Doctoral Thesis

Snow interception and meltwater transport in subalpine forests

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Snow Interception
and Meltwater Transport
in Subalpine Forests

A dissertation submitted to the
SWISS FEDERAL INSTITUTE OF TECHNOLOGY ZURICH
for the degree of
DOCTOR OF NATURAL SCIENCES

presented by
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Dr. Martin Schneebeli, co-examiner

1997
Preface

The frame of this thesis is the project “Water regimes in subalpine forests: snow interception, meltwater and surface discharge” which was carried out within the frame work of the National Research Program 31 “Climate changes and natural disasters” (Stadler et al., 1997).

The idea of the project was the characterization and investigation of the transport processes beginning from the onset of the precipitation onto the canopy, its way through the crown to the snowpack and finally the processes within the soil. It was initiated by Hannes Flühler (Department of Soil Physics at Institute for Terrestrial Ecology ITOe, ETH Zurich), Martin Meyer-Grass (Swiss Federal Institute for Forest, Snow and Landscape Research WSL, Birmensdorf) and Martin Schneebeli (Swiss Federal Institute of Snow and Avalanche Research SLF\(^1\), Davos). The investigations at the soil surface and in the soil were performed by Daniel Stadler (Soil Physics, ITOe, Zurich) whereas I (SLF, Davos) looked at the processes in the tree crown and the snowpack and in between. The results of Daniel Stadler’s investigations are given in Stadler (1996).

The studies aimed to a better understanding of the physical relations between water stored in the tree crown, snowpack and soil in order to judge the consequences a climate change might have for hydrological processes in subalpine forests in winter. The longer the project proceeded our understanding improved and it became clear how difficult it is to make any predictions about the consequences of climate change in the scale of an alpine valley or even a single forest.

The way through my thesis work was a continuous confrontation with new ideas, new scientific methods and also problems. The way included a lot of ups and downs like a long trail in the Alps—a period of my life which I never want to miss.

\(^1\)The institute is a branch of the Swiss Federal Institute for Forest, Snow and Landscape Research WSL, Birmensdorf
Many people have contributed to this work. I would like to express my thanks and acknowledges to:

**Dr. Martin Schneebeli** for initiating the project and leading me through the jungle of the project. He always had an open door and open ear for my ideas and problems. Innumerable discussions about various scientific problems and many other topics provided a comfortable and fruitful working background. His comments greatly improved the quality of the manuscript.

**Prof. Dr. Hannes Flühler** for initiating the project and providing the possibility to conduct this work in his group despite of the fact that my working place was in Davos and not in Zurich. He gave me great freedom to develop my ideas. Especially in the final part of the work he provided an excellent support in reviewing the manuscript. His very valuable comments substantially improved the linguistic and scientific readability.

**Dr. Martin Meyer-Grass** for initiating the project and being an important and helpful discussion partner not only in scientific questions.

**Prof. Dr. Gode Gravenhorst** for taking over the co-examination and reviewing the manuscript of this thesis. His kindness offered the possibility to start a collaboration with the Institute of Bioclimatology at the University of Göttingen.

**Dr. Walter Ammann** for providing the possibility for carrying out this work at SLF. His involvement made an additional financial support of the work possible.

**Dr. Daniel Stadler** for being a helpful and open-minded partner in the project. He had an open ear also for my field of research. Several ventures with him gave a collaborative and comfortable working atmosphere.

**Dr. Perry Bartelt** for introducing me into the technique of finite element modeling with the model FLOWERS. He also reviewed carefully parts of this thesis.

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Walter Caviezel, Urs Suter and Angelo Maccagnan for their help in setting up the measurement devices in the laboratory and field. They were never tired to provide technical support in case of problems with the measurement equipment.

Marcia Phillips for helping me in linguistic questions.

Birgit Aschenbrenner, Walter Peschke, Diethart Peters, Christian Quadri for their support during their practical work at SLF.

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All other colleagues at SLF for sharing the working environment and providing a comfortable atmosphere.

Swiss Federal Institute for Forest, Snow and Landscape Research for financial support of the exchange with the Swedish University of Agricultural Sciences in Uppsala.

Swiss National Science Foundation for financial support of the project.

Finally I want to express my gratitude to my wife Eva and my daughters Manuela and Simone for their patience. They gave me a harmonious basis for my work.

Davos, November 1997
Michael Bründl
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Contents

Kurzfassung vii

Summary xi

Overview 1

1 Introduction 3
  1.1 Review of the literature ........................................ 3
  1.2 Measurement techniques ........................................ 7
  1.3 Physics of snow interception ................................... 9
  1.4 Methodological requirements ................................... 14

2 Observing Snow Interception in Spruce Crowns 17
  2.1 Introduction ....................................................... 18
  2.2 Methods and instrumentation setup ............................ 18
    2.2.1 Digitizing and image enhancement ............................. 20
    2.2.2 Image analysis ................................................. 22
  2.3 Results ............................................................. 25
  2.4 Discussion ......................................................... 27
  2.5 Conclusions ......................................................... 30

3 Comparison of Snow Interception at Davos and Alptal 31
  3.1 Introduction ......................................................... 32
  3.2 Experimental sites and methods .................................. 33
  3.3 Snow interception events at Davos and Alptal .................. 36
    3.3.1 Winter characteristics ....................................... 36
    3.3.2 Interception events in both winters ........................ 37
  3.4 Comparison of an interception event at Davos and Alptal .... 41
  3.5 Statistical modeling .............................................. 48
    3.5.1 Tree regression ................................................. 48
    3.5.2 Prediction of event duration ................................ 49
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.6</td>
<td>Discussion</td>
<td>53</td>
</tr>
<tr>
<td>3.7</td>
<td>Conclusions</td>
<td>56</td>
</tr>
<tr>
<td>4</td>
<td>Estimating the Intercepted Snow Mass on Spruce Branches</td>
<td>57</td>
</tr>
<tr>
<td>4.1</td>
<td>Introduction</td>
<td>58</td>
</tr>
<tr>
<td>4.2</td>
<td>Investigation sites and methods</td>
<td>60</td>
</tr>
<tr>
<td>4.3</td>
<td>Calibration of branch displacement</td>
<td>61</td>
</tr>
<tr>
<td>4.4</td>
<td>Modeling branch displacement</td>
<td>62</td>
</tr>
<tr>
<td>4.5</td>
<td>Modeling the intercepted mass</td>
<td>65</td>
</tr>
<tr>
<td>4.6</td>
<td>Conclusions</td>
<td>71</td>
</tr>
<tr>
<td>5</td>
<td>Visualization of Meltwater Drip in the Snowpack</td>
<td>73</td>
</tr>
<tr>
<td>5.1</td>
<td>Introduction</td>
<td>73</td>
</tr>
<tr>
<td>5.2</td>
<td>Experimental site and methods</td>
<td>75</td>
</tr>
<tr>
<td>5.3</td>
<td>Results and Discussion</td>
<td>76</td>
</tr>
<tr>
<td>5.4</td>
<td>Conclusions</td>
<td>87</td>
</tr>
<tr>
<td>6</td>
<td>Final Remarks</td>
<td>89</td>
</tr>
<tr>
<td></td>
<td>List of Symbols</td>
<td>93</td>
</tr>
<tr>
<td></td>
<td>List of Figures</td>
<td>94</td>
</tr>
<tr>
<td></td>
<td>List of Tables</td>
<td>97</td>
</tr>
<tr>
<td></td>
<td>Bibliography</td>
<td>99</td>
</tr>
<tr>
<td></td>
<td>Curriculum Vitae</td>
<td>111</td>
</tr>
</tbody>
</table>
Kurzfassung


der Kugeln ergibt eine Zeitserie der Astbewegung, die einen Index für die interzeptierte Schneemenge darstellt.


Die statistische Modellierung des Zusammenspiels zwischen meteorologischen Faktoren und der Ereignislänge erwies sich als problematisch. Die Vorhersage der Ereignisdauer durch Anwendung von binären Baummodellen als Alternative zur multiplen Regression zeigt, dass die Ereignisdauer nur für Ereignisse kürzer als drei Tage zufriedenstellend vorhergesagt werden kann. Längere Ereignisse konnten mit dieser Methode nur mit teils grossen Ungenauigkeiten vorhergesagt werden, da die Variabilität der meteorologischen Faktoren steigt und sich die Eigenschaften der Interzeptionsereignisse mit zunehmender Länge verändern.

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Summary

This work was conducted in the years 1992-1996 within the project "Water regimes in subalpine forests: snow interception, meltwater and surface discharge" (Stadler et al., 1997). The project was supported by the Swiss National Science Foundation within the frame of the program 31 "Climate changes and natural disasters". The aim of this project was the investigation of the phase change and transport processes between tree, snowpack and soil in a subalpine forest in winter. In this thesis the processes within the tree crown and the interaction with the snowpack are investigated.

In the first part the pertinent literature is reviewed, and the physical processes in the tree crown are described. The first investigations on snow interception described the difference of snow accumulation under and outside of a tree crown. The physical processes were described in a qualitative manner. Later on the intercepted mass was measured with different methods. A common method was and is weighing a cut tree and therefore directly measuring the intercepted mass. Most of these studies were conducted in the continental, dry climate of Northern America, where up to 30% of snow precipitation is lost for discharge in summer due to sublimation and evaporation. Experiments in the 90's contributed mainly to the understanding of the physical processes.

The second part presents a method for observing and measuring the intercepted mass. At two sites in the Swiss Alps a spruce crown was continuously observed by a video camera during the winter. The image analysis allowed to monitor variations of loading and unloading of the crown. Image analysis was also used to quantify the deflection of the branches under snow load by extracting the positions of balls which were attached to the branches. Analysis of the position of the balls yielded a time series of the branch movement which is an expression of the intercepted snow mass.

However automated analysis of images recorded under natural, heterogeneous light conditions posed problems. The main problem are low contrasts between the balls and the background during the day which make automated analysis impossible. Automated analysis was only possible with images
recorded at night. In these images contrast between balls and the nearly black background is sufficient. Hence, video observation proved to be a valuable tool in continuous observation of dynamic processes over a long time sequence.

In the third chapter the observations made at the two sites, Davos and Alptal, were compared to each other as well as to the meteorological conditions of the long term yearly and monthly average. The measurements show that there is no unique relation between temperature, precipitation and the number of interception events. An interception event was in this context defined as a time period between first snow accumulation in the crown and the time when the tree was bare of snow again. During November through February the lower mean air temperature explain the longer duration of snow cover in the tree crown compared to Alptal where event duration was shorter. In spring the relation between temporal snow cover and mean air temperature indicates that air temperature alone does not allow the prediction of the duration of snow retention in the canopy relative to the duration of the winter period. Lower global radiation caused a longer, mean temporal snow cover of the crown compared to that at Davos. In spring global radiation played an important role at both sites.

Statistical modeling of the interplay of meteorological factors and interception event duration is a difficult task. Predicting the event duration by using binary tree regression as an alternative to multiple regression shows that event duration could only be predicted for events shorter than three days. Longer events are predicted with insufficient precision because variability of the meteorological factors increases and the characteristics of the events change with increasing event duration.

The branch motion which was measured by analyzing the video images was the basis for the estimation of intercepted mass on branches. A north and south exposed branch of the Davos tree were loaded with weights and the deflection was measured. Deflection of the branch was thus calibrated. The results of these calibrations were used as input into a Finite Element Model by which Young’s modulus of the branches under certain temperature conditions was calculated. Using these simulations a function for the relation of branch temperature and Young modulus was obtained. This relation could then be used to calculate the temporal variation of Young’s modulus during an interception event. Using the results of the numerical model in the statistical model facilitated the calculation of the intercepted mass on a branch. The results are in the same magnitude as those obtained by hand (2.5 to 4.5 kg snow). We calculated a maximum of intercepted snow mass of 4.7 kg on a single 230 cm long branch.
Especially during spring events a large amount of intercepted snow drips as meltwater to the ground. In a dye tracer experiment we stained the snow-free branches before a snowfall. Melting snow on branches dissolved the tracer and the colored meltwater drops fell into the snowpack beneath. The induced meltwater channels were analyzed by field observation and photography indicating that the meltwater percolated along preferential flow paths through the isothermal snowpack. All meltwater seeped through the snowpack within the projected area and no water ran off downslope beyond the crown edge. At the base of the southern exposed shallower snowpack a basal ice layer developed whereas at the northern slope no basal ice layer at the base of the snowpack could be detected. On the basal ice layer some lateral flow occurred extending only as far as the crown edge. Together with the observations in the tree crown the experiments suggested that meltwater stemming from the canopy flows directly through the snowpack into the forest soil.
Overview

This work is divided into six chapters which stand for themselves and hence, can be read separately. Chapter three through five are prepared for publication in journals. The content of the individual chapters is summarized below.

Chapter 1: This chapter contains four sections: Section one is a review of the pertinent literature about snow interception. Section two describes the commonly used measurement techniques, section three the physical processes of snow interception. In the last section the methodological requirements for this work are presented.

Chapter 2: This chapter describes a method for the observation and analysis of snow interception. The characteristics of the methods in terms of their practicability under natural conditions and encountered problems are discussed.

Chapter 3: The first part summarizes the observations of the two winter periods at two different sites and describes the relation of the meteorological factors with regard to the observed processes. The role of the controlling factors were analyzed using the data from the example of a single interception event. Observations of both mountaineous forest sites at two different altitudes and hence different winter conditions were compared to each other. With a statistical approach the sensitivity of an interception event to weather conditions and the relation between event duration and meteorological factors was analyzed. The robustness of the statistical model was tested by predicting the interception event duration for both sites.

Chapter 4: This chapter describes the estimation of the intercepted mass in the crown based on measurements of branch deflection under snow load. Based on calibration of branch deflection under defined loads the Young’s modulus of the branches was calculated using a Finite Element Model. This allowed to estimate the temperature dependence of the
mechanical characteristics of spruce branches and their movement under different snow loads. Results of the simulations were used to calculate the intercepted mass using a statistical model.

Chapter 5: Water retained in the crown which is not sublimated or evaporated drops to the ground either as snow or as meltwater. This induces structural changes in the snowpack which itself governs the meltwater percolation in the snowpack. A dye tracer technique was used to visualize flow patterns of dripping meltwater in the snowpack. The results are compared with results obtained from experiments in an open area snowpack.

Chapter 6: This chapter presents some concluding remarks.
Chapter 1

Introduction

1.1 Review of the literature

The accumulation of precipitation in forests and the discharge from forested catchments is an important topic in the hydrological literature because it determines water supply for inhabited and uninhabited areas of high and middle latitudes of the northern and southern hemisphere. Snow plays a central role as a temporal water storage and the release of water at the end of the winter or in spring. The literature about forest and snow can be divided into three parts: (i) studies on meso-scale snow distribution in forests, (ii) studies on snow interception as a part of the hydrological cycle in forests and (iii) influence of forests on formation of avalanches. Since snow distribution is of minor interest in this work only a brief overview is included here.

First studies on the influence of trees on snow distribution were done by Kittredge (1953) who found a statistical relation between snow depth, snow water equivalent, evaporation, and disappearance of snow under and beside tree crowns using a large data set. A summary on investigations on snow as a hydrological factor is given in Corps of Engineers, U.S. Army (1956).

The influence of clearings on snow accumulation in forests was investigated by numerous authors. They found that the size of openings strongly influences snow accumulation and melt rates in forests. Hansen and Ffolliott (1968) measured increased snow accumulation in forest strips with widths of 1 to 1.5 times tree height. Comparing several aspects they found that snow accumulation is greater in west exposed openings than in south or southwest aspected openings. Gary (1974, 1980) confirmed these observations and measured 15-35% greater accumulation in openings having a width of one, three, and five times the tree height, Golding and Swanson (1978) measured a 45% greater snow accumulation in an opening in the size two times the tree height.
than in an uncut stand. In a later work the authors explained differences of snow water equivalent in north and south exposed clearings as a function of direct solar radiation (Golding and Swanson, 1986).

The influence of storm intensity and stand characteristics on snow interception was discussed by McNay et al. (1988) who found that the amount of new snow in a forest can be expressed as a function of mean crown cover. The capacity of a stand to intercept snow can be predicted by statistical inference based on storm characteristics and mean crown cover. Harestad and Bunnell (1981) mentioned that water equivalents of the snowpack (SWE) can be predicted based on canopy cover.

Literature on snow interception has been reviewed by Kittredge (1948) as cited in Kittredge (1953). Common to the first studies on snow interception was the estimation of the snow quantity retained in the canopy by comparing snow deposition under a canopy and in an opening. Using rain gauges in a 65 to 75 year old secondary growth ponderosa pine stand Rowe and Hendrix (1951) measured 84% (of snow precipitation) as throughfall, 4% as stemflow, and accounted the remaining 12% to interception losses. Kittredge (1953) reported of a 34% interception in a mixed conifer canopy, and a 31% interception in a sugar and ponderosa pine forest both in the Central Sierra Nevada, USA.

Goodell (1959) gave a detailed description of the interception process and on the role of solar radiation in a forest canopy. He reported that 30% of the annual snowfall can evaporate directly from the canopy. He also observed that snow close to needles and branches melted rapidly. Depending on the meteorological conditions the melted snow between the needles can evaporate.

Miller (1961) summarizes earlier research and states that the snow load in a canopy is greatest just below 0°C when wind speed is 1 to 2 m s⁻¹. Greatest loadings in the crown occur when cold snow settles on warm trees because contact of cold snowflakes with warm foliage creates a thin meltwater film which when refrozen gives a good adherence. A broader state of the art is given by Miller (1964) who describes influencing factors on snow interception qualitatively.

The first study trying to quantify snow interception directly was performed by Satterlund and Haupt (1967) in northern Idaho who suspended a Douglas fir and a western white pine by a thin cable and measured the weight of the tree during snowfall events. This device (called “interceptograph”) allowed measurements of the intercepted mass with a hourly resolution. They compared it with precipitation records. Their results suggested an S-shaped increase when plotting interception storage versus snowfall. Additional measurements including the collection of drip from the crown using a plastic sheet showed
for Douglas fir that 32% of precipitation was intercepted and 68% reached the
ground as throughfall. From the intercepted portion finally 4.5% evaporated
and the rest reached the ground due to unloading (Satterlund and Haupt,
1970).

The first study observing snow interception over the course of the winter
were done by Hoover and Leaf (1967) at the Fraser Experimental Forest in
Colorado, USA. They observed the process at the branch and needle surfaces
in detail and found that snow accumulates at the base of the needles in the
first phase of the storm, but may sift out of the needle space later due to wind.
Snow that persists longer than 24 hours in the crown is balanced on the tip
of the needles rather than anchored between the needles. Observations with
a 16 mm camera showed that on 55% of the days from November to May the
trees were covered with snow. This also showed that drip and unloading of
intercepted snow was the major process. Evaporation was considered to play
a minor role but was not quantified.

Further experiments including observations of snow interception were per¬
formed by Tennyson et al. (1974) with a super 8 mm time-lapse camera. Ac¬
cumulation in the tree crown was found to be nonlinear with a rapid initial
catch and a decreasing storage during the continuing storm which confirmed
the S-shaped increase suggested by Satterlund and Haupt (1967). Most of the
intercepted snow was found to become unloaded to the ground. The rate of
evaporation and sublimation was considered to be less but was not quantified
in this study.

The amount of intercepted snow was measured by Strobel (1978) calcul¬
ating the difference of the water equivalent under the canopy and in an open
area just after the snowfall. He found interception values of 70% of the pre¬
cipitation in a spruce forest at the northern border of the Swiss Alps. The
accumulation in the crown was described with a monotonous increase but he
assumed that storage values were probably overestimated because drip and
unloading could not be measured by the chosen method.

The accumulation process of snow was investigated in detail by Kobayashi
(1987) using boards. Laboratory experiments demonstrated that the efficiency
of snow accumulation decreased when the width of the boards and also when
the air temperature decreased, because snow crystals tended to bounce off the
boards even when the boards were covered with dendritic crystals. Maximum
efficiency of interception could be found when air temperature approached
towards 0°C.

Detailed studies on the sublimation process were conducted by Schmidt
et al. (1988) who put a 1 m high artificial coniferous tree on a highly sensi-
tive balance with a resolution of 0.1 g. With this apparatus they measured sublimation with a temporal resolution of 10 to 15 min. These measurements were used to build a model for predicting sublimation from the whole crown based on sublimation from a 1 mm diameter ice sphere (Schmidt, 1991). The authors found sublimation rates up to 30% relative to precipitation for a cold dry environment.

However, the accumulation of snow onto natural crowns differs from that onto an artificial crowns. Schmidt and Gluns (1991) investigated the influence of tree species on snow interception by comparing accumulation on cut branches of Engelmann spruce (*Picea engelmannii* Parry), subalpine fir (*Abies lasioscarpa* (Hook.) Nutt.), lodgepole pine (*Pinus contorta* var. *latifolia* Engelm.), and artificial branches. They found that accumulation corresponded with the S-shaped curve given by Satterlund and Haupt (1967). Apparently, the stiffer artificial branch caught more snow than natural branches. The observed load on branches decreased linearly with increasing snow density because elastic rebound of crystals was greater at higher densities. They developed a model that predicts interception in relation to snow density and characteristic parameters of the branch. Analysis of variance of 22 storm events explained significant differences for different storms but not for tree species.

Sublimation of intercepted snow in dry climate of northern America is an important factor in the hydrological balance because it regulates water supply during drier seasons. Schmidt and Troendle (1992) estimated that in the Canadian boreal forest a snow water equivalent of 4.6 cm sublimated back to the atmosphere and, hence, contributed to water vapor concentration in the atmosphere. Dominant factors for sublimation of intercepted snow are wind speed, air temperature, humidity, radiation and the extent and nature of the snow surface exposed to these factors. The fractal nature of intercepted snow allows the calculation of an exposure coefficient of intercepted snow using digitized photographs which permit calculation of the sublimation rate of interception when intercepted mass and sublimation of a single ice sphere is known (Pomeroy and Schmidt, 1993).

Using a suspended tree Pomeroy and Gray (1995) measured accumulation of snow on a black spruce in Saskatchewan, Canada and showed that one-third of the annual snowfall was sublimated in two months.

Investigations on snow interception under less dry conditions are published by Lundberg (1993) who put a spruce tree on a balance combined with a tray beneath catching the drip of intercepted snow. The analysis of governing factors in the climate of northern Sweden showed that humidity and aerodynamic
resistance are the dominating factors for evaporation and sublimation of intercepted snow whereas air temperature, wind speed, and net radiation are less critical (Lundberg and Halldin, 1994). Evaporation could be described with a one-dimensional combination equation based on the Penman-Monteith equation. However they state explicitly that these results cannot be extrapolated to regions with different climatic conditions.

Sensitivity studies of the aerodynamic resistance were performed by Lundberg (1996) who found that calculation of evaporation using the aerodynamic resistance for rain led to an overestimation of the evaporation rate by a factor of 2.6. Using a ten times larger aerodynamic resistance gave good agreement between measured and calculated values. These results are confirmed by studies of Calder (1990).

A similar approach was used by Nakai et al. (1994) who estimated evaporation of intercepted snow from a Todo-fir (Abies sachalinensis Masters) in Sapporo, Japan. They calculated an evaporation rate of 3.5 mm d\(^{-1}\), a value which is quite close to the values measured by Lundberg and Halldin (1994) of up to 3.3 mm d\(^{-1}\). The aerodynamic resistance was also considerably higher than that for rain and in the same magnitude as that reported by Calder (1990) and Lundberg (1996).

Table 1.1 presents an overview about the work on snow interception cited above.

### 1.2 Measurement techniques

A recent review summarizing measurement techniques of snow interception and evaporation are given by Lundberg (1993) and for interception and evaporation measurements from tree crowns in general by Lundberg (1996). Measurement techniques of snow interception can, according to Lundberg (1993), be divided into the following classes:

**Weighing techniques:** Trees are cut at the base and put on a balance (Lundberg, 1993; Lundberg and Halldin, 1994; Nakai et al., 1994). The balance measures the weight of the tree including the intercepted snow. Lundberg (1993) used in addition a tray to determine throughfall and dripping meltwater or snow clumps, respectively. All these measurements were performed with natural trees of about 8 m height while Schmidt (1991) used a one meter high synthetic tree. The resolution of Lundberg's weighing devices was 0.1 kg, that of Schmidt 0.1 g over a range of 6 kg. As an alternative, Satterlund and Haupt (1967, 1970) and Pomeroy and
Table I. Overview about work on snow interception. The column "processes observed" identifies the processes which were investigated.

<table>
<thead>
<tr>
<th>Location of Investigation</th>
<th>snow interception (yes/no)</th>
<th>interception parameters measured</th>
<th>Model of radiation measured</th>
<th>Author(s)</th>
</tr>
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<td>yes</td>
<td>Exp, net radiation</td>
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<td>Schmidt (1999)</td>
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</tbody>
</table>

It can be assumed that the mentioned data were available in a larger dataset or report. However, the results were not included in this paper. The table shows the studies, "radiation" indicates whether radiation played a dominant role.
Gray (1995) described measurements of intercepted snow mass using a suspended natural tree.

**Optical methods:** This method is rarely used compared to the weighing methods. Hoover and Leaf (1967) used 16 mm motion pictures to observe snow interception over the course of a winter. Tennyson et al. (1974) used time-lapse photography to observe snow interception during several events. Pomeroy and Schmidt (1993) also used photographic techniques but for determining fractal characteristics of intercepted snow. Investigations in the laboratory were done by Kobayashi (1987) who photographed snow accumulation on wooden sticks and narrow board pieces. A method measuring the intercepted mass retained in the canopy directly was used by Calder (1990) who used the gamma-ray attenuation method.

**Indirect measurements** Most of the indirect techniques measured the intercepted mass by comparing precipitation in the open area and under the canopy assuming that no changes occur in the canopy and on the ground between the end of the storm and the measurements. Calder and Wright (1986), Wheeler (1987), and Calder (1990) measured the fresh snow with spatially distributed snow boards, other authors used rain gauges (Rowe and Hendrix, 1951).

### 1.3 Physics of snow interception

The accumulation and redistribution of snow in a tree crown is the result of complex interactions of various meteorological factors and of the canopy morphology. Snow which has accumulated in the crown may either sublimate or evaporate to the atmosphere or will eventually be incorporated to the snowpack on the ground, either by drip of meltwater or by unloading of snow clumps. Hence, we can distinguish between (i) accumulation, (ii) sublimation and evaporation, and (iii) transfer to the ground.

**Accumulation of snow in the crown** During the accumulation of snow on the branch the albedo is continuously increasing. Kondratyev (1969) gives for top of snow-free fir crowns an albedo of 10% in the spectral range of 300 - 2000 nm, Liou (1992) for coniferous forests an albedo of 5-15%. Fresh snow has an albedo of 98% (Kondratyev, 1969). During the initial phase of the accumulation process snow covers only a part of the branch. The mean albedo of the branch can be estimated as the mean of needle-albedo and snow-albedo.
The albedo of a snow-covered canopy will never be the same as snow because parts of the canopy are not covered with snow. Guttenberger (1994) suggests an albedo of 30% for a fully snow-covered canopy.

The different radiation characteristics of a snow-covered branch at its upper and its bottom side is an another complicating factor. While at the upper side the albedo reaches nearly the values of pure snow (assuming a completely snow-covered branch), the albedo at the bottom side is a mixture of the albedo of branch, needles and snow which is visible through the twigs. The albedo of the bottom side of the branch can be estimated as a mean of these three values. No measurements of the albedo of the bottom side of the branch are reported in the consulted literature.

The radiation field within a coniferous crown is a complex mixture of areas with a relatively low albedo at the bottom side of branches and a high albedo above (see Figure 1.1). Let us consider one branch in the center of the crown (abbreviated as BC for branch center) which has a branch above (BA for branch above) and a branch below (BB for branch below). Then, we can assume the following fluxes: incoming short wave radiation is partly penetrating through the intercepted snow of BC and partly being reflected at the surface of intercepted snow of BB. The same fluxes occur for BB and BA having branches located below and above, respectively. Reflected short wave radiation from BB reaches the underside of BC. Due to low albedo (high emissivity of the wood) short wave radiation is absorbed and longwave radiation is emitted from the branch. Because snow is a black body in the longwave range ($\epsilon = 0.98$, Kondratyev, 1969) longwave radiation is absorbed and the snow melts. Longwave radiation fluxes are also emitted by the trunk and snow-free parts of the branch.

Radiation fluxes in a snow-covered canopy are a complex flow field of direct and reflected shortwave and longwave radiation from trunks, branches, twigs, and needles. Another portion of the direct incoming short wave radiation is reflected by the snowpack on the ground. Albedo of intercepted as well as albedo of snow on the ground alters with age. The albedo of the snowpack on the ground changes due to needles and twigs which falls from the canopy.

The angle of intercepting snow surfaces also influences the energy exchange between snow and atmosphere because penetration of radiation depends on inclination. When the surface is perpendicular to the incoming solar radiation absorption is considerably higher than for smaller angles.

During snowfall the branches are bending down due to intercepted snow load. The deflection of the branch is governed by the snow burden, its snow water equivalent and the temperature and moisture content of the branch.
Figure 1.1: Water and energy fluxes in a tree canopy retaining intercepted snow. Incoming short wave radiation is reflected from the surface of the intercepted snow. Longwave radiation is emitted by the twigs, branches and the trunk and is absorbed by the snow. Intercepted snow can either sublimate, evaporate or drip as meltwater or drop as snow clumps to the ground. BA denotes “branch above”, BC denotes “branch center”, and BB denotes “branch below”.

Branch temperature has an important influence on the elasticity of the branch (Schmidt and Pomeroy, 1990) but the influence of moisture content can be neglected for water contents higher than 40% (Kollmann, 1960). The loading process is limited by the critical inclination when snow remains in its location. Snow layered at angles greater than 45° becomes unstable depending on the internal friction of the snow. Highest values are obtained for dry, fresh snow, whereas wet snow with high water content is less stable.

**Sublimation and evaporation** Intercepted snow may sublimate or evaporate, i.e. snow is melted and the meltwater being caught between the needles evaporates to the atmosphere. Sublimation of ice to water vapor at 0°C requires 2838 kJ per kilogram of ice and standard atmospheric pressure which is a high amount of energy in winter (Hobbs, 1974; Pomeroy and Gray, 1995). The rate of sublimation is controlled by advection of turbulent heat to the ice crystal, the turbulent transport of water vapor from the crystal and the radiation exchange. Hence, limiting factors for sublimation are the available energy and the relative humidity above the surface of the ice crystal. This implies that sublimation reaches its maximum during conditions with air temperature slightly below 0°C, at low relative humidity, and high wind speeds. Since intercepted snow has a large ratio of surface area to volume, the sublimation rates may be much higher for intercepted snow than for snow on the ground under comparable meteorological conditions. In cold regions snow may remain for several days or weeks in the canopy which favors large amounts of snow to be sublimated. Experiments in the dry, continental climate of the USA and Canada shows that up to one third of the annual snowfall can sublimation directly from the canopy (Pomeroy and Schmidt, 1993; Pomeroy and Gray, 1995). An example of a day with a high sublimation rate is given by Schmidt (1991). In one day 500 g of snow sublimated from a synthetic coniferous tree initially carrying 540 g of snow under conditions of rising air temperatures up to +8°C, dropping relative humidity to 10%, and a wind speed of 1.7 ms⁻¹. Net radiation during the phase of maximum weight loss was approximately zero. Sublimation rates in more humid climates are lower. Satterlund and Haupt (1970) gave 4.5% of precipitation for sublimation from Douglas fir in northern Idaho.

In most cases sublimation and evaporation occur simultaneously. In the literature there is often no explicit distinction between sublimation and evaporation. The losses of snow from crowns investigated by Goodell (1959) are called sublimation by Schmidt (1991) and evaporation by Lundberg and Halldin (1994). All of them mean the same. However, Goodell (1959) suggested that
both processes occur concurrently. He reports from an event where 56% of the intercepted snow on a branch evaporated and sublimated within 2 hours and 40 minutes. Meltwater evaporated from the snow surface and branch before droplets could be formed. No meltwater drip was observed.

Due to the low albedo of branches (section 1.1, page 10) incoming short wave radiation is emitted from the branches as longwave radiation which melts the snow on the branch. The transition from ice to water at 0°C and standard atmospheric pressure needs 333.5 kJ per kilogram of ice (Hobbs, 1974) which is much lower than the amount of energy necessary for sublimation. Therefore it is probable that snow always melts when radiation hits the branch. Dripping requires the formation of droplets. No droplets may form under conditions favorable for evaporation (Goodell, 1959). The difference between latent heat of sublimation and latent heat of melting gives the latent heat of evaporation which is 2504.5 kJ per kilogram of water. Snow melted and evaporated from branches may condense again at the surface of the intercepted snow and therefore remain on the branch.

Redistribution to the ground Whether snow is melted and subsequently dripping from the branch depends on the availability of energy as well as on wind speed. Increasing wind speed enlarges the water vapor saturation deficit in the surrounding air of the snow or branch. Highest dripping rates of meltwater occur during warm conditions with high radiation and no wind. Advecting warm air and high radiation warms branches and needles which induces snow melting (page 10). Part of the meltwater drips to the ground. When adherence of snow to the branch becomes weaker or when the branch angle is increasing, snow clumps will drop to the ground. Observations showed that a fully snow-covered tree may unload within six hours (Miller, 1964).

Some meltwater at the branch surface may be taken up by the branch. During winter the water content of branches is decreasing (Herrick and Friedland, 1991) which can cause freeze injuries. Experiments by Katz et al. (1989) showed that water uptake by twigs is likely to occur but possibly only in small quantities. However, no systematic investigations on this problem were found.

Rapid advection of cold air during dripping events causes refreezing of meltwater which leads to icicles hanging from twigs and needles (Figure 1.2).
1.4 Methodological requirements

The requirements for our experimental setup were based on the intention to investigate the physical processes which couple the compartments tree, snowpack, and soil in a forest. This implied:

- that the compartments tree, snowpack, and soil are kept undisturbed,
- that the observation methods for tree measurements are non-invasive,
- that observations and measurements are continuous over the whole winter period,
- and that the time resolution is sufficiently high to follow the dynamics of the transport processes.

These requirements were met by using a video camera for continuous observation of a spruce tree combined with measurements of the meteorological factors. Based on observations and measurements conducted at two sites in the Swiss Alps at two different altitudes, the snow storage changes in the canopy, soil, and snowpack compartment were described by means of statistical and
physical models. A more detailed description of the methods is given in the respective chapters.
Leer - Vide - Empty
Chapter 2

Observing Snow Interception in Spruce Crowns

Extended version of the paper:

Abstract

Snow interception plays an important role in the hydrological cycle of sub-alpine forest stands. In spruce forests up to 40% of the precipitation may be intercepted and can remain in the canopy for several weeks whereas in deciduous forests only 0 - 10% of snow precipitation is intercepted. Under winter conditions water storage and transfer within and between the various compartments such as the canopy, snowpack, and soil varies significantly depending on the current and preceding weather conditions. In order to study the dynamics of snow storage in spruce crowns we developed a non-destructive, remotely operated method.

During two winter seasons the crown of a spruce tree was monitored with a color video camera connected to a time-lapse video recorder. Illuminated colored plastic balls were attached at selected branches. The plastic balls were visible both, on the daytime as well as on the nighttime video images. The ball position were analyzed quantitatively and served as an indicator for the snow load of the individual branch.

The video images were digitized from the video tape with a modular frame grabber including a color acquisition module. After image enhancement (filtering, thresholding) the images were analyzed with a commercial image ana-
lyzing program. The illuminated balls were extracted and the coordinates of their centers determined which showed the movement of the branches during a snowfall event. The angle between branch and trunk changed strongly due to the weight of the snow. Here, we discuss the methodological aspects of the sequential automated analysis.

2.1 Introduction

The amount of discharge from forested basins in spring is determined by subtracting the mass of intercepted snow which sublimated from the canopy from the amount of snow which directly reached the ground or which fell from the canopy (Lundberg and Halldin, 1994). To judge the impact of snow interception on the hydrological cycle we ought to understand the interplay between snow storage and the corresponding fluxes of water and snow. In order to study these processes the snowpack on the branches and under the tree must remain undisturbed. Therefore, non-invasive time-lapse video recording was occasionally used for observing and measuring snow storage continuously in tree crowns even during snowfall and melt events. In past investigations with similar objectives time-lapse photography was used to explore relation the relation between meteorological factors and intercepted snow loads in crowns of ponderosa pine (Pinus ponderosa) (Tennyson et al., 1974). Based on their observations these authors calculated a snow load index which expressed the ratio of forest canopy covered by snow to total canopy area.

Video technology was already used for observing dynamic processes such as the motion of insects (Beyer, 1990), particle tracking of air bubbles under a water surface (Hering et al., 1995), and three-dimensional particle tracking velocimetry (Maas, 1992). Since unloading of intercepted snow may occur quite rapidly, its observation should be continuous with a relatively high temporal resolution. Video recording offers the possibility of continuous observation and later analysis of the images of all pertinent information for an extended experimental period.

The goal of this paper is to present our instrumental setup and to discuss the possibilities and problems concerning video image analysis for quantifying the mentioned hydrological processes.

2.2 Methods and instrumentation setup

Field instrumentation
For the observations of snow interception a 18 m high spruce tree (Picea abies)
was selected at a forest site near Davos (Switzerland) at an altitude of 1659 a.s.l. (Davos-Seehornwald). At a distance of 10 m from the tree trunk a color CCD video camera (Sony¹ SSC-C350P Hyper HAD) with a 500 by 582 pixel resolution was mounted 250 cm above ground onto a pole. The camera was equipped with a 12.5 to 75 mm zoom objective with a power supply of 220 V transformed to 12 V. The camera was installed in a weather-proof case and remained on-site for the whole winter. Front lenses were heated to avoid condensation.

The tree was recorded in a window of 5.4 m in the horizontal and 4.1 m in the vertical direction. The camera was connected by a coaxial cable to a time-lapse video recorder (Panasonic AG-6720) located in a heated hut 80 m from the camera (Figure 3.1, page 34). Every 3.2 s an image was recorded in S-VHS format and stored on a 180 min cassette. This time resolution lasted for an observation period of ten days. The chosen lapse time interval is a compromise between a sufficiently high time resolution and available storage capacity on the video-cassette. Unloading processes in the tree crown could be recognized with this time resolution.

The intercepted snow mass is indicated by the position of a branch. The deflection of the branch is a function of:

- the elasticity module of the branch which depends on branch temperature (Schmidt and Pomeroy, 1990) and water content,
- the branch diameter,
- and the snow load and distribution on the branch.

To measure the position of a branch it is necessary that reference markers can be clearly recognized in the image. For this purpose plastic balls with a diameter of 6 cm were suspended 40 cm below two branches. During the first winter we used red colored polystyrene balls. This color was difficult to interpret on the images because red comet-like shadows appeared around the balls (Figure 2.5, page 28). This is an artifact of the video recording system, because translation of the video signal into RGB-coordinates (red–green–blue) did not work properly.

The yellow balls used in the second winter season were equipped with 2 W light bulbs mounted inside to improve the contrast in the image. The yellow

¹Mentioning the trade names of the equipment here and in the following text does not imply endorsement by the involved Swiss Federal Research Organization but is given for the reader's convenience
color was found to give the best contrast in the image with no color shadows in the close surrounding of the ball.

The tree was illuminated with two floodlights at night. To improve contrast at night the floodlights were switched off every 5 min for a duration of 5 min. This resulted in a well discernable circular region in the image. To position the image position several reference markers at defined absolute coordinates were mounted in the tree crown. Air temperature, humidity, global radiation, and wind velocity were measured 5 m from the instrumented tree.

**Hard- and software for image analysis**

The equipment consisted of a video recorder (Panasonic AG-7355) operated by a computer. Between the video recorder and the computer a time-base corrector (Iden IVT-7P) was inserted to avoid distortion of the video signal which is a known problem when images are digitized from a video tape (Jähne, 1993). The computer hardware consisted of a 80486 PC with a modular frame grabber (Imaging Technology ITI MFG-3M-V with an ITI AM-CLR-VP color module) connected to two monitors. A TMS34010 32 bit graphics microprocessor is integrated on the frame-grabber board which allows digitizing in real time. Image processing was done with the program Optimas (Optimas Corporation, 1995).

### 2.2.1 Digitizing and image enhancement

To analyze a time series of images from a video tape it is necessary to select and inspect a sequence of several frames. The continuous counter on the tape, the so-called time code, can be saved either during recording or later. We recorded the linear time code (LTC) on the sound track of channel 2 on the tape which gives every frame its own number. For the analysis reported in this work we have chosen a time interval of 10 min, which produces six images for one hour. The maximum precision of the LTC is ±1 frame.

The aspect ratio of the computer monitor was measured with a rectangular grid and once corrected before the analysis. In order to improve the interpretation efficiency and to minimize contrast problems a small region of interest (ROI) was defined for every ball which included maximum and minimum deflection of the ball. After having selected an image, contrast and brightness were adjusted. To suppress noise an average filter was used in order to make light intensity more constant over the desired object.

Examples of three digitized images recorded under different light conditions are shown in Figure 2.1.
Figure 2.1: Reproduction of three video images illustrating a snow-capped spruce crown recorded under different light conditions. The top figure has been taken during daylight, the middle figure at nighttime with floodlight illumination, and the bottom figure at nighttime without floodlight illumination.
2.2.2 Image analysis

The analysis of the images was conducted in two ways. Visual analysis of time sequence of video images gave an impression about the processes and their spatial and temporal variation in the crown. Two examples of time sequences are given in Figure 2.2.

For quantitative analysis the position of the balls had to be calculated. To identify the balls in the ROI the intensity of the three color channels red, green and blue in the area of each ball was selected interactively. The color intensity (color threshold) had to be calculated separately for different light conditions during day and nighttime. Corresponding to this threshold every ROI was binarized (Russ, 1995), i.e. greyvalue of the pixels with the chosen color threshold were set to 255 which corresponds to white. Pixels with an other color were set to black. Although the threshold was set very carefully some pixels remained which did not belong to the balls. These pixels were removed with an erode filter. To bring the balls back to appropriate size a dilate filter was used afterwards (Russ, 1995) which added white pixels homogeneously at the edge of the ball.

Due to different light conditions the projected area of a ball varied in the range of 6.8 and 72.8 cm$^2$ which was found by manually measuring the size of several balls under different illumination conditions. The way the projected area of the ball represented a perfect circle is described in the image analysis program with a dimensionless number ("circularity"). Also depending on the light conditions this value varied between 13.5 and 16.5. With a logical search condition all areas within a ROI which corresponded to the calculated threshold and the calculated values of area and circularity were selected. The center of mass of every ball was calculated and its coordinates were written to a file. The chronological course of the analysis procedure is shown in Figure 2.3.

The determination of the center of mass was performed by ascertaining the coordinate of the center of the desired area (in this case the plastic ball) which is assumed by the algorithm to be a polygon. That means that e.g. in a square with a edge length of 7 pixels the coordinate of a point which is surrounded by 3.5 pixel on each side is calculated. The calculation corresponds to a sub-pixel accuracy. Since illumination conditions and therefore the greyvalue are not constant over the area of a ball, the area boundary is never a circle. The image series describes the motion of the ball during a certain period. As a methodological example we select one branch with four suspended balls and discuss the outcome of one snowfall event.
2.2 Methods and instrumentation setup

Figure 2.2: Image sequence of snow unloadings in the morning of January 27, 1993. On image 1a the snow falling from the upper branches is seen as a blurred white shadow at the upper edge of the image. Branches located below are unloaded by this chute. A similar situation for the left hand side of the tree is illustrated in images 2a - 2d.
Recording of Images in the Field
Recording of Linear Time Code (Office)

Color Synchronization with Time-Base Corrector

Digitizing of Images with Frame-Grabber
Adjusting of Contrast and Brightness
Calibration of Image

Definition of Region Of Interest (ROI)

Average Filter for Removing Noise
Thresholding in Channel Red-Green-Blue

Binarizing, Erode- and Dilate Filtering

Searching for White Areas (Greyvalue 255) and
a Certain Area and a Certain Circularity

Extraction of Coordinate of Center of Mass
of the Detected Area

Write Coordinates to a File

yes (if No. of ROI < 8)

Next Image

Figure 2.3: Concept of image recording, image digitizing, enhancement, and analysis. Nighttime images without floodlight illumination could be analyzed automatically, daytime images had to be analyzed by hand (semiautomated analysis).
2.3 Results

Table 2.1: Maximum ball displacements for the snowfall event from February 28, 11:00 to March 1, 1994, 6:15. Vertical (y) and horizontal displacement (x) increases with distance from the trunk. Ball 4 is suspended at a distance of 60 cm, ball 3 118 cm, ball 2 158 cm and ball 1 203 cm from the trunk.

<table>
<thead>
<tr>
<th></th>
<th>ball 1</th>
<th></th>
<th>ball 2</th>
<th></th>
<th>ball 3</th>
<th></th>
<th>ball 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>x [cm]</td>
<td>31.1</td>
<td>y [cm]</td>
<td>105.5</td>
<td>x [cm]</td>
<td>20.0</td>
<td>y [cm]</td>
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<tr>
<td></td>
<td>3.0</td>
<td></td>
<td>39.7</td>
<td></td>
<td>7.8</td>
<td></td>
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</tr>
</tbody>
</table>

2.3 Results

Figure 2.2 shows a time sequence in the morning of January 27, 1993. On image 1a we see that the right part of the tree is fully covered with snow. At the top of the image a cloud of falling snow can be recognized. In the next image (1b) the branch (marked with an arrow) is unloaded due to the impact and weight of snow dropping from the upper branches. A similar event is shown in images 2a-2d of Figure 2.2. The heavily loaded branches are unloaded and carry considerably less snow after the snow stripping event. The images of this sequence illustrate that unloading processes may occur at different times in the tree crown. Since air temperatures were constant, short wave radiation zero, and wind velocity low it is probable that unloading occurred due to overloading of branches in the upper part of the crown.

A closer look at a loading process of a spruce branch occurring during snowfall is given in Figure 2.4. This snowfall event took place from February 28, 11:00 to March 1, 1994, 6:15. A total of 7 cm of fresh snow corresponding with a water equivalent of 15 mm fell during this time period in the nearby open area. For the first 6.5 h the ball coordinates were digitized manually by marking the ball center every 30 min (see points above dashed line in Figure 2.4b). This was necessary because of the heterogeneous daylight conditions within the stand which prevented automated digitizing. Ball coordinates which could not unambiguously be identified were set to be “missing values”. From February 28, 18:25 to March 1, 1994, 6:15 the balls were automatically digitized by the above mentioned algorithm at 10 min intervals (points below dashed line in Figure 2.4). During the snowfall the branch intercepted snow which caused a bending of the branch. The total displacement of the balls is shown in Table 2.1.

The movement of ball 1 at the edge of the branch was obviously greatest. The inclination was changing from \( \alpha_1 = 78.2^\circ \) to \( \alpha_2 = 132.3^\circ \) (\( \Delta \alpha = 54.1^\circ \)). Especially \( \alpha_2 \) is quite large because this is the inclination of the branch but
Figure 2.4: Displacement of balls suspended at a single branch during the snowfall event from February 28, 11:00 to March 1, 1994, 6:15. Figure (a) shows the movement of ball 1 at the tip of the branch. Fast movement during \( t_1 \) indicates that the branch continuously collected falling snow without unloading. During the interval \( t_2 \) snowfall intensity and interception was smaller. Figure (b) shows the movement of the entire branch. The upper line shows the initial branch position, the lower line the position after the snowfall. The inclination of the tip segment changed from \( \alpha_1 \) to \( \alpha_2 \). In some cases measurement errors occurred e.g. due to wind.
not that of the snow surface at the branch edge which must have been larger. This is important when snow is being deposited onto a heavily loaded branch because falling snow will bounce off when the snow surface is inclined too steeply which prevents further accumulation (Kobayashi, 1987).

2.4 Discussion

The video observations of the spruce crown during the winter periods 1992 through 1995 proved to be a valuable tool for qualitative as well as for quantitative analysis of snow interception. Camera and recorder functioned properly for the entire period. Analysis of the images, however, was a challenging task for several reasons.

A video signal contains not only image information but also a synchronization signal for beginning and end of the image line. A “phase locked loop switch” located on the Frame Grabber is used to synchronize the image lines (Jähne, 1993). The end of line in an image of video recordings on tape is, however, poorly defined which makes a synchronization necessary. This task was performed by a Time-Base-Corrector which converted the input signal from the video tape into a correct synchronized color signal which could be digitized by the Frame Grabber.

The precision of the applied method depends on the accuracy by which the ball coordinates can be determined. This in turn depends (i) on the precision of the absolute image coordinates and (ii) on the algorithm which identifies the balls and calculates their center of mass. The geometric distortion of two subsequent digitized images was very low. Due to the image resolution (736 by 578 pixel) and the size of the ROI (544 cm by 408.5 cm) one pixel has the size of 7.4 by 7.1 mm. To check the digitizing accuracy the position markers were determined in every image. Their coordinates varied in the order of the pixel size (7.4 by 7.1 mm) with a standard deviation of 2.2 mm in the horizontal and 3.5 mm in the vertical direction.

The major problem in this application were the changing light conditions under which the balls had to be detected. After digitizing red comet-like shadows appeared at the right-hand side side of the polystyrene balls (Figure 2.5). This might indicate that translation of the crominance and luminance signal of the S-VHS signal into the RGB-color space were not performed correctly. Since the translation of the video signal into RGB-coordinates includes an interpolation of the signal within an image line it is probable that the red signal of the balls were also imported in the pixels of the region at the right-hand side of the balls. Since scanning of an image line runs from left to right this
might explain the red shadows at the right edge of the balls. Experiments with a CCD video camera with three chips for each of the red, green, and blue channel showed that red areas were reproduced as quite discernable regions. A much better result was obtained when using a digital Kodak DCS-200 camera. This suggests that the problem of red shadows is due to the specifications of the used camera.

Because of these problems it was not possible to determine a color threshold which was characteristic for the red balls. The contours of the red balls were less distinct. Tests with image enhancement yielded no satisfactory results neither for daylight images nor for nighttime images. On nighttime images a better contrast was obtained but automated detection was hardly possible. The positions of the balls had to be identified and extracted by hand.

The procedure was improved by using yellow illuminated balls. But the problem of object recognition still existed in case of the daylight images, because the contrasts between snow, ball and tree were still too small and fuzzy. In an example a thresholding with values extracted from the balls provided an error of 77% which means that 720 from 933 pixel in the ROI had the same colors in the RGB color space as the balls. A further problem is that the area of the balls is often not distinctly leaving an undefined region which cannot unambiguously attributed neither to the ball nor to the surrounding area. Images recorded at daylight had therefore to be digitized by hand. However, searching the image by a certain time code, digitizing of the image and
Figure 2.6: Frequency distribution of grey values of an image at daylight (a), at nighttime with illumination (b) with yellow balls and at nighttime without illumination (c). Greyvalue 0 corresponds to black, greyvalue 255 corresponds to white. It is obvious that in daylight images the contrast is weak and somewhat better in the images taken at nighttime with illumination (b). At nighttime without illumination (c) the contrast is the best and the balls can be computationally recognized.

Also export of the ball coordinates could be done automatically (Figure 2.3, page 24).

The difficulties of yellow ball recognition are illustrated in Figure 2.6. It shows the frequency distribution of grey values for daylight and night images with and without floodlight illumination.

Figure 2.6a clearly suggests that in daylight images the contrast between balls and the surrounding environment is very low. We see a high number of pixels in the black region (low greyvalues) and a second peak in the white range. At nighttime with floodlight illumination (Figure 2.6b) the contrast is much better but for automated recognition still too low. Only nighttime
images without floodlight illumination (Figure 2.6c) provided a sufficient con-
trast. Most parts of the image are black and only the illuminated balls stand
out with few bright pixels. Automated recognition worked well for these im-
ages. The balls recorded at night with floodlight illumination stand out with
a better contrast than the balls in the daylight images but automated recog-
nition still remained impossible.

2.5 Conclusions

Analysis of video recordings of spruce branches during snowfall showed that
differences in unloading processes between different branches can be detected.
The time lapse rate of 3.2 s was fast enough for the investigated process.

Quantitative analysis, however, was a much more difficult task. The auto-
mated detection of moving balls under natural, heterogeneous light conditions
proved to be very difficult to handle because contrasts were rather small. Since
light conditions change during the day the threshold range has to be adapted.
Best results can be obtained in a bright–dark environment which suggests
that recording results are greatly improved at night. The accuracy of video
recording was high enough for this application. Images were analyzed with a
precision of at least one pixel in size.

For automated object recognition in a natural light environment a fully
digital camera may yield better results. Objects emitting better separated
wavelengths could yield better results. Fully automated detection of objects
in a forest stand, however, is still a task to be solved in the future.

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Chapter 3

Comparison of Snow Interception at Davos and Alptal

Manuscript:
*Snow Interception in a Spruce Crown under Different Weather Conditions*

Abstract

Snow retained in a forest canopy alters the albedo and therefore the energy balance of a forested area in winter. In this paper the interplay between meteorological factors and snow interception is investigated using data measured at two sites in the Swiss Alps during two winter periods.

The weather characteristics of the two seasons are compared with the longterm annual means. From October through February the intercepted snow was, in the average, retained in the canopy for longer periods of time at the colder Davos site as compared to the Alptal site at a lower prealpine and therefore warmer site. During the spring months March and April radiation played the dominant role for unloading of intercepted snow. Global radiation at Alptal was lower during this period due to a greater number of foggy days. This led to a longer lasting snow cover in the tree crown.

Attempts to predict the duration of snow cover in the canopy with a statistical model showed that events up to three days can be predicted quite well, while the estimation of the duration of longer events was unreliable. Events longer than five days include most often several snowfall events and therefore had their own characteristics.
3.1 Introduction

Snow interception being part of the hydrological cycle of forests is most often discussed in terms of a reduction in the water balance of catchments (Schmidt and Troendle, 1992). The snow water equivalent (SWE) of a snowpack in a forest depends on snow throughfall and subsequent unloading from the branches, and also on the evaporation and sublimation losses of intercepted snow. The deposition of snow in the crown and its redistribution as well as sublimation and evaporation is influenced by air temperature, air humidity, wind speed, global radiation (Miller, 1964; Lundberg, 1993; Pomeroy and Gray, 1995), and by the aerodynamic resistance (Lundberg and Halldin, 1994; Lundberg, 1996). The aerodynamic resistance for intercepted snow is about ten times higher than for intercepted rain (Calder, 1990; Lundberg, 1996).

Wind velocities of 1 to 2 m s\(^{-1}\) favor snow interception while higher wind velocities erode intercepted snow (Miller, 1961; Pomeroy and Gray, 1995). When air temperatures rise close to 0°C intercepted snow is warmed up and high incident solar radiation melt it (Pomeroy and Gray, 1995). Incident radiation heats the branches to temperatures above 0°C even at air temperatures below freezing (Strimbeck et al., 1993) and induces melting at the snow–branch interface (Claasen and Downey, 1995). The crown morphology affects the incrown deposition as well, but to a lesser degree than storm characteristics as shown by experiments conducted with Picea engelmannii, Abies lasioscarpa and *Pinus contorta* (Schmidt and Gluns, 1991).

The albedo of forest stands is an important variable for the energy exchange between canopy and atmosphere. Especially in winter it is highly variable due to the changing snow cover of the tree crowns. Guttenberger (1994) estimated the albedo of a snow-covered crown to be 30%. The albedo of a snow-free canopy is about 5%. To model the energy exchange of large areas the albedo of the canopy has to be taken into account.

Large-scale simulations of climate change suffer from a lack of information concerning the albedo and spatially averaged surface temperatures of forests in winter. These properties are both input variables at the lower boundary as well as output variables depending on the development of the snow cover on the ground and in the canopy. The output of General Circulation Models (GCM) cannot be more than only a general trend of air temperature and precipitation averaged over large regions. More precise predictions for smaller regions in a resolution of 100 km can hardly be obtained from GCMs. Gyalistras et al. (1996) suggested a statistical procedure to downscale climatic variables over this range. His approach allows an estimation of local monthly or daily weather
characteristics. But even this approach yields no more than average values of air temperature, precipitation and radiation but not the controlling variables of the in-crown environment.

The objective of this paper is to estimate the consequences of climate change for snow interception processes and to improve our understanding of how meteorological factors influence snow cover of a tree crown. We focus on finding a relation between the duration of the snow cover retained in the crown and the meteorological conditions based on observations made during two winters at two sites located at different altitudes in the Swiss Alps. We expect that a shift of air temperature and precipitation in time and its influence on the snow interception can be approximated when we understand the mechanics of these processes under different thermal regimes.

3.2 Experimental sites and methods

The observations and measurements of snow interception were carried out at Davos (Davos-Seehornwald, 1659 m a.s.l.) and Alptal (edge of Erlenbachtobel, 1185 m a.s.l.) (Figure 3.1). Davos represents the colder and drier climate in our study (mean annual air temperature: +3.2°C, mean annual precipitation: 1016 mm), Alptal the warmer and more humid winter climate (mean annual air temperature: +5.1°C, mean annual precipitation: 2000 mm). The observations and measurements made at two sites of different altitude were meant to represent winter conditions at two different temperature levels.

At both sites a spruce tree (Picea abies [N.] Karst.) facing an approximately 10 m wide canopy opening was observed continuously throughout the winter. The tree at Davos-Seehornwald was 18 m high with an average branch length of 180 cm. The crown diameter was 500 cm, the breast height diameter of the trunk 20 cm, and the first green branch located at a height of 300 cm above ground. The site located on a small hill top is dry and the root zone shallow with a permeable soil. The Alptal site is on a slope with a shallow root zone in a wet gleyic soil. The trees at Davos-Seehornwald are in average 245 years old while at Alptal they are 180 years old (Stark et al., 1991). The spruce tree at Alptal was smaller (15 m height) with a crown diameter of 600 cm and the first green branch at a height of 190 cm above ground.

The observations at both sites were conducted with a video camera which was placed in a weatherproof case and posted in a distance of 10 m from the tree (Figure 3.1). The camera recorded a 5.4 m wide and 4.1 m high section of the tree at a height of about 4 m. Images were recorded every 3.2 s with a time-lapse video recorder and the data of ten days were stored on a 180 min
Figure 3.1: Location of the experimental sites (Figure a) and the schematic of the experimental setup (Figure b). The site at Davos (1659 m a.s.l.) represented the colder, drier climate in our study, the site Alptal (1185 m a.s.l.) the warmer, more humid climate. At both sites a video camera monitored the spruce permanently throughout the winter and meteorological data were measured continuously. Total snow depth were measured at both sites with an ultrasonic snow gauge. At Davos the fresh snow depth was additionally measured manually on a board after each snowfall event.

Map basis: Digital data of the Swiss National Map: ©Federal Office of Topography, Wabern, Switzerland
3.2 Experimental sites and methods

video cassette. To facilitate the quantitative analysis of the snow cover in the
tree crown, light-weight plastic balls were suspended at one north, one south
and two west facing branches at different distances from the trunk. The branch
movement due to snow loading and unloading was documented by analyzing
video images (chapter 2) which made it possible to correlate observed processes
in the crown with meteorological factors.

Meteorological factors like air temperature, air humidity, wind speed, and
solar radiation were measured 5 m from the tree. Snow depth was measured
with an ultrasonic sensor and depth of fresh snow was measured manually
after each snowfall on a 50 cm by 50 cm board in the opening. The data were
recorded with Campbell CR10 and 21X dataloggers. In addition, data from
a nearby weather station of the Swiss Meteorological Agency (SMA, Zurich)
located at a distance of 850 m from the experimental site were available.

The branch temperature was measured with thin PT100 thermistors (1
mm diameter) which were inserted into the wood of a north and a south facing
branch of each tree at different distances from the trunk. The experimental
setup was the same at both sites and is shown in Figure 3.1. At Alptal
additional data from a nearby meteo tower were also available.

Statistical modeling

One of the main questions of this work is the influence of the meteorological
factors on the event duration. In this section we describe the applied method
of binary tree regression which was used as an alternative to multiple linear
regression. The advantage of binary tree regression is an easier interpretable
result since it illustrates the n-dimensional structure of the data in a single
two-dimensional tree.

The basics of this method are described in Breiman et al. (1984), and the
implementation of the method in the statistical language S-Plus is given in
Clark and Pregibon (1992) and Venables and Ripley (1994). Here only a short
overview is presented.

The method bases on the Gaussian distribution of the data so the response
variable “event duration” \( y \) can be written:

\[
y \sim N(\mu_e, \sigma^2)
\]

with \( \mu_e \) being the mean value of event duration of a dataset and \( \sigma^2 \) the vari-
ance.

The mean values of air temperature \( am \) [°C], global radiation \( rm \) [W m\(^{-2}\)],
wind velocity \( wm \) [m s\(^{-1}\)] and the sum of fresh snow \( ns \) [cm] of an event were
used as predictor variables.
The idea of the method is splitting the whole dataset into subsets of data by an algorithm called “recurse partitioning”. The criterion of a split which consists of “parent nodes” and two “child nodes” is the minimization of the mean squared error of the descendent nodes (child nodes) relative to that of the parent nodes.

For this example the criteria of a split could be written as:

\[
\text{if } (ns > 24) \text{ and } (am > -9) \text{ and } (rm < 135) \text{ then the predicted value of } y_t \text{ is 12.}
\]

This example is shown with grey fields in Figure 3.10 (page 50).

A further criterion is the change of deviation of a left and a right split of the child nodes to that of the parent node.

The deviation function can be written in the form:

\[
D(\mu_i; y_i) = (y_i - \mu_i)^2.
\] (3.2)

For a given node the parameter \(\mu_i\) is constant for all observations and is given by the node average. The deviation of a node is the sum of the deviations of all observations in the node and can be written in the form

\[
D(\hat{\mu}; y) = \sum D(\hat{\mu}; y_i).
\] (3.3)

The splitting is proceeded by comparing the deviation of the parent nodes with that of the child nodes with a left and a right split

\[
D(\hat{\mu}_L, \hat{\mu}_R; y) = \sum D(\hat{\mu}_L; y_i) + \sum D(\hat{\mu}_R; y_i).
\] (3.4)

The chosen split at a given node is that split that maximizes the change in deviation

\[
\Delta D = D(\hat{\mu}; y) - D(\hat{\mu}_L, \hat{\mu}_R; y)
\] (3.5)

where the subscripts \(L\) and \(R\) indicate the left and the right split.

Recent applications of this method can be found in Michaelsen et al. (1994), Elder et al. (1995), and Rosenthal and Dozier (1996).

### 3.3 Snow interception events at Davos and Alptal

#### 3.3.1 Winter characteristics

To characterize the climatic conditions during the winter seasons 1993/94 and 1994/95 at the experimental site Davos we compare the air temperature and
3.3 Snow interception events at Davos and Alptal

the snow depth averaged over the periods October to December, January to February, and March to April with the corresponding longterm data of the years 1935 to 1954, 1955 to 1974, and 1975 to 1994 (Figure 3.2 and 3.3). The 60 years period was divided into three periods to better classify the data of our experimental periods to various periods in the past.

The early winter period 1994 (October - December) was significantly warmer ($p < 0.05$) in comparison with 1935 to 1954. Snow depth in early winter 1993 was low, but extremely low during October to December 1994. From January to February air temperatures were significantly higher than from 1935 to 1954 ($p < 0.05$). The late winter period (March and April) of winter 1993/94 was significantly warmer ($p < 0.05$) compared to 1975 to 1994, that of 1994/95 was colder but the difference is statistically not significant relative to none of the three periods. Mean air temperature of the entire winter period was on the average in winter 1993/94 and higher in winter 1994/95. Snow depth in winter 1993/94 (Figure 3.3) was normal until February 1994 and below normal in the spring period. In winter 1994/95 it was below the normal from October to December, on the average from January to February and slightly above the average (no significance at 5% level) from March to April.

For assessing the weather conditions at Alptal during the observation period 1993 to 1995 we compared the air temperature with the record 1985 to 1992 obtained at the same site (Figure 3.4, page 40). At Alptal no snow data are available. As stated for Davos the early winter period 1994 (October to December) was unusually warm. In January and February the air temperatures were clearly higher in both winters compared with the preceding decade. The warm March 1994 raised the late winter mean of temperature (March to April) to values above normal in contrast to the following year. Both winter periods were warmer on the average than those of the preceding period. The mean air temperature of the winter season was above 0°C at Alptal whereas at Davos it was below 0°C. The average air temperatures in January and February were closer to 0°C and often above freezing at Alptal. Therefore precipitation at Alptal was alternately rain and snow while at Davos snowfall clearly dominated.

3.3.2 Interception events in both winters

During the first winter 1993/94 26 interception events were observed at Davos-Seehornwald and 15 at Alptal. An “interception event” is in this work defined as the period from beginning of snow deposition onto the tree crown until the crown is free of snow again. One interception event can therefore be consisted of several snowfall events. The meteorological factors, the event duration
Figure 3.2: Daily mean air temperature at Davos for three 20 year periods and for the observation periods in winter 1993/94 and 1994/95. From October to December 1994 it was unusually warm, whereas during March and April 1995 it was colder than in the preceding decades. The bright grey boxes describe the interquartile range and the whiskers are drawn when values exceed a certain value (inter-quartile range multiplied by 1.5). Outliers are drawn with a single line and the median is represented by the white line.
Figure 3.3: Daily mean snow depth at Davos for three 20 year periods and for the observation periods in winter 1993/94 and 1994/95. In winter 1993/94 there were significant less snow during March to April and in winter 1994/95 there were significant more snow than on the average. The bright grey boxes describe the interquartile range and the whiskers are drawn when values exceed a certain value (inter-quartile range multiplied by 1.5). Outliers are drawn with a single line and the median is represented by the white line.
Figure 3.4: Daily mean air temperature at Alptal for the period 1985 to 1992 and for the observation periods in winter 1993/94 and 1994/95. Like at Davos October to December 1994 was significantly warmer than the average. In contrast to Davos no long-term database were available. The bright grey boxes describe the interquartile range and the whiskers are drawn when values exceed a certain value (inter-quartile range multiplied by 1.5). Outliers are drawn with a single line and the median is represented by the white line.
Table 3.1: Number of interception events at Davos (D) and Alptal (A) during the two winters.

<table>
<thead>
<tr>
<th>Period</th>
<th>D 93/94</th>
<th>A 93/94</th>
<th>D 94/95</th>
<th>A 94/95</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oct.-Dec.</td>
<td>9</td>
<td>4</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Jan.-Feb.</td>
<td>7</td>
<td>7</td>
<td>13</td>
<td>9</td>
</tr>
<tr>
<td>March - April</td>
<td>10</td>
<td>4</td>
<td>9</td>
<td>8</td>
</tr>
</tbody>
</table>

(duration of an interception event), and the temporal snow cover of the tree crown of both sites are shown in Figure 3.5, and the number of events in Table 3.1. According to the lower air temperature at Davos the number of events was greater and the snow cover of the tree crown during October to December lasted longer at Davos while the mean event duration was shorter than at Alptal.

In January and February the event duration was in the average longer at Davos due to lower air temperatures. At both sites we observed long periods of snow retention in the crown. During such periods several snowfalls were observed with the crown remaining snow-capped in between.

In March and April duration and distribution of events differed between the two sites. At Davos ten events occurred compared to four at Alptal where the mean event duration was longer due to a lower average global radiation.

The results of the second winter are shown in Figure 3.6 and Table 3.1 for both sites. During the warm months October to December six events were recorded at Davos and six events at Alptal. Events lasted longer at Davos because of colder temperatures. During January and February the tree crown was snow-covered on 74% of the days at Davos and 59% of the days at Alptal where the snow melted earlier due to higher air temperatures. Air temperature is very likely the main factor for the unloading mechanism of intercepted snow in January and February. In March and April 1995 we counted nine events at Davos with an average duration of 1.6 days, at Alptal eight events with a duration of 2.1 days. The cumulated number of days with snow-covered crowns was higher at Alptal due to lower values of global radiation.

3.4 Comparison of an interception event at Davos and Alptal

In the previous section interception events and their duration were compared on the time scale of winter periods. In this section the features of single
Figure 3.5: Box plots of air temperature, global radiation, event duration and temporal snow cover of the tree crown for winter 1993/94 at Davos and Alptal. The left side represents data from Davos, the right side from Alptal. The 100% basis for the temporal snow cover of the tree crown was the duration of these periods (for example January to February). The whiskers are drawn when values exceed a certain value (inter-quartile range multiplied by 1.5). Outliers are drawn with a single line and the median is represented by the white line.
3.4 Comparison of an interception event at Davos and Alptal

Figure 3.6: Box plots of air temperature, global radiation, event duration and temporal snow cover of the tree crown for winter 1994/95 at Davos and Alptal. The left side represents data from Davos, the right side from Alptal. The 100% basis for the temporal snow cover of the tree crown was the duration of these periods (for example January to February). The whiskers are drawn when values exceed a certain value (inter-quartile range multiplied by 1.5). Outliers are drawn with a single line and the median is represented by the white line.
interception events which simultaneously occurred at both sites are compared. We select the event of April 9 to April 14, 1994 because it represents a typical spring event with a high dynamic in loading and unloading of the tree crown.

**Davos**

Figure 3.7 shows the vertical movement of two branches observed at Davos together with the meteorological factors observed during that event. The north facing branch is at a height of 4.0 m above ground and the south facing branch at a height of 5.8 m. The observation starts on April 9, 1994, 20:00 and ends on April 14, 1994, 18:00. Both balls attached to the south and north branch were mounted 30 cm from the branch tip, the length of the north branch was 180 cm that of the south branch 230 cm. Until April 12 only minor movements of the branches were observed which indicate small deposits of intercepted snow. During the day, branches move upwards due to melting and wind erosion. On April 12, 1994, 18:00 an intensive snowfall started (41 cm of fresh snow overnight). Snow was continuously intercepted by both branches during that night. In the morning of April 13, both branches dumped the heavy load of snow. Wind velocity was low, air and branch temperature were below 0°C, not causing any snow melt. During the day snowfall continued with a maximum intensity around noon and continued during the night of April 13/14 (23 cm of fresh snow). The branches moved only slightly downwards which indicates that the interception capacity of the branches was exceeded and no more snow accumulated on the branches.

On April 14, 1994, at 10:00 the sky cleared and global radiation increased. Air and branch temperature raised to values above freezing which induced snow melt. Until the early afternoon almost all snow was dropped from the tree crown onto the ground. After unloading the snow both branches reached the same position as before the snowfall. On April 15 and 18 little snowfall was observed, but only little snow was intercepted which disappeared after 1 hour.

**Alptal**

In Figure 3.8 branch movements and meteorological factors are shown for the interception event at Alptal. From April 9 to 11, we observed an intensive movement of the branches with repeated loading and unloading which was observed also at Davos. The greater amplitude of movement of the branches at Alptal is due to their smaller diameter. Melting of intercepted snow was caused by global radiation and branch temperatures above 0°C. At Davos the
Figure 3.7: Branch movement and meteorological factors during the interception event from April 9, 20:00 to April 14, 1994, 24:00 at Davos. The lines in the top most figure indicate the movement of a ball mounted 30 cm from the branch tip, the small dots in the lowest figure the temporal resolution of the data of one hour. The grey bars are indicating a loading period (a) and an unloading period (b). It can be seen that global radiation and branch temperature were the dominant factors for unloading of intercepted snow.
Figure 3.8: Branch movement and meteorological factors during the interception event from April 9, 5:30 to April 14, 1994, 15:00 at Alptal. The lines in the topmost figure indicate the movement of a ball mounted 30 cm from the branch tip, the small dots in the lowest figure the temporal resolution of the data of one hour. The grey bars indicate unloading periods during the event.
3.4 Comparison of an interception event at Davos and Alptal

Figure 3.9: Fisheye photographs of the north (left) and the south facing branch (right) of the Davos tree. Each of both photos was taken from the center of the branch. The points in each figure indicate the position of the sun in a resolution of one hour. The photos show the great difference of solar radiation for both branches on April 14. The bottom of each image faces to north, the top of each image faces to south.

snow storm started earlier, that is in the evening of April 11 and continued until April 13, 1994, 12:00 with a break during the morning of April 13. The angle of both branches increased strongly, the south branch moved 78 cm downwards, the north branch 40 cm. The south branch retained more snow than the longer north branch exposed towards the opening. Both branches unloaded the snow for the first time in the evening of April 12. During the morning of April 13 both branches released snow due to exceeded interception capacity. Increased wind velocity caused additional unloading. Both branches were loaded again at noon of April 13.

Like at Davos snow melting started in the morning of April 14 due to air and branch temperatures above freezing. During this morning the global radiation at Alptal was only 200 W m\(^{-2}\) compared to 1000 W m\(^{-2}\) measured at Davos whereas mean air temperatures were almost the same at both sites. Therefore the tree crown at Alptal retained the snow until noon when a new snowfall started. Some snow fall was also observed on April 15 and 18, hence the crown was snow-capped until April 18.

The interception event from April 9 through 14 at Davos showed that unloading processes at the northern and the southern side of a tree occurred at different times depending on snow load and solar radiation which varies greatly in the crown. The heterogeneous distribution of radiation underneath the tree canopy was visualized with fisheye photos. Two photos taken in the
center of the north and the south branch at the Davos tree are shown in Figure 3.9. The photo taken from the northern branch indicates that the branch receives no direct sunlight throughout the whole day. Branch temperatures at the northern side are therefore lower especially during sunny days. The southern branch is exposed to direct solar radiation from 10:00 to 12:00. This leads to an increase of branch temperature causing the melting of intercepted snow (Figure 3.7).

3.5 Statistical modeling

3.5.1 Tree regression

In this section the influence of the meteorological factors on the event duration will be correlated by using tree regression (section 3.2, page 35).

As predictor variables we used the data measured at the weather station of the Swiss Meteorological Agency (SMA) in Davos. For analyzing the Alptal data we used the weather data of the nearby meteo tower. Because relative humidity is highly variable and difficult to measure we used air temperature, global radiation, wind speed and fresh snow as predictors for the event duration. The variables of the model are shown in Table 3.2.

The tree regression analysis was performed with data of winter 1993/94 and 1994/95. During the two winters at Davos 54 events were counted, at the Alptal site 38 events. When the splitting process of binary tree regression is continued without any limitations the number of terminal nodes (boxes in Figure 3.10, page 50) would correspond to the number of observed events. Models which are strongly fitted to a dataset (for example dataset “Davos 1993/94”) might become unstable when they are used for predictions with other datasets (for example dataset “Davos 1994/95” or “Alptal 1993/94”). Hence, we implemented limits in the splitting procedure by setting the minimum deviation of predicted event duration to 0.01 days for further splitting at a given node (mindev = 0.01 in function “tree.control”) (Statistical Sciences, 1993). That
means that calculated event durations of a node (left and right hand side of the split) must differ by at least 0.01 days. When the difference is smaller no split is calculated. Further limitations were a minimum number of four observations left before a split is done (minsize = 4 in function "tree.control") (Statistical Sciences, 1993). By these limitations a tree with 17 terminal nodes was created for Davos (Figure 3.10) and nine terminal nodes for Alptal. The binary tree in Figure 3.10 shows that the amount of fresh snow was the most dominant criterion to divide the data set into two main branches: the shorter events on the left side (new.snow < 3.25 cm) and the longer events (new.snow > 3.25 cm) on the right side. Also for the next splits the amount of fresh snow yielded the most significant criterion. As the partitioning of the tree proceeds the deviance of the nodes is decreasing which means that the significance of a node split is also decreasing.

The binary tree fitted to Davos data contained four splits by the fresh snow, five splits by the mean global radiation, four by the mean wind velocity and three by the maximum air temperature, respectively.

### 3.5.2 Prediction of event duration

After these calculations the data of both sites were used to predict the event duration for the other site in the corresponding winter. That means that for example the tree which was fitted to the Davos data from both winters was used to predict the event duration at Alptal using the record from Alptal measured during one winter. This procedure was done for both sites and both winters and is hereafter named as "crosswise prediction".

The results of the predictions have to be regarded on the background of the distribution of the predictor variables in the data space at both sites. The distributions of the two data populations show a good overlap in all cases. For the mean air temperature the overlap is about 60%, for the mean global radiation about 40%, for the wind velocity about 50%, and for the sum of fresh snow about 90%.

All simulations show quite good agreement between observed and simulated event duration for events lasting shorter than three days (Figure 3.11). Longer lasting events were less well predicted and show underestimation and overestimation of the event duration as well. A correlation test (Pearson's product-moment correlation) of observed and predicted values yielded coefficients of 0.76 for Davos 1993/94, 0.76 for Davos 1994/95, 0.75 for Alptal 1993/94, and 0.62 for Alptal 1994/95, respectively. The p-values of all tests were smaller 0.01 which indicates high significance.
Figure 3.10: Binary regression tree fitted to the Davos data set. The numbers in the ellipses indicate the event duration [d] before the split, and the numbers in the boxes the event duration for a terminal node. The number below the ellipses represents the deviation of the split which decreases as tree size increases. The number below a box represent the deviation of a terminal node. The criterion for an event lasting for example 12.05 days are indicated with grey bars.
Figure 3.11: Observed and predicted event duration at Davos and Alptal. Using the fit to the Davos dataset obtained by binary tree regression the event duration for Davos (left figures) for one winter was predicted using data of one winter from Alptal as input and vice versa (right figures). All figures show fairly good agreement between observed and predicted values for events shorter than three days. During the events which are marked with circles rain occurred which might explain that duration of these events was less well predicted.
Figure 3.12: Differences between observed and predicted event duration obtained from crosswise prediction of event duration of both sites. The left figures are representing predictions for Davos using data from Alptal, the right figures predictions for Alptal using data from Davos. The outliers of cross-wise prediction are marked with ovals. Symbol "R" labels events when rain occurred, symbol "S" labels events with snowfall only. The sign of the deviations indicate under (+) or overprediction (-) of event duration. The broken lines indicate a difference of 3 days. The vertical lines represent the three winter periods (section 3.3)
3.6 Discussion

Analysis of the less well predicted events included days with rainfall. Rain occurred on 71% (Davos 1993/94), 80% (Davos 1994/95), 67% (Alptal 1993/94), and 88% (Alptal 1994/95) of the events when the difference between observed and simulated event duration was greater than three days (Figure 3.12). This includes rain-on-snow events as well as events when snowfall changed to rain. During the rest of these events precipitation fell only as snow. The distribution of the outliers shows no clear dependence on the winter season. Only data from Davos 1993/94 suggest a maximum frequency during December to February. The reason for an underprediction might be that adhesion of intercepted snow to the wet branch was strong because the snowflakes were melting during the first contact with the wet needles and branches and refroze again when air and branch temperature dropped below freezing (Miller, 1964). This adhesion exceeds that between cold snow and cold, dry branches where snow slipped more easily.

3.6 Discussion

There is no obvious relation between number and duration of interception events and the meteorological factors over an entire winter period. While the cumulated duration of snow cover of the tree crown in a winter period lasted longer at lower mean air temperatures, the mean event duration in such periods showed no clear dependence on air temperature (Figure 3.5, page 42 and 3.6, page 43). Observations from Alptal showed that from October through December precipitation fell often as rain while at Davos it fell more often as snow. This is the main reason for a higher frequency of snow interception events at Davos. Intercepted snow was unloaded when air temperature and/or global radiation increased as shown for the April event at both sites (Figure 3.7, page 45 and 3.8, page 46). Global radiation is on average lower at Alptal than at Davos because of greater cloudiness at Alptal. This caused a greater event duration at Alptal during March and April (both winters) and during October through December in winter 1993/94. In March and April of winter 1993/94 the difference in mean global radiation was significantly higher than in winter 1994/95 (Figure 3.5 and 3.6) which induced a greater difference in the mean event duration of the two sites. Although the mean air temperatures were considerably higher at Alptal the snow remained longer in the tree crown than at Davos, where the frequency of interception events was higher (Table 3.1, page 41). Although mean values averaged over two to three months characterize the weather pattern only very roughly it indicates the weight of the respective factors for the interception and unloading process.
The comparison of the processes at both sites showed that processes vary strongly. The direct distance between the Davos site and the Alptal site is about 90 km. Different processes within 100 km indicate that GCM's must have a higher resolution than 100 km when energy exchange processes between forest and atmosphere are considered.

The influence of global radiation on the unloading of intercepted snow was also demonstrated using the observations of individual interception events (section 3.4, page 41). A fully snow-covered tree is stripped from its snow load within only a few hours from morning until the early afternoon (Figure 3.7, page 45). During such events branch temperatures above 0°C melt the intercepted snow. Increased branch temperatures increase the branch elasticity (Schmidt and Pomeroy, 1990), causing additional bending of the branch and therefore a steeper inclination. Intercepted snow becomes unstable which favors unloading.

Studies investigating the evaporation and sublimation of intercepted snow like for example Lundberg and Halldin (1994) and Lundberg (1996) show that the intercepted snow lasted for more than one day in the crown. However, these studies were performed under the weather conditions in northern Sweden which are clearly different from those in the alpine climate. The maxima of sublimation rates range between 0.3 mm h⁻¹ (Lundberg and Halldin, 1994), 0.56 mm h⁻¹ (Lundberg, 1996), 0.5 mm h⁻¹ (Calder, 1990), and 0.7 mm h⁻¹ (Nakai et al., 1994). The large evaporation rates measured by Lundberg (1996) were obtained under conditions with an average net radiation of 168 W m⁻², high wind velocities up to 4.6 m s⁻¹ and a vapor pressure deficit of 90 Pa. Assuming an evaporation rate of 0.5 mm h⁻¹ for the morning of April 14 with approximately 21 mm of snow in the crown we would expect a sublimation or evaporation of 14% of the intercepted snow. This amount is about half of the evaporation and sublimation rates measured by Schmidt (1991) and Pomeroy and Gray (1995) who measured up to 30 % sublimation from the canopy for a cold, continental climate in Northern America. In the climate of middle latitudes in Europe the evaporation of intercepted snow is most likely lower. Although there are periods when snow is retained up to 15 days in the crown also at lower sites like Alptal the loading and unloading process is much more dynamic than in the cold and dry climate of North America and Northern Sweden. The rate of unloading considerably limits the loss of water due to sublimation and evaporation.

Guttenberger (1994) quantified the relations between the amount of precipitation, snow melt and evaporation and amounts of snow unloaded from the crown for a low site east of Munich at an altitude of 550 m a.s.l.. For
several winters he calculated that from a total of 176.1 mm precipitation 8.4 mm melted in the crown, 21.7 mm dropped to the ground, and 9.5 mm evaporated. In total, 22% of the precipitation were kept in the crown, but only 5% less than in the open field reached the forest ground which corresponds to the evaporated or sublimated amount of snow.

The meltwater from intercepted snow mostly reaches the ground. Herrick and Friedland (1991) found that the water content of branches decreases during the winter. Katz et al. (1989) have shown that a fraction of the meltwater is taken up by twigs. Experiments by Häsl er (1996) showed that under favorable weather conditions photosynthesis occurs also in winter. Hence, twigs and branches may take up some of the snow meltwater.

Using the statistical procedure of tree regression for modeling the response of the event duration to meteorological factors produced reasonable results. But it also demonstrates the difficulties of modeling complex phenomena based solely on statistical interdependence between intercepted snow and meteorological factors. It turned out that the number of events was statistically too small to obtain relations of sufficient significance. Michaelsen et al. (1994) stated that 300 to 400 observations are needed in order to make full use of regression trees, but they assume that data sets in the order of 100 observations may still yield reasonable results. A larger data base improves the fitting of the tree regression for a complex problem as in the context of modeling snow interception event duration based on mean values of meteorological factors as predictors.

Cross-wise prediction of event duration using the fitted tree of one site to forecast event duration for the other site yielded consistent results only for events shorter than three days. Short events are characterized with a single snowfall and subsequent unloading of the snow while longer events are a sequence of several snowfall events not separated by complete unloading. Periods when snow was retained for more than 5 days are rare and therefore ill defined. The variability of the weather characteristics is greater during long events which causes problems in defining the forcing weather variable. As a consequence, quantifying the weather characteristics relevant for the considered processes with weather data averaged over the entire duration of an interception event is definitely more reliable for shorter event durations.

\(^1\)personal communication
3.7 Conclusions

The comparisons of the in-crown snow storage and weather data of winter 1993/94 and 1994/95 at two different sites showed that the controlling factors varies in the course of the winter. The event duration showed a higher sensitivity to air temperature in January and February and to global radiation in March and April. From October to December number and duration of snow interception events are neither correlated to mean air temperatures nor to global radiation. This suggests that especially during spring events precise measurements of global radiation are essential for modeling the unloading of intercepted snow. The results also indicate that the processes within 100 km are very different. This has to be taken into account when statements on energy exchange between forest and atmosphere based on GCM's are done.

Statistical modeling showed that it is possible to extract the controlling weather factors. For both sites the amount of fresh snow, air temperature and global radiation were the most dominant factors for the duration of interception events. Wind velocity turned out to be less significant. The prediction of event duration from these meteorological factors was only successful for events shorter than three days. Longer events could not be described satisfactorily by statistical modeling. Physically based models which also define the radiation regime in the canopy like for example suggested by Hardy et al. (1997) might yield better results for modeling snow interception in middle latitudes.

Acknowledgments

This work was supported by the Swiss National Science Foundation within the framework of the National Research Program 31 “Climate changes and natural disasters”. We highly appreciate the skilled technical support by Walter Caviezel, Urs Suter and Angelo Maccagnan of the Swiss Federal Institute for Snow and Avalanche Research SLF, Davos. We also thank Diethart Peters and Christian Quadri for their field assistance, the Swiss Meteorological Agency and the Swiss Federal Institute for Forest, Snow and Landscape Research WSL for providing meteorological data.
Chapter 4

Estimating the Intercepted Snow Mass on Spruce Branches

Manuscript:
Estimating the Intercepted Snow Mass on Spruce Branches Using Video Images and Finite Element Modeling

Abstract

Previous investigations of snow interception quantified the intercepted snow load by weighing a cut tree together with the snow retained in the crown. Investigating the hydrological processes between tree, snowpack and soil in winter, however, requires non-destructive methods for repetitive and continuous observations. We use non-invasive video recording for observing the bending of tree branches to quantify the snow storage change of the canopy and the flux of snow and water between canopy and snowpack compartment.

Throughout two winter periods we recorded branch deformation caused by the intercepted snow load. Branch displacements were modeled using a finite element method. Young's modulus of elastic deformation was iteratively determined for various temperatures by comparing the bending of the branches induced by calibration weights with modeled displacement. With this function we calculated the displacement of spruce branches for given temperatures and snow loads. The intercepted snow load on a branch with a length of 230 cm reached a maximum of 4.7 kg of intercepted snow. Strong varying mechanical properties of the branches within a tree crown indicated the limitations of this method. The calibrations must be adapted to every branch.
4.1 Introduction

In spring snow interception in coniferous stands sensitively controls discharge from forested basins. Hence, quantifying the sublimated, evaporated or redistributed fractions of the intercepted mass are important terms in the water balance of a forested basin. Investigations on snow interception found in the literature focus primarily on estimating evaporation and sublimation of snow retained in the crown (Calder, 1990; Lundberg and Halldin, 1994; Nakai et al., 1994; Pomeroy and Gray, 1995; Schmidt, 1991). In these studies the intercepted mass was either measured with a tree cut off at its base put on a balance or, also with an artificial coniferous tree (Schmidt, 1991). Weighing the intercepting system yields precise measurements of the intercepted mass and of the evaporative losses from the crown. Destroying the natural system prevents the investigation of the water transport processes between crown, snowpack and soil for extended periods of time. Hence, we have developed a non-destructive method to measure respectively the intercepted mass stored on single branches under natural conditions (chapter 2). This method is based on measuring the displacement of branches caused by snow load which depends on its mechanical characteristics and in turn on air temperature, water content and wood density of the branch.

The mechanical behavior of wood is mostly discussed in terms of wood as a construction material (Kollmann, 1951, 1960). The physical properties of dead wood are given by Sell (1989) and Kollmann (1960) who found a linear relation between air temperature and Young's modulus for dead, moist wood at a water content of 117% of dry weight:

\[ E_{\text{mod}} = 13.604 - 0.027T_a \] (4.1)

where \( E_{\text{mod}} \) [GPa] is the Young's modulus (elasticity modulus) of the branch and \( T_a \) [°C] the ambient air temperature. The water content of the wood also governs the elasticity in the dry range. Above 35% of dry weight, however, it can be regarded as constant (Kollmann, 1951).

For biomechanical investigations Young's modulus (hereafter called \( E_{\text{mod}} \)) is a critical parameter which describes the effective resistance of a material to deflection. It can be expressed as:

\[ E_{\text{mod}} = \frac{\sigma_b}{\epsilon_b} \] (4.2)

where \( \sigma_b \) [N m\(^{-2}\) = Pa] is the normal tension and \( \epsilon_b \) (dimensionless) the linear strain caused by the deflection.
Table 4.1: Wood density $\rho$ [g cm\(^{-3}\)] of a spruce branch in relation to its distance from the trunk after Bosshard (1974). $\rho_1$ is the density at the transition trunk-branch, $\rho_2$ and $\rho_3$ are the densities with increasing distance from the trunk.

<table>
<thead>
<tr>
<th></th>
<th>$\rho_1$</th>
<th>$\rho_2$</th>
<th>$\rho_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upperside</td>
<td>0.80</td>
<td>0.66</td>
<td>0.65</td>
</tr>
<tr>
<td>Underside</td>
<td>1.03</td>
<td>0.99</td>
<td>0.94</td>
</tr>
</tbody>
</table>

Generally, the density of the branch wood and, therefore, $E_{mod}$ varies over the length of a branch (Table 4.1).

Analogous to the density the stiffest parts of the branch with highest $E_{mod}$ are near the trunk. With increasing distance from the trunk $E_{mod}$ decreases (Schmidt-Vogt, 1986). The density of the upper side of the branch differs from that of the underside because of reaction wood formation at the underside (Table 4.1). Young's modulus is therefore larger at the underside of the branch. The reaction wood at the underside of the branch expands and causes upward bending compensating the additional gravitational force due to growing of the branch (Archer and Wilson, 1982). The fraction of reaction wood in a branch decreases with distance from the trunk which affects $E_{mod}$.

The mechanical properties of living wood have been investigated especially in the last years. Cannell and Morgan (1987) measured $E_{mod}$ of knot-free branches (branches with no lateral twigs) cut from 12-16 year old *Picea sitchensis*, *Pinus contorta*, *Larix decidua*, and *Betula pendula*. They found that $E_{mod}$ for *Picea sitchensis* varies between 3.9 and 6.7 GPa when the outer bark is included in the calculations and to 5.7 to 10.0 GPa when the outer bark is excluded. Branches from *Betula pendula* were the stiffest, branches from *Pinus contorta* had the lowest $E_{mod}$. They also found a positive linear relation between $E_{mod}$ and wood density and a negative linear relation between $E_{mod}$ and water content. However, the water content explained only 11% of $E_{mod}$ variation which means that its influence is minor compared to the influence of the wood density. In relation to other measurements with green timber these values are quite low but the branches used in the study were rather young which would explain the low Young’s modulus.

The influence of tapering (decrease of diameter) are examined by Morgan and Cannell (1987). Experiments with plastic rods showed that the degree of tapering determined displacement and the curvature of the upper parts of the plastic rods under comparable loading. The degree of taper was defined as (Cannell et al., 1988):

$$K = \frac{r_p - r_o}{r_o}$$  \hspace{1cm} (4.3)
where $r_p$ [m] is the radius at the thin end and $r_o$ [m] is the radius at the thick end of the segment. The bending under its own weight can be calculated with:

$$\delta = \frac{pL^4}{8E_{mod}I}$$

(4.4)

where $p$ [kg m$^{-1}$ g$^{-1}$] is the distributed load on the branch (product of mass per unit length and acceleration due to gravity), $L$ [m] is the shoot length, $E_{mod}$ [GPa] is Young's modulus, and $I$ [m$^4$] is the moment of inertia which for a beam of circular cross section is given by

$$I = \pi \frac{d^4}{64}$$

(4.5)

with $d$ [m] being the diameter of the beam.

The mechanical properties of fir branches under different temperature conditions were estimated by Schmidt and Pomeroy (1990) who calculated a linear relationship between branch temperature and $E_{mod}$ of the branch:

$$E_{mod} = 2.650 - 0.842T_b$$

(4.6)

where $E_{mod}$ is obtained in [GPa] and $T_b$ [°C] being the branch temperature. They found that $E_{mod}$ remains constant above 0°C but increases to values of 12.75 GPa when branch temperature drops to -12°C. However, these authors did not take into account that Young's modulus changes with distance from the trunk due to different ratio of reaction wood. For their experiments they used a subalpine fir (*Abies lasioscarpa* (Hook.) Nutt.).

The aim of this study is to employ this information concerning the mechanical deformation of living wood to estimate the amount of snow intercepted by branches. These estimates are a basis for estimating the intercepted mass on trees based on branch displacements measurements.

### 4.2 Investigation sites and methods

The experiments were conducted in a subalpine spruce forest near Davos at an altitude of 1659 m a.s.l. (Davos-Seehornwald). The trees at this site are in the average 120 to 370 years old (Stark et al., 1991). The investigated tree is located at the top of a hill next to a 10 m wide opening in the canopy. The average length of its branches is 180 cm ranging from 50 cm to 250 cm, the diameter at breast height is 20 cm, and the crown diameter 500 cm.

During the winter 1993/94 and 1994/95 the spruce was permanently observed with a video camera and the images were stored on a video tape. The
4.3 Calibration of branch displacement

Table 4.2: Distances d [cm] of the balls from the trunk for both branches at Davos-Seehornwald

<table>
<thead>
<tr>
<th>Exposure branch</th>
<th>d₁</th>
<th>d₂</th>
<th>d₃</th>
</tr>
</thead>
<tbody>
<tr>
<td>North</td>
<td>93</td>
<td>64</td>
<td>133</td>
</tr>
<tr>
<td>South</td>
<td>158</td>
<td>118</td>
<td>203</td>
</tr>
</tbody>
</table>

The aim of these recordings was to obtain continuous information of snow loading and unloading in the tree crown and the interplay with meteorological factors (chapter 3). To achieve quantitative analysis of the images at several branches plastic balls were suspended whose position was analyzed by image analysis yielding a time series of the branch movement over the course of an interception event (chapter 2). An “interception event” was defined as the period from the beginning of snow accumulation on the branches to the time when the crown was cleared from snow.

As described in section 4.1, $E_{\text{mod}}$ highly depends on the branch temperature and the tree species. Since the mechanical properties of the branches at the experimental site were unknown calibration measurements under different temperature conditions were conducted.

4.3 Calibration of branch displacement

The calibration measurements were carried out on a south and a north exposed branch using weights of 200 to 1200 g in 100 g steps. They were attached to the branch at the ball positions (Figure 4.1). The bending of the branch was determined on the video frames from the ball position either by automated image analysis or manually (chapter 2). The branch temperature during the experiments ranged from -8.0°C to 0°C.

The measured field data of these calibration experiments were used as inputs for calculating Young's modulus (elasticity modulus) of the branch. Important data for the calculation of $E_{\text{mod}}$ are the diameter, wood density and weight of the branch which includes the weight of the main branch and the twigs. These data were obtained by cutting a similar branch from a neighboring tree and measuring the weight of branch and twigs. The diameter of the branch was measured in 10 cm intervals beginning at the trunk. The relation of diameter to distance from the trunk is shown in Figure 4.2. The deviation from an ideally linear decrease can be explained by knots and branching where the branch gets thicker.
Figure 4.1: Schematic of a branch with suspended balls. Weights in the range from 200 to 1200 g (in 100 g steps) were suspended at the ball positions. The vertical displacement of the balls was either manually measured or by image analysis. The horizontal distances of the balls from the trunk are given in Table 4.2.

4.4  Modeling branch displacement

Young's modulus was determined by a finite element model using the program FLOWERS (Anderheggen et al., 1993). Each branch was divided into finite elements with a length of 5 cm with a 1 cm long element at the transition trunk to branch. The branch was assumed to have a circular cross-section, so every element represented a truncated cone. The branch was regarded to have linear elastic properties. However, the finite elements could undergo large displacements meaning that "geometric" nonlinearities were included in the analysis. The branch strains were assumed to remain small. Model input included the cross-sectional area \( A = \pi d^2/4 \) [m\(^2\)] and the second moment of inertia \( I = \pi d^4/64 \) given in equation 4.5.

The weight of the branch itself was included in the model by assuming a constant wood density of 800 kg m\(^{-3}\). The weight of the lateral branches and twigs was considered as a permanent static load on the branch. Young's modulus and shear modulus defined as Poisson's ratio had to be given for every element as well. The dimensionless Poisson's ratio can be written as

\[
\mu = -\frac{\epsilon_S}{\epsilon_N}
\]  

(4.7)
4.4 Modeling branch displacement

Figure 4.2: Relation of branch diameter to distance to trunk for both branches used in the experiment at Davos-Seehornwald. The diameter of a segment increases rather linearly with the distance from the trunk. Deviations from the "ideal linear" decrease are caused by knots in the wood and by branching.

where $\epsilon_S$ [m] is the transverse contraction and $\epsilon_N$ [m] the linear tension.

After each simulation run the calculated displacement at the outer ball was compared with the measured displacement. When the deviation was greater than 1%, $E_{mod}$ was adjusted and iteration carried out until the deviation was less than 1% of the total displacement of the branch. The simulations were conducted separately for each branch and each experiment. During a single simulation run the ball weights were increased in 50 g steps up to the final calibration weight of 1200 g per ball and 3600 g on the branch.

The calculated $E_{mod}$ decreased linearly with increasing branch temperature (Figure 4.3). A linear regression model for the north branch yields

$$E_{mod} = 8.19 - 1.14 T_b$$  \hspace{1cm} (4.8)

and for the south branch

$$E_{mod} = 6.40 - 0.20 T_b$$  \hspace{1cm} (4.9)

with the notation given in equation 4.6. These calibrations are only valid in the experimental temperature range of $-8.0^\circ C$ to $0^\circ C$. 
Figure 4.3: Relation of Young’s modulus to branch temperature in the range between -8.0°C to 0°C calculated by equation 4.8 and 4.9, respectively. $E_{mod}$ of the northern branch was considerably larger than that of the southern branch probably because of a larger fraction of reaction wood in the northern branch.

Figure 4.3 and the equations 4.8 and 4.9 show that the northern branch has a larger Young’s modulus than the southern branch. A probable reason is that the north exposed branch has a large fraction of reaction wood in the segments closer to the trunk because it is hanging downwards even when unloaded. The video observations over the two winter periods (chapter 3) indicate that the north exposed branch kept the snow longer than the south exposed branch. The duration of branch deflection certainly modifies the formation of dense reaction wood which increases $E_{mod}$. On the south exposed side warm air temperatures and incident radiation causes warming of the branches and favors rapid unloading. This might explain the lower $E_{mod}$ of the southern branch.

The measured $E_{mod}$ of the north branch shows very high values which exceed the values found by Cannell and Morgan (1987). They found values of 3.9 to 6.7 GPa for *Picea sitchensis*. However, in their case the temperature range around 20°C was considerably different from our experimental conditions. Schmidt and Pomeroy (1990) found a $E_{mod}$ up to 12.75 GPa for *Abies lasioscarpa* (Hook. Nutt.) when branch temperature dropped to -12°C. However, these authors neglected the weight of the branch itself which in our case had a considerable influence on the simulation results. Neglecting the branch weight (including lateral shoots) yielded an $E_{mod}$ which was half of
4.5 Modeling the intercepted mass

that obtained taking branch weight into account. Compared to $E_{\text{mod}}$ of other coniferous trees, wood of spruce branches is the stiffest (Cannell and Morgan, 1987; Casterá and Morlier, 1991; Kollmann, 1960). The southern branch shows lower $E_{\text{mod}}$ values in the range described in the literature. Since our experimental tree is considerably older compared to those referred to in the quoted papers the estimated Young’s moduli are reasonable.

A plot of a simulation run is given in Figure 4.4. The three graphs show the displacement of the ball farthest from the trunk (a), in the middle of the branch (b) and closest to the trunk (c). As described above the simulation was repeated by trial and error until measured and simulated displacement of the outer ball differed by no more than 1%. The deformation curves of the middle and the inner ball suggest that simulated displacement was less than measured displacement which means that the model was too stiff towards the trunk. This behavior could in its trend be observed at both branches during all simulations.

The reason for these systematic deviations are the varying mechanical properties of the branch which could not be described by the model. For every simulation run $E_{\text{mod}}$ was set equal for all elements of the branch. Attempts using different Young moduli for different parts of the branch were not successful since the simulated and measured displacements did also not coincide in these simulation runs. As a consequence, we kept $E_{\text{mod}}$ constant over the entire branch length. The mechanical properties of the branch have possibly adapted to the specific loading conditions. Accumulation of intercepted snow is a significant load for a branch. Since the main load is concentrated at the end of the branch it is probable that the branch reacts to distribute the load more uniformly over the length of the branch. A small bending radius in the center of the branch may cause breaking. There seems to be a complex interaction between the biological and physical properties of the branch. Mechanical properties can be regarded to be a compromise between loading and physiological response at the specific location of the branch. These specific properties, however, are not taken into account by the model.

4.5 Modeling the intercepted mass

The calculated $E_{\text{mod}}$ obtained from the calibration experiment and its relation to temperature were used as inputs to the finite element model FLOWERS to calculate the weight of intercepted snow during an interception event. For this example we used data of an event from April 10 to April 14, 1994 since this was a typical spring event with heavy loading of the branch. Corresponding
Figure 4.4: Example of the branch calibration modeled by FLOWERS (Anderheggen et al., 1993). The simulated displacement of the ball farthest from the trunk (a) was fitted to the corresponding observation. The displacement of the inner positions was underpredicted (Figure b and c). The inner parts of the branch were simulated as being too stiff. The mechanical properties of the branch are apparently varying over the length of the branch.
4.5 Modeling the intercepted mass

Figure 4.5: Time series of Young's modulus during the interception event from April 10 to April 14, 1994. The plot shows the strong coupling of the response of $E_{mod}$ to the branch temperature as it was used as input for the calculation of the intercepted mass.

to air temperature and incident radiation the branch temperature changes significantly during such an event. Based on the linear relations (equations 4.8 and 4.9, page 63) we calculated the response of $E_{mod}$ to the branch temperature (Figure 4.5).

As we can see from Figure 4.5 $E_{mod}$ of the northern branch varied between 6.0 and 18.0 GPa and that of the southern branch between 4.5 and 9.0 GPa. We used these intervals and calculated the force on both branches using FLOWERS by increasing $E_{mod}$ for each run by 1 GPa. These simulations yield a dataset which relates the weight acting applied at a given position to the displacement for a constant stiffness (constant $E_{mod}$). Plotting these variables defines a three-dimensional surface which is illustrated in Figure 4.6.

The results of the numerical simulation, i.e. a displacement of a ball for a given force $W$ (mass of snow) and a given Young's modulus $E_{mod}$ were used as input for a statistical model. Since the data described a three-dimensional surface with a non-linear relation between force and displacement we used local regression models as it is implemented in the statistical language S-Plus (function “loess”) (Statistical Sciences, 1993). This method provides the possibility to fit a regression surface to a dataset where variables are non-linearly related to each other. The idea of the method is that the surface through a
Figure 4.6: Results of the Finite Element simulation of the force $W$ on a branch causing a given displacement for a given Young's modulus. The numbers at the edge of the respective lines denote the force $W$ [N].

point in the predictor space is fitted by interpolation from neighboring surfaces of the data space. Applied to this example response and predictor variables in the local regression model are related by

$$
\hat{W}(d_j, E_{mod}) = G(d_j, E_{mod}) + \delta_j
$$  \hspace{1cm} (4.10)

where $G$ is the regression surface and $\delta_j$ are random errors. For a given $d_j$ and a given $E_{mod}$ in the predictor space, $\hat{W}(d_j, E_{mod})$ is the expected force (equivalent to weight). For the fitting procedure in this paper the following characteristics of the fitted surface were specified:

- Gaussian distribution of the residuals
- locally quadratic relation of the predictors (relationship between force $W$ and displacement $d_j$ is non-linear)
- number of neighboring areas which are used for interpolation (according to the syntax in S-Plus it was set to $\alpha = 1$, which was found to produce a well fitted model).

The method is explained in detail by Cleveland et al. (1992).

We fitted a local regression model using the force $W$ as the response variable and $E_{mod}$ and displacement $d_j$ as the predictors. The result of the calculations was a surface in the space of the predictors. The model produced
Figure 4.7: Residuals of the local regression model fitted to the results of the numerical simulation of force on branches for a given Young's modulus (Figure a) and a given displacement (Figure b). The normal quantile plot of the residuals is illustrated in Figure c. The lines in Figure a and b are a spline smooth and indicate that residuals are distributed around 0 which suggests a good fit of the data. The reason for the large residuals marked by circles and ellipses in Figure a and b is that the model is less good fitted for displacements less than 10 cm which is a result of the calibration starting with a mass of 200 g. Figure c suggests that residuals are Gaussian distributed as assumed.
Estimating the Intercepted Snow Mass on Spruce Branches

Figure 4.8: Branch displacement and mass of intercepted snow from April 10 to April 14, 1994. The thick black line indicates that the intercepted load reached its maximum on April 14, 1994 with 4.7 kg of snow. Intercepted snow was unloaded during the morning of April 14, 1994 due to intense incident shortwave radiation. The grey line shows the branch deflection which corresponds to the intercepted snow mass.

an excellent fit because the data are very homogeneous (Figure 4.6). The residuals of the model exhibit a Gaussian distribution which confirms the assumption (Figure 4.7c). Plotting the residuals against the predictors $E_{mod}$ and $d_j$ (Figure 4.7a and b) indicates that data are quite homogeneously distributed around 0 which implies a good agreement between observed and modeled values of the response variable $W$.

The fitted model was applied to determine the intercepted snow load during the event from April 10 to April 14, 1994. The results are illustrated in Figure 4.8. The grey line shows the motion of the south branch during the event and the black line the total force acting on the branch due to intercepted load. Both lines show that until April 12, 20:00 only little snow was intercepted by the branch. Snowfall started in the evening of April 12, 1994 and continued with some interruptions until April 14, when the snow load on the branch reached its maximum. At this time an additional force of 46 N bent the branch downwards which corresponds to a snow mass of 4.7 kg.

For comparison we measured the intercepted mass on spruce branches at a tree located in a distance of 600 m to the experimental tree. At this site (experimental plot at SLF, Davos Flüelastrasse) we could measure the intercepted load by hand immediately after snowfall because this site is rapidly accessible. We put a large plastic bag over a snow-covered branch and shook
4.6 Conclusions

Modeling intercepted mass by using observed displacements of branches demonstrates that the complex biomechanics can be approximated. Simulation of the branch bending produced very different Young moduli for two different branches of the same tree. Simulations showed as well that the stiffness of different segments of a branch may vary under field conditions. This implies that $E_{mod}$ may not be constant over the length of the branch. Cannell and Morgan (1987) stated that wood density decreases with increasing distance from the trunk. Since $E_{mod}$ is linearly and positively correlated with wood density it is probably decreasing with increasing distance from the trunk. An attempt with $E_{mod}$ varying in this sense over the length of the branch showed, however, that the model could not be fitted to the measured displacement of the three balls under the attached load. The mechanics of branches is most likely a complex adaptation to the very local environmental conditions. From this point of view it can be assumed that the relation between Young's modulus and branch temperature found by Schmidt and Pomeroy (1990) are only valid for their specific experiment.

In spite of these problems the statistical model representing the relationship $W(E_{mod}, d_j)$ yielded satisfactory results. The intercepted snow load collected from comparable branches indicates that simulated loads were reasonable and in a realistic magnitude.

Acknowledgments

This work was supported by the Swiss National Science Foundation within the frame work of the National Research Program 31 “Climate changes and natural disasters”. We highly appreciate the skilled technical support by Walter Caviezel, Urs Suter and Angelo Maccagnan of the Swiss Federal Institute for Snow and Avalanche Research SLF, Davos. We thank also Birgit Aschenbrenner and Walter Peschke for their field assistance.
Leer - Vide - Empty
Chapter 5

Visualization of Meltwater Drip in the Snowpack

Manuscript:
Routing of Canopy Drip in the Snowpack below a Spruce Crown

Abstract

Snow which is retained by a forest may either sublimate or evaporate directly from the crown or drop as snow clumps or meltwater to the ground. Redistributed snow and meltwater affect the snow structure and prevent formation of mechanically weak layers which is the prerequisite for avalanche formation in forests.

In this paper we describe the results of dye tracer experiments conducted in a subalpine forest near Davos, Switzerland. Before a snowfall event we stained snow-free branches of a spruce with a dye tracer solution. After snowfall the colored meltwater dripping from the branches down onto the snowpack stained the percolation pathways of the meltwater in the snowpack. Photographs of the snow profiles indicate that the meltwater seeped almost vertically through the isothermal snowpack to the soil surface not exceeding the projected crown edge. Meltwater of different events moves along different preferential flow channels in the snow suggesting that old channels are non-conducting and additional meltwater fronts create new channels.

5.1 Introduction

Discharge from snow-covered forested basins during winter and spring originates primarily from water stored within the snowpack. The snow water
equivalent of a snowpack is the amount of water which accumulated during the winter period either as snow or refrozen rain. Under a tree the snow water equivalent is smaller because some of deposited snow is intercepted by the tree crown. Intercepted snow will eventually sublimate or evaporate, being dropped as snow clumps or dripping as meltwater onto the snow surface and seeping into the snowpack. These processes modify the structure of the snowpack (Zingg, 1958; in der Gand, 1978; Imbeck, 1984, 1987). Albert and Hardy (1993) investigated the structure of the snowpack in a deciduous stand. The inhomogeneous layering of the snowpack below trees prevents the formation of a continuous layer of low tensile strength which favors the release of snow slabs (Gubler and Rychetnik, 1991). Dripping meltwater forms meltwater channels in the snowpack which after refreezing are assumed to stabilize the snowpack. Experiments determining snowpack stability below and immediately outside of the area projected by the crown of larch trees have shown that such snowpacks have greater tensile strength (Schweizer et al., 1995). A further difference to the snowpack in open areas is that organic materials like lichens, needles and little twigs may be deposited onto the surface and integrated in the snowpack. These debris modifies the albedo and the radiation regime within the snowpack. A schematic profile of a snowpack below and outside a spruce tree is shown in Figure 5.1.

Studies of water transport in snowpacks using dye tracers were done by Gerdel (1954) and later by Colbeck (1972, 1976, 1979). Both Colbeck (1979) and Wankiewicz (1978) described the transport of the meltwater as a combination between homogeneous flow (matrix flow) and a flow along preferred channels (preferential flow). Wankiewicz (1978) postulated a conceptual model

![Figure 5.1: Snow profile below and outside a spruce crown (after Imbeck (1987)). The structure of the snowpack outside the projected crown edge is more homogeneous than that below the crown. Typical for the snowpack below the crown are embedded harsh clumps, organic debris buried in the snowpack and meltwater cones protruding from the surface into the snowpack.](image-url)
that allows a snow horizon to impede, to favor or to have no effect on down-
ward flow. The meltwater flow pattern depends on the permeability of the
adjacent snow layers, on the slope and the roughness of these layers and on
the presence of ice layers. Marsh and Woo (1984a) visualized the flow patterns
in an arctic snowpack with a dye tracer. Based on field observations Marsh
and Woo (1984b) developed a one-dimensional model incorporating the flow
of meltwater in flow fingers, ice layer growth within and at the base of the
snowpack, and the interaction of meltwater with the soil. The formation of
a basal ice layer at the bottom of a snowpack was found to have a dominant
influence on snowmelt runoff processes (Woo et al., 1982).

Dye tracer experiments were recently carried out in an alpine snowpack
by Schneebeli (1995) and in a snowpack of the Sierra Nevada, California by
snowpack and found even in a snowpack inclined by only 2% that meltwater
is transported over lateral distances of several meters. On a 61% inclined
slope a maximum horizontal meltwater transport of 20 meters was observed
within 12 hours. McGurk and Marsh (1995) cut thick horizontal sections and
photographed the finger distribution of the snowpack.

All these studies were performed in open area snowpacks. The study by
Hardy et al. (1992) was one of the few in which a forest snowpack was ex-
amined. They observed a travel distance of 9.1 m downslope within 4 hours.
Their experimental plots were located in gaps between tree crowns.

The influence of the tree crowns have not been investigated in these studies.
In particular no information on the effects of spruce crowns on meltwater
channeling is available. Here we present the results of dye tracer experiments
carried out in a subalpine snowpack at the edge of a spruce crown. The
objective of this investigation is to analyze the meltwater transport in the
snowpack in the transition zone between canopy and open area.

5.2 Experimental site and methods

The experiments were carried out at Davos-Seehornwald (1655 m a.s.l., Fig-
ure 3.1, page 34). To represent the processes at sites of different aspects we
chose a north facing slope (inclination 51%) and one exposed to the south
(inclination 49%). The two sites were located at a distance of 50 m from each
other. A schematic of the experimental plots is shown in Figure 5.2. The
experiments were performed in the following manner:

Before a snowfall event three branches of a spruce tree (Table 5.1) were
stained either with the dye tracer Brilliant Blue FCF (CI Food Blue 2) (Flury
Table 5.1: Characteristics of experimental fields and spruce trees at Davos- Seehornwald.

<table>
<thead>
<tr>
<th>Exposure</th>
<th>Height [m]</th>
<th>Breast diameter [cm]</th>
<th>Crown diameter [m]</th>
<th>Distance to first green branch [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>North</td>
<td>17</td>
<td>26</td>
<td>3.0</td>
<td>2.6</td>
</tr>
<tr>
<td>South</td>
<td>22</td>
<td>36</td>
<td>5.0</td>
<td>3.4</td>
</tr>
</tbody>
</table>

and Flühler, 1994) or with Azofloxine (CI Acid red 1) (Table 5.2). The dye tracers were dissolved in water at a concentration of 12 g l⁻¹. During tracer application the snowpack beneath the tree was covered with a plastic sheet. It prevented the dye from seeping into the snowpack. After it had dried on the branches, the plastic sheet was removed. Profile excavation started when the crown was bare of snow. Below the tree as time progressed further downslope snow profiles were excavated separated 20 cm from each other perpendicularly to the slope (Figure 5.2) until the pit was 3 m. Four reference markers were attached onto the vertical face of the profile to secure the position and scale for image analysis. The profiles were photographed on slide films and stored in a digitized format on Photo CD. In order to enhance contrast between dye and snow the photos were taken at nighttime with flashlight. The stratigraphy of the snow cover was described according to the International Classification of Seasonal Snow on the Ground (Colbeck et al., 1990).

The contrast of the images recorded on Photo CD were further enhanced using filter routines in the image analysis program Photoshop (Adobe Systems Inc.). To identify the stained area of the flow paths the colors of the image were converted from the Red–Green–Blue color space (RGB) into the Hue–Saturation–Intensity color space (HSI). Then a threshold was set which corresponded to the unstained white areas of the image. Pixels of white areas corresponded with this threshold were set to foreground pixels and the area of these pixels was extracted from the image using the image analysis program Optimas (Optimas Inc.). The not extracted area represents the visualized flow pathways.

5.3 Results and Discussion

The two experiments presented here were carried out in winter 1994/95. In experiment A, conducted at the northern site the branches were sprayed first with Brilliant Blue (experiment A1) and 37 days later with Axofloxine (experiment A2, see Table 5.2). Between experiment A1 and A2 eight snowfall events with a total water equivalent of 72 mm were observed. The second experiment
5.3 Results and Discussion

Figure 5.2: Schematic of the experimental setup for dye tracer experiments at Davos-Seehornwald in winter 1994/95. Snow profiles were excavated 20 cm from each other perpendicularly to the slope. The snow profiles were photographed and analyzed by image analysis.

Table 5.2: Date of the experiments in spring 1995 and concentration of applied dye tracer (g l⁻¹). The numbers of the experiments are used as abbreviation in the text.

<table>
<thead>
<tr>
<th>Experiment No.</th>
<th>Date of application</th>
<th>Tracer</th>
<th>Concentration (g l⁻¹)</th>
<th>Date of profile</th>
<th>Aspect</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>February 21</td>
<td>Brilliant Blue</td>
<td>12</td>
<td>April 5</td>
<td>North</td>
</tr>
<tr>
<td>A2</td>
<td>March 27</td>
<td>Azofloxine (red)</td>
<td>12</td>
<td>April 5</td>
<td>North</td>
</tr>
<tr>
<td>B</td>
<td>March 27</td>
<td>Azofloxine (red)</td>
<td>12</td>
<td>April 4</td>
<td>South</td>
</tr>
</tbody>
</table>

(experiment B) carried out at the southern site included two snowfall events between March 27 and April 4 with a water equivalent of 59 mm in total. On February 21 the snowpack at the southern site was already isothermal while snow temperatures at the northern site were still below freezing. At the northern site the snowpack became isothermal by March when air temperatures were above 0°C (Figure 5.3).

At the northern site meltwater percolation in the snowpack began towards the end of February when intercepted snow melted on the branch and dropped down to the snowpack (Figure 5.3). Observations of snow interception by
Figure 5.3: Meteorological conditions between the dye tracer applications in experiments A and B. Air temperature exceeded 0°C during the sunny days after March 10 so that snowpack became isothermal. During days with air temperatures above freezing intercepted snow melted and dripped from the branches inducing meltwater infiltration into the snowpack. All data are mean daily values indicated by the small points in Figure b.
a neighboring spruce tree at a distance of 10 m (chapter 3) from the plot indicated that the crown was snow-free on March 2.

The snow profile of the snowpack of experiment A (left part of Figure 5.4) shows a deeper snowpack than at the southern site (right side of Figure 5.4). The temperature distribution was isothermal at the time of excavation and melt crystal shapes prevailed. No basal ice layer was found in this profile. As in the profile of experiment B a homogeneous layer of fresh snow covered underlying more granular layers.

The snow profile of experiment B (right part of Figure 5.4) shows a melt crust at the surface and beneath a layer of fresh snow deposited between March 28 and April 2. In this layer some rounded crystals but also partially melted crystals were found. The other layers could be clearly distinguished from the upper layer and all contained melt crystals with the exception of the basis of the snowpack where an ice layer was found. The temperature distribution in the profile was isothermal.

Figure 5.5 illustrates four profiles located in the central part of the profile trench at the northern experimental site (experiment A). The red dye tracer infiltrated quite homogeneously into the superficial layer of fresh snow (experiment A2). Only at few locations the meltwater broke through the horizon between the new and old snow. The flow pattern below the surface layer observed in experiment A1 (blue dye) and A2 (red dye) were different. At the south facing site (Figure 5.6) red dye infiltrated more homogeneously into the old snow than at the northern site which suggests that the meltwater at the northern site percolated in narrower channels. The red color reached the ground only at a few locations. In the layers of the old snow the blue colored meltwater showed a very heterogeneous, preferential flow pattern. The north exposed snowpack may have become isothermal at a later stage so that more separate flow channels were formed. The flow pattern within the shown 60 cm of horizontal distance is highly variable as seen by comparing the four profiles to each other. At the bottom of the snowpack no lateral transport of the meltwater was observed possibly because basal ice layer was impeding infiltration. The soil at this site was not frozen which is probably a consequence of a better insulation by the deeper snowpack. Subsequently the meltwater infiltrated into the soil.

Figure 5.6 illustrates four profiles located in the central part of the profile trench at the southern experimental site (experiment B). The profiles were excavated 20 cm from each other. The position of the profile labels indicates the projection of the crown edge. The tree itself is located on the left hand side of the image. The meltwater infiltrated relatively homogeneously into the
Figure 5.4: Snow profiles of dye tracer experiment A and B. The figure on the left shows the snow profile at the north facing slope (excavation April 5, 1995), that on the right hand side the snow profile at the south facing slope (excavation April 4, 1995). The temperature distribution was isothermal in both snowpacks, the most frequent crystal shape were rounded melt crystals. The symbols and table headings are based on the International Classification of Seasonal Snow on the Ground (Colbeck et al., 1990).

layer of fresh snow (matrix flow). At some locations the meltwater percolated into the underlying old snow but the flow pattern was rather diffuse because the infiltration occurred in an isothermal, wet, and coarse layer. The widest and most diffuse flow path developed below the crown edge where the meltwater seeped through the entire snowpack. Apparently, the dye tracer moved laterally on the basal ice layer, but broke through the ice layer and infiltrated into the soil at several points.

**Mechanism of water transport**

The structure of a forest snowpack is by far more heterogeneous than a snowpack in open areas (Figure 5.1, page 74). The occurrence, thickness and quality
Figure 5.5: Color slide photographs of snow profiles excavated during the dye tracer experiment A at the northern site. The photos show the middle portion of the 2 m wide and 3 m long downslope profiles excavated on April 5 between 5:30 and 8:00 directly below the crown edge. The profile trench was excavated perpendicularly to the slope. The crown edge is indicated by the profile label located exactly below the crown edge. The distance of the replicated profiles was 20 cm from each other.
Figure 5.6: Color slide photographs of snow profiles obtained during the dye tracer experiment B at the southern site. The photos show the middle portion of the 2 m wide and 3 m long downslope profiles excavated on April 4 between 5:30 and 8:00 directly below the crown edge. The profile trench was excavated perpendicularly to the slope. The crown edge is indicated by the profile label located exactly below the crown edge. The distance of the replicated profiles was 20 cm from each other.
of ice lenses and -crusts, the presence of macropores, and the variation of grain shapes and -sizes is more pronounced underneath a canopy than in an open area. The scale of variation is in the range of centimeters which means that water transport varies accordingly depending on the spatially variable grain shapes and sizes.

The transport of water in snow can be described by the model by Wankiewicz (1978). Depending on the gravity-flow pressure of two adjacent layers the horizon between these two layers will either impede, accelerate or will have no effect on the downward flow. The gravity-flow pressure (Wankiewicz, 1978) is defined as:

\[ p_v = p_b \left( \alpha \frac{k}{q} \right)^{1/\eta} \]  \hspace{1cm} (5.1)

with \( p_b \) being the bubbling pressure \([\text{Nm}^{-2}]\) of the snow matrix (air entry pressure), \( k \) \([\text{m}^2]\) the permeability of the media, \( q \) \([\text{m} \cdot \text{s}^{-1}]\) the volume flux (positive downward), and \( \eta \) (dimensionless) the pore size distribution index. The constant \( \alpha \) is defined by

\[ \alpha = \frac{\rho_w g}{\xi} \]  \hspace{1cm} (5.2)

with \( \rho_w \) \([\text{kg} \cdot \text{m}^{-3}]\) being the water density, \( g \) \([\text{m} \cdot \text{s}^{-2}]\) the acceleration gravity, and \( \xi \) \([\text{kg} \cdot \text{m}^{-1} \cdot \text{s}^{-1}]\) the dynamic viscosity of water. When the gravity-flow pressure for a flux in an underlying layer is greater than that in the layer above, then the boundary will impede the flow. The water will accumulate above the boundary between the two layers or will flow laterally downhill when the horizons are inclined. Applied to a layer of new, fine snow lying on an old, coarse snow the water will be retained in the fine textured horizons above the old snow. In Figure 5.5 and 5.6 we see that meltwater percolated through the matrix of the fresh snow and penetrated through few preferential ports into old snow. This pattern corresponds well with the pattern described by Wankiewicz (1978). Due to its isothermal temperature distribution the old snow in Figure 5.6 can be regarded as a single, relatively thick layer. We observed no lateral flow neither on ice lenses nor in differently textured adjacent layers with the exception of some lateral movement on the basal ice layer but not in the zone of the crown edge. The area within crown projection exhibits more pronounced soil frost and was more impedent to infiltration than the area outside. Some meltwater percolated also through the "ice layer" which is consistent with the observations by Colbeck (1978) who showed that water flows through a 50 mm thick sloping ice layer. Therefore it is likely that, in our case, the meltwater infiltrated into the frozen soil within the reach of crown projection.
Characteristics of flow patterns

The meltwater visualized in experiment A reveals two additional phenomena: (i) The formation of clearly discernable flow fingers in a cold snowpack (T < -1° C) and (ii) the fact that different meltwater channels are active at different times. The flow pattern in fresh snow was similar to that in experiment B. The flow pattern in old snow however showed only a few red fingers which did not coincide with the position of the blue fingers. That means that the red colored meltwater induced formation of new flow fingers. From February 21 to March 27 (blue color, experiment A1, Figure 5.5, page 81) when several snowfall events occurred the meltwater percolated in spatially isolated channels through the snowpack. In this period at the beginning of the experiment the snowpack was not isothermal which lead to well separated fingers. At a more shaded location under low flow rate conditions the variability of the local water fluxes is increasing as reported by Marsh and Woo (1985). They concluded that melt rates and flow variability are inversely related to each other which means that low melt rates induce high flow variability and vice versa (Marsh and Woo, 1985). In a cold, subfreezing snowpack the meltwater wetting front in the snow matrix is lagging further behind the finger tips than in an isothermal snowpack (Figure 5.5 and 5.6). These fingers may transport some meltwater all the way down to the soil surface even when the snow temperature is below freezing (Marsh and Woo, 1984a) but at the same time the formation of a few narrow channels slows the response of the snowpack to water input down. Colbeck (1978) showed that a snowpack consisting of fine, dry snow prolongs and diminishes the response of meltwater outflow. In a wet snowpack outflow responded soon after the onset of meltwater flow.

Water flow through such channels increases their grain sizes. The liquid water content has an immediate effect on grain growth (Marsh, 1988). That means an increasing water content enhances the rate of grain growth (Colbeck, 1978). Therefore, the permeability of the flow finger core increases during its formation (McGurk and Marsh, 1995). Some of the latent heat of infiltrating meltwater is probably lost due to refreezing of meltwater seeping laterally into the cold matrix and thereby partially sealing the channel from its surroundings. This effect leads to water flow at the outside of the finger (McGurk and Marsh, 1995). After a freezing–thawing cycle, as occurred during experiment A, active fingers were sealed and new fingers were created. The red colored meltwater in experiment A did not seep through the channels stained by the previously displaced blue colored meltwater. This confirms the observations by Schneebeli (1995) who applied various dye tracers onto an open area snowpack and observed that meltwater after one or several thaw/freeze-cycles
(day/night) did not flow in the same channels as before. Local co-existence of these dyes was limited and, hence, mixing of subsequent meltwater waves is less pronounced than the formation of new flow paths through the original matrix.

**Wetted areas**

The percolated area of the snowpack under trees was measured by image analysis (section 5.2, page 76). The values shown in Table 5.3 are in the range of the values measured in the open area snowpack by Schneebeli (1995). His experiments showed a higher variability of the percolated area of 11% up to 81% under conditions where snow temperature was below 0°C. McGurk and Marsh (1995) reported mean wetted areas between 15% and 25% of the horizontal cross-sectional area. These data depend highly on the snow characteristics. In dry, cold snow flow fingers cover in total a smaller area than in an isothermal snowpack. Additionally, the size of flow fingers may be enlarged in wet snow (McGurk and Marsh, 1995).

**Basal ice layer**

The snowpack at the south facing plot was less deep which led to basal ice formation on the frozen soil in contrast to the north-facing plot where the soil did not freeze primarily due to a better insulation of the deeper snowpack which reduced the energy losses of the snow surface. The pattern of frozen soil correlated quite well with the depth of the snowpack. Stadler et al. (1996) found at a neighboring plot that frost depth under a tree was up to 45 cm deeper than in the adjacent canopy opening because of the shallower snowpack underneath the tree crown. Once meltwater reaches the frozen soil the heat flux is directed from the wetted snowpack base into the ground. Hence, the heat of fusion of the meltwater at the boundary is lost and the snowpack–soil interface freezes. This causes the formation of basal ice as observed by Marsh and Woo (1984a) in an arctic snowpack. Basal ice layers also results quite often after rain-on-snow events in temperate climates when rainwater percolated through a snowpack on a frozen soil (Albert and Hardy, 1993). An additional prerequisite for basal ice formation is a permeability difference at the snow–soil boundary so that percolating meltwater cannot infiltrate into the soil.
Table 5.3: Stained area (blue and red color) expressed as % of the analyzed transect area. The stained area is interpreted as being a wetted matrix (experiment A: Brilliant Blue, experiment B: Azoloxine). The snowpack at the south-facing plot was isothermal during the entire experiment whereas the snowpack at the north-facing plot became isothermal during the experiment. The profile numbers refer to the profiles shown in Figure 5.5 and 5.6, page 81 and 82.

<table>
<thead>
<tr>
<th>Experiment A (northern plot)</th>
<th>Experiment B (southern plot)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. profile</td>
<td>Wetted area [%]</td>
</tr>
<tr>
<td>7</td>
<td>57.1</td>
</tr>
<tr>
<td>8</td>
<td>52.6</td>
</tr>
<tr>
<td>9</td>
<td>60.8</td>
</tr>
<tr>
<td>10</td>
<td>32.3</td>
</tr>
<tr>
<td>Mean</td>
<td>50.7</td>
</tr>
<tr>
<td>St.dev.</td>
<td>13%</td>
</tr>
</tbody>
</table>

Influence of snow interception on meltwater flow

A canopy affects water flow through the snowpack in multiple ways. Spatially uneven snow accumulation yields a mosaic of uneven snow depths and hence a patchwork of areas with differing energy balance with all the consequences described above. As opposed to an evenly layered snowpack in open areas the snowpack underneath a canopy is irregularly structured. Especially under spruce trees with significant amounts of intercepted snow, some of it is being transformed to wet snow while still remaining on the branch. With subsequent unloading of intercepted snow, snow clumps are dumped from branches and embedded in the snowpack. Dripping meltwater infiltrates into the snowpack which is a mixture of variably sized grains and harsh clumps. In such a structure highly permeable flow paths exist which rapidly drain the infiltrated meltwater. This water is available for infiltration into the soil or for surface runoff.

In forest snowpacks flow channels also develop from organic material falling from the crown. Because needles, twigs, and lichens have a lower albedo than snow the higher heat absorption and emitted long wave radiation creates little melt cones. These depressions are entry ports of preferential flow paths. The next snowfall buries this material in the snowpack causing an uneven boundary between fresh and old snow which again favors the formation of preferential flow paths. Observations in the field showed that most of the flow channels originated in such predefined structures.

Meltwater dripping from the crown into the snowpack is comparable to a rain-on-snow situation although with more localized inputs. Meltwater from
the canopy imports not only water but also latent heat into the snowpack which in turn accelerates grain growth in response to the additional available water. The response of the snowpack to that water input is, as mentioned before, related to the age and structural characteristics of the snowpack (Colbeck, 1978). Water percolates quite fast through a wet snowpack and meltwater outflow occurs soon after input at the surface. In dry, cold snowpacks the peak of outflow is diminished and the lag between input and output is prolonged. In late spring when the snowpack is isothermal dripping meltwater may pass the snowpack and infiltrate into the soil. Depending on the conditions in the upper layer of the soil the meltwater infiltrates or drains laterally. Due to the interdependence between interception, snow depth, and frost penetration the lateral drainage at the soil surface is most pronounced underneath the tree and least in the areas between tree crowns (Stadler et al., 1996).

Dripping meltwater, vertical meltwater flow and refreezing of meltwater in the snowpack prevent formation of weak layers which means that the mechanical stability of the snowpack increases under the crown. Since no lateral meltwater flow exceeding the crown edge could be observed it can assumed that the crown influences only the snowpack beneath including a few centimeters outside. The snowpack between the projected tree crown areas are therefore hardly influenced by the crowns, except for the fact that the spatial extension of undisturbed layers is smaller and fragmented compared with open areas outside the forest stand.

5.4 Conclusions

Based on the visualized flow patterns generated under the influence of meltwater dripping from spruce crowns we draw the following conclusions:

1. The spatial variability of flow patterns of meltwater from tree branches in a snowpack under a spruce stand is high but similarly irregular as observed in an open area snowpack. Hence, preferential flow is a widespread feature of alpine snowpacks.

2. The formation of flow channels is to a large extent predefined by channels originating from falling snow clumps and deposited organic debris. Dripping meltwater creates small funnels at the snowpack surface which are preferential ports of entry for meltwater.

3. Lateral flow at layer boundaries occurred within the crown projection area but none of them outside. This may be a consequence of the isothermal conditions in the snowpack under the crown. At the periphery of the
crown projection the layers – being more or less homogeneous within the
crown covered area – are discontinuous. Hence, lateral meltwater trans-
fer across the highly disturbed snowpack underneath the crown edge is
unlikely.

4. Shallow snowpacks favor the formation of a basal ice layer and hence
surface runoff, whereas at sites with greater snow depths no basal ice
layers were observed.

5. The stabilizing effect of meltwater drip for formation of avalanches is re-
stricted to the projected crown area including a few centimeters outside.

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Chapter 6

Final remarks

This thesis contributes to a better understanding of phase change and transport processes of intercepted snow in subalpine forests. We decided to use a qualitative and semi-quantitative approach. Therefore we put the focus on process observation rather than on quantification. We chose a method which did not disturb the investigated system. The video recordings allowed a continuous observation of loading and unloading processes taking place in a spruce crown. It demonstrated the variability of these processes in space and time. Neither accumulation of snow in the crown nor its relocation to the ground was homogeneous. The accumulation depends mainly on the wind field in the canopy which caused several unloadings during a snowfall event from some branches while other branches remained permanently loaded until the end of the snowfall. The video technique had a sufficient temporal resolution to illustrate these phenomena.

The analysis of single interception events showed that unloading of intercepted snow after a snowfall event is mainly due to an energy input of high radiation and air temperature and that wind played a minor role at these particular sites. Due to frequent events, especially in spring, unloading of branches by dumping snow packets or dripping meltwater became the dominant processes investigated in this study. Qualitative analysis of the video images combined with analysis of the meteorological data indicate that incident short wave radiation leads to a temperature increase of the branches which causes snow melting and finally unloading. This process is highly variable within the crown due to the heterogeneous radiation field a certain branch is exposed to which could be visualized by fish-eye photography. The fish-eye photos provided evidence that detailed studies of energy transport in a snow-covered tree canopy requires a model with a high resolution in the order of 0.5 m. For several days snowfree and snow-covered parts of a tree coexist at
a distance of only a few meters from each other. Their completely different albedo has a great impact on the energy exchange with the atmosphere.

The comparison of the processes at Davos and Alptal showed that processes and characteristics of interception events are different depending on the weather conditions and the winter period. At Alptal we observed a transition from rain to snow at the beginning of an interception event in January and February which did not occur at Davos. Freezing of the intercepted rain drops and subsequent snowfall caused a stronger adhesion of the snow to the needles as it is formed when cold snow falls on cold needles and a cold branch. Rain on snow during the event induces a high input of sensible heat into the intercepted snow which causes rapid melting and unloading. Rain occurring in the beginning of the event did not prolong duration of snow retention.

The important difference between the two sites was the radiation regime. At Alptal global radiation during March and April was lower which prolonged snow cover of the tree crown. This effect is of great importance for climate change studies which make assumptions on the energy balance between forest and atmosphere. Energy exchange processes between forest and atmosphere highly depend on the albedo of the canopy which itself depends on snow cover of the crown. In areas with a larger number of cloudy days intercepted snow will be kept longer in the crown even at larger air temperatures. Based on a statistical model we found that next to the amount of fresh snow during an event the global radiation to be the most important meteorological factor whereas air temperature and wind speed played a minor role in our studies. It is important to note that these results cannot be extrapolated to regions with different climatic conditions without adjustment to the respective local conditions.

Statistical modeling of the event duration with mean values of air temperature, global radiation, wind speed and sum of fresh snow demonstrated that it is possible to obtain a statistical relation between the factors. The model allowed predictions of the event duration, however, only for events shorter than three days. More precise predictions also for longer events need a larger database. More precise predictions of snow retention could probably also be achieved with physical models which take the radiation regime of the canopy into account.

In order to quantify the intercepted snow mass we calculated the intercepted mass on a branch by analyzing the branch deflection. The experiments showed a high variability of the mechanical properties of branch wood which suggests that the method must be calibrated for every tree and probably for every branch. The variation between the calibration experiments also indicate
that the physical properties of branch wood reflects the present physiological reaction of the tree to prevailing load distributions. A quantification of this method requires more experiments under controlled conditions, for example tree weighing experiments on a balance.

Tracing the pathways of the water in the snowpack demonstrated flow patterns of dripping meltwater. In an isothermal spring snowpack the infiltrated meltwater percolates nearly vertically in less separated channels than in a colder snowpack where flow occurs in more distinct preferential channels. It has been clearly shown that percolation took place within the projected crown area and did not exceed the crown edge. It is likely that the formation of little funnels at the surface of the snowpack due to dripping meltwater favors formation of meltwater channels whereas in the adjacent open area snowpack meltwater channels are caused by differences in grain size and density.

The research on snow interception currently proceeds in different ways. One approach is the modeling of sublimation and evaporation loss, the other is the attempt to combine snow models with radiation models in order to understand the interplay between processes in the snowpack and the meteorological factors. A further step would be the integration of snow interception into these models. Especially studies about effects of climate change on the hydrology of subalpine forests must take into account the interaction of the compartments atmosphere, tree, snowpack and soil. This work contributes to these ongoing efforts and should be understood as a basis for hydrological model development for subalpine forests in middle latitudes.
Leer - Vide - Empty
List of Symbols

The following list defines the symbols used in this thesis. The dimensions given in brackets denote the usually used units.

**Latin Symbols**

- \( A \): cross-sectional area of a branch \([m^2]\)
- \( am \): mean air temperature of an interception event \([°C]\)
- \( d \): diameter of a branch segment \([m]\)
- \( d_j \): displacement of a branch \([m]\)
- \( D \): deviation function for tree regression (function "tree" in S-Plus) \([-]\)
- \( E_{mod} \): Young's modulus of a branch \([\text{GPa}]\)
- \( g \): acceleration gravity \([\text{m} \cdot \text{s}^{-2}]\)
- \( G \): function for the regression surface (function "loess" in S-Plus) \([-]\)
- \( i \): index for interception event \([-]\)
- \( I \): moment of inertia for a beam of circular cross section \([m^4]\)
- \( K \): degree of taper of a branch segment \([-]\)
- \( k \): total permeability \([m^2]\)
- \( L \): shoot length \([m]\)
- \( ns \): sum of fresh snow of an interception event \([cm]\)
- \( p \): distributed load on a branch (mass per unit length and acceleration due to gravity) \([\text{kg} \cdot \text{m}^{-1} \cdot \text{g}^{-1}]\)
- \( p_b \): bubbling pressure \([\text{N} \cdot \text{m}^{-2}]\)
- \( p_v \): gravity-flow pressure of meltwater \([\text{N} \cdot \text{m}^{-2}]\)
- \( q \): volume flux of meltwater \([m^{-1}]\)
- \( rm \): mean global radiation of an interception event \([\text{W} \cdot \text{m}^{-2}]\)
- \( wm \): mean wind velocity of an interception event \([\text{m} \cdot \text{s}^{-1}]\)
- \( r_p \): radius at the thin end of a branch segment \([m]\)
- \( r_o \): radius at the thick end of a branch segment \([m]\)
- \( T_a \): ambient air temperature of a branch \([°C]\)
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_b$</td>
<td>temperature of a branch</td>
<td>°C</td>
</tr>
<tr>
<td>$W$</td>
<td>given force on a branch (mass of snow)</td>
<td>N</td>
</tr>
<tr>
<td>$\hat{W}$</td>
<td>fitted force on a branch (mass of snow)</td>
<td>N</td>
</tr>
<tr>
<td>$y_i$</td>
<td>duration of an interception event</td>
<td>d</td>
</tr>
</tbody>
</table>

**Greek Symbols**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>constant 5.4710^6 at 0.0°C</td>
<td>m$^{-1}$s$^{-1}$</td>
</tr>
<tr>
<td>$\delta$</td>
<td>bending of a branch under its own weight</td>
<td>m</td>
</tr>
<tr>
<td>$\delta_j$</td>
<td>random error in local regression model (function &quot;loess&quot; in S-Plus)</td>
<td>[-]</td>
</tr>
<tr>
<td>$\Delta D$</td>
<td>change of deviation between the left and the right split in binary tree regression</td>
<td>[-]</td>
</tr>
<tr>
<td>$\epsilon$</td>
<td>emissivity</td>
<td>[-]</td>
</tr>
<tr>
<td>$\epsilon_b$</td>
<td>linear strain of a branch caused by deflection</td>
<td>[-]</td>
</tr>
<tr>
<td>$\epsilon_N$</td>
<td>linear tension of a branch segment</td>
<td>m</td>
</tr>
<tr>
<td>$\epsilon_S$</td>
<td>traverse contraction of a branch segment</td>
<td>m</td>
</tr>
<tr>
<td>$\eta$</td>
<td>pore size distribution index</td>
<td>[-]</td>
</tr>
<tr>
<td>$\mu$</td>
<td>Poisson’s ratio</td>
<td>[-]</td>
</tr>
<tr>
<td>$\mu_e$</td>
<td>mean value of event duration of a dataset</td>
<td>[-]</td>
</tr>
<tr>
<td>$\mu_i$</td>
<td>mean value of an event duration in a split of the binary tree regression model</td>
<td>d</td>
</tr>
<tr>
<td>$\hat{\mu}$</td>
<td>mean value of all event durations in a split of the binary tree regression model</td>
<td>d</td>
</tr>
<tr>
<td>$\hat{\mu}_L$</td>
<td>mean value of all event durations in the left split of the binary tree regression model</td>
<td>d</td>
</tr>
<tr>
<td>$\hat{\mu}_R$</td>
<td>mean value of all event durations in the right split of the binary tree regression model</td>
<td>d</td>
</tr>
<tr>
<td>$\xi$</td>
<td>dynamic viscosity of water</td>
<td>kg m$^{-1}$s$^{-1}$</td>
</tr>
<tr>
<td>$\sigma^2$</td>
<td>variance of event duration in binary tree regression</td>
<td>d$^2$</td>
</tr>
<tr>
<td>$\sigma_b$</td>
<td>normal tension of a branch</td>
<td>N m$^{-2}$</td>
</tr>
<tr>
<td>$\rho$</td>
<td>wood density of a spruce branch</td>
<td>g cm$^{-3}$</td>
</tr>
<tr>
<td>$\rho_w$</td>
<td>water density</td>
<td>kg m$^{-3}$</td>
</tr>
</tbody>
</table>
List of Figures

1.1 Water and energy fluxes in a tree canopy retaining intercepted snow. ........................................... 11
1.2 Icicles at the under side of the branch caused by melting and refreezing of meltwater ...................... 14

2.1 Reproduction of three video images illustrating a snow-capped spruce crown recorded under different light conditions. .................. 21
2.2 Image sequence of snow unloadings from a spruce crown. .......... 23
2.3 Block diagram of image recording, image digitizing, enhancement, and analysis. ............................... 24
2.4 Displacement of balls suspended at a branch during the snowfall event of February 28, 11:00 to March 1, 1994, 6:15. .................. 26
2.5 Example of a nighttime image with red polystyrene balls .......... 28
2.6 Frequency distribution of grey values of an image under different illumination conditions. ...................... 29

3.1 Location of the experimental sites and the schematic of the experimental setup. ............................... 34
3.2 Daily mean air temperature at Davos for three 20 year periods and for the observation periods in winter 1993/94 and 1994/95. 38
3.3 Daily mean snow depth at Davos for three 20 year periods and for the observation periods in winter 1993/94 and 1994/95 . . . 39
3.4 Daily mean air temperature at Alptal for the period 1985 to 1992 and for the observation periods in winter 1993/94 and 1994/95 .................. 40
3.5 Box plots of air temperature, global radiation, event duration and temporal snow cover of the tree crown in winter 1993/94 at Davos and Alptal. .................. 42
3.6 Box plots of air temperature, global radiation, event duration and temporal snow cover of the tree crown in winter 1994/95 at Davos and Alptal. .................. 43
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.7</td>
<td>Branch movement and meteorological factors during the interception event from April 9, 20:00 to April 14, 1994, 24:00 at Davos.</td>
</tr>
<tr>
<td>3.8</td>
<td>Branch movement and meteorological factors during the interception event from April 9, 5:30 to April 14, 1994, 15:00 at Alptal.</td>
</tr>
<tr>
<td>3.9</td>
<td>Fisheye photographs of a north and a south facing branch of the Davos tree.</td>
</tr>
<tr>
<td>3.10</td>
<td>Binary regression tree fitted to the Davos data set.</td>
</tr>
<tr>
<td>3.11</td>
<td>Observed and predicted event duration at Davos and Alptal.</td>
</tr>
<tr>
<td>3.12</td>
<td>Differences of observed event duration and simulated event duration as result from crosswise prediction using data from Davos and Alptal.</td>
</tr>
<tr>
<td>4.1</td>
<td>Schematic of a branch with suspended balls as used for branch calibration.</td>
</tr>
<tr>
<td>4.2</td>
<td>Relation of branch diameter to distance from trunk for both branches used in the experiment at Davos-Seehornwald.</td>
</tr>
<tr>
<td>4.3</td>
<td>Relation of Young’s modulus to branch temperature for both branches used in the experiment at Davos-Seehornwald.</td>
</tr>
<tr>
<td>4.4</td>
<td>Example of the branch calibration modeled by FLOWERS (Anderheggen et al., 1993).</td>
</tr>
<tr>
<td>4.5</td>
<td>Time series of Young’s modulus during the interception event from April 10 to April 14, 1994.</td>
</tr>
<tr>
<td>4.6</td>
<td>Results of the Finite Element simulation of the force ( W ) on a branch causing a given displacement for a given Young’s modulus.</td>
</tr>
<tr>
<td>4.7</td>
<td>Residuals of the local regression model fitted to the results of the numerical simulation of force on branches for a given displacement and a given Young’s modulus.</td>
</tr>
<tr>
<td>4.8</td>
<td>Branch displacement and mass of intercepted snow from April 10 to April 14, 1994.</td>
</tr>
<tr>
<td>5.1</td>
<td>Snow profile below and outside a spruce crown (after Imbeck (1987)).</td>
</tr>
<tr>
<td>5.2</td>
<td>Schematic of the experimental setup for dye tracer experiments at Davos-Seehornwald in winter 1994/95.</td>
</tr>
<tr>
<td>5.3</td>
<td>Meteorological conditions between the dye tracer applications in experiments A and B.</td>
</tr>
<tr>
<td>5.4</td>
<td>Snow profiles of dye tracer experiments A and B.</td>
</tr>
</tbody>
</table>
5.5 Color slide photographs of snow profiles excavated during the dye tracer experiment A at the northern site. . . . . . . . . . . . 81
5.6 Color slide photographs of snow profiles obtained during the dye tracer experiment B at the southern site. . . . . . . . . . . . 82
Leer - Vide - Empty
**List of Tables**

1.1 Overview about research on snow interception. .......................... 8

2.1 Maximum ball displacements for the snowfall event from February 28, 11:00 to March 1, 1994, 6:15. ................................. 25

3.1 Number of interception events at Davos and Alptal during the two winters. ........................................ 41

3.2 The variables and their resolution used as input for binary tree regression. ........................................ 48

4.1 Wood density $\rho$ [g cm$^{-3}$] of a spruce branch in relation to its distance from the trunk after Bosshard (1974). ............... 59

4.2 Distances $d$ [cm] of the balls from the trunk for both branches at Davos-Seehornwald. ........................................ 61

5.1 Characteristics of experimental fields and trees at Davos- Seehornwald. .................................................. 76

5.2 Date of the tracer experiments in spring 1995 and the applied dye tracer concentration (g l$^{-1}$). ................................. 77

5.3 Stained area expressed as % of the analyzed transect area. ... 86
Leer - Vide - Empty
Bibliography


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