models; however, the complexity necessary in their design has also led to major disadvantages in their practical application. These models have difficulty in producing continuous streamflow hydrographs for entire years or snowmelt seasons because of complex linkages between various hydrological processes that are amplified by the fine grids used and the need for large basins, e.g., >1000 km^2. It is easier to produce model-generated snow water equivalent maps for a basin, and these are sometimes used as the end product. As a result, the model produced output is often compared with other simulated data and not with actual streamflow. Because a number of authors have shown that complex models do not outperform simple hydrological models, it seems that some range of snowmelt runoff models is necessary for various applications. That range should include simple degree-day models on one end and complex fully distributed physical models at the other extreme. In between, there may be a valuable niche to be filled by a simple, computationally efficient but distributed snowmelt runoff model able to produce continuous hydrographs with a daily timestep on large river basins. Such a model has been designed as a modification to the widely used degree-day-based Snowmelt Runoff Model (SRM). The so-called radiation version of SRM is a distributed model using hydrological response units (HRU). It requires input of temperature, precipitation, snow-covered area, and net radiation (or cloudiness, humidity, and pressure to estimate net radiation) to HRUs based on elevation and aspect. It can use remotely sensed snow-cover extent data directly from existing World Wide Web sites. As with the original SRM, the model produces continuous hydrographs and operates very rapidly on a personal computer. Although more complex in a number of ways than the original SRM, it is also somewhat easier to apply because some elements of user hydrological judgment have been eliminated. Examples of input requirements, output on a variety of basins, and resulting hydrological responses to climate change scenarios are provided for the radiation version of SRM. This new version of SRM provides an intermediate type of snowmelt runoff model that may find significant applications in snowmelt streamflow forecasting and evaluations of hydrological response to climate changes. It would be useful to perform an intercomparison of snowmelt runoff models covering a full range of complexities for streamflow forecasting or climate change evaluations.

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Distributed Simulation of Snowcover Mass and Energy Balance in the Boreal Forest

Timothy Link[1] and Danny Marks[2]

The accurate distributed simulation of snowpack deposition and ablation beneath forest canopies is complicated by the fact that vegetation canopies strongly affect the snow surface energy balance. The canopy alters the radiation balance of the snowcover and reduces the wind speed at the snow surface. Simple canopy adjustment algorithms for solar and thermal radiation and wind speed are used in conjunction with topographically corrected radiation estimates and commonly available land-cover classifications (canopy species and height) to distribute subcanopy solar and thermal radiation, air and soil temperature, humidity, wind speed, and precipitation. The spatially distributed climate surfaces are used to drive a 2-layer coupled energy- and mass-balance snowmelt model over the BOREAS northern and southern study areas for the 1994–1995 snow season. Model results are validated using both automatic and manually collected snow-depth data. The simulated timing and rate of snowpack development and ablation at both study areas are well represented beneath the canopy types where validation data are present.

Results from the distributed snowcover simulations indicate that canopy structure can delay seasonal snowmelt in forested areas up to three weeks, relative to open areas. The differences primarily result from net snowcover radiation variations attributed to altered solar and thermal radiation regimes beneath forest canopies. Variations in snowmelt also result from differences in turbulent heat fluxes caused by reduced windspeeds within forest canopies. Other ablation differences arise from subtle topographically controlled radiation variations. Rigorous evaluation of model performance beneath the full range of canopy types requires information regarding the spatial distribution of snow-covered areas during the ablation period. This study demonstrates that given basic landcover parameters, relatively simple canopy adjustments coupled with an energy balance model can be used to estimate climate conditions and snowcover processes over heterogeneous boreal regions.

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Characterizing Wind-Induced Snow Redistribution with Digital Terrain Analysis to Enhance Spatial Snow Modeling

Adam Winstral[1], Kelly Elder[1], and Robert Davis[2]

Snowmelt runoff forecasts form the foundation of agricultural practices, flood forecasts, and reservoir management for temperate mountainous regions throughout the world. Accurate geographical assessment of on-the-ground snow water equivalence (SWE) is the foundation for physically based runoff modeling.

Previous work has documented a distinct decrease in the strength of the physical relationships between modeled basin parameters (i.e., elevation, net radiation, and slope) and measured snow accumulations above timberline. This reduction is attributed to the effects of wind-induced redistribution above timberline, which heretofore have not been accounted for in modeling efforts. We attempt to characterize the effects of wind-induced snow redistribution through the use of two GIS-derived terrain parameters in our models of distributed SWE in the Tokopah Basin, a headwater catchment of the Kaweah River, California. The study basin encompasses an area of 19.1 km^2 with elevation ranging from 2630 to 3495 m. The research area is in the alpine zone; 88 percent is classified as void of canopy cover, 10 percent as containing 1–9 percent canopy cover.

The cosine of the angle between the zenith and the local horizon, and a directionally constrained average slope gradient are focused on the predominant upwind direction in order to define the degree of exposure or sheltering for a given site. The average slope gradient takes on both positive and negative values based on the elevation difference weighted by distance of cells located within a user-defined area, and the cell of interest. These redistribution parameters are individually regressed on observed SWE to determine their applicability in further modeling. Regression trees that include and exclude the redistribution parameters are then constructed and compared, based on the observed accumulation patterns from snow surveys collected in April 1997 and May 1998.

Regression models that include redistribution parameters have a better fit to the observed snow distribution than those formulated with just the elevation, net radiation, and slope predictors. The difference between the models was small for the 1997 survey, considerable for the 1998 survey. The similarity of the 1997 models coincides with that year's climatic factors, which restricted the amount of snow available for redistribution. Individual parameter analyses found strong agreement between the redistribution parameters and observed snow accumulation and direct correspondence with sub-basin specific wind patterns. Though the radiation index and redistribution parameters are correlated due to the strong southerly component of local winds, the overall evidence indicates that the employed redistribution parameters do approximate the effects of wind-induced snow redistribution and did improve basin-wide models of snow distribution.

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A High-Resolution Distributed Snowmelt Model in an Alpine Catchment

Michael Colee[1, 2], Robert Harrington[3], Thomas Painter[1, 2], and Jeff Dozier[1, 2, 4]

Spatially distributed estimates of snow cover and snowmelt and understanding the processes governing them are increasingly important for a variety of applications from hydrologic and land use change models to landscape evolution and climate change models. A physically based snowmelt model, SNTHERM, is run for each 30-m pixel in the Tokopah Valley, an alpine catchment in the Sierra Nevada of California. The catchment is approximately 1900 ha, roughly 75% of which is above timberline. Soil and vegetation classifications of two sub-basins within the study area were done; the soil classification was field based and the vegetation classification was based on aerial photo interpretation. These surfaces were then used to select spectral endmembers for classification of soil type and vegetation cover using a snow-free AVIRIS scene of the area. Three field surveys during April, May, and June of the 1997 melt season obtained depth and density measurements of the snowpack suitable for estimating the distribution and ablation of snow water equivalence (SWE) for the basin. The April and May datasets are used here for model initialization and validation, respectively. The initial snow surface was interpolated from a gridded field survey of 429 depth and 8 density samples distributed over the area with the krigging method. Initial snow-covered area (SCA) was derived from TM data and albedo was derived from AVIRIS data. Clouds obscured the study area in the April AVIRIS scene. Therefore, albedo values from proximal cloud-free areas outside the study area were mapped into the basin. Temperature, relative humidity, and wind speed were distributed over the basin based on observed lapse rates using a least squares fit calculated at hourly timesteps from three stations within the basin. Hourly radiation inputs to the model were calculated with the topographically corrected clear-sky radiation model, TOPORAD, and adjusted for cloud cover based on measured solar and longwave radiation from two sites in the basin. Model performance was evaluated by comparing outputs at one month with the May field data set of 317 depth measurements and 76 density measurements, AVIRIS-derived SCA and grain size, and TM-derived SCA for that period. Temporal accuracy of the model was also coarsely assessed by comparing model outputs to measured basin hydrographs over the course of the one-month run. The snowmelt model was not coupled with a hydrological model, therefore routing of snowmelt out of the basin was instantaneous. Understanding the spatial and temporal dynamics of a snowpack at fine resolutions will be increasingly important for the study of climate change and its impact on the ecology and meteorology of alpine areas.

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A Comparison of Four Snow Models Using Observations from an Alpine Site

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Snow can greatly increase the albedo of a surface, reduce its roughness, insulate the underlying ground from the atmosphere, and store or release large amounts of water. Models of snowpack processes are thus needed for a wide range of applications, from forecasting floods and avalanches to simulating long-term changes in climate, and many different models have been developed. To investigate the performance of snow models, the International Commission on Snow and Ice working group on Snow and Climate is planning a snow model intercomparison project (SnowMIP). A detailed comparison will be made between a wide range of snow models using data from several sites with different climates and characteristics. The results and discussion presented here are taken from a pilot study with more modest aims; results from four models with differing complexities are compared with observations made during two contrasting winters at a site in the French Alps.

The following are models compared:

- UKMO — A simple model used in the Hadley Centre climate model and the UK Meteorological Office forecast model;
- ISBA — A physically based model developed for use in the Météo-France ARPEGE GCM;
- INM — Another physically based model, developed at the Instituto Nacional de Meteorología for hydrological forecasting;
- CROCUS — A sophisticated snow model developed at the Centre d'Études de la Neige for avalanche forecasting.

Hourly measurements of air temperature, humidity, windspeed, precipitation, shortwave radiation, and longwave radiation were used to drive the models. Model results are compared with observations of snow depth, water equivalent, surface temperature, albedo, and runoff.

The models all perform reasonably well in simulating the duration of snow cover for both winters studied, but they differ in their predictions of peak accumulation. Differences in how the models represent storage of liquid water in snow and exchanges of energy with the atmosphere lead to significant differences.

A paper discussing the results of this comparison and making recommendations for SnowMIP has been submitted to Climate Dynamics.

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The Water Balance of a Subarctic Town

Annette Semadeni-Davies[1] and Lars Bengtsson[1]

High-latitude towns experience unique water management problems related to the storage of precipitation as snow for upwards of five months each winter. By providing an overview of pathways and the relative importance of different hydrological parameters, a water balance is valuable to the design and operation of urban water management systems. Urban water balances differ from their rural counterparts, specifically due to the extreme spatial heterogeneity and artificial sources and flow paths. Urban catchments are generally characterized by high peak discharges and fast response times. Snow further complicates urban water balances. For instance, snow accumulation and melt is influenced not only by topography but also by the presence of buildings and snow handling measures.

The monthly water balance of Lulea, Sweden, is investigated. Half the annual precipitation is snow; thaw is usually at the end of April. The study period was June 1992–June 1996. Of interest were the seasonal differences in runoff volumes, flow pathways, and flow through the urban pipe system to the wastewater treatment plant and natural receiving waters. Data available included daily precipitation, air temperature, and inflow to the Uddebo wastewater treatment plant, and monthly potential evapotranspiration, groundwater levels, and long-term water supply statistics.

The snowpack was simulated with a degree-day temperature index. This method is unsuitable for urban hydrology as it represents spatial and temporal scales that are discordant to the processes in operation; however, as the results are reported as monthly values, inaccuracy is assumed to be minimal. Snowmelt-induced runoff from urban areas is largely new water. During thaw, urban soils rapidly become saturated and can freeze, leading to overland flow and increased storm- and wastewater flow. Soil was modeled with a single-layer bucket model. Water can enter pipes either directly through inlets or indirectly as infiltration. Sewer infiltration was approximated by removing the supply and direct stormwater component from the measured inflow at Uddebo. This method does not account for water lost to CSO or pump station overflows; however, observations show that most overflows occur in April.

It was found that the volume of discharge is greatest during spring thaw, but autumn rains coupled with lowered evapotranspiration cause a secondary flow peak; rainwater on permeable surfaces infiltrates whereas the sheer quantity of water during thaw causes inundation and increased stormwater; the urban drainage system is most likely to overflow during thaw and the weeks after. Recharge is most likely to occur after melt, but ground frost can limit flow some years. There is a bi-modal pattern with a second peak in autumn.

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Using an Analytical Solution to Model a Season of Snowmelt

Mary R. Albert [1]

There are many snowmelt models described in the literature. The detailed models use numerical techniques to solve the governing differential equations of water flow through snow, while operational, lumped models ignore the physics of melt movement through the pack. While the detailed models hold the potential for more realistic simulations, the matrix solutions inherent in the detailed models consume much more computer time than the algebraic expressions used in the lumped models. In an effort to bridge the gap between the need for accurate melt assessments and the need for computationally simple models for distributed applications, an analytical solution to the problem of water flow through snow was presented (Albert and Krajeski 1998), and illustration of the solution in a snowmelt model, SNAP (Snowmelt Numerical-Analytical Package), was described for several outflow events. The purpose of this paper is to apply SNAP in simulating a full snow season, and to compare the model results with snow depth and snowmelt lysimeter outflow measurements.

The field site for the snow measurements is the Sleepers River Research Watershed in northern Vermont, where the seasonal winter snowpacks typically are 1 to 1.5 meters in depth, and are usually highly layered, including ice lenses. Meteorological measurements (air temperature, relative humidity, wind speed, incoming and reflected solar radiation, incoming and emitted longwave radiation, and precipitation) are used to drive the model. Results of the model are compared to field data from snowmelt lysimeter measurements of water flow from the base of the pack, and to ultrasonic snow depth measurements. Snowpack stratigraphy, density, grain size, and permeability data were obtained from snow pit measurements at various times throughout the season.

For the comparisons discussed here, model parameters were not tuned to the snow conditions; rather all parameters were left at steady default positions throughout the course of the season in order to identify those parts of the snowmelt season that require layering or metamorphic effects in order to predict melt. In general, model results compare well with the field measurements. Snow depth measurements over the course of the accumulation–ablation season agree with model results for most of the season, with the main differences due to difficulties in ascertaining whether precipitation events were snow or rain (model calculations assumed that precipitation for air temperature less than 0.5°C was snow). For rain on snow and for ripe snow conditions, the measurements and model compare to within 95%. For the peak snowmelt season, model and measurements compare to within 90%, with the main differences due to differences in predicted outflow at the start of the main melt season, where layers are degrading and the surface albedo is changing. Future improvements and simulations will focus on snow property evolution and layering/fingering effects in snowpack outflow.

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A Spatially Distributed Energy Balance Snowmelt Model for Application in Mountain Basins

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Timothy Link[2], and Dave Garen[4]

Snowmelt is the principal source for soil moisture, groundwater recharge, and streamflow in mountainous regions of the western United States. Information on the timing, magnitude, and contributing area of melt under variable or changing climate conditions is required for successful water and resource management. A coupled energy and mass-balance model, ISNOBAL, is used to simulate the development and melting of the seasonal snowcover in several mountain basins in California, Idaho, and Utah. Simulations are done over basins varying from 1 to 2,500 km^2, with simulation periods varying from a few days for the smallest basin, Emerald Lake watershed in California, to multiple snow seasons for the Park City area in Utah. The model is driven by topographically corrected estimates of radiation, temperature, humidity, wind, and precipitation. Simulation results in all basins closely match independently measured snow water equivalent, snow depth, or runoff during both the development and depletion of the snowcover. Spatially distributed estimates of snow deposition and melt allow us to better understand the interaction between topographic structure, climate, and moisture availability in mountain basins of the western United States. Application of topographically distributed models such as this will lead to improved water resource and watershed management.

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Comparison of Geostatistical and Binary Regression Tree Methods in Estimating Snow Water Equivalence Distribution in a Mountain Watershed

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Understanding snow water equivalence (SWE) distribution is imperative for snowmelt models to efficiently predict the volume and timing of runoff. Many factors contribute to the variation of SWE, including elevation, slope, aspect, vegetation type, surface roughness, and energy exchange. Studies of seasonal snow cover are manageable in areas with gentle terrain because the importance of factors controlling snow distribution is greatly diminished. However, understanding the processes controlling the spatial distribution of snow is difficult in rugged alpine regions.

The spatial distribution of peak SWE in a mountain watershed was modeled and compared using geostatistical and binary regression tree methods. In April 1997 and 1998, intensive snow surveys were conducted in the Loch Vale Watershed (6.9 km^2), Rocky Mountain National Park, Colorado. This glacially scoured watershed lies in the Front Range immediately east of the Continental Divide with elevations between 3091 and 4003 m. Sample locations of snow depth and density were chosen to be representative of the range of elevations, slopes, and aspects of the watershed with safety constraints. All field measurements were registered to a 10-m resolution digital elevation model.

In the geostatistical approach to modeling SWE distribution, snow depths were spatially distributed over the watershed by kriging interpolation. The spatial variability of snow depth, in the form of a variogram, was used to weight adjacent sampled values for interpolation. This technique, known as kriging, has the advantage of giving an actual measure of the reliability of the estimated values because the individual interpolation errors can be calculated. The second approach incorporates binary regression tree methods. The independent variables of elevation, slope, net solar radiation, and vegetation cover were used to model the dependent variable, snow depth, as they show a physically based relationship with snow distribution. These relationships are often nonlinear; however, the binary regression tree method can describe nonlinear relationships between the independent and dependent variables. Using regression analysis, snow densities were mapped across the watershed. Combining the modeled depths and densities with snow-covered area produced estimates of the spatial distribution of SWE.

Total basin SWE values were similar for both techniques; however, within basin distribution of SWE from the two methods showed important differences. Complex energy balance, steep slopes, and variably strong winds in the watershed contribute to a large degree of heterogeneity in snow depth. This large heterogeneity in snow depth complicated the kriging interpolation process. Binary regression trees can more accurately handle abrupt changes in the primary variable, snow depth. Therefore, the regression trees were able to explain more of the observed variance in the measured snow depths.

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Investigating Relationships between Landscape, Snowcover Depletion, and Regional Weather and Climate Using an Atmospheric Model

Ethan M. Greene[1], Glen E. Liston[1], and Roger A. Pielke, Sr.[1]

The effects of landscape change have long been acknowledged as an important element of the climate system, and in recent years the climate-related effects of anthropogenic changes to the land surface have become an important research topic. This study strives to improve our understanding of the effects of landscape changes on winter and spring snow-related processes and on regional weather and climate.

A climate version of the Regional Atmospheric Modeling System (CLIMRAMS) is used to investigate the effects of landscape change on seasonal snow depletion and its corresponding effects on atmospheric and hydrologic processes. Two simulations of the 1996 spring melt season in the Rocky Mountains and Northern Great Plains are compared. The first simulation utilizes the present-day vegetation distribution, and the second uses the same vegetation distribution with the exception that all forested regions are replaced by grassland. This numerical deforestation affects 18% of the domain.

In the model the vegetation changes alter the leaf area index, transmissivity to incoming solar radiation, roughness length, and surface albedo. Additional snow-related differences occur because the snow lying over grass, and the snow under the forest canopy, exist in dramatically different radiative and thermal regimes. The snowcover changes resulting from the simulated deforestation influence the surface radiation balance, which leads to changes in surface sensible and latent energy fluxes, evaporation/transpiration rates, melt rates, and air temperature. The landscape changes cause the air temperature to be cooler in the winter and warmer in the summer.

Through hydrologic-transport processes, the effects of the landscape change teleconnect to unmodified regions. The surface snow-free date and runoff season were dramatically affected. The snow-free date came nearly three weeks early in the deforested case, and the runoff season decreased by nearly four weeks. The deforestation also modifies snowcover depletion rates, which in turn cause variations in maximum values of runoff production. This numerical deforestation experiment suggests that landscape changes can significantly alter the surface energy and moisture budgets, hydrologic cycle, and regional weather and climate.

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Regional InfoMet Subsystem for Modeling Environmental Processes

Vladimir Konovalov [1]

The territory of Central Asia within 35–44°N and 66–81°E has been taken to develop a regional subsystem of meteorological information, **InfoMet**, which describes spatial and temporal variability of air temperature T, humidity H, precipitation P, and total cloudiness C. The fields of T, P, and H are presented in the subsystem as the long-term monthly norms that were computed in the nodes of a regular grid. These grids were obtained for every month of the year and for several given altitudes. It is supposed that the spatial variability of T, P, and H within each elevation zone depends only on latitude φ and longitude λ. Such presentation of T, P, and H fields allows solving of the following problems: (a) Extrapolation of values X (i.e., T, P, or H) from m basic meteorological points $X_m(Z_{0m}, \varphi_m, \lambda_m)$ to the n arbitrary points $X_n(Z_{0n}, \varphi_n, \lambda_n)$ at certain altitude $Z_0 = const$; (b) Analytical approximation of vertical profile of X in the point with coordinates Z_0, φ, λ. A set of $X_L(t, Z_L, \varphi_L, \lambda_L)$ values for L altitudes in the t months is used here. Quality of computed long-term series of precipitation and air temperature in control points turned out to be completely acceptable.

The proposed method has the following advantages: it makes it possible to extrapolate precipita–tion and air temperature data of one or several basic stations to the whole mountainous territory of Central Asia; improves extrapolation quality due to averaging of computational results for several basic meteorological stations; makes it possible to get numerical estimates of annual course of T and P in high alpine basins where there are no meteorological stations or their number is not sufficient to set up local relationship of $T(z)$ and $P(z)$.

Long-term series of T, P, and H at several basic meteorological stations were included in InfoMet. **InfoMet** also comprises long-term series of monthly C values at 36 meteorological stations located within elevation range 1–4 km a.s.l. and matrices of cross-correlation coefficients of C at all 36 stations during the year. These matrices are necessary to determine area size for which cloudiness data extrapolated from an individual meteorological station are representative. The **InfoMet** subsystem is used widely in the REGMOD model to compute hydrological regime and annual mass balance of Pamir-Alai glaciers. Area of contemporary glaciers of this mountain region estimates as 14,800 km^2 and its volume as 700 km^3. Here are located the upper watersheds of the largest Central Asian rivers: Amudarya, Vakhsh, Pyandge, Zeravshan, and the left-side tributaries of the Syrdarya river, where is formed about 70% of total runoff volume in the Aral Sea basin. The norm of glaciers melted contribution in the runoff of listed rivers is varied between 18–37% and in low water years it grows to 29–55% from annual runoff. Thus, estimates and forecast of water resources state of Pamir-Alai glaciers play a key role in the compilation and realization of water management and hydropower projects.

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Numerical Modeling of the Snow Cover Depth on Mountain Slopes

Eleanora Semakova [1]

Snow-cover depth is one the most important characteristics of the hydrological and avalanche-forming role of solid precipitation. The relationships between snow-cover depth and morphometric relief parameters in certain points (sites of the remote snow stakes) and snow-cover depth on the meteorological site of the hydrometeorological station were estimated on the base of the discrete points group. Due to the sufficient irregularity of the points of these stakes' installation, it is possible to extrapolate the obtained relationships to any random point of the investigated region. The estimation of morphometric parameters of such points is made automatically using the digital model of the relief.

The digital relief model is based on an irregular scheme, which determines the position of points located on meridians of topographic maps and defined by the laws of differential geometry. For the graphical presentation of the snow depth on PC display, the linear interpolation of the calculated values in characteristic relief points is applied. The algorithm was derived, the principle of which lies in gradual coloring of the areas around these points with the color determined by the accepted interval value of the snow depth. The originated areas form the homogeneous sectors of the prescribed values of the snow depth. The conclusion is drawn about the possibility of application of the operational maps for the snow-cover depth distribution in the avalanche basin for detailed avalanche forecasting.

The maps of the snow-cover depth distribution are constructed for a definite date on the example of one of the avalanche basins surrounding Dukant avalanche station in the Western Tien Shan area. The numerical experiments have shown sufficient convergence with the real data.

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Posters:

Scaling Problems in Snow Hydrology

Distribution of Snow in the Upper Marble Fork Basin, California

Al Leydecker[1] and James O. Sickman[1]

We have measured snow-water-equivalent (SWE) of the spring snowpack in the Upper Marble Fork basin (1900 ha) on the western slope of the Sierra Nevada since 1993. Over a thousand snow-depth measurements were taken at maximum accumulation each year in grid patterns, or along traverses; sampling points for the earlier surveys were spatially located by mapping or with corrected and noncorrected gps coordinates; since 1994 corrected gps coordinates were used throughout. Two to five sampling points, usually spaced 6–10 m apart, were used to estimate the mean depth over a DEM pixel (typically 30 × 30 m). We were unable to spatially distribute snow density due to the difficulty of accumulating sufficient measurements in the deep (2–6 m) snowpack, and our analysis of snow distribution is based solely on depth. This overstates any correlation between SWE and terrain because the deeper snow is typically less dense; however, the error is minor because density varies within a narrower range than snow depth (coefficient of variation of ~0.08 for density vs. ~0.39 for snow depth).

Snow-depths in the basin, the headwater catchments, and along individual traverses were usually normally distributed, and aside from broad generalities of deeper snow below avalanching slopes and shallower snow at lower elevations and on slopes subject to winter melt, snow depth in the basin was predominately random; net winter solar radiation and other terrain-based parameters, e.g., slope, aspect, and elevation, typically explained less than 15% of the variability. Only for the steep topography of the Emerald (120 ha) and Pear (136 ha) glacial cirques could a linear regression model be developed (using solar radiation and elevation, $r^2 \approx 0.33$). Even here, the regression depended upon a major dichotomy between the northern south-facing portion and the remainder of the catchment; within these two subregions depth was more or less random. Regression tree models were inferior to linear regression; although generating high r^2 values (> 0.6), tree models consistently failed cross-validation tests, i.e., trees formed with randomly chosen subsets of 75% of the data were used to model snow depth at nonselected points, which were then correlated with actual measurements (typically, $r^2 < 0.15$). Kriging performed poorly as a method of distributing snow depth because variograms, derived from numerous traverses over the years, typically had an auto-correlation range of 30 to 40 m, i.e., rarely extending beyond the adjacent pixel. Contour mapping of snow depth with various methods, e.g., linear kriging, variogram kriging, minimum curvature, produced cross-validation correlation coefficients (r) of < 0.15. In contrast to the poor correlation of snow depth with terrain, there was a consistent year-to-year relationship between the mean basin snow depth and mean depths in the subbasins, e.g., the Emerald catchment had a mean depth equal to 131 ± 1% (± SE) of the overall mean, which lends promise to snow distribution modeling based on stratified sampling of the major subregions and random redistribution based on the mean and standard deviation.

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Spatial and Temporal Dependence Characteristics of Passive Microwave Derived Prairie Snow Cover: A Comparison of Three Winter Seasons

C. Derksen[1], M. Wulder[2], E. LeDrew[1], and B. Goodison[3]

The unique influence of snow cover on energy exchange processes means that varying patterns in snow cover distribution have climatological implications at local, regional, and global scales. The evolution of seasonal terrestrial snow cover also influences the hydrological cycle with respect to water storage and melt release. A means of monitoring regional, continental, and hemispheric snow cover at spatially and temporally sensitive resolutions is therefore desired. Satellite passive microwave derived snow water equivalent (SWE) imagery shows potential in providing these data through all weather imaging capabilities, wide swath width, and frequent scene revisits.

In this study, we use five-day averaged (pentad) SWE imagery derived from Special Sensor Microwave/Imager (SSM/I) brightness temperatures to assess the spatial and temporal dependence characteristics of snow cover for a ground validated Prairie study area. Three winter seasons of SSM/I data (December, January, and February 1988/89, 1989/90, and 1990/91) are currently available in the Equal Area SSM/I Earth (EASE) Grid projection required for investigation of terrestrial snow cover, and are compared in this study. Temporal patterns within each season are isolated through principal components analysis (PCA). Component loadings indicate the strength of association between each component and original time series image, thereby indicating the temporal persistence of the snow cover pattern isolated by each component. SWE clusters within pentads are isolated through computation of the Getis statistic (G_i^*). The Getis statistic, a local indicator of spatial association, provides a measure of the spatial dependence of each pixel to the surrounding pixels, and also indicates the relative magnitude of the SWE values in a given pixel neighborhood. Variable window size in the computation of G_i^* allows for spatial association to be computed at a range of distances from the center pixel.

The passive microwave imagery and two analysis techniques provide a means of quantitatively monitoring snow cover evolution, while also identifying a high degree of interannual variability in the dominant spatial and temporal modes of Prairie snow cover. DJF 1988/89 is characterized by persistent snow cover with noncontiguous spatial clusters; DJF 1989/90 is composed of spatially coherent snow cover with low temporal persistence, while DJF 1990/91 is characterized by generally sparse snow cover. The results of this study confirm that synoptically sensitive data, which passive microwave sensor can provide, are essential for the remote monitoring of Prairie snow cover. The analysis methods explored can be utilized to provide significant climatological and hydrological information.

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Modeling Cold Season Heat Fluxes over an Arable Field in Central Sweden

Manfred Stähli[1], David Gustafsson[2], and Per-Erik Jansson[2]

A climate change will significantly alter the surface conditions at high latitudes, but the predictions include many uncertainties. The energy exchange between land surface and atmosphere is not well understood, especially not during winter conditions. Our specific purpose is to quantify the heat exchange at the surface of an arable field in mid-Swedish conditions, during both snow and snow-free conditions, and to link the detailed process description of the plot scale with the spatial distribution observed over a field of some hectares. Our study is a part of a currently running EU-project (WINTEX) studying winter land surface–atmosphere interactions of a boreal landscape at different scales.

Extensive snow and soil physical, as well as meteorological, measurements have been set up at an arable field station 5 km north of Uppsala (central Sweden). Measurements at selected points (profiles) are made of soil temperature, soil water content, and groundwater level. In addition a transect study of snow depth is made and turbulent heat fluxes are measured with eddy-correlation technique. The measurements have been running during winter season 1997/98. A one-dimensional numerical SVAT (soil-vegetation-atmosphere transfer) model has been parameterized for the site and will now be used for interpretation of the variation of the heat exchange over the field. Only vertical heat exchange is simulated, neglecting the advective fluxes between snow-covered and snow-free areas. Comparing these model results with eddy-correlation measurements may indicate if the strictly vertical heat flux description is appropriate for the scale of the studied field or not.

There were mostly snow-free conditions during the winter, and only one four-week period in January–February with continuously snow-covered ground. Preliminary attempts to close the energy balance of the surface, using measured net radiation and estimated soil heat fluxes, indicate that the eddy-correlation measurements underestimate the turbulent heat fluxes. Possible errors are the partitioning between latent and sensible heat fluxes and the heat flux to/from the snow/frozen soil surface. The soil heat flow is simulated using the SVAT model, which includes freezing/melting of soil water. Simulation results will also be compared to other eddy-correlation measurement from the same site. Much effort so far has been spent on the quality control of eddy-correlation measurements, and one conclusion was that it is difficult to do these measurements during wintertime.

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HYDALP—A European Project on Snowmelt Runoff Modeling Using Satellite Data

H. Rott[1], M. Baumgartner[2], R. Ferguson[3], G. Glendinning[1], B. Johansson[4], O. Pirker[5], S. Quegan[3], and G. Wright[6]

HYDALP (Hydrology of Alpine and High Latitude Basins) is a project of the Centre for Earth Observation (CEO) Programme, which is part of the Environment and Climate Programme of the European Community. The project focuses on the operational application of remote sensing data in synergy with conventional data for hydrological modeling and forecasting in basins where snow and glacier melt are important sources of runoff. Test basins are located in the Austrian and Swiss Alps, in Scotland, and in Northern Sweden, revealing significant differences in topography, land cover, and climate. Satellite data are used to derive physiographic basin characteristics and to monitor the snow cover and glaciers. Data sources are Synthetic Aperture Radars (SAR) of ERS and Radarsat, NOAA AVHRR, and various high-resolution optical sensors, including Landsat TM and SPOT HRV. Automatic and semiautomatic methods have been developed to derive digital snow-cover maps from the different sensors. C-band SAR offers the advantage of regular repeat observations and is the optimum sensor for monitoring the extent of melting snow, but cannot be applied in Alpine areas for mapping dry snow. The synergy of optical and SAR data provides optimum information on the extent and melting conditions of the seasonal snow cover and on glacier conditions.

The runoff calculations are based on the hydrological models SRM (Snowmelt Runoff Model) of Rango and Martinec and HBV of the Swedish Meteorological and Hydrological Institute. Model modifications for efficient use of the remote sensing products are under development. Promising results have been obtained in preliminary model runs, carried out with both SRM and HBV to simulate daily runoff in the Austrian test basin, using snow-cover information from SAR and optical sensors as input. During the 1999 snowmelt season, pre-operational tests are planned to investigate the usefulness and cost-effectiveness of the remote sensing information for daily runoff forecasts.

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Representativeness of Arctic Weather Station Data for the Computation of Snowmelt in a Small Area

Ming-ko Woo[1], Daqing Yang[2], and Kathy L. Young[3]

This study determines how representative the snowmelt values computed using arctic weather station data are of the melt in the surrounding area. Simultaneous measurements of meteorological variables were made at several sites to permit comparisons of their calculated snowmelt with the weather station at Resolute, Northwest Territories, Canada. Like most other stations, the Resolute site is located near the coast, at an airport and close to human settlement, making it warmer and its snow albedo lower than its adjacent sites. Its snowmelt rates are higher than those of a flat site away from the airport. This latter site has snowmelt conditions more typical of the rolling terrain nearby, but its melt rates are higher than those for an inland site where the snow remains longer than at the coastal zone. Through these simultaneous observations and systematic comparisons, this study indicates that the point data from coastal, arctic stations are unlikely to be representative of their surrounding areas. Thus, caution should be exercised when applying such information directly to the computation of snowmelt for entire grid cells of macro-hydrologic models.

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Validation of Snow Extent Algorithms

Jiancheng Shi[1]

For climatic, hydrological, and snow hazard investigations, the snow-covered area is one of important parameters. Our investigation will assist monitoring of snow processes over alpine watersheds scale to regional and global scales by means of remote sensing technique. This paper will mainly focus on validation of snow-covered area mapping algorithms that have been developed over past few years for a variety of different sensors. The ground truth data was obtained from a VNIR color photo that is taken simultaneously as AVIRIS and MAS image data on ER-2. This color photo covers 15 km × 15 km and can be digitized with a pixel resolution from 1.5 to 4 m. We can access large amounts of the ground truth data by using these very high spatial resolution digitized photo images along with spectral information from AVIRIS and MAS image data. The image data of TM, ASTER, AVHRR, and MODIS were simulated by taking the considerations of both the spectral response functions and spatial point spread functions of these sensors. We performed the snow mapping algorithms that have been developed recently for the sensors of TM and AVHRR by Rosenthal, and MODIS by Hall. We validated the accuracy of the snow mapping algorithm under a variety of viewing and illuminations, land cover, atmospheric, and terrain conditions. Depending on the application, the advantages and disadvantages will be discussed. Through this study, a database will be established, thus providing excellent data for development, verification, and evaluation of snow mapping algorithms for different satellite sensors.

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Snow Water Equivalents Modeled at the Mesoscale with Geographic Information Systems

Jason Carey[1]

Snow water equivalent (SWE) is spatially distributed within the mountainous basins of climates marked by a seasonal snowpack. This distribution is directly linked to mesoscale physiography such as slope, solar aspect, elevation, canopy, wind transport zones and avalanche tracks, and to time. In the Oquirrh Mountains near Salt Lake City, the SWE distribution of seven subbasins has been modeled with Geographic Information System technology and a Digital Elevation Map of the area. The purpose of the model is to obtain accurate estimates of SWE for smaller basins. The modeled subbasins are on the order of 1 km^2. Individual maps of mesoscale physiography were developed as the controls of SWE distribution. Daily water-year 1997 data from three SnoTel stations were compared with the SWE physiographic maps. Using snow accumulation theory and a statistical analysis of ground measured data, individual SWE distribution models were fit with the mesoscale maps of solar aspect, elevation, vegetation, and basin area. The SWE distribution models, representing either loss or gain, were then combined in chronological order to model total snow accumulation for a period. Peak SWE was calculated for March 7, 1997, using the mesoscale accumulation model. A total SWE of 1882.74 acre-feet, 35.6% of average Bingham Canyon annual precipitation, was calculated for peak. Modeled site locations had a very good linear correlation (0.97) with measured site data. A ridge line cornice model contributed 51.99 acre-feet SWE, 2.7% of peak. The Snow Estimation and Updating System (SEUS) is implemented by the Colorado Basin River Forecast Center for macroscale SWE calculations. SEUS modeled 3569.35 acre-feet, 190% of the mesoscale model, for the same area and period. This study shows that the scale of the study area determines the influence of the mesoscale distribution on basin-wide SWE determination.

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Spectral Reflectance of Melting Snow in a High Arctic Watershed on Svalbard: Some Implications for Optical Satellite Remote Sensing Studies

Jan-Gunnar Winther[1], Sebastian Gerland[1], Jon Børre Ørbæk[2], Boris Ivanov[3], Alberto Blanco[4], and Julia Boike[5]

Field campaigns were undertaken in May–June of 1992 and 1997 in order to study spectral reflectance characteristics of snow surfaces before and during melting. The investigations were performed on snow-covered tundra at Ny-Ålesund on Svalbard located at about 79°N. Spectral surface reflectance (or albedo) was measured with two spectroradiometers covering wavelengths from 379 to 1110 and 350 to 2500 nm, respectively. Supporting measurements such as snow thickness, density, content of liquid water, grain size and shape, stratification of snow pack as well as cloud observations and air temperature were monitored throughout the field campaigns.

Spectral measurements demonstrate that the near-infrared albedo is most affected by the ongoing snow metamorphism while the albedo in the visible wavelength range is stronger affected by surface pollution. Daily albedo measurements from 1981–1997 show that the albedo normally drops from 80% to bare ground levels (~ 10%) in 2 to 3 weeks. The date when the tundra becomes snow-free varies from early June to early July. The effect of cloud cover on surface albedo is illustrated by an incident when the weather condition changed from clear sky to 100% overcast within 2 hours on June 9, 1992, resulting in a 7% increase of the snow albedo (370–900 nm). Additionally, the bi-directional reflectance of snow was measured by taking spectral scans for viewing angles 0° (nadir), 15°, 30°, 45°, and 60° for viewing directions facing the sun and at azimuths 90° and 180°. The increase in albedo relative to the nadir for all measurements is found to be 8, 15, 19, and 26% for viewing angles 15°, 30°, 45°, and 60°, respectively. The largest anisotropy is seen for metamorphosed snow in measurements facing the sun.

Consequently, under such conditions it is necessary to correct for anisotropic properties of snow if satellite-derived albedo is going to be considered as absolute values. Also, the large variability registered in surface albedo during melt-off is of importance when interpreting and calculating surface albedo from satellite images as well as for energy balance modelling and for parameteri-zation of albedo in climate models.

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Hydrological Modeling of a Large Basin: Application to the French Rhône River

Pierre Etchevers[1], Florence Habets[1], Eric Martin[1], Joël Noilhan[1], Catherine Golaz[2], Etienne Leblois[3], Etienne Ledoux[2], Catherine Ottlé[4], and Daniel Vidal-Madjar[4]

The goal of the French program GEWEX/Rhône is to develop a method to estimate the hydrological budget of a large European river using existing datasets. The Rhône basin (86,500 km^2) has been chosen because it presents several interesting features: a strong climatic contrast between the north part (under oceanic influence) and the south part (under Mediterranean influence), a heavy influence of the snow on the Alps and Jura mountains river flows, and a limited underground domain. The strong heterogeneity of the domain is an advantage for the potential climatic applications of the project because it allows study of a great variety of phenomena and scenarios.

The adopted methodology is based on the use of 4 «linked» models: the meteorological analysis system SAFRAN generates the relevant meteorological parameters with the hourly time step at 8 km resolution by using the observations of the French National Weather Service (Météo-France). The surface energy and mass fluxes (evapo-transpiration, drainage, and overflow) are calculated by ISBA, the land surface scheme developed by Météo-France. It uses precise maps of the soil texture and the vegetation cover (resolution of 2 km). The snow-covered surfaces are specially treated by using Crocus, a physically based model originally developed for operational avalanche risk forecasting. Lastly, the hydrological model MODCOU calculates the water outflow in the soil and the river flows with a variable spatial resolution depending on the topography (between 1 km and 8 km).

The results obtained with this rather sophisticated tool are presented for a 14-year simulation (from 1981 to 1994) and compared with a rich set of flow measurements (86 hydrographical stations). Water and energy budgets are studied for some sub-basins of the domain in the light of inter-annual variability. Particular attention will be paid to the snow cover simulation and its major influence on the alpine rivers flow.

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Estimating the Mean Areal Snow Water Equivalent by Using Satellite Images and Snow Pillows

Thomas Skaugen [1]

For operational flood forecasting and flood warning in Norway, it is crucial to be aware of the amount and coverage of snow at all times throughout late winter and spring. For considering flood hazards related to snowmelt in spring, knowledge of the amount of snow, or the mean areal snow water equivalent (SWE), is particularly important. Remote sensing sensors cannot, with current methodology, provide estimates of the mean areal SWE except at a very coarse resolution (passive microwave sensors with 25-km resolution). This paper presents a methodology that combines information from satellite images with that of the frequency of precipitation events, and gives an expression for the estimate of the mean areal SWE.

By modeling the snow accumulation process in time and space as sums of random gamma distributed variables, the mean areal snow water equivalent (SWE) can be estimated. In the methodology we make use of the fact that sums of gamma distributed variables with a certain set of parameters also are gamma distributed variables with parameters being functions of the original and the number of summations. The measured snow depth/SWE at a point and at a certain time t can thus be seen as the accumulation, or the sum, of snowfall events from the beginning of the snowfall season to the time t. The integration of these points over an area at time t is seen as another summation.

From snow pillows and precipitation gauges, the value of daily accumulated precipitation/snow has been found to be well represented by a two-parameter gamma distribution. This distribution has been found to be representative for large areas. The number of events where the precipitation was accumulated can be estimated from snow pillows situated in the area. The mean snow coverage over an area, which represents the summation of the individual points over an area, can be derived from satellite images represented in a GIS. The methodology is tested for eight satellite scenes and for two nested catchments (4,723 km ≤ and 19,832 km ≤) in a mountainous area in southern Norway. The results are compared to simulated snow reservoirs using a rainfall-runoff model, and are found to agree well. Large discrepancies in the computed snow reservoirs between the proposed method and the rainfall runoff model are found in late spring and are probably due to errors in the estimated mean snow coverage derived from the satellite images.

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This report comprises the abstracts of all papers presented at a special four-day conference on snow hydrology held in Vermont, U.S.A., 6–9 October 1998. The purpose of this conference was to provide a forum for sharing new knowledge on snow-cover properties and processes, chemical processes in the seasonal snow cover, biotic interactions with the seasonal snow cover, distributed snowmelt models, and scaling problems in snow hydrology. To encourage exchange between disciplines, papers were sought that addressed the relation between processes—physical, chemical, and biological—and the integration and distribution of these processes over different spatial and temporal scales.

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