SCHWEIZERISCHER NATIONALFONDS
ZUR FÖRDERUNG DER WISSENSCHAFTLICHEN FORSCHUNG

Grant application

Division II: Mathematics, Natural sciences and Engineering

Project title	Snow distribution dynamics under forest canopy
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Co-applicants	XXXXXXXXXXXXXXX
	XXXXXXXXXXXXXXX
Submission date	30.09.2012

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1. Summary of the research plan

Forested headwaters that are snowmelt dominated produce 60% of the freshwater runoff of the world. Forested areas also act as vast storage units and within the northern hemisphere and can house 17% of total terrestrial water storage in the form of snow and ice during the winter season. However, the state of forest structures within these zones are continually changing due to effects from climate change, land use management as well as a variety of natural disturbances which creates uncertainty regarding the fate of this major water cycle component. The necessity to fully understand the interplay between forest structures and snow is augmented by alarmingly high global water withdrawal predictions ranging from an 18-50% increase for just 13 years from now in 2025. Arriving at accurate estimations of snowmelt and runoff rate variations from forested areas is of great importance to hydrologic forecasters throughout the world, but in spite of this and the recognized impacts of these areas, many forest snow processes are still poorly understood.

With the emerging need to understand and quantify snow-vegetation interactions, a significant number of land surface models have included forest canopy representations and their effect on seasonal snow. The model inter-comparison initiative SnowMIP2 constituted the first comprehensive assessment of the capabilities of these models to reproduce snow cover dynamics under canopy and revealed important shortcomings. Enhancing the consistency of model simulations between locations, years and differing forested and open areas needs to be addressed as this deficiency limits the applicability of current models used for water resources monitoring as well as impact studies in forested areas. Specifically, traditional forest snow melt models typically utilize site based representations of the canopy. But unless the field area has homogenous canopy coverage, a simplified representation of canopy structure can hamper the ability of current land surface models to accurately quantify the effect of forest canopy on snow accumulation and melt.

Recent advances in high resolution availability of LiDAR data will allow us to investigate and create new parameters of canopy characteristics over varying scales in order to more accurately represent the natural heterogeneity of forest systems. These characteristics will be integrated with field based ground penetrating radar (GPR) measurements of snow distribution to arrive at improved predictions of snow cover dynamics under heterogeneous canopy. The development of improved canopy structure descriptors will also reduce the reliance on site specific calibration and allow for more accurate data transference and upscaling to larger scale model applications. While we currently have high resolution LiDAR data available for the entirety of Switzerland it will be possible to transfer these results to other areas as data becomes available.

Bridging the gap between site-level research and large scale representations of forest snow processes models constitutes a major scientific challenge valuable to hydrologists and ecologists throughout the world. Within SLF, these results will be immediately available to the operational snow hydrological model utilized within the Swiss hydrological forecasting system. Beyond more accurate estimations of snow melt rates within varying forest structures, the outcomes can also be used to assess ecohydrological effects of forest and ecotone structure changes on snow distribution in order to more accurately quantify climate and land use change impacts.

2. Research plan

2.1 Current state of research in the field

2.1.1 Significance and rationale

Mountain forests are critically linked to the hydrologic cycle providing vital ecosystem services such as natural water storage and water supply. Similarly, snow and ice provide a crucial component to the world's freshwater reserve and is essential to sustain ecosystem and human societal demands. Within the Northern hemisphere it is estimated that 20% of the seasonal snow cover is located within forested areas and can account for 17% of total terrestrial water storage during the winter season (Guntner, et al., 2007, Rutter, et al., 2009). In the United States, for example, streamflow from forest land provides almost 2/3 of the total freshwater supply with much of this coming from snow dominated watersheds. On a global scale, forested headwaters which are snowmelt dominated produce [illegible]0% of the total runoff (Chang, 2003).

The presence of forest canopy can greatly influence the quantity and timing of runoff generation and severely hamper accurate estimations of the water balance fraction coming from these areas as compared to open areas (e.g. Whitaker, et al., 2005). This is amplified if seasonal snow constitutes a significant proportion of the annual precipitation which is the case for many mountainous systems. As a model to other mountainous ecosystems, roughly 1/3 of Switzerland's land mass is covered by forests, 1/3 of the total annual precipitation is snowfall, and 1/3 of the winter precipitation fallen on subalpine forest is lost due to evaporation of intercepted snow. The ability to effectively predict snowmelt and runoff rate variations from forested areas is of great importance to hydrological forecasters throughout the world. But in spite of the recognized impacts of forest snow processes, water and energy interactions between the atmosphere, canopy and subcanopy are still poorly understood (cf. 2.1.5).

From this need, a significant number of land surface models have included forest canopy interactions. However, most of these models are based on a simplified representation of vegetative cover which is insufficient at accurately quantifying snow cover dynamics under heterogeneous canopy. This deficiency limits the capabilities of modelers involved in activities such as water resources monitoring, lake and reservoir management, and flood forecasting. Accurate representations of forest snow processes are also necessary for land surface interaction models which focus on impact studies or regional climate modeling which are becoming increasingly important. Currently the FAO projects global water withdrawal to increase by over [illegible]0 percent by 2025 (Rosengrant, et al., 2002) with 18% of these increases seen in developed countries due to both increased storage and energy demand.

2.1.2 Snow hydrology under canopy

Accumulation and ablation of seasonal snow cover within forested areas exhibits very different dynamics as compared to snow within open areas (Jonas, et al., 2011). The surrounding forest structure acts to both exacerbate and diminish involved physical processes, creating much greater spatial snow pack heterogeneity compared to open areas. Within the canopy, falling snow is partly intercepted by the canopy and can then either evaporate, melt and drip, or fall to the forest floor. The canopy also absorbs varying percentages of the shortwave radiation while redistributing the longwave radiation patterns. The presence of trees also changes the wind fields above the snow surface and typically acts to constrain the turbulent heat and moisture fluxes as compared to open areas (Li, et al., 2008). Litter fall from trees such as needles and bark also acts to change the inter canopy surface albedo of the underlying snow creating heterogeneous shortwave radiation absorption patterns on the snow surface. In consequence, the maximum snow water equivalent and the subsequent melt water volumes can be drastically different as compared to open areas. The timing of full snow melt (melt out) can also be shifted by several weeks within these areas (Rutter, et al., 2009). Snow accumulation and ablation rates under canopy depend on a variety of factors which directly affect the land surface energy and water balance such as canopy structure parameters, terrain shading, and solar zenith angle. These complex interactions influence snowcover heterogeneity at the sub-meter scale, creating intrinsic difficulties when forest snow processes are generalized within larger areas.

Due to interception of snowfall in the canopy, canopy density typically has an inverse relationship to snow water equivalent (SWE) and snow depth (HS) (Lopez-Moreno, et al., 2008). During the accumulation phase, the spatial distribution of snow often mirrors canopy gaps and many studies have shown average snow depth differences greater than 50% between open and forested areas (Hedstrom, et al., 1998, Musselman, et al., 2008). However snow interception rates vary not only with canopy density but also with snow crystal size, density of falling snow and wind speed (Marsh, et al., 1999, Pomeroy, et al.,1995). Canopy intercepted snow is subject to much higher sublimation rates due to increased exposure to wind and solar insolation (Montesi, et al., 2004). In subalpine forests found in Switzerland, forest canopy interception alone can account for the evaporation of up to 40% of total winter precipitation (Lopez-Moreno, et al., 2008). However, the proportion of forest sublimated snow varies greatly with latitude, climactic conditions, duration of the winter season and interception efficiency of the canopy. Due to these variations, total sublimation of annual snowfall estimates vary from 4% to 50% worldwide (Montesi, et al., 2004, Pomeroy, et al., 1995, Suzuki, et al., 2003). The remainder of the intercepted snow can unload, contributing to the ground based snow storage (Strasser, et al., 2011).

Forest snow distribution patterns are not just driven by interception related processes. During ablation, radiation shielding, longwave radiation transfer from exposed trunks, and reduced turbulent heat exchange can all act to increase the spatial variability of snow under the canopy (Pomeroy, et al., 2009, Sicart, et al., 2004). Contrary to findings during accumulation, several studies have shown an increased snow holding capacity in comparison to open areas during the melt due to micrometeorological effects under the canopy. Veatch et al., (2009) demonstrated that due to snowpack shading, forest edges have the ability to hold up to 25% more snow than open areas even though forest openings within forest stands usually present the largest accumulation values before the melt.

Many studies have used sky view factor or effective leaf area index (LAI) as a main parameter for radiation transfer of incoming solar radiation through the canopy (Hellström, et al., 2000). Lundberg et al., (2004) as well as Pomeroy et al., (2002) have presented direct empirical relationships relating the interception sublimation fraction to canopy closure and leaf area index. Several studies have also directly related LAI to canopy density. Pomeroy et al., (2002) defined canopy density in terms of effective winter LAI and has been used in many subsequent snow studies. Other commonly used parameterizations include further adaptations of the Beer-Lambert Law (Flerchinger, et al., 2009) or the two two-stream approximation of transmission (Niu, et al., 2004). See Rutter et al., (2009) for a more comprehensive review.

Accumulation and ablation is also highly correlated to the surrounding terrain. Like snow in open areas, topography is still one of the main drivers of snow pack variation under canopy and only a limited number of studies have quantified both canopy cover dynamics and topographic variation on the watershed scale (Jost, et al., 2007, López-Moreno et al., 2008). Jost et al., (2007) found that elevation was the most important predictor of snow accumulation, while canopy cover and aspect explained the majority of the variance during the ablation phase and also found that they were reasonable proxies for incoming solar radiation within their field area. However, Strasser et al., (2011) found that unlike open areas, exposure effects on (all aspects but the south) snow under canopy are only significant in areas where canopy closure values are quite small.

Given the complexity of these interactions as outlined above, forest snow processes are particularly challenging to represent within land surface models. A comprehensive assessment of the performance of these models to reproduce snow water storage and release in forests for a range of different canopy characteristics is available through the SnowMIP2 initiative (Rutter, et al., 2009). Despite some encouraging results, this initiative also revealed some important model shortcomings such as poor consistency of model performance between locations and years.

2.1.3 Relevant measurement methods

Field based

There are a variety of ground based snow measurement techniques. Manual measurements are relatively easy to implement and provide accurate measurements of SWE and HS. These measurements can also be collected automatically at meteorological stations. Typically these stations are equipped with a sonar which measures HS as the distance between the snow surface and the instrument. In other cases, snow pillows are attached to the stations and measure the overlying weight of snow and provide good estimations of SWE and snow density. Regardless of the technique, all provide data from a single point of measurement creating unique challenges when trying to account for the inherent spatial variability of snow under canopy.

New field based techniques have arisen in order to account for the natural variability of snow distribution. Ground penetrating radar (GPR) is suitable for monitoring HS, SWE and snow density in dry snow and can allow for a high resolution output of these factors over space. A variety of researchers including ourselves are currently working on improvements of wet snow estimations with the GPR (Lundberg, et al., 2010). Nonetheless, GPR is capable of fairly fast characterizations of large areas, thus obtaining good estimates of not just snow characteristics but the variations of these in space (Godio, et al., 2009, Kruetzmann, et al., 2011, Lundberg, et al., 2006). Limited research has been performed integrating GPR under the forest canopy. However, the SLF has optimized a novel radar setup scheme for GPR use under the canopy; please see section 2.3.5 for more information.

The multidimensional arrangement of overhead forest canopy characteristics controls a variety of physical under canopy energy and water balance drivers. Conventional direct measurements schemes for estimating the overhead canopy structure are severely labor intensive and typically involve destructive sampling of the overstory. However, there are a variety of indirect measurement schemes and their utility is dependent upon the canopy qualifier in question. In general, canopy closure measurement techniques are an overhead measure of an aerial field of view as compared to canopy cover which are non angular overhead estimations. For the purpose of this proposal, we will use canopy gap fraction (CGF) and canopy closure (CC) as defined by Jennings et al., (1999) and Gscwantner et al., (2009) respectively. Closure parameters which integrate an angular field are better able to account for light transmission from all directions as well as giving an opportunity to empirically translate CC into LAI values (Pomeroy, et al., 2002). Indirect field estimations of canopy structure can be performed from a variety of means such as, hemispherical photography, the LAI-2000 plant canopy analyzer, or a spherical densitometer and each have particular strengths and weaknesses depending on the specific structure element in question. To date, a variety of remote sensing studies have related physical canopy characteristics to hemispherical photography. Due to this, hemispherical photography is becoming a standard reference for vegetative studies based upon airborne LiDAR (light detection and ranging) imagery (Korhonen, et al., 2011, Leeuwen et al., 2010, Morsdorf, et al., 2006, Solberg, et al., 2009, Zhao et al., 2009).

Remote sensing

Remote sensing (RS) can allow for quantifications of physical properties of snow over extensive areas. The large potential coverage of RS techniques and the ability to accurately replicate measurements in space allow for the spatial variability of snow to be monitored. There are a large variety of remote sensing applications suitable for estimation of snow covered area, HS and SWE. Many RS techniques such as the suite of MODIS and landsat derived outputs have integrated static vegetative controls that give the end user an idea of snow cover within forested areas (Dietz, et al., 2012, Nolin, et al., 2010). To date, most large scale RS techniques are fairly coarse in resolution and do not allow for the contrast needed to accurately decipher the canopy/snow pack dynamics and represents a current research gap. However LiDAR observations have the power to fill this gap. Within the infrared and near infrared spectrum, multiple scattering of the light traveling through the snowpack is restricted to a few millimeters with similar accuracies found on the ground surface giving LiDAR the capacity for highly accurate measurements (Dozier et al., 2004).

Terrestrial laser scanning (TLS) has been used in a variety of studies to obtain a detailed analysis of snow depth. Many researchers have used TLS to gather high resolution snow depth data for alpine basins particularly where avalanche risk inhibits access (Egli, et al., 2012, Prokop et al., 2008). Its potential for a high resolution output is particularly suited for ablation studies where variations in melt patterns need to be quantified on a small scale. TLS has also been used extensively for tree canopy studies where results have compared well to point based LAI and canopy closure estimates derived from hemispherical photography (Seidel, et al., 2012). However, little research has been performed which uses TLS to quantify snow pack under canopy.

Airborne Laser Scanning (ALS) is able to collect information over much larger spans of terrain than a terrestrial scanner. Resolution is not as fine than that of ground based scanning and the perspective is different, observing the canopy from above, opposed to TLS, which is commonly placed within or beneath the canopy. However, the obtained point densities allow resolutions of final data sets that enable the deciphering of sub tree grid size characteristics. In addition, ALS based approaches can effectively estimate single tree characteristics such as canopy height, canopy bulk density, canopy base height, available canopy fuel estimates, canopy closure and leaf area index (Erdody et al., 2010, Kato, et al., 2009, Korhonen, et al., 2011, Leeuwen and Nieuwenhuis et al., 2010, Morsdorf, et al., 2006, Morsdorf, et al., 2004). Other airborne LiDAR based research has used flyover data for direct estimation of HS (Hopkinson et al, 2009). Reasonable results have been gathered from these studies, but require LiDAR data at the exact time of HS analysis which negates the ability for time scale analyses of the underlying snow pack unless multiple LiDAR flyovers of the field area are initiated through the winter and spring season. While most remote sensing in this field is used solely for the purpose of direct snow or canopy classification, relatively little research has integrated the two (Coops, et al., 2009, Varhola, et al., 2010). It is possible that high resolution airborne laser scans of only the surface (terrain and vegetation) can allow for adequate inferences of the underlying snow pack thus reducing the need for multiple flyovers.

2.1.4 Relevant ongoing research

Given the interest in forest snow processes and its relevance for integration in land surface models, a network of researchers worldwide (of which the applicants are part of) are actively involved in research projects motivated by shortcomings revealed in the frame of SnowMIP2. A selection of ongoing projects related to this proposal are briefly outlined below. The majority of the latest work has revolved around improved radiative transfer models under canopy**.** Link et al., (University of Idaho, USA) have been creating a new forest radiation model (Form) in order to classify slope angle and aspect's influence on snow melt under canopy. Reid, Essery and Rutter et al., (University of Edinburgh, Northumbria University, UK) have been comparing a variety of radiative transfer models as well as parameterizations of these models under canopy. They have also been collecting an extensive new data set of field based manual measurements of canopy structure from TLS and hemispherical photography as well as snow cover and radiation under canopy at two field plots within Scandinavia. Musselman et al., (University of California, Los Angeles, USA; University of Saskatchewan, CA) have been working on the derivation of a new ray tracing model of direct beam canopy transmisivity from airborne LiDAR data in a field area within Sequoia National Park, USA. Further, Musselman and Molotch et al., (University of Saskatchewan, CA; University of Colorado, USA) have begun collecting an extensive data set from ecohydrological instrument clusters across the Western US to begin larger scale classifications of forest snow parameterizations. Kirchner and Bales et al (University of California, Merced, USA) used airborne LiDAR to directly extrapolate snowpack under various forest types by comparisons of pre and post snow fly over's.

2.1.5 Research gaps and hypothesis

The interactions between forest snow processes and their contrasting impacts on snowpack evolution under canopy are not fully understood. As outlined above, there is a significant body of research on forest canopy-snow interactions. With the emerging need to understand and quantify forest snow processes for a large range of applications (see 2.1.1), A significant number of land surface models have included forest canopy representations and its effects on seasonal snow. However, as noted by Rutter et al., (2009) prior to SnowMIP2 the performance of such models when tested over a range of hydro-meteorological and forest canopy conditions has been essentially unknown. This inter-comparison initiative revealed a particular need for significant improvements in:

- Predicting the maximum SWE under forest canopies relative to the respective SWE in open terrain.
- Understanding the partitioning of snow precipitation into water equivalent that i) immediately reaches the ground, ii) is initially intercepted by the canopy but later unloaded to the ground, and iii) remains intercepted until evaporation.
- Enhancing the consistency of model simulations between locations, years, and between forested and open sites.

In order for these models to be suitable in an operational context, or for impact studies, consistent performance under varying boundary conditions is of great importance. Hence, the use of current land surface models is severely limited, unless the above model shortcomings are mitigated.

While forest snow processes are essentially 3-dimensional phenomena, models tested in the framework of SnowMIP2 were single-point models (part of which also exist in a distributed version). A general research need relates thus to optimally representing spatial variability of canopy structure for individual sites. Likewise, bridging the gap between models developed and tested at the site-scale and the representation of forest snow processes in models suitable for coarse scale applications constitutes a major scientific challenge. The different scales involved in the spatial variability of snow accumulation and melting processes under heterogeneous canopy and the limited availability of suitable data have complicated the development of reliable upscaling strategies.

Most forest snow process models are based on spatially static canopy qualifiers in order to arrive at a variety of physical parameters such as interception capacity, snow unload, throughfall, and canopy albedo, etc. However, if the field area (or grid cell) is not homogenous, generalized canopy assessments such as LAI will fail when averaged. This deficiency hits at the heart of many of the above modeling needs highlighted from the SnowMIP2 project and we feel that basic improvements of canopy characterizations must first be made. Based on the above findings and our further investigations, we have arrived at two research hypothesis:

H1: A simplified representation of canopy structure can hamper the ability of current land surface models to accurately quantify the effect of forest canopy on snow accumulation and melt. As an illustration, two forested sites with identical LAI but different canopy gap size distributions will display systematically different SWE values. However, many current models will have difficulties in contrasting these two sites. We thus hypothesize that the integration of enhanced canopy structure parameters enables significant model improvements at the site scale.

H2: Moreover, we can see that the upscaling of process understanding gained at site level to larger scale applications can fail, if it involves the averaging of local canopy characteristics. In analogy to the above illustration, SWE simulations based on a single model run using averaged canopy parameters will be systematically offset as compared to SWE averaged over individual model runs using local canopy parameters. We thus hypothesize that more detailed representations of the heterogeneity of canopy structure at small scale allows for significant model improvements at coarse scale.

Based on the above research needs and hypothesis we will present our research goals and analytic approach in sections 2.3.1 and 2.3.2.

2.2 Current state of your own research

2.2.1 Research on forest snow processes by WSL/SLF

The WSL Institute for Snow and Avalanche Research SLF is part of the Swiss Federal Institute for Forest Snow and Landscape Research and functions as a bridge between research and applied science. Due to this structure, its strength lies in inter and intra disciplinary work oriented towards implementation of research based solutions.

In the late nineties, the WSL/SLF started to investigate physical processes that drive snow cover dynamics in forests. Respective studies focused on interception processes (Brundl, et al., 1999, Pfister et al., 1999), interaction between soil frost and melt water percolation (Nyberg, et al., 2001), and radiation transfer through forest canopies (Stahli, et al., 2009). As highlighted throughout this proposal, one of the biggest problems in studying physical forest snow processes is the enormous spatial heterogeneity of the relevant driving forces and the state variables below canopy. Shading and insolation values, for example, can substantially change at length and time scales measured in meters and hours (or less) creating difficulty gathering datasets representative at the forest scale. This motivated us to develop a new and innovative experimental approach using a radiation measuring device mounted on a vehicle that continuously moves back and forth along a rail. This device was first installed in the Alptal catchment in 2004 and was recently relocated to the Seehorn field site in 2007; see section 2.2.2. It is one of very few existing devices for autonomous longterm measurements which can capture the spatial variability of sub-canopy radiation resolving both, upward and downward components of shortwave and longwave radiation.

Along with experimental research on physical forest snow processes, the WSL/SLF has also developed several models which integrate forest snow hydrology interactions. Initial studies have followed stochastic approaches for estimating SWE in subalpine forests (e.g. Stähli, et al., 2002). A major cornerstone of the forest snow hydrology research at WSL/SLF constituted the development of a numerical canopy model for physical forest snow processes by D. Gustafsson from 2001 onwards. The model is comprised of a representation of all major processes governing the mass and energy budget of forest snow covers. Together with a conceptual runoff module, the canopy model has been integrated in two SLF snowcover models: a) SnowPack (Bartelt et al., 2002, Lehning, et al., 2002) is a 1d-multilayer snowcover model, which solves the heat and mass transfer equations and represents processes like snow metamorphism, settling, and phase change dynamics; and b) Alpine3D (Lehning, et al., 2006), is a distributed version of SnowPack coupled via a 3d-radiation transfer scheme for complex alpine terrain. With these coupled models, the WSL/SLF has developed powerful numerical tools e.g. for SWE or meltwater estimations of entire mountain catchments (Bavay, et al., 2009, Magnusson, et al., 2010).

Due to our background, instrumented field sites and historic data collection infrastructure we were able to contribute to the forest snow model inter-comparison initiative SnowMIP2 in a variety of ways. First, the WSL longterm research site Alptal, was selected as one of five international locations, for which SnowMIP2 participants provided model simulations for a site based snow melt output comparison and analysis. The combination of available data series for model input (meteorological data), model validation (SWE and radiation data) at a pair of adjacent forest and open sites made Alptal an ideal test case for SnowMIP2. Secondly, led by T. Jonas (first applicant of this proposal), the SLF also participated in SnowMIP2 performing simulations with the snowcover model SnowPack. These contributions to SnowMIP2 have resulted in, to date, two group publications (Essery, et al., 2009, Rutter, et al., 2009), two follow-up publications (Jonas, et al., 2011, Stähli, et al., 2009), several contributions to international conferences and further integration within a vital network of international specialist in forest snow processes, all that the proposed study will certainly benefit from. Furthermore, it has shed light on both the strengths and weaknesses of the current forest snow process models available and given us the necessary direction to work on the current gaps within these models (see section 2.1.5).

2.2.2 Relevant longterm research sites run by WSL/SLF

WSL/SLF has a long-standing tradition in forest snow hydrology. Over 40 years ago, an extensive snow hydrological monitoring program was started in the subalpine watershed Alptal (central Switzerland). Since then, SWE has been measured along 15 transects in forested and open areas covering different canopy characteristics, elevations, slopes and aspects on a bi-weekly to monthly schedule. A comprehensive analysis of these data is given by Stähli and Gustafsson (2006). Based on the same data, Lopez-Moreno and Stähli (2008) explored the effect of terrain parameters such as exposure to insolation and altitude on the ratio between the maximum SWE in forests relative to respective open sites. The snow hydrological data collected in Alptal over the decades is highly valuable and constitutes an important test dataset for the proposed study as well as for ongoing and future research. For more details on this research site please visit: http://www.wsl.ch/info/organisation/versuchsanlagen/testgebiet_alptal/index_EN.

The Seehornwald site in Davos is currently a member of six national and international environmental observatory networks and has combined the instrumentation and expertise from various fields in environmental research into a site repeatedly recognized as one of the best instrumented sites worldwide for studying forest snow processes. Snow and meteorological process monitoring from the Seehorwald research site began in 1986 after the creation of a 35m tower within the canopy, where the majority of the point based meteorological sensing equipment is located. Please see www.wsl.ch/seehornwald/network/index_EN for a detailed list of the available long term measurements within the site. In 2007, the 4 component radiometer described in section 2.2.1 was installed and weekly HS and SWE monitoring began at a series of snow courses adjacent to the radiometer track and within a forest clearing.

2.2.3 Further relevant activities of WSL/SLF

Since 2008, the SLF has run an operational snow hydrological service (OSHD). The primary task of the OSHD is to monitor the spatio-temporal distribution of snow water resources in Switzerland contributing to enhanced flood forecasts and sound management of lakes and reservoirs (Jonas, et al., 2009). The service is fully integrated into the Swiss federal warning framework for natural hazards coordinated through the Steering Committee, Intervention against Natural Hazards (LAINAT). The OSHD provides periodic bulletins that include among others, SWE distribution maps, regional snow melt rates, and SWE climatologies for comparative analysis. For more information on the operational snow hydrological service, please see http://www.wsl.ch/fe/gebirgshydrologie/schnee_hydro/oshd/index_EN. Currently, the OSHD uses a simplistic representation of forest snow processes in its models. As outlined in section 2.1.1, respective methodological improvements would be highly relevant and needed. Since the OSHD and the first applicant of this proposal reside within the same research group of SLF, a seamless integration of results from the proposed study in an operational application is guaranteed. In the framework of its current method development program, the OSHD is ready to invest further efforts to implement results from this study in its models.

A second SLF research project is directly related to the data collection scheme outlined in the research plan (cf. 2.3). The project aims at improving the use of GPR technology for snow distribution measurements and constitutes a major benefit for the proposed study: The GPR platform we intend to use is a direct result of the effort within our GPR project, see 2.3.5 for more information.

2.2.4 Related research of ETHZ / ITES

The Forest Ecology Group at ETH Zürich is conducting both field-based as well as modeling-based research on the factors and processes that shape the long-term (i.e., decades to centuries) dynamics of mountain forests, with a focus on the European Alps. Its leader, Prof. Harald Bugmann, has published more than 120 ISI papers, and has edited or co-edited 10 books or Special Issues of scientific journals, dealing with mountain forest ecology, ecological modeling, or tree population dynamics. In the Forest Ecology Group, a series of studies has emphasized the importance of snow for the performance of Norway spruce (*Picea abies*) regeneration (Cunningham et al., 2006a,b), and the group also has experience with the testing and application of hydrological models (Zierl & Bugmann, 2005, Zierl et al., 2007). In addition, models of vertical canopy structure embedded in forest succession models (Bugmann 2001) were developed and refined by H. Bugmann and later by members of his group, aiming at providing an accurate yet simple representation of these characteristics as drivers of competition (Bugmann, 1996, Risch et al., 2005, Wehrli et al., 2005, Didion et al., 2009, Rasche et al., 2012). Lastly, spatial indices of tree-tree competition were developed from stand structural information (Weber et al., 2008). The experience with the analysis and modeling of forest structural characteristics will be valuable for the present project in the context of deriving forest characteristics to be imputed into the statistical modeling of snow cover attributes; and vice versa, the information obtained from the present project will be instrumental for the Forest Ecology Group when deriving and implementing an accurate yet simple model of snow cover duration, which currently is still lacking in most forest succession models, in spite of its importance in temperate and boreal mountain systems.

2.2.5 Related research of UZH / RSL

RSL is carrying out research on the interaction of the laser pulse with the vegetation canopy, which facilitates better estimates of biophysical products such as leaf area index (LAI) and fractional cover. The main workload in that direction is currently done in an ESA STSE project called "3D Vegetation Laboratory". The project builds a virtual environment based on two forest sites in Europe (one in Switzerland) and will enable the testing of new retrieval algorithms for biophysical variables from small footprint, full waveform ALS data. The ALS data used in that project is of the same instrument as the data to be used in this project (Riegl LMS Q 560), so synergies between the two projects will certainly be evident. In addition, RSL is currently researching the derivation of so-called canopy structure types (CSTs), a generalized, but robust description of the vegetation structure. It is expected that these products will be of relevance to the proposed work as well.

2.2.6 Proof of concept

In preparation for this proposal, a pilot study was implemented which tested and optimized a variety of novel snow and canopy characterization techniques. This proof of concept, a) created firsthand experience with data post processing as well as a realistic understanding of the effort required, b) allowed us to demonstrate the feasibility of the proposed data sampling procedures, c) should limit the risk of running into unexpected problems associated with data collection and evaluation. Results and implications of this pilot study are embedded in the research plan, sections 2.3.3 to 2.3.5.

2.3 Detailed research plan

2.3.1 Research goals

Based on the research needs and hypothesis formulated in 2.1.5 the following research goals will be pursued:

G1: Investigate the spatial distribution of snow accumulation and depletion rates as related to specific structural aspects of the overlying canopy such as density and gap fraction.

G2: Develop enhanced representations of canopy structure in order to improve forest snow model performance at the site scale.

G3: Develop improved upscaling schemes in order to integrate the enhanced canopy structure parameters over large areas with heterogeneous canopy cover.

Tackling these goals require datasets that cover a considerable range of canopy structure characteristics and topographic controls at a high resolution allowing for the results to be transferable to applications such as the Swiss operational flood forecasting or snow water resources monitoring. Therefore, we suggest the following data approach:

D1: Use existing high-resolution airborne LiDAR data sets to generate spatially explicit canopy characterizations with country wide availability.

D2: Use ground-based GPR to efficiently characterize total and differential HS and SWE within predefined field areas on a regular sampling schedule.

D3: Use high resolution georeferencing techniques in order to effectively link field based snow distribution data with aerial canopy characterizations.

The analytic approach will be outlined in detail in the subsequent section 2.3.2. Technical aspects in regards to data collection and preprocessing can be found in sections 2.3.3 to 2.3.5. We have invested major effort in a pilot study in order to optimize data sampling procedures as well as demonstrate feasibility of the proposed data collection, data processing, georeferencing and data agglomeration methods. While we have no space to reveal all details, results from of this pilot study have been also integrated in sections 2.3.3 to 2.3.5 and a detailed visual can be seen in Figure 2.

2.3.2 Analytic approach

Goal 1: Integrating D1-D3 will result in snow accumulation / depletion rates underneath varying canopy at the sub-meter scale (For technical details see 2.3.3 - 2.3.5). For each point within the field areas, we will create a 2d characterization of the overhead canopy structure. Empirical relationships will then be built that directly relate snow accumulation and ablation rates to the canopy overlying structure. Corresponding to our first hypothesis (H1) we will create canopy-related predictor variables that feature more complexity than LAI as a single descriptor. Of course, at this point it is unclear which variables will turn out to be most suitable, before we have conducted a thorough statistical analysis of the snow data and the affiliated canopy characteristics. However, we intend to intensively investigate the potential of gap size distribution and gap fractionation related parameters as well as a canopy integrated potential incoming solar radiation (PISR). Along with the above analysis, we will identify the optimum spatial scale at which the overlying canopy structure is to be evaluated to gain best correlations with snowpack dynamics on the ground.

Goal 2: Since accumulation rates on the ground measured in the absence of significant unloading mirror interception rates, we expect G1 to result in empirical findings that can be directly integrated and tested within the SLF model framework SnowPack for an enhanced site-scale canopy interception module. The physically-based SnowPack, for instance, uses an interception capacity which is directly proportional to LAI in combination with parameterizations following Pomeroy et al (1998) (cf. Stähli et al., 2009 for more details). Furthermore, SnowMIP2 demonstrated the reliance of most all models on empirical relationships for mass balance processes related to interception allowing further integration of the findings from G1 to other models as well.

Enhancing parameterizations of radiation transfer for improved snow melt estimates within physically-based models would require distributed sub-canopy radiation measurements beyond the scope of this project. Similar considerations also apply to other parameterizations of energy transfer processes. However, the canopy-related predictor variables from G1 directly related to depletion rates, will be integrated and tested within a conceptual model framework. We will use the snow melt model currently in use and developed by the operational snow hydrology service within our snow hydrology group (cf. 2.2.3) for integration and testing.

Decades of weekly snow course data from our longterm research sites (cf. 2.2.2) will provide additional test cases for our model improvements.

Goal 3: At the core of our research approach is its focus on upscaling issues in order to integrate the above results into larger scale applications. In accordance with our hypothesis H2, we will investigate the potential of stratified modeling approaches. As a starting point, we will run Snowpack for individual grid points starting from a fine to a coarse grid resolution. The SWE averaged over the modeling domain will be inter-compared from the model results for each grid resolution and then verified against distributed snow measurements collected in the field. We will then cluster grid cells derived from LiDAR data with similar canopy characteristics and perform individual model runs only for similar grid cell groupings. These groupings can be based upon a variety of canopy characteristics, allowing for a performance analysis using different clustering techniques against the fully distributed approach. The optimized stratified modeling approach will allow for a computationally efficient integration of high resolution information within a coarse grid environment. These procedures are potentially applicable for any existing forest snow model and the stratified approach can be performed independent of G1 and G2. Nevertheless, we intend to work primarily with our canopy snow models developed in-house (Snowpack, OSHD snowmelt model). Any such improvements can be immediately applied to other forested area in Switzerland, due to the current availability of country-wide high resolution LiDAR data (at 2.0m lateral resolution), or any other area for which LiDAR data becomes available.

2.3.3 Sampling sites

A series of six 2500m^2 field areas will be equipped for a 3 year study period. All sites will be prepared with a geo-located sampling grid (Fig. 1) comprised of preset transects with 10 meter separation lengths between them forming a rectangular grid (Fig. 2). Within these field areas, all ground based measurements will be taken along the transects to allow efficient field sampling and data paring.

An initial analysis of the digital surface model (which represents all surface features located on top of the terrain) derived from the LiDAR data set will be used to generate gridded tree stand density values for the identification of the field areas. The selection of the field areas will be stratified according to two elevation ranges and three canopy density ranges, resulting in 6 unique combinations of density/elevation classes. A further stratification, especially with aspect, would certainly augment the potential of this study. However, as a result of the pilot study, we feel 6 is the maximum number of sites that can realistically be handled regarding the effort required for repeated measurement campaigns. Nonetheless, point based measurements of the snow pack and canopy in tandem with generalized field area characteristics within each of the grids should allow for a good heterogeneity of physical forcing mechanisms on the underlying snow distribution to be monitored.

2.3.4 Canopy characterization

LiDAR data sets

This study will incorporate two different LiDAR data sets differing in spatial resolution and coverage. Analytic tier one will integrate a high resolution LiDAR dataset of 0.5m horizontal resolution which is available for approximately 29km^2 surrounding the area of Davos / Klosters, which was initially made available through a joint initiative of the Amt für Wald (Kanton Grison), the local authority of Klosters and the Remote Sensing Laboratories of the University of Zürich. Analytic tier two will additionally integrate a LiDAR data set with a resolution of 2m which is available through TopoSwiss for all of Switzerland. Both datasets will serve similar purposes and analysis methods to derive canopy structure parameters from LiDAR point cloud data are essentially identical. Specifically, the results and methodology of the tier one analysis will be up-scaled into tier two along with ongoing data collection from the long term field sites located under various canopy, terrain and elevation regimes throughout Switzerland (see section 2.2.2). Due to this two tiered approach, only the tier one analysis will be described in detail.

LiDAR data post processing

The tier one study will utilize LiDAR data received from a series of flyovers from September 2010. The average point resolution of the point cloud on the horizontal plane is 0.5m with an estimated accuracy of 0.01m on the vertical axis. The fine scale resolution of this data set will allow for direct ground based point to pixel comparisons. A variety of canopy related analyses such as canopy closure and canopy gap fractionation will be made at both the point scale as well as at various grid scales. This has been part of the ongoing work in collaboration with Felix Morsdorf, co-applicant of this proposal, and his working group. A series of initial scripts have already been adapted in order to analyze the point cloud data for canopy structure information as needed for this project. First evaluations for a subsample of the LiDAR dataset can be visualized within Figure 2.

The tree canopy density and structure analysis will be further integrated with an analysis of under-canopy PISR. In the past, remote sensing methods have been applied to the estimation of light within forests, but only recently have 3-

dimensional data sets been integrated in these studies (Lee, et al., 2009). The PISR estimations will take into account the surrounding topography as well as the overlying vegetation where current methodologies integrated from the hemispherical viewshed algorithm developed by Rich and Fu et al., (Fu and Rich, 2002, Fu and Rich, 2000, Rich, 1994) will be utilized. In order to reduce the requisite computational needs for a point cloud based analysis in a large-scale application, we will utilize a stepwise integration of insolation calculations across the domain along with empirically based insolation models to retrieve information regarding PISR underneath specific trees as e.g. in Hellstöm et al., (2000) or Pomeroy et al., (2002).

The tier two analysis will integrate LiDAR flyover data comprising the majority of Switzerland from spring 2006. The average resolution is 2.0m on the horizontal plain with a 0.01m elevation resolution. A similar analysis approach will also be used within this data set. Certainly, estimates of canopy structure parameters and PISR will not have the same accuracy as with the tier one dataset. However spatial aggregation of both datasets to gridded averages, comparisons in overlapping area and available field data (see next subsection) will help to upscale the results from the tier one study to larger scales. Data recorded at the long term field sites mentioned in section 2.2.2 will provide a means of independent validation.

Ground based canopy characterization

In order to verify LiDAR generated canopy characteristics, we will use hemispherical photography to measure canopy closure and canopy gap fraction on a series of points located on the preset sampling grids within the field areas. Hemispherical photography is easily reproducible over time and provides a digitized output which allows for multiple reprocessing schemes to be integrated such as field of view angle adjustments. The canopy closure and gap fraction values will be directly compared with the values generated from the LiDAR data. Furthermore, these data will also be evaluated in the context of the PISR estimations under canopy.

Within our proof of concept study, we tested the use of TLS to determine snow and canopy structural information from inside the forest. The site was equipped with 13 georeferencing targets and scans were obtained from 9 different positions. Merging those scans into one rectified image resulted in highly accurate results, reaching a lateral accuracy of ±2cm and even higher point cloud densities. However, due to the high amount of effort involved with regularized TLS sampling campaigns within multiple sites, we have decided to abandon the possibility of using TLS for the proposed research.

2.3.5 Distributed snow monitoring

GPR system

Figure 1: GPR platform developed from the pilot study for operation on snow underneath canopy. Measurements are triggered every cm along the sampling grid lines. Data markers are set upon passing intersections, allowing for very accurate georeferencing of GPR-based snow data obtained along the transects.

Ground penetrating radar will be used to estimate HS and SWE in the field areas. Our setup will allow for a continuous series of data as well as generation of location information for precision georeferencing to the overhead LiDAR canopy characterization. For this, we invested major effort in a pilot study in order to optimize data sampling procedures as well as demonstrate the feasibility of the GPR methods. Within this pilot study, a series of GPR campaigns with different measuring platforms and setups was required to find the best tradeoff between the following arguments: i) good control and maneuvering performance of the platform, particularly near trees, ii) good signal to noise ratio in the radargram output, iii) sampling with as little disturbance of snow cover as possible, iv) accurate geo-location of data, and v) data collection that allows for efficient post-processing. The optimized design is shown in Figure 1. It consists of a single pair of separable shielded antennas (Mala AB, Sweden, here 1.3 GHz antennas are used) in a simple protection case mounted on a mini ski. The ski is directed using a pole mounted via an articulated joint. Apart from the antennas and the trigger mechanism all other electronic components are carried by the operator on person and do not put additional weight on the ski. More advanced GPR system setups, such as multi antenna / frequency approaches, were also tested. However, the highly reduced maneuvering flexibility and profiling speed greatly outweighed the positive effects on the data post-processing efficiency. As a consequence, periodic manual snow measurements are required to supplement the GPR profiling.

This work will take place on a regular sampling schedule. The GPR will be used along the length of each transect within the gridded field areas. Supplementary manual HS / SWE measurements will be collected using standard snow probes and SWE samplers for more efficient data post processing of the GPR data and verification purposes. Ideally, but weather permitting, all snow measurements will be made on a storm wise basis during the accumulation period and will change to predefined measurement intervals when the ablation onset is inferred.

Data Integration

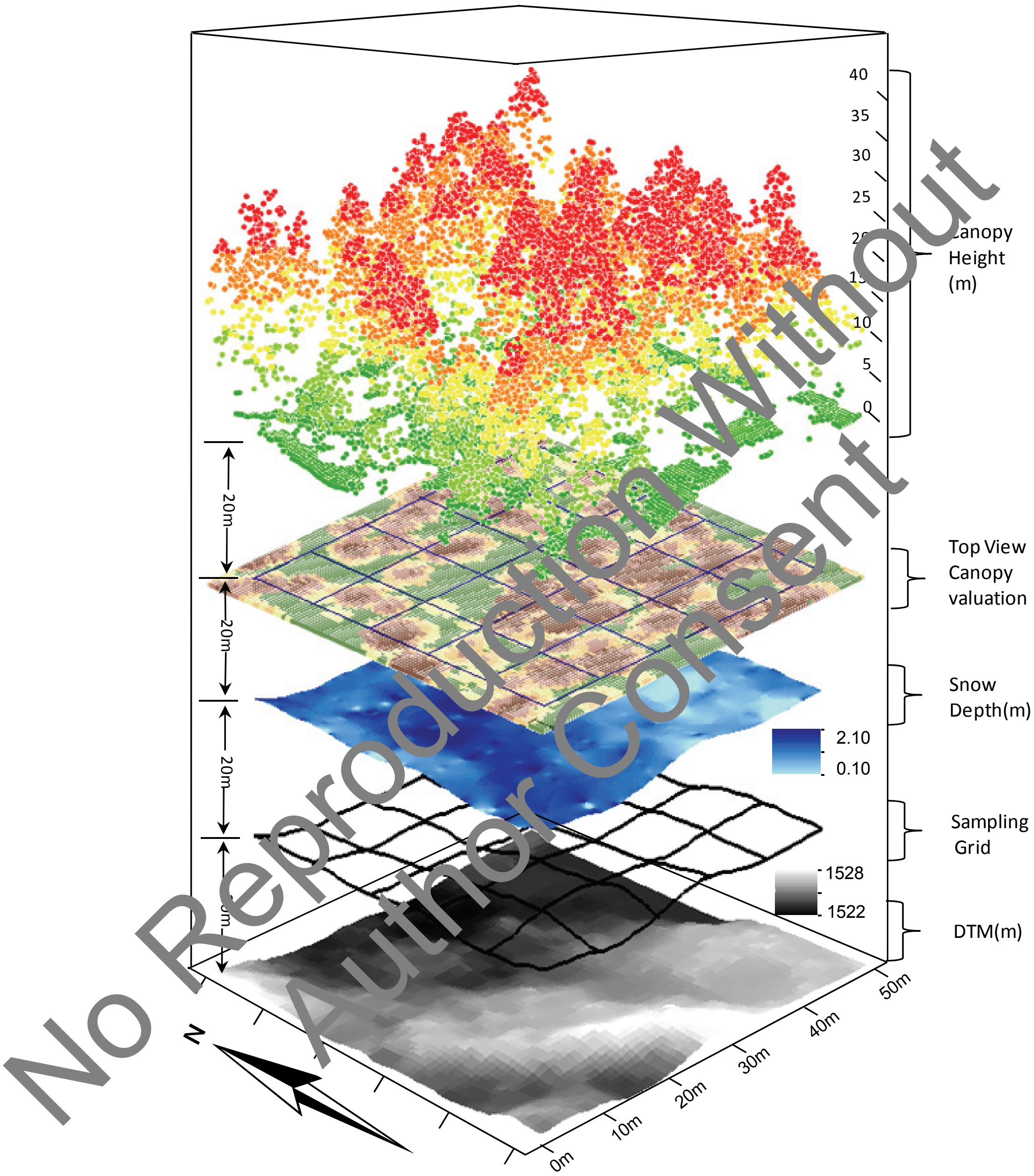

Figure 2: Data integration from Winter 2011/12 pilot study

Matching coordinates of ground-based measurements such as snow measurements and hemispherical photos with LiDAR data to be referenced in a global coordinate system incorporates certain challenges. As the use of GPS and DGPS systems are typically hampered under thick canopy, our pilot study showed that DGPS locations obtained in thinner forest / canopy gaps in combination with total station referencing allows for a suitable accuracy to locate and setup the sampling grid within our field sites. For this study, we will attempt a coordinate matching of all data to an accuracy of 50 cm or better. Within our pilot study, the alignment of the LiDAR datasets with DGPS-based coordinates turned out to be well within these accuracy requirements.

Figure 2 presents a spatial integration of all data collected and post-processed from a fully equipped test field site that was used during our pilot study. Available LiDAR data has been evaluated to a regular grid and in this figure we show canopy height in both a 2d and 3d projection respectively, as well as the underlying DTM. Based on an evaluation perimeter and a threshold height above ground, parameters like canopy closure or gap fractionation are easily available. Snow depth measurements taken along the sampling grid were interpolated to 2d and projected on top of the 3d DTM for presentation purposes only. For analysis purposes, data from each 50x50m study plot provide a time series of HS/SWE for thousands of points along the transects together with a number of parameters per point describing the surrounding canopy structure, topography, PSIR, etc.

2.4 Schedule and Milestones

Year	2013			2014				2015				2016
Quarter	II	III	IV	I	II	III	IV	I	II	III	IV	I
Data acquisition												
Field work	*											
Data post processing												
LiDAR data parsing	**											
Data analysis												
Goal 1: empirical analysis												
Goal 2: integration in models												
Goal 3: upscaling approaches												
Milestones												
Conference presentations			G1				G2			G3		
Papers submitted						G1				G2	G3	
PhD thesis submitted												
*	site survey and data acquisition starts in Oct. 2012 at WSL expenses											
**	continuation of ongoing effort											

Table 1: Project schedule and milestones

2.5 Relevance and Impact

The proposed study addresses particular shortcomings of canopy process representations in current land surface models, as identified by the SnowMIP2 initiative. Enhancing the understanding of spatial variability in snow accumulation and depletion processes under canopy is particularly important with respect to snow hydrological model applications. The innovative combination of LiDAR-based canopy structure data with extensive snow measurements allows for significant progress regarding recognized problems of upscaling from the site to grid scale. In particular, we expect the improvements made within this study to impact four specific levels.

First: Addressing the consistency of model performance between locations, years, and sites by integrating advanced canopy structure data over large scales, will stimulate research among the active network of scientists currently working on canopy snow processes (cf. 2.1.4). Bridging the gap between site-level research and representations of forest snow processes in models suitable for coarse scale applications constitutes the accomplishment of a major scientific challenge. Integrating new data acquisition techniques such as LiDAR and GPR, as well as demonstrating direct applicability to such challenges by facilitating and improving the data gathering and integration methods can be directly applied to subsequent forest snow process studies. The dissemination of the proposed research results will become publically available from publications in scientific journals as well as conference contributions.

Second: Integration of methodological improvements within the model utilized and developed by the operational snow hydrological service run by SLF will provide a direct benefit for the hydrological forecasting system in Switzerland, which includes flood forecasts as well as lake and reservoir management (cf. 2.2.3). As mentioned above, in Switzerland roughly 1/3 of the land mass is covered by forests while 1/3 of the winter precipitation fallen on subalpine forest is lost due to evaporation of intercepted snow. At the same time, the presence of forest greatly influences the timing of snowmelt runoff. Due to these interplays an improved representation of forest snow processes in operational snow melt modeling would constitute a great achievement for the Swiss hydrological forecasting system.

Third: Improved consistency in the performance of forest snow models will directly add to hydrologic impact studies, which rely on accurate representations of various ecosystem parameters in order to demonstrate the impacts of these changes on snow distribution over times. A key ecosystem service from forested areas is water storage and supply. But forest coverage and forest structures are changing due to land use policy, forest management, climate change as well as a variety of natural disturbances. The potential to more accurately assess the ecohydrological interactions between forest and ecotone structure changes and the subsequent effects on the snow distribution is particularly relevant and of great use to both forest and water managers throughout the world.

Fourth: Our multidisciplinary approach which integrates expertise in snow hydrology, remote sensing, and forest structure research is a key feature of the proposal. These three areas are directly related to the professional background of each of the proposal applicants, forming strong scientific support for the envisaged PhD study. While the proposed study concentrates on snow hydrology under canopy, the cooperation may lead to further research topics within this interface, such as snow feedbacks on forest evolution or impact of forest management scenarios on water resources.

3. References

Bartelt P, Lehning M (2002) A physical SNOWPACK model for the Swiss avalanche warning Part I: numerical model. Cold Regions Science and Technology 35: 123-145

Bavay M, Lehning M, Jonas T, Lowe H (2009) Simulations of future snow cover and discharge in alpine headwater catchments. Hydrological Processes 23: 95-108

Bugmann H (1996) A simplified forest model to study species composition along climate gradients. *Ecology* 77: 2055-2074

Bugmann H (2001) A review of forest gap models. *Clim. Change* 51: 259-305

Brundl M, Bartelt P, Schneebeli M, Fluhler H (1999) Measuring branch defection of spruce branches caused by intercepted snow load. Hydrological Processes 13: 2357-2369

Chang M, (2003) Forest Hydrology: An Introduction to Water and Forests. CRC Press, Boca Raton

Coops NC, Varhola A, Bater CW, Teti P, Boon S, Goodwin N, Weiler M (2009) Assessing differences in tree and stand structure following beetle infestation using lidar data. Canadian Journal of Remote Sensing 35: 497-508

Cunningham C, Zimmermann NE, Stoeckli V, Bugmann H (2006) Growth of Norway spruce (*Picea abies* L.) saplings in subalpine forests in Switzerland: Does spring climate matter? *Forest Ecology and Management* 228: 19-32

Cunningham C, Zimmermann NE, Stoeckli V, Bugmann H (2006) Growth response of Norway spruce saplings to artificial browsing, black snow mold, and ground vegetation in two forest gaps in the Swiss Alps. *Canadian Journal of Forest Research* 36: 2782-2796

Didion M, Kupferschmid AD, Zingg A, Fahse L, Bugmann H (2009) Gaining local accuracy while not losing generality – extending the range of gap model applications. *Canadian Journal of Forest Res*earch 39: 1092-1107

Dietz AJ, Kuenzer C, Gessner U, Dech S (2012) Remote sensing of snow - a review of available methods. International Journal of Remote Sensing 33: 4094-4134

Dozier J, Painter TH (2004) Multispectral and hyperspectral remote sensing of alpine snow properties. Annual Review of Earth and Planetary Sciences 32: 465-494

Egli L, Jonas T, Gruenewald T, Schirmer M, Burlando P (2012) Dynamics of snow ablation in a small Alpine catchment observed by repeated terrestrial laser scans. Hydrological Processes 26: 1574-1585

Erdody TL, Moskal LM (2010) Fusion of LiDAR and imagery for estimating forest canopy fuels. Remote Sensing of Environment 114: 725-737

Essery R, Rutter N, Pomeroy J, Baxter R, Stahli M, Gustafsson D, Barr A, Bartlett P, Elder K (2009) SnowMIP2 - An evaluation of forest snow process simulations. Bulletin of the American Meteorological Society 90: 1120-+

Flerchinger GN, Xaio W, Marks D, Sauer TJ, Yu Q (2009) Comparison of algorithms for incoming atmospheric long-wave radiation. Water Resources Research 45: 13

Fu PD, Rich PM (2000) The Solar Analyst 1.0. Manual Helios Environmental Modeling Institute (HEMI), USA

Fu PD, Rich PM (2002) A geometric solar radiation model with applications in agriculture and forestry. Computers and Electronics in Agriculture 37: 25-35

Godio A (2009) Georadar measurements for the snow cover density. American Journal of Applied Sciences 6

Gschwantner T, Schadauer K, Vidal C, Lanz A, Tomppo E, di Cosmo L, Robert N, Duursma DE, Lawrence M (2009) Common tree definitions for national forest inventories in Europe. Silva Fenn 43: 303-321

Hedstrom NRP, Pomeroy J (1998) Measurements and modeling of snow interception in the boreal forest. Hydrologic Processes 12: 1611-1625

Hellström R (2000) Forest cover algorithms for estimating meteorological forcing in a numerical snow model. Hydrologic Processes 14: 3239-3256

Hopkinson C, Chasmer L (2009) Testing LiDAR models of fractional cover across multiple forest ecozones. Remote Sensing of Environment 113: 275-288

Jennings SB, Brown ND, Sheil D (1999) Assessing forest canopies and understorey illumination: canopy closure, canopy cover and other measures. Forestry 72: 59-73

Jonas T, Marty C, Magnusson J (2009) Estimating the snow water equivalent from snow depth measurements in the Swiss Alps. Journal of Hydrology 378: 161-167

Jonas T, Essery R (2011) Snow cover and snowmelt in forest regions; In: Singh VP, Singh P, Haritashya UK, (eds) Encyclopedia of Snow, Ice and Glaciers, Series Encyclopedia of Earth Sciences Series; Dordrecht Heidelberg, Springer, 1033-1036

Jost G, Weiler M, Gluns DR, Alila Y (2007) The influence of forest and topography on snow accumulation and melt at the watershed-scale. Journal of Hydrology 347: 101-115

Kato A, Moskal LM, Schiess P, Swanson ME, Calhoun D, Stuetzle W (2009) Capturing tree crown formation through implicit surface reconstruction using airborne lidar data. Remote Sensing of Environment 113: 1148-1162

Korhonen L, Korpela I, Heiskanen J, Maltamo M (2011) Airborne discrete-return LiDAR data in the estimation of vertical canopy cover, angular canopy closure and leaf area index. Remote Sensing of Environment 115: 1065-1080

Kruetzmann NC, Rack W, McDonald AJ, George SE (2011) Snow accumulation and compaction derived from GPR data near Ross Island, Antarctica. Cryosphere 5: 391-404

Lee H, Slatton KC, Roth BE, Cropper WP (2009) Prediction of forest canopy light interception using three-dimensional airborne LiDAR data. International Journal of Remote Sensing 30: 189-207

Leeuwen M, Nieuwenhuis M (2010) Retrieval of forest structural parameters using LiDAR remote sensing. European Journal of Forest Research 129: 749-770

Lehning M, Bartelt P, Brown B, Fierz C, Satyawali P (2002) A physical SNOWPACK model for the Swiss avalanche warning Part II: Snow microstructure. Cold Regions Science and Technology 35: 147-167

Lehning M, Volksch I, Gustafsson D, Nguyen TA, Stähli M, Zappa M (2006) ALPINE3D: a detailed model of mountain surface processes and its application to snow hydrology. Hydrological Processes 20: 2111-2128

Li WP, Luo Y, Xia K, Liu X (2008) Simulation of snow processes beneath a boreal Scots pine canopy. Advances in Atmospheric Sciences 25: 348-360

Lopez-Moreno JI, Latron J (2008) Influence of canopy density on snow distribution in a temperate mountain range. Hydrological Processes 22: 117-126

Lopez-Moreno JI, Stahli M (2008) Statistical analysis of the snow cover variability in a subalpine watershed: Assessing the role of topography and forest, interactions. Journal of Hydrology 348: 379-394

Lundberg A, Granlund N, Gustafsson D (2010) Towards automated 'ground truth' snow measurements-a review of operational and new measurement methods for Sweden, Norway, and Finland. Hydrological Processes 24: 1955-1970

Lundberg A, Nakai Y, Thunehed H, Halldin S (2004) Snow accumulation in forests from ground and remote-sensing data. Hydrological Processes 18: 1941-1955

Lundberg A, Richardson-Naslund C, Andersson C (2006) Snow density variations: consequences for ground-penetrating radar. Hydrological Processes 20: 1483-1495

Magnusson J, Jonas T, Lopez-Moreno I, Lehning M (2010) Snow cover response to climate change in a high alpine and half-glacierized basin in Switzerland. Hydrol Res 41: 230-240

Marsh P (1999) Snowcover formation and melt: recent advances and future prospects. Hydrologic Processes: 2117-2134

Montesi JE, K.; Schmidt, R.A. (2004) Sublimation of intercepted snow within a subalpine forest canopy at two elevations. Journal of Hydrometeorology 5: 763-773

Morsdorf F, Kötz B, Meier E, Itten KI, Allgöwer B (2006) Estimation of LAI and fractional cover from small footprint airborne laser scanning data based on gap fraction. Remote Sensing of Environment 104: 50-61

Morsdorf F, Meier E, Kötz B, Itten KI, Dobbertin M, Allgöwer B (2004) LIDAR-based geometric reconstruction of boreal type forest stands at single tree level for forest and wildland fire management. Remote Sensing of Environment 92: 353-362

Musselman KN, Molotch NP, Brooks PD (2008) Effects of vegetation on snow accumulation and ablation in a mid-latitude sub-alpine forest. Hydrological Processes 22: 2767-2776

Niu G-Y (2004) Effects of vegetation canopy processes on snow surface energy and mass balances. Journal of Geophysical Research 109

Nolin AW (2010) Recent advances in remote sensing of seasonal snow. Journal of Glaciology 56: 1141-1151

Nyberg L, Stähli M, Mellander PE, Bishop KH (2001) Soil frost effects on soil water and runoff dynamics along a boreal forest transect: 1. Field investigations. Hydrological Processes 15: 909-926

Pfister R, Schneebeli M (1999) Snow accumulation on boards of different sizes and shapes. Hydrological Processes 13: 2345-2355

Pomeroy J, Gray D (1995) Snow accumulation, relocation and management. National Hydrology Research Institute Science Report No. 7. Environment Canada: Saskatoon. 144 pp.

Pomeroy J, Hedstrom, N, Gray, D (1998) Coupled modelling of forest snow interception and sublimation. Hydrologic Processes 12: 2317-2337

Pomeroy J, Gray D, Hedstrom N, Janowicz J (2002) Prediction of seasonal snow accumulation in cold climate forests. Hydrological Processes 16: 3543-3558

Pomeroy J, Marks D, Link T, Ellis C, Hardy J, Rowlands A, Granger R (2009) The impact of coniferous forest temperature on incoming longwave radiation to melting snow. Hydrological Processes 23: 2513-2525

Prokop A (2008) Assessing the applicability of terrestrial laser scanning for spatial snow depth measurements. Cold Regions Science and Technology 54: 155-163

Rasche L, Fahse L, Zingg A, Bugmann H (2012) Enhancing gap model accuracy by modeling dynamic height growth and dynamic maximum tree height. *Ecological Modelling* 232: 133-143

Rich P, Hetrick W, Saving S (1994) Using viewshed models to calculate intercepted solar radiation: applications in ecology. American Society for Photogrammetry and Remote Sensing: 524-529

Risch A, Heiri C, Bugmann H (2005) Simulating structural forest patterns with a forest gap model: a model evaluation. *Ecol. Modelling* 181: 161-172

Rutter N, Essery R, Pomeroy J, Altimir N, Andreadis K, Baker I, Barr A, Bartlett P, Boone A, Deng HP, Douville H, Dutra E, Elder K, Ellis C, Feng X, Gelfan A, Goodbody A, Gusev Y, Gustafsson D, Hellstrom R, Hirabayashi Y, Hirota T, Jonas T, Koren V, Kuragina A, Lettenmaier D, Li WP, Luce C, Martin E, Nasonova O, Pumpanen J, Pyles RD, Samuelsson P, Sandells M, Schadler G, Shmakin A, Smirnova TG, Stähli M, Stockli R, Strasser U, Su H, Suzuki K, Takata K, Tanaka K, Thompson E, Vesala T, Viterbo P, Wiltshire A, Xia K, Xue YK, Yamazaki T (2009) Evaluation of forest snow processes models (SnowMIP2). J Geophys Res-Atmos 114: 18

Seidel D, Fleck S, Leuschner C (2012) Analyzing forest canopies with ground-based laser scanning: A comparison with hemispherical photography. Agricultural and Forest Meteorology 154-155: 1-8

Sicart J, J.; Essery, R.; Hardy, J.; Link,T.; Marks, D. (2004) A Sensitivity Study of Daytime Net Radiation during Snowmelt to Forest Canopy and Atmospheric Conditions. Journal of Hydrometeorology 5: 774-784

Solberg S, Brunner A, Hanssen KH, Lange H, Næsset E, Rautiainen M, Stenberg P (2009) Mapping LAI in a Norway spruce forest using airborne laser scanning. Remote Sensing of Environment 113: 2317-2327

Stahli M, Gustafsson D (2006) Long-term investigations of the snow cover in a subalpine semi-forested catchment. Hydrological Processes 20: 411-428

Stahli M, Jonas T, Gustafsson D (2009) The role of snow interception in winter-time radiation processes of a coniferous sub-alpine forest. Hydrological Processes 23: 2498-2512

Stähli M, Schaper J, Papritz A (2002) Towards a snow-depth distribution model in a heterogeneous subalpine forest using a Landsat TM image and an aerial photograph. In: Winther JG, Solberg R (eds) Annals of Glaciology, Vol 34, 2002, Annals of Glaciology:65-70.

Strasser U, Warscher M, Liston GE (2011) Modeling snow–canopy processes on an idealized mountain. Journal of Hydrometeorology 12: 663-677

Suzuki KN, Yuichiro; Ohta, Takeshi; Nakamura, Tsutomu; Ohata, Tetsuo (2003) Effect of snow interception on the energy balance above deciduous and coniferous forests during a snowy winter. Paper presented at the IUGG - Water Resource Systems, Sapporo, Japan 2003

Varhola A, Coops NC, Bater CW, Teti P, Boon S, Weiler M (2010) The influence of ground- and lidar-derived forest structure metrics on snow accumulation and ablation in disturbed forests. Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere 40: 812-821

Veatch W, Brooks PD, Gustafson JR, Molotch NP (2009) Quantifying the effects of forest canopy cover on net snow accumulation at a continental, mid-latitude site. Ecohydrology 2: 115-128

Weber P, Bugmann H, Fonti P, Rigling A (2008) Using a retrospective dynamic competition index to reconstruct forest succession. *Forest Ecology and Management* 254: 96-106

Wehrli A, Zingg A, Bugmann H, Huth A (2005) Using a forest patch model to predict the dynamics of stand structure in Swiss mountain forests. *Forest Ecology and Management* **205**: 149-167

Whitaker A, Sugiyama H (2005) Seasonal snowpack dynamics and runoff in a cool temperate forest: lysimeter experiment in Niigata, Japan. *Hydrological Processes* **19**: 4179–4200

Zhao K, Popescu S (2009) Lidar-based mapping of leaf area index and its use for validating GLOBCARBON satellite LAI product in a temperate forest of the southern USA. Remote Sensing of Environment 113: 1628-1645

Zierl B (2005) Global change impacts on hydrological processes in Alpine catchments. Water Resources Research 41

Zierl B, Bugmann H, Tague CL (2007) Evaluation of water and carbon fluxes in the ecohydrological model RHESSys. *Hydrological Processes* **21**(24): 3328–3339