積雪の構造と変質に関するワークショップ

Workshop on snow structures and metamorphism

Abstracts

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National Research Institute for Earth Science and Disaster Prevention
Snow and Ice Research Center

『積雪の構造と変質に関するワークショップ』
Workshop on snow structures and metamorphism
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開場 Open 9:00～

挨拶 Opening 9:30-9:40 佐藤篤司 Atsushi Sato

＜第一部／Session 1＞

荒川　逸人 Hayato Arakawa	9:40-10:10	積雪の固有透過度に関する研究 A Study of permeability of seasonal snowcover
尾関　俊浩 Toshihiro Ozeki	10:10-10:40	雪氷の NMR イメージングー積雪内の水の可視化ー NMR Imaging of snow and ice layer – visualization of liquid water distribution in wet snow by compact MRI system
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山口　悟 Satoru Yamaguchi	11:30-12:00	積雪内の水の移動に関する研究 A study of water movement in snow cover
昼休み　Lunch	12:00-13:30	

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青木　輝夫 Teruo Aoki	13:30-14:00	気候モデリングのための積雪変態・アルベドモデル Snow metamorphism and albedo process (SMAP) model for climate modeling
兒玉　裕二 Yuji Kodama	14:00-14:30	既存積雪モデルの比較 Inter-comparison of snow cover models for the snowpack in Sapporo, Japan
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佐藤　篤司 Atsushi Sato	16:30-17:30	雪粒子から雪害さらに地球環境研究を試みて My attempted research work from snow particles to snow disasters and earth environment.

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積雪の固有透過度に関する研究

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要旨

固有透過度は，多孔質体の通気度や水理伝導度から流体に関わる性質を取り除くことによって求められる物理量である．その大きさは流体の流れやすさを示すことから，積雪内の対流や融雪水の浸透といった積雪内の流体の移動に関する物理過程を理解する上で重要である．更に，固有透過度の大きさは間隙のあらゆる特徴を包括した物理量であることから，積雪の構造を示すとも考えられ，比表面積と固有透過度の散布図によって雪質を定量的に分類する試みも行われてきた．しかし，固有透過度は巨視的な物理量である．様々な物理過程を解明するには，固有透過度と微視的な構造との関係を明らかにすることが重要である．

そこで本研究では，固有透過度と微細構造との関係を明らかにすることを目的として，北海道における乾き雪を対象に，通気度の測定と片薄片試料の画像解析をおこなった．これによって，固有透過度を粒径と密度による雪質に依存しない関係式を導くことができた．また，得られた関係を円管束モデルと比較することによって，間隙の特徴の一つである迂回率の試算もおこなった．

キーワード： 固有透過度; 粒径; 間隙幅; 迂回率（屈曲率）

A Study of permeability of seasonal snowcover

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Abstract

An intrinsic permeability is calculated from the air permeability or the saturated hydraulic conductivity, and it doesn't contain the properties of the fluid. It describes the rate of movement of fluid through a porous medium. Therefore, it is an important parameter for understanding physical processes concerning such fluid movement in the snow cover as convection, infiltration and so on. In addition, it contains all features of the pore space. Because it is thought that it shows the microstructure of the snow cover, the attempt to classify snow types quantitatively by the scatter chart of a specific surface area and an intrinsic permeability has been done. However, an intrinsic permeability is a macroscopic parameter. It is important to clarify the relation between the intrinsic permeability and the microstructure to ravel a variety of physical processes.

The purpose of the this study is to clarify the relation between the intrinsic permeability and the snow microstructure. The measurement of the air permeability and the image analysis on section plane were performed in Hokkaido for the dry snow in Hokkaido prefecture, Japan. As a result, the relation between the intrinsic permeability and the grain diameter and the density was clarified. It did not depend on snow type.
Moreover, the obtained relation was compared with capillary tube model, and the tortuosity that was one of the features of the pore was estimated.

KEYWORDS: intrinsic permeability; grain size; pore size; tortuosity

雪氷の NMR イメージングー積雪内の水の可視化－

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要旨

積雪内の融解水は雪粒子間の毛管力と雪層間の毛管バリアーによってその流路が複雑に規定される．さらに融解水量によって皮膜流下，懸垂などの不飽和から，飽和した流れまで変化する．すなわち，この現象には 3 次元的な積雪のマイクロストラクチャーと融解水の分布が重要となる．

本研究で紹介する小型 NMR イメージング装置は, プロトンからの信号を可視化することを目的としており，医療用の MRI と同様に水や油から信号を取得して 3 次元データを構成することができる．一方，氷粒子からの信号は本装置ではノイズレベル以下であり，可視化されない．この装置は 1 T 永久磁石を用いて内径 24 mm のサンプルフォルダーを使用する場合，空間分解能$(100\ \mu m)^3$で撮像できることから，空隙に油を充填してざらめ雪粒子の 3 次元分布を撮像することが可能である [1]．また積雪の 3 次元構造は X 線トモグラフィーが良い成果を上げている [2)3]．一方，MRI は氷内の水の分布を可視化することを得意とする [4]．本研究では 10 cm×9 cm の回転楕円形の広い静磁場均一領域を有する 0.2 T 永久磁石を用い，ぬれ雪中の水の分布の撮像を試みた結果を報告する．サンプルフォルダーは直径 6.5 cm，高さ 18 cm の円筒形（すなわち 500 ml ペットボトル）を使用した．撮像には TR / TE = 200 ms / 10 ms，NEX : 8，イメージマトリクス : 128 × 128 × 128，画素サイズ$(600\ \mu m)^3$の 3D スピンエコー法を用いた [5]．

キーワード : ぬれ雪; NMR Imaging; コンパクト MRI; 3 次元構造

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NMR Imaging of snow and ice layer

– visualization of liquid water distribution in wet snow by compact MRI system –

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Abstract

A snowpack that consists of large polycrystals is intricate in its microstructure. Grains, water, and air interaction affect water saturation and capillary force, and meltwater movement is complicated. Colbeck[1)] suggested categorizing the saturation regimes in wet snow as either pendular or funicular, i.e. low or high saturation, respectively. Waldner *et al*.[2)] distinguished two flow regimes: a matrix flow and a preferential flow, i.e. film and capillary flow or flow fingers. These flows contribute to the vertical network. In contrast, the capillary barrier is effective at forming horizontal connections. NMR imaging is a very useful method to visualize the water distribution in snowpack. We have developed a compact NMR imaging system set up in a cold room to maintain the sample at a constant temperature.

The system consists of a permanent magnet, a gradient coil set, and an RF probe installed in cold room. Two permanent magnets are used for the system. The first magnet has the following specifications[3)]: field strength = 1.04 T, gap width = 60 mm, and the RF coil is a 30-mm-diameter ten-turn solenoid. It is used for 3D high-resolution imaging: image matrix = 256^3 and voxel size = $(123\ \mu m)^3$. The second magnet has the following specifications: field strength = 0.2 T, gap width = 120 mm, and the RF coil is a 76-mm-diameter eight-turn solenoid. It is used for 3D wide area imaging: image matrix = 128^3 and voxel size = $(600\ \mu m)^3$. In this study, we present preliminary result of visualization of liquid water distribution in wet snow by compact MRI system. Since the NMR signal from the ice is negligible compared with that from melt water, the water distribution appears as bright regions[4)].

KEYWORDS: wet snow; NMR Imaging; compact MRI system; 3D strucutre of snow.

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土壌の分野における不飽和透水係数のモデル化に関する研究

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要旨

土のような不飽和多孔質体中の水分移動を予測するためには，その水分特性曲線（水分量と圧力水頭の関係）と不飽和透水係数を精度良く表現することが重要である．不飽和土の透水係数のモデル化においては，土はしばしば管径の異なる多数の円筒毛管の束と見なされる．この際，毛管群の径と各本数は水分特性曲線と毛管圧から求められる．毛管内の水の流れはポワズイユ則で与えられ，このとき毛管壁面と流れの間に抵抗が生じる．すなわち，各径の毛管内の抵抗の総和が不飽和透水係数となる．従って，土中では水分量が低下するにつれ管径の大きな毛管から順に排水が進み，透水係数が指数関数的に減少する．

毛管モデルは，単純化の過ぎる概念モデルであり，測定不能な変数を含むなど，そのままでは数値計算に適したモデルとは言い難い．そこで，数値計算に適したいくつかのモデルが提案されているが，その多くは毛管モデルの概念を踏襲している．これらの不飽和土の透水係数モデルでは，土中の間隙径分布は水分特性曲線から導かれる．この際，低圧の残余水分量を一定値で与える水分特性関数を用いると，低水分領域の透水係数を過小評価するため注意を要する．

ところで，土が 0 度以下に冷やされると，土中間隙に氷が発生・成長する．毛管モデルにおいては，こうした氷は毛管中央に生じ，毛管内の流れは円環流れに変化する．0 度付近においては，氷を含まない径の毛管が多数存在するため，凍土と未凍土の不飽和透水係数の差異はほとんど認められない．しかしながら，温度が低下するにつれ，円環流れの寄与が無視できなくなるため，凍土の透水係数は同じ圧力水頭の未凍土の透水係数より大きくなる．また，凍結を伴う土中の水分移動の数値計算においては，凍土への水分移動を抑制するため，しばしば抵抗係数を未凍土の透水係数に乗じて凍土の不飽和透水係数を表現する．しかしながら，この抵抗係数の物理的意味や与え方は未だよくわかっていない．そこでここでは，凍土，未凍土の不飽和透水係数のモデルと理論をまとめ，実験，数値計算によりこれらの関数とパラメータについて検討する．

キーワード：不飽和土; 凍土; 水分特性曲線; 不飽和透水係数

Modeling hydraulic conductivity for frozen unsaturated soil

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Abstract

Obtaining accurate functions for soil hydraulic properties is necessary to calculate water flow in variously saturated soils. Unsaturated hydraulic conductivity of unfrozen soil is sometimes conceptualized using the capillary bundle model, in which soil pores are treated as a bundle of capillary tubes of varying sizes. The size and number of tubes are given from the retention curve. Water flow in a capillary tube can be considered to follow Poiseuille's law and produces hydraulic resistance between the flow and the tube wall, leading to unsaturated hydraulic conductivity. Although this model contains many of the same properties found in a real soils, it differs in several ways from real soil water flow and is not very suitable for numerical simulation. Thus, closed-form models are proposed for soil retention models. Some of these models have also been developed based on a concept similar to the capillary bundle model. However, we must be careful when expressing low soil water content, as models, which have constant residual water content, underestimate hydraulic conductivity.

At subzero temperatures, ice may form in soil pores and grow with lowering temperature. In the capillary bundle model, the freezing point in the capillaries is depressed according to the Gibbs-Thomson effect and when stable ice forms in a capillary, it forms in the center of the capillaries, leaving a circular annulus open for liquid water flow. As the temperature decreases, more and more ice forms, and the water flux consequently decreases. In frozen soil near 0°C, water predominantly flows through ice-free capillaries, so the hydraulic conductivity of frozen soil is similar to that of unfrozen soil with a water content equal to the unfrozen water content of the frozen soil. However, at low temperatures, ice forms in almost all capillaries, and the hydraulic conductivity of frozen soil is greater than that of unfrozen soil with the same water potential. Additionally, an impedance factor is often used in numerical codes with the purpose of reducing hydraulic conductivity in frozen soil. However, the physical meaning of the factor is still unclear. Thus, we review models on the hydraulic properties of frozen and non-frozen soils and discuss them from viewpoints of column experiments and numerical calculations.

KEYWORDS: variously saturated soil; frozen ground; soil water retention curve; unsaturated hydraulic conductivity

積雪内の水の移動に関する研究

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要旨

積雪底面に水が到達することによって発生する全層雪崩の予測には，積雪内部の水の移動および積雪底面からの水の流出を正確に知る必要がある．また積雪の強さを表すせん断強度は含水率が増加すると指数関数的に弱くなることから，濡れざらめ層の弱層が原因で生じる表層雪崩の予測精度の向上には，積雪内部の水が各層にどれ位分布するかを正確に予測することが不可欠である．

体積含水率（θ_v）とサクション(h)との関係を表す水分特性曲線(*WRC*)は，物質内の水分移動特性を表す重要な物性値である．そのため *WRC* の積雪特性依存性を明らかにすることは，積雪内部の水の移動のモデル化のために必要不可欠である．本研究では，粒径(d)や密度(ρ)および雪質を変えた雪のサンプルの *WRC* の測定を行うことにより，*WRC* と積雪特性の関係を明らかにする事を試みた．実験結果から積雪の *WRC* は，砂とよく似た振る舞いすることが分かったため，土壌の分野で使用されている Van Genuchten model (VG model)を用いて，積雪の *WRC* のモデル化を試みた．その結果，*WRC* の形状を決定する VG model 内の二つのパラメータの値（α と n）は,サンプルの粒径と密度に大きく依存するが雪質には余り依存しないことが分かった．そこで，積雪の特徴を表すパラメータとして d/ρ を導入した結果，空気進入圧に関係するパラメータ α は,d/ρ が増加するに伴い増加するのに対し, $\mathrm{d}\theta_v/\mathrm{d}h$ の関係を表す n の値は，d/ρ が増加するに伴い減少する傾向があることがわかった．このことから，積雪の *WRC* は，粒径と密度の関数としてモデル化できる可能性が示唆された．

また，粒径を変化させた積雪で不飽和透水係数(K) の測定を行い，*WRC* から K を求める手法として，どのようなモデルがよいかの考察を行った．その結果，適当なパラメータを選択してやれば，土壌分野の不飽和流のモデルの一つである Mualem model を積雪に応用出来る可能性が示された．

キーワード：積雪内の水の流れ；水分特性曲線；不飽和透水係数

A study of water movement in snow cover

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Abstract

Accurate description of water movement through snow is essential to improve the forecast of full depth avalanches, which is mainly triggered by water reaching the bottom of snow cover. Furthermore, the shear strength of snow becomes weaker by an exponential function of volumetric water content, and a wet snow layer sometimes becomes sliding surface of an avalanche. Therefore, the distribution of water content in snow cover as a result of water movement through that snow cover is also essential information for accurate forecasting of surface avalanches.

The water retention curve (*WRC*), which shows the relationship between the volumetric water content (θ_v) and suction (h), is a fundamental part of the characterization of hydraulic properties. Therefore, the formulation of the *WRC* as a function of snow characteristics is essential for establishing a model of water movement through snow cover. In this study, to examine dependence of *WRC* on snow characteristics, we made snow samples controlled their characteristics (grain size (d), density (ρ), and snow type (granular snow or compacted snow)), and measured their *WRC*s. Our experiments revealed many similarities between the *WRC* of snow and that of sand. Consequently, to analyze the *WRC* of snow, we applied the soil physics models, van Genuchten model (VG model), which is standard models to analyze *WRC* of soil, to the *WRC* of snow. Two parameters in the model, which affect the functional shape of WRC, have a strong relationship with not only sample grain size but also its density. On the other hand, WRC does not show strong dependence on snow type. From these results, we introduced the parameter (d/ρ) to express the shape of *WRC*. The parameter related to the value of reverse of air entry suction increases with increase of d/ρ while the parameter related to the gradient of θ_v vs h ($d\theta_v/dh$) decreases with increase of d/ρ. Our results suggest that the *WRC* of snow can be described as a function of grain size and density.

We also measured unsaturated hydraulic conductivity (K) of snow to examine Mualem model which can describe K based on *WRC*. Comparison results between measurements and calculated K using Mualem model show the possibility that the model can be applied to calculate K of snow using appropriate parameters for snow.

KEYWORDS: water movement in snow cover; water retention curve; unsaturated hydraulic conductivity.

気候モデリングのための積雪変態・アルベドモデル

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要旨

近年の地球温暖化に伴い，雪氷の急激な融解が進んでいる．気候モデルはこのような状況を必ずしも正確に再現できていない．その一つの原因として，気候モデルの中での積雪アルベドの取り扱いの問題が挙げられる．多くの気候モデルでは積雪のアルベドを経験的な式で表現している．しかし，積雪アルベドは積雪粒径と不純物濃度に強く依存し，さらに積雪中でのそれらの層構造や積雪深にも依存している．このためこれら物理量の効果を陽に取り込んだ積雪アルベド物理モデルの構築が必要である．

本研究では積雪アルベドが積雪粒径，不純物濃度，層構造等の関数として変化するアルベドモデルと，主に積雪粒径の層構造を計算するための積雪変態モデルを組み合わせた積雪変態・アルベドモデル（Snow metamorphism and albedo process (SMAP) model）について紹介する．SMAP モデルはエアロゾル輸送モデルと結合した大気大循環モデルの中に実装することができ，積雪中の不純物濃度は光吸収性エアロゾルである黒色炭素と鉱物性ダストの沈着過程から計算される．積雪粒径は積雪変態過程によって雪温の鉛直分布から計算され，その雪温は積雪表面，内部，下部境界面における熱収支とアルベドモデルから出力される短波放射加熱から計算される．気候モデルへのこれら複数のプロセスの導入により，その過去・現在再現ならびに将来予測計算において，積雪被覆率・積雪量や積雪アルベドだけでなく，積雪内部の状態についてもシミュレーションできる．

積雪アルベドモデルは気候モデルの波長域である可視，近赤外域における広波長帯域のアルベドを求めるためにルックアップデーブル（LUT）法を用いている．その広波長帯域アルベドは精密な大気-積雪系の放射伝達モデルによって計算された高波長分解能の波長別アルベドを波長積分して求めている．LUT の中では，マルチサブスペクトラルバンド（可視，近赤外域をそれぞれ数個のバンドに分割したもの）における広波長帯域アルベドが積雪粒径，不純物濃度，積雪深，太陽天頂角，日射条件の関数として保存されている．任意の層構造，積雪深に対応するため，adding 法で不均一層の効果を計算し，さらに，積雪内部において放射量が可視・近赤外域の中で波長分布が変化する効果も，上記のマルチバンドモデルによって考慮している．アルベドモデルの精度については，（1）精密な放射伝達モデルによる計算結果と，（2）札幌における過去 3 冬期間の放射収支観測及び積雪断面観測結果との比較によって検証した．

キーワード：アルベド; 短波放射加熱; 積雪粒径; 積雪不純物; 積雪変態

Snow metamorphism and albedo process (SMAP) model for climate modeling

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Abstract

Drastic melting of snow/ice is occurring due to recent global warming. Such the situation cannot be accurately simulated with general circulation models (GCMs). One of the reasons for this is attributed to issue of snow albedo schemes in GCMs, in which snow albedo is calculated by some empirical methods. However, snow albedo strongly depends on snow grain size, snow impurity concentration and their layer structures with snow depth in snowpack. It is thus needed to develop the physically based snow albedo model explicitly incorporating the effects of those snow parameters.

In the present study, snow metamorphism and albedo process (SMAP) model is introduced. SMAP model consists of snow albedo scheme and snow metamorphism scheme. The former calculates broadband albedos as functions of snow grain size, snow impurity concentrations, snow layer structures, etc, and the latter predicts the vertical profiles of snow temperature, grain size, density and snow water equivalent (SWE). SMAP model could be incorporated into GCM coupled with aerosol transport model, and snow impurity concentrations are calculated from depositions of the atmospheric light absorbing aerosols such as black carbon and mineral dust. Vertical profile of snow grain size is calculated by snow metamorphism process from vertical profile of snow temperature, which is calculated from heat budget at the top, bottom and inside of snowpack together with solar radiative heating calculated in albedo scheme. Since those processes can be calculated in closed system, it is possible to simulate not only albedo, but also layer structures of key snow parameters with climate modeling.

Snow albedo model in SMAP model employs a look-up table (LUT) method to obtain broadband albedos for the visible and near-infrared spectra used in GCM. The broadband albedos are calculated by spectrally integrations of spectral albedos calculated with an exact radiative transfer model for the atmosphere-snow system. In LUTs, broadband albedos are stored in multi-sub spectral bands (several spectral bands in each visible and near-infrared spectra) as functions of snow grain size, snow impurity concentrations, SWE, solar zenith angle, and illumination condition. To apply to any layer structure and any snow depth for albedo calculation, the effect of inhomogeneous layers is calculated by adding method. The effect that spectral distribution of radiation in the visible and near-infrared spectra changes in snowpack, is calculated by multi-spectral band model mentioned above. Accuracy of calculated albedos is evaluated by comparisons with (1) albedos calculated with an exact radiative transfer model and (2) albedos obtained from radiation budget observation and snow pit work performed in Sapporo, Japan during three winters from 2006 to 2009.

KEYWORDS: albedo; solar radiative heating; snow grain size; snow impurities; snow metamorphism.

既存積雪モデルの比較

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要旨

既存の積雪変態モデルは比較的湿潤な日本の雪を再現できるのかを調べるために，4 つのモデルを札幌の北海道大学低温科学研究所の露場で収集された，2005/06，2006/07，2007/08 の１１月から 4 月までのデータに適用して検証を試みた. 用いたモデルは SNOWPACK, SNTHERM, HAL, 2LM である. 2005/06 の冬は例年並みの積雪, 2006/07 の冬は寡雪, 2007/08 の冬は 12 月 1 月が少雪, 2 月 3 月は多雪だった急激な融雪で早く消雪した. モデルを動かすためのフォーシングデータは気温，湿度，風速，日射量，大気放射量，気圧，降水量である．雨雪判別は山崎(1998)の方法，降水量の捕捉率補正は Yokoyama et al. (2003)に拠った．モデルの出力は積雪深，積雪水量，液体水量，アルベド，表面温度，顕熱と潜熱フラックスである．使用したモデルはそれぞれ特徴ある出力を示したが，最大積雪深の出現日は全てのモデルで近い日付を示した．しかし，最大積雪水量は大きく異なった．消雪日は最大積雪水量と融雪期のアルベドの大きさに拠った．2 LM は実際よりも消雪が早く，融雪期のアルベドは実際よりも低かった．SNOWPACK は積雪水量とアルベドを融雪期に過大評価した．HAL は積雪水量とアルベドを過小評価し，消雪日が早かった．SNTHERM は高いアルベドを示し，特に融雪期が高かった.

キーワード：積雪モデル; モデル比較; 日本の積雪

Inter-comparison of snow cover models for the snowpack in Sapporo, Japan

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Abstract

Four snowpack model outputs were inter-compared in order to assess their performance for the snowpack in Sapporo, Japan, for 3 years. Since snowpack is locally characterized by their own local climate, we have tried to know if the snowpack model is needed to adjust for the Japanese rather wet snowpack. The models used were: SNOWPACK, 2LM, HAL, and SNTHERM. The forcing data for running the models were collected at the hydrometeorology observation site of the Institute of Low Temperature Science, Hokkaido University, Sapporo in winters (from November to April) of 2005/06, 2006/7 and 2007/08. The winter of 2005/06 was characterized by normal snow accumulation, the winter of 2006/07 was smaller snow accumulation, but ablated later and the winter of 2007/08 was started accumulation later, ablated earlier. The items of the forcing data are: air temperature, relative humidity, wind speed, global radiation, atmospheric radiation, barometric pressure, precipitation (liquid and solid). The partition of liquid or solid precipitation were followed by Yamazaki's method (1998). The precipitation data were adjusted by considering the gauge catchment (Yokoyama et al., 2003). The model outputs are: snow depth, snow water equivalent, liquid water contents, albedo, sensible heat flux and latent heat flux. Though each model showed their own characteristics, all the models showed the good timing of the maximum snow depth, but different maximum snow depth. The error in the timing of snow ablation was depending on the maximum snow depth and the error in albedo in the melting period. 2LM showed an earlier snow ablation due to lower albedo in the melt period. SNOWPACK showed much larger SWE and larger albedo than the observed. HAL showed smaller SWE and smaller albedo than the observed and ablated earlier. SNTHERM showed higher albedo especially in the melt period.

KEYWORDS: snow cover model; inter-comparison of several models; snow cover in Japan.

Progress in measuring and modelling Alpine snow dynamics at SLF DAVOS

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Abstract

The dynamical development of the mountain snow cover is a fascinating research field in which the multiple process interactions are far from being understood. The build-up and melt of the seasonal snow cover is the main ingredient to natural hazards such as avalanches and spring flooding. The water stored in snow is on the other hand an invaluable resource during the summer months.

While mountain snow cover dynamics been investigated for many decades, we only now have the technology to measure high resolution snow distribution in steep terrain. High resolution airborne and terrestrial LASER scanner data are used in this contribution to assess snow distribution in a high Alpine catchment. For the first time, the snow surface development is studied for subsequent individual storms. It is observed that the very persistent snow distribution found at the time of maximum accumulation in two consecutive years is obtained by individual snow falls, which are overall less similar and show differences as a function of weather type. The largest contribution to the snow distribution at maximum snow depth stems from similar northwest storms, though. These observations motivate the use of simple terrain parameters to predict accumulation pattern. The Winstral parameter showed a remarkable predictive skill for the general snow deposition pattern, although no quantitative prediction of snow depths was possible. Also from the LASER scanner data, scaling properties for snow depth and snow depth changes inferred from uni- and omnidirectional variograms quantitatively show that (i) overall snow depth may become what conventionally has been termed "smoother" during accumulation, (ii) snow depth changes have no clear trend and (iii) a general trend towards larger scale breaks is observed.

A more complete picture of the observed snow distribution and the associated snow transport processes results with the help of the numerical models ARPS and Alpine3D. On the basis of four grid resolutions, it was possible to investigate the effects of numerical resolutions in the calculation of wind fields and in the calculation of the associated snow deposition. The most realistic wind field and deposition patterns were obtained with the highest resolution of 5 m. These high resolution simulations confirm that the earlier hypothesis that preferential deposition is active at the ridge scale and true redistribution - mainly via saltation - forms smaller-scale deposition patterns such as cornices. Already at a scale of a few tenths of meters, preferential deposition plays a major role.

The Alpine3D model has also been used to successfully investigate the spatial distribution of melt-water production, which leads to wet snow avalanches and for one case study a remarkable agreement between avalanche occurrence and melt production could be documented. The timing of melt-water production is improved by using a Japanese SNOWPACK version, which solves the Richards' equation. It is therefore expected that numerical modelling will provide a more reliable basis for avalanche forecasting in the near future. By simply running the one-dimensional SNOWPACK model on a few weather stations, valuable information on local to regional avalanche danger from dry avalanches is obtained, which is not available from observations only. It could further be shown that the correct simulation of weak layers such as surface hoar is a crucial ingredient in that context.

The increased process understanding gained through the process research is currently used to make predictions on future Alpine snow covers on the basis of common climate change scenarios. The scenarios for the second half of the century suggest that a much reduced but not completely disappearing Alpine winter snow cover will lead to more pronounced spring runoff and water scarcity during the summer.

KEYWORDS: snow distribution; snow water equivalent; snow surface; laser scanning; snow transport; preferential precipitation deposition; roughness scaling; wet snow avalanches; Alpine3D; SNOWPACK; avalanche warning.

Development and Importance of Snow Microstructure

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Abstract

Originating as atmospherically formed crystals, snowflakes accumulate on the ground to form a granular ice structure, which is in constant transformation. This is the case since ice in the natural environment is always relatively near its phase change temperature, causing the snowpack to continuously rearrange its granular configuration. Environmental conditions may dictate that the grains develop a generally rounded shape with ample bonding; or under different circumstances new faceted crystals may develop that are indicative of snow with a low structural integrity. Snow on the ground may strengthen or weaken; in fact both processes may occur simultaneously within the snowpack. It is the microstructural arrangement that ultimately determines the stability and scale of an avalanche and the energy exchange of the snowpack with the environment. The sensitivity of the snow to environmental conditions causes a seasonal snowpack to develop a layered stratigraphy, where both the inter-granular and inter-layer strength is essential to determining the avalanche potential and influences the heat flux in the snowpack. Weak layers that develop while at the snow surface may become problematic from an avalanche perspective when subsequently buried, providing a fragile layer that cannot support the overburden of subsequent snowfalls or triggers. The microstructure of the near surface snow affects the albedo and bidirectional reflectance. An understanding of the energy interaction between the snow and the environment is necessary to determine the likely metamorphism.

KEYWORDS: snow; metamorphism; microstructure; near surface metamorphism

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