CHALMERS
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Assessing Factorial Snow Model 2.0 Performance in Forest Terrain

With Experimental Sub-Canopy Micro-Meteorological Observations

Bachelor's Thesis in Civil and Environmental Engineering

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Department of Architecture and Civil Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
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Department of Architecture and Civil Engineering,
Division of Geology and Geotechnics.
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Cover: Picture of Co-worker Robin and Benedikt taking snow grid measurements close to the open site field station in Laret, with Weissfluh Mountain as backdrop.

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Abstract

This thesis is assessing the snow model FSM 2.0 in predictions of snow dynamics in forest terrain. Two versions of the model have been used. One with default settings and another with alternative local parameterizations of canopy characteristic for input data. Experimental data acquisition was conducted in sub-alpine forest terrain, during the 2019 snow season, Landwasser Valley of Graubunden Canton in Switzerland. Site locations were selected to cover dense and canopy gap structures. Processing and analyzing of field data was done in parallel to the field work. Observed data proves the significance of implementing local parameters in forest snow modeling. Results from the FSM 2.0 assessment show that using local canopy characteristics for the site characteristics input data, improves model predictions for incoming longwave radiaton for both dense and canopy gap sites. It also clearly improves incoming shortwave radiation for dense sites, and makes a fair prediction for canopy gap sites.

Keywords: Snow Hydrology, Snow model, forest snow, snow dynamics, snow in forest, sub-canopy meteorological data, Snow Energy Balance, canopy characteristics, LiDAR, small scale canopy parameters .

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Robin Meadal, for his loyalty and friendliness, helping the project at large by visiting the stations and collecting data. Robin also taught me how to conduct SWE measurements, which gave further understanding and insight in to why being able to model snow accurately is important and time effective. *Benedict Frederich* for his help in the field, and fiddling with station cameras. My supervisor *Giulia Mazzotti* for her help on debugging MatLab scripts and her invaluable f-2-f teaching and explanations of complex concepts. *Johanna Malle* on showing me the ropes in Latex table creations and her good spirit in the office. *Tobias Jonas* for accepting my stubbornness in finishing the thesis with a tight deadline, and his willingness to let me practice the presentation at a group meeting, which lead to crucial feed back from him, along with the rest of the Snow Hydrology research group. *Kalliopi Koutantou* for her unquestionable cheerfulness, support and the opportunity to be her co-pilot in the field.

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Hanna Martina Yttring, Davos, May 2019

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Constants

c_p	Heat capacity of air	$1005\, J/K/kg$
ρ_{air}	Density of air (assumed constant)	$1.2754\, kg/m^3$
σ	Bolzmann constant	$5.67 \times 10^{-8}\, W/m^2/K^4$

Symbols from Equations

τ_c	Transmission (fraction) of canopy for incoming SWR	-
κ	Canopy radiation extinction coefficient	Default (FSM 2.0): 0.5
θ	Solar Angel	$^\circ$(Degrees)
α_c	Reflection by canopy of incoming SWR	see page Equation 2.4
f_{veg}	Canopy Cover Fraction (FSM 2.0)	1 - e(- LAI)
f_{cs}	Forest canopy	same as LAI input (FSM 2.0)
α_{c0}	Reflection (albedo) of Snow-free canopy	Default (FSM 2.0): 0.2
α_{cs}	Reflection (albedo) of Snow-covered canopy	Default (FSM 2.0): 0.4

Acronyms with the page number of their appearances.

Abbreviations

CC Canopy Closure. 7, 15, 16

FS1 Forest Site 1, (in a canopy gap). 11–13

FS2 Forest Site 2, (dense forest site, under canopy). 11, 12

FSM 2.0 Factorial Snow Model 2.0. 3, 4, 7–11, 14–16, 21

LAI Leaf Area Index. 6–8, 15, 16

LiDAR Airborne Light Detecting and Ranging data. 16

LWR Longwave Radiation. 5, 7, 9, 13, 15

MCH Mean Canopy Height. 7, 15, 16

OS Open Site. 11

SLF SLF - WSL Institut für Schnee- und Lawinenforschung, WSL Institute for Snow and Avalanche Research. 11, 14

SVF Sky View Fraction. 7, 8, 15, 16

SWE Snow Water Equivalent. 2, 15

SWR Shortwave Radiation. 5–9, 13, 15

WSL Swiss Federal Institute for Forest, Snow and Landscape Research WSL. 16

1

Introduction

1.1 Background and Motivation

Earth is often referred to as the Blue Planet as majority of the planet surface is covered by water. However, only around 2.5% of the water on earth is freshwater, and the majority of this is stored deep underground or in glaciers difficult to access [1]. The terrestrial water cycle consists of all phases of water, see Figure 1.1. Climate change increases the global temperature which will intensify the water cycle's movement and magnitude of water transportation in and out of its reservoirs. This impact will differ greatly depending on the location. Generally polar areas and tropics will experience an increase in precipitation whereas subtropics will become drier [2].

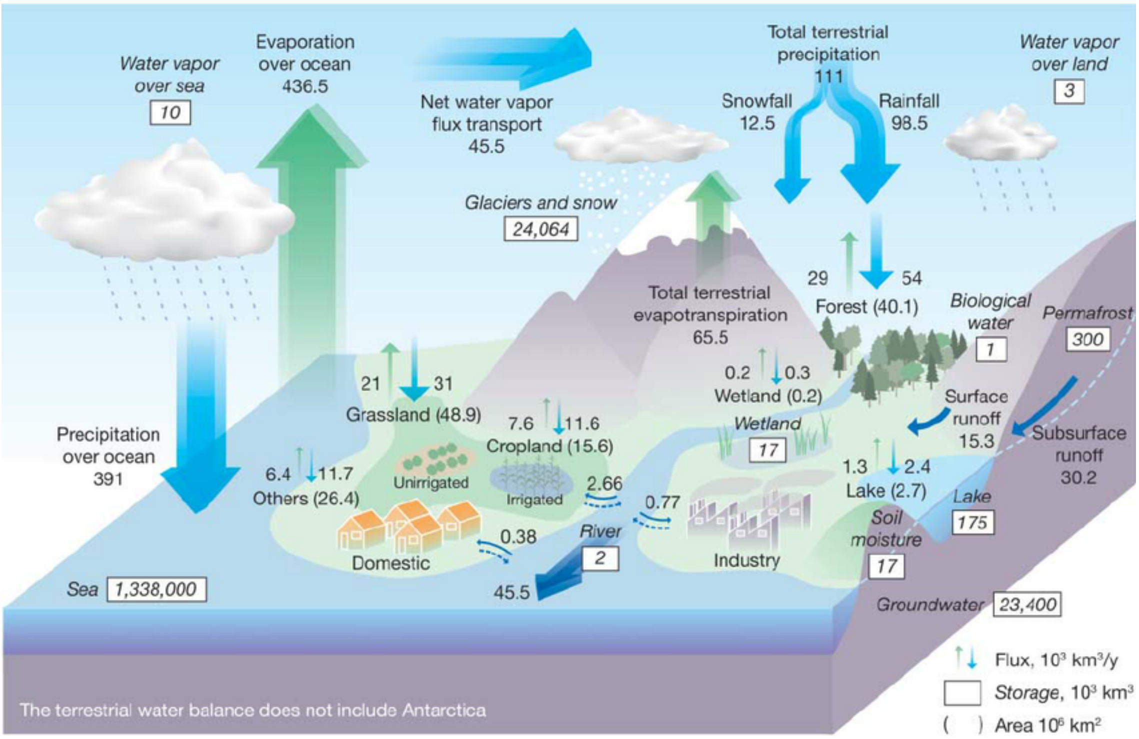


Figure 1.1: Global terrestrial flow of water (excluding Antarctica). We are currently withdrawing more freshwater from renewable freshwater resources than the climate system can replenish. Snow is an important storage for freshwater. The numbers are shown in the 1000s of km^3 per year. [1]

The flow of water should be the main focus in water resources assessments. The climate system puts an upper limit on the circulation rate of available renewable freshwater resources (RFWR). Although current global withdrawals are well below the upper limit, more than two billion people live in highly water-stressed areas because of the uneven distribution of RFWR in time and space. Climate change is expected to accelerate water cycles and thereby increase the available RFWR. This would slow down the increase of people living under water stress; however, changes in seasonal patterns and increasing probability of extreme events may offset this effect. Reducing current vulnerability will be the first step to prepare for such anticipated changes.

Freshwater is vital for all living organisms. Snow is an important part of freshwater in the hydrological cycle of high-altitude and alpine regions [3]. It is therefore important to be able to model snow. Perhaps especially so as the climate change will make precipitation events more unpredictable in these regions. The area that experience seasonal snow in the Northern Hemisphere is vast, see Figure 1.2. The majority of this region is also covered in forest as can be seen in Figure 1.3. Accurate snow models in forest terrain will predict flood risk during the spring season melt, and help hydro-power plants make better decisions. Over time, climate change effects on freshwater storage in snow could be observed. An improvement of snow models in forests will advance predictions of how the hydrological cycle will adapt to following changes in forest cover due to logging, management, wildfires etc.

Snow is a storage reservoir for freshwater. If large snow packs melt quickly, the runoff could exceed ground water replenishment rates resulting in floods. Pomery and Granger published in 1997 that the peak annual runoff in boreal forest is associated with spring snow melt [5]. In Canada, 40 to 60 percent of the annual stream flow in forests is due to the spring snow melt event [6]. With warmer temperatures snow will accumulate later in the fall, and melt earlier in the spring, potentially affecting the timing and potentially the intensity of seasonal runoff. The increase in air temperature will increase the occurrence of intense precipitation events, and increase the soil temperature, affecting the accumulation of snow [7]. Snow accumulation in forest terrain is further complicated by canopy characteristics, which affect the sub-canopy micro meteorological climate.

Snow Water Equivalent (SWE), is a measurement of the amount of water contained within the snowpack. Theoretically it would be the volume of water if the entire snowpack would melt instantaneously. SWE can be calculated by taking snow measurements by collecting snow samples and weighing the snow. This is a time consuming process and is only done in specific locations. With meteorological, and canopy characteristics data, snow models can predict SWE and snow melt for large areas efficiently [9]. Several snow models have been created to calculate the snow dynamics from meteorological data. However, in forests terrain, the canopy cover affects all fluxes that determine the mass and energy exchange between the snowpack and the atmosphere. This makes the snow modelling in forests particularly complex. Meteorological used as driving inputs to snow models are mainly acquired from stationary weather stations located in open sites. Snow data are also usually acquired from open site landscapes. Therefore there is less data available to help model development validate their model performances in forest sites. Current

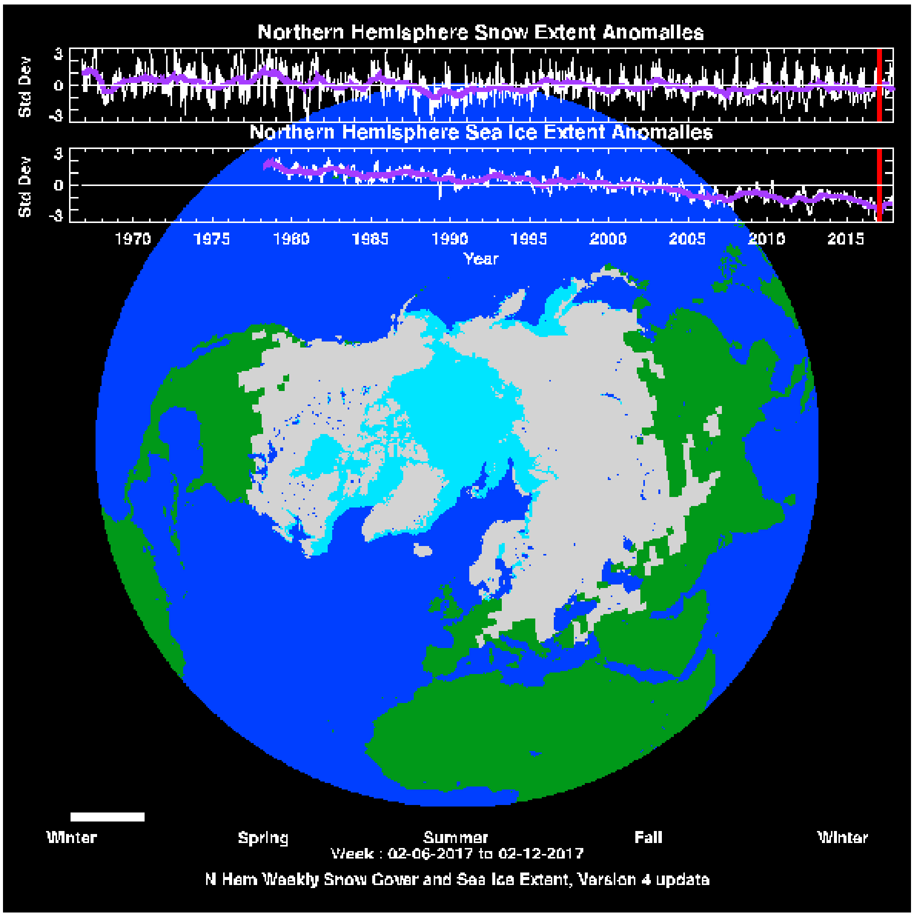


Figure 1.2: Snow covered surfaces in the Northern Hemisphere from February 2017. The picture is acquired from NASA National Snow and Ice Data Center's online tool: EASE-Grid 2.0, which generates the figure from brightness temperature captured on a weekly basis with a grid cell of 25x25km from satellite Nimbus-7 [4].

snow models all have room for improvement for accurately presenting the snow dynamics in forest areas [10]. This thesis will investigate the sub-canopy climate in forest terrain with different canopy characteristics and validate FSM 2.0 modelling performance of snow in sub-alpine forest terrain.

1.2 Research Objectives and Aims

A reason for the under performance in current snow models in forest terrain could be due to unsatisfactory way of representing forest characteristics models. Factorial Snow Model 2.0, created by Richard Essary [11], allows alternative process parameterization (input data) to the model. FSM 2.0 is based on commonly used equations (in the land surface modelling) such as prognostic albedo calculations based on CLASS and ISBA [12], yet its flexible structure makes it an ideal tool to test alternative process parameterizations against each other. This study is performed by collection of meteorological data from four different forest sites (two of which are used in the analysis) with varying canopy structures, comparing the observed data

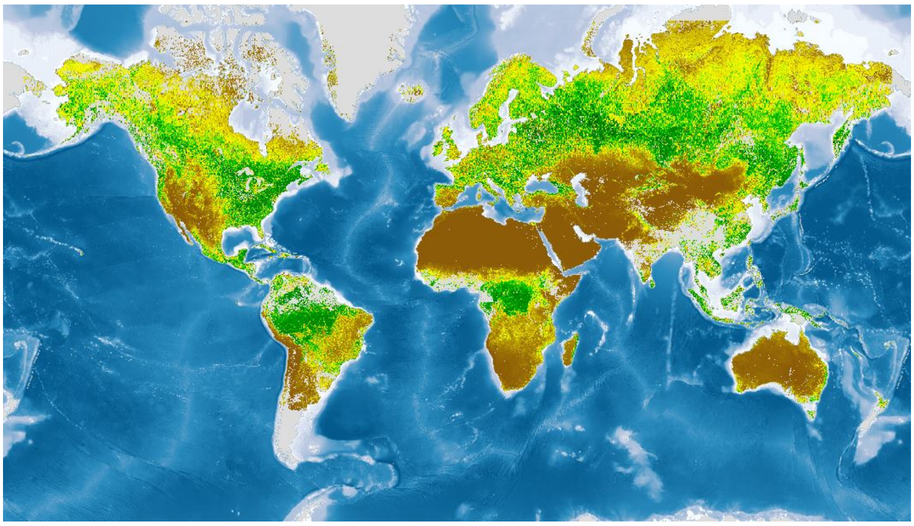


Figure 1.3: Map of global Leaf Area Index (LAI) from July 2018, acquired through *Copernicus Global Land Services, LAI 300m* (2019) [8]

with the output from FSM 2.0. The goal of this thesis is to asses how different strategies of implementing the canopy structure affect FSM 2.0 ability to reproduce the complex, local sub-canopy micro meteorological climate and therefore its impact on the snow cover dynamics.

Research Questions

- How do observed incoming long-and short-wave radiation fluxes to the snow surface, differ between canopy densities and meteorological conditions?
- How well does FSM 2.0 reproduce sub-canopy incoming radiating fluxes for contrasting canopy structures and meteorological conditions?

1.3 Outline of Thesis

After the introduction, a theory chapter will present the physics for local sub-canopy climates in forests. The methods used to acquire real data and data analysis will be explained in detail in the third chapter. Chapter four, results and discussion, presents the most important findings during the assessment of FSM 2.0. Graphs will visualize FSM 2.0 performance, discussion will be incorporated in the chapter. Lastly, the conclusions will be stated concise and clearly before references.

2
Theory

2.1 Snow Processes in Forest Terrain

Snow cover dynamics are determined by its mass balance and its energy balance. Mass balance being the balance of incoming and outgoing masses, comprised of snow precipitation, snow sublimation and snow melt. This thesis will focus on the energy balance, which is comprised of the fluxes determining the energy exchange at the interfaces between snowpack, atmosphere and ground, see Figure 2.1.

Internal energy of the snow pack, per unit area and time (see Equation 2.1), is the sum of the six fluxes and is called the Snow Energy Balance Equation.

$$dU/dt = SWR + LWR + THF + PCH + GHF + PHF \tag{2.1}$$

- SWR - Shortwave Radiation (W/m^2)
- LWR - Longwave Radiation (W/m^2)
- THF - Turbulent Heat Fluxes (Sensible and Latent) (W/m^2)
- GHF - Ground Heat Flux (W/m^2)
- PHF - Precipitation Heat Advection (W/m^2)
- PCH - Phase Change Heat of Snow (W/m^2)

Forests affect the meteorological variables impact on the snowpack, making modelling snow dynamics in forest more complex than in an open landscape.

Tree canopies intercept precipitation and simultaneously create shaded areas on the ground. The shaded areas receive less amount of Shortwave Radiation (SWR) which creates a spatial exposure of SWR. Shaded snow areas may be exposed to higher amount of Longwave Radiation (LWR) than non-shaded areas, if the shading is a result of nearby trees. LWR is constantly emitted by canopies and tree trunks. Canopies also affect the ground snow albedo because of unloading of twigs, pine cones and branches along with other debris, shading parts of the snow surface.

The precipitated snow masses, intercepted by the canopies, will either melt, sublimate to the atmosphere, or unload on the ground. Unloading occurs when the snow mass reaches the branch's maximum load capacity. Unloading of snow masses contributes to spatial variation of the ground snow pack, which can be further enhanced by spatial exposure of SWR, leading to a patchy snow cover in the spring, exposing the ground surface. Patches in snow cover have a strong effect on the sensible heat flux, as bare ground increases the mean air temperature which in turn increases the sensible heat flux, and ultimately speeds up the snow melting process [13]. All these processes are strongly dependent on the canopy structure. Because canopy structure can be very heterogeneous with in a forest stand, all these processes can exhibit strong local variations making forest snow modelling very challenging.

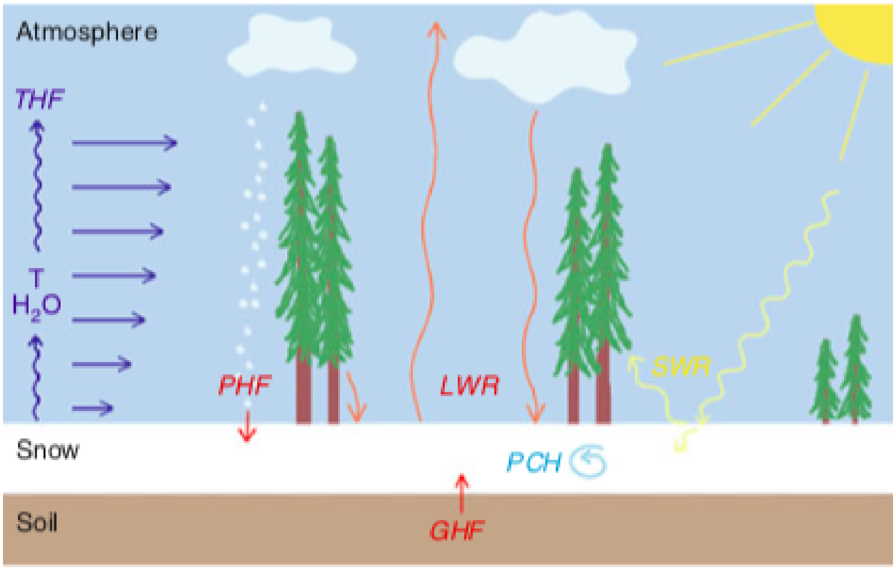


Figure 2.1: The components of the energy balance of snow, seen in Equation 2.1. These processes from these components are strongly affected by the forest canopy characteristics, which makes the energy balance equation complex to solve for forest environments. The figure is acquired from the article *Snow Cover and Snowmelt in Forest Regions (2011)* by R. Essery and T. Jonas [14].

The first three fluxes in the Snow Energy Balance Equation (Eq. 2.1), SWR, LWR and THF, impact the snow dynamics the most, which is why these are the focus of this thesis.

2.2 Canopy Characteristics

Canopy characteristics impact the micro-meteorological climate in forests, thereby influencing snow processes of accumulation and melting. This section will present parameters used to describe the canopy characteristics.

Leaf Area Index (LAI)

Leaf Area Index (LAI) is a commonly used parameter to determine how much SWR penetrates to the ground. The definition is; leaf area per unit of ground surface or for needle-leaf forests; the needle-area per unit of ground surface [15]. Theoretically, an LAI of 1 would mean that $1m^2$ ground would be completely covered of leaves if they were arranged perfectly. However, leaves and or needles in canopies are overlapping each other, resulting in Leaf Area Index over 1 not covering the ground perfectly as in theory. In reality there is always smaller or larger gaps in canopies for SWR to penetrate through. But LAI is still the most conventional approach to explain the canopy leaves/needles covrage. LAI can be established with hemispherical photos, see Figure 3.12, calculated into binary values. Which is the process used in this thesis.

Sky View Fraction (SVF)
Sky View Fraction (SVF) is by definition the visible fraction of the sky seen from a specific point below the canopy. Just like LAI, SVF can be calculated with hemispherical photos, which has been done in this study.

Canopy Closure (CC)
Canopy Closure (CC) is defined as the fraction of ground the canopy masks, when looking from above the canopy down to the ground. CC is based on the canopy height model derived from LiDAR data.

Mean Canopy Height (MCH)
Mean Canopy Height (MCH) is the arithmetic mean of tree heights in a specified area (radius). Canopy height models in this thesis are based on processed LiDAR data from September 2010. More details on LiDAR and the calculations of canopy characteristics will be presented in Chapter 3: Methods.

2.3 Snow Modelling

There are currently many working snow models for the industry to use. However, every single one experience problems modelling snow in forests because of its complex nature [10]. Factorial Snow Model 2.0 (FSM 2.0) is not an exception, but it has a multi-model approach which allows the user to control many aspects of the input data, a feature making this model user friendly and adaptable.

FSM 2.0 is coded in FORTRAN90 and the result is processed, analyzed and assessed against observed data in MatLab. FSM 2.0 input data of site characteristics in terms of canopy structure parameters to calculate the snow energy balance for which it derives outputs such as sub-canopy incoming shortwave radiation, SWE, sub-canopy incoming longwave radiation, sub-canopy air temperature, etc. Equation 2.2 an example where input data of canopy structure, LAI, is used to calculate the transmission of SWR through the canopy. In this thesis SVF and CC is calculated through binarized hemispherical photos and used as input data to FSM 2.0. They are estimated by the model if they are not given as an input. LAI and MCH however, are required input data for the model to run. Driving meteorological data for the model, such as precipitation, wind speed, relative humidity, air pressure, air temperature, incoming LWR and SWR [11] are collected from a permanent weather station located in an open site in Davos. Details of meteorological data acquisition will be presented in detail in Chapter 3: Methods. This section will present the theory of how the model FSM 2.0 process the input data to predict the three most affluent components in the snow energy balance.

Shortwave Radiation
Shortwave Radiation (SWR) can easily be measured with sensors, but it can also be calculated with information of Leaf Area Index. SWR lies within the range of 0.2μm and 0.3μm, but because it has travelled through the atmosphere it will reach the snow directly and in diffused (scattered) form. Because driving meteorological data is acquired from an open site weather station, the incoming SWR (above canopy) contains both the diffused and the direct component. However, in the model calculations of sub-canopy incoming SWR it will treat the incoming SWR (above) as it is diffused, resulting in a sub-canopy SWR with less over estimations than if the two components would be treated separately. The transmission (τ_{cdir}) of direct incoming SWR can be calculated with Beer-Lambert's Law [14] with the input data of LAI and solar angle, see Equation 2.2. The equation used by the model in this thesis is, Eq. 2.4, where the transmission factor of SWR through the canopy is treated constant see Eq. 2.3, independent on current solar angle.

$$\tau_{cdir} = e(-\kappa \cdot LAI/sin\theta) \tag{2.2}$$

- κ = Empirical radiation extinction parameter derived from orientation and clumping of canopy characteristics [14] which is by default 0.5 for FSM 2.0 [12].
- LAI = Leaf Area Index
- θ = Solar Angle

Canopy transmission of diffused incoming SWR is calculated similarly, by removing the division of solar angee. If Sky View Fraction, SVF, is an input data (like it is in this thesis, derived from hemispherical photos) FSM 2.0 will use the SVF value as the constant transmission fraction through the canopy for incoming diffuse SWR [12].

$$\tau_c = SVF \tag{2.3}$$

Factorial Snow Model 2.0 calculates incoming sub-canopy SWR with Equation 2.4 [12], additionally accounting for reflection of the top of snow covered canopy.

$$SWR_{sci} = (1 - \alpha_c)\tau_c \cdot SWR_{atm} \tag{2.4}$$

- SWR_{sci} = Sub-canopy Incoming SWR (W/m^2)
- α_c = Fraction of reflected SWR of the snow covered canopy (albedo)
  $\alpha_c = f_{veg}[(1 - f_{cs})\alpha_{c0} + f_{cs}\alpha_{cs}]$
- τ_c = Transmission fraction through canopy for diffuse SWR
- SWR_{atm} = Above Canopy Incoming SWR (W/m^2)

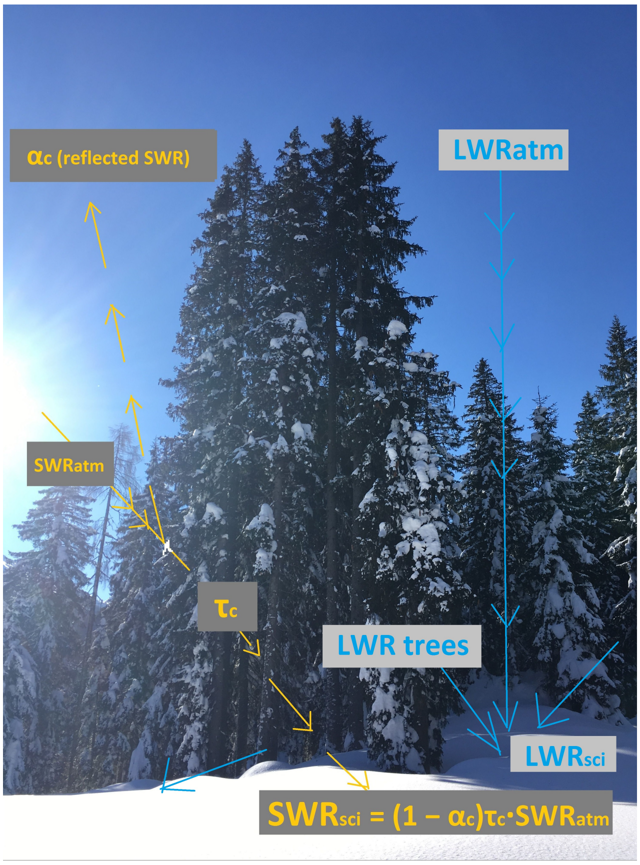


Figure 2.2: An illustration of incoming SWR and LWR to the snow surface in forests. Incoming SWR are partly reflected back to the atmosphere by the snow covered canopy (α_c), and partly transmitted through the canopy (τ_c), before reaching the snow surface on the ground (SWRsci, SWR sub-canopy incoming). Incoming comes from surrounding trees, and the atmosphere. When clouds are present they emit LWR too.

Longwave Radiation

Longwave Radiation (LWR) is emitted by all objects. Incoming LWR affecting the ground snow in forests comes from the atmosphere and surrounding trees. LWR is constantly emitted, while SWR is only emitted during sunlit hours. The LWR from trees are dependent on SWR from the day, as it heats up the tree canopy and trunks.

Longwave Radiation ranges between 4 and 100μm. FSM 2.0 uses atmospheric LWR (LWR_{atm}) as one of the driving meteorological data collected by weather station.

FSM 2.0 uses Stefan Boltzmann law to estimate the LWR_{sci}, which affects the snow processes on the ground. FSM 2.0 needs data of the above canopy Longwave Radiation, (LWR_{atm}), to give an output of $LWR_{sub-canopy}$, see equation 2.5.

$$LWR_{sci} = (SVF)(LWR_{atm}) + (1 - SVF)\sigma\, T^4_{canopy} \tag{2.5}$$

- SVF = Sky View Fraction

- LWR_{atm} = incoming LWR above canopy, usually measured at local weather stations (W/m^2)
- $\sigma = 5.67 \cdot 10^{-8} (W/m^2/K^4)$ Boltzmann constant
- T_{canopy} = Temperature of canopy (°K)

Canopy temperature is an important component of Equation 2.5, which varies vertically in boreal trees [16]. However, the extensive study on canopy temperature by Webster (2017) concludes that air temperature can sufficiently be used as T_{canopy} [16]. FSM 2.0 is aimed to be developed into a full landscape model which is why it estimates T_{canopy} thorugh coupling of the snowpack and the canopy in the energy balance, see Equation 2.1. LWR is a major contributor to the melting processes in forest terrain as it is continuous day and night. Therefore equation 2.5 is of extra interest.

Turbulent Heat Fluxes

Turbulent Heat Fluxes of the energy balance of snow in forests have two components, latent and sensible. The latent component is driven by wind and humidity gradients and has previously been studied at SLF. This thesis will focus on the sensible component which is driven by temperature gradient between snow surface and air.

$$H_{sensible} = \rho_{air} c_p C_H U_a (T_{surface} - T_{air}) \tag{2.6}$$

- ρ_{air} = Density of air (1.2754 kg/m^3)
- c_p = Heat capacity of air ($1005 J/K/kg$)
- C_H = Transfer coefficient
- U_a = Wind speed (m/s)
- $T_{surface}$ = Surface temperature (°K)
- T_{air} = Air temperature (°K)

3
Methods

The methods used in this thesis comprises three main parts; experimental data acquisition in the field, data processing and analyses of the field data, and methods used to acquire needed canopy characteristic and meteorological input data for Factorial Snow Model 2.0 (FSM 2.0).

3.1 Experimental Data Acquisition

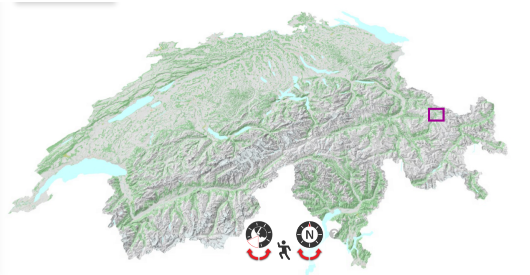
Collection of micro-meteorological data was conducted throughout the 2019 spring snow season in a sub-alpine forest in South Eastern Switzerland, see Figure 3.1. Collection sites varied in canopy structure in attempt to capture the forest's heterogeneity.
The campaign captured sub-canopy micro-meteorological data at each station synchronously with only minor data gaps during inclement weather, when some meteorological sensor could not operate accurately. The sites during the campaign were carefully selected to include a variety of canopy structures;

- OS, Open Site (in an open area, with no nearby trees)
- FS1, Forest Site 1 (straight under a canopy gap in semi-dense forest)
- FS2, Forest Site 2 (in dense forest)

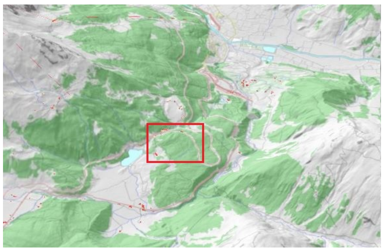
After 8 weeks stations at FS1 and FS2 were moved to new sites (named FS3, FS4 respectively) which had similar canopy characteristics but slightly different (greater canopy gap and a bit less dense location). However, the analyses and processing of acquired data will be limited to the first 8 weeks, which is why only these sites are presented. The forest sites FS1, FS2 and the OS were all located within a radius of approximately 800m of each other in Laret, see Figure 3.2. Laret was chosen because of its accessibility and already established SLF projects, which enables the field data from this project to be used in other projects.

3.1.1 Meteorological Stations

Each meteorological station was built and wired in-house at SLF. The stations were designed to be transportable in rough terrain and easy to set up, see Figure 3.3. The stations were equipped with sensors measuring wind speed and direction, air temperature, long wave and shortwave radiation, as well as snow bulk temperature.



(a) Research project location in Switzerland



(b) Field Site Location in Landwasser Valley, Graubunden Canton.

Figure 3.1: Location of the stations. Maps are retrieved from The Swiss Federal Geographical Information online map tool, Geodata © swisstopo [17]

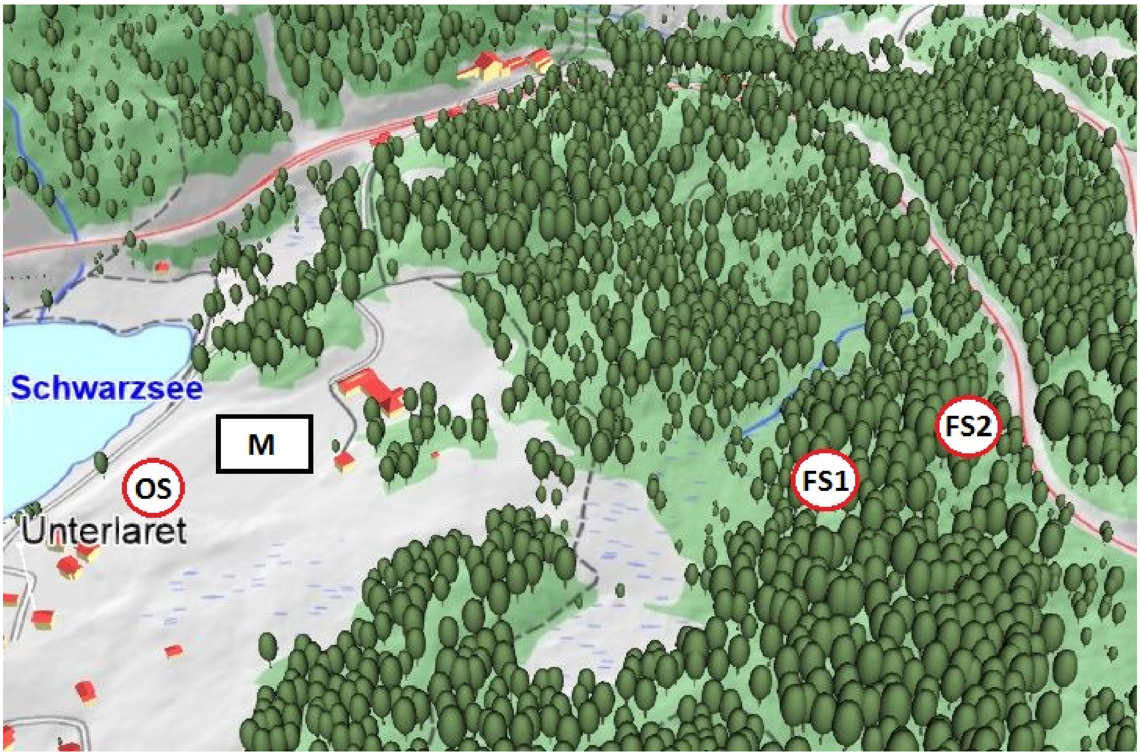


Figure 3.2: The three circles represent the three station sites, Open Site (OS), Forest site 1 FS1 and Forest site 2 FS2. The new permanent meteorological station in Laret is marked with a capital M. This station only started operations in the 2019 season. The map is generated with the online map tool from The Swiss Federal Geographical Information Geodata © swisstopo [17].

(a) During set-up of the open site station

(b) FS1 station in operation

Figure 3.3: Overview of the mini-meteorological stations OS and FS1 at their specific locations in Laret.

In addition, the station at Forest Site 1, (in a canopy gap) was also equipped with an infrared sensor, capturing the snow surface temperature.

All sensors attached to the stations carried a specific task. The wind sensor, *Gill WindSonic ultrasonic anemometer* (Figure 3.4) collected wind speed and direction within the range of 0-60m/s, from 0-360° with an accuracy of +/- 2%. The air temperature sensor, *Vaisala INTERCAP Temperature Probe HMP60*, (Figure 3.5) placed approximately 1.5m above the snow surface recorded the sub-canopy air temperature.

The Shortwave Radiation (SWR) and Longwave Radiation (LWR) sensors, *Kipp and Zonen CMP3 Pyranometer, and CGR3 Pyrgeometer respectively,* (Figures 3.8 and 3.9) capture incoming radiation. It is important for the surfaces of the sensors to be leveled horizontally and cleared from any snow, ice or other debris in order to measure accurate radiation. A camera (Figure 3.6) was therefore attached to the pole, facing the sensors, programmed to take a picture every 60 minutes. The pictures effectively identified time periods when data from the sensors were not accurate and had to be filtered out due to snow/ice formation on top of the sensor's lenses.

Every 3-4 days the stations were visited for battery replacement and downloading of the collected meteorological data. The data logger, Campbell CR1000, was placed in an insulated black box, protected from inclement weather (Figure 3.7). The black box also hosted the battery, sensor lens cleaning cloths and all excessive cable cords. The box itself was covered by a white cloth to reflect incoming radiation and to

Figure 3.4: Wind sensor

Figure 3.5: Air temperature Sensor

Figure 3.6: Camera

Figure 3.7: Box with logger

Figure 3.8: Side-view of SWR and LWR sensors

Figure 3.9: Top view of SWR, LWR sensors

minimize heating. A laptop with sufficient hard drive memory was used to transfer the data from the stations to the office. During visits any eventual snow and ice build-up on sensors were carefully removed with lens cloths.

3.2 Data Processing and Analysis of Field Data

Sub-canopy micro-meteorological data was recorded in parallel at 15 seconds, and at 1 minute intervals by the logger located in the blackbox, see Figure 3.7. This caused the file saved by the logger to become large when doing the download every 3-4days. A field laptop with the required hardware was used to download the logger's file. The file was then loaded up from laptop to SLF hard drives. From here, an analysis of the camera photos was done to identify time periods when the sensors' lenses were covered by snow or ice and therefore feeding the logger with inaccurate data. Identified inaccurate data was then filtered out before the files were compiled in chronological order and processed through a script, written in MatLab, into 1hr aggregations. The time periods filtered out can be seen in Figure 3.10 as gaps in the graphs. The accurate data was chosen to be combined into 1 hour aggregations because it is one of the time outputs of FSM 2.0. Finally, interesting data was extracted from the campaign and used in the assessment of the snow model.

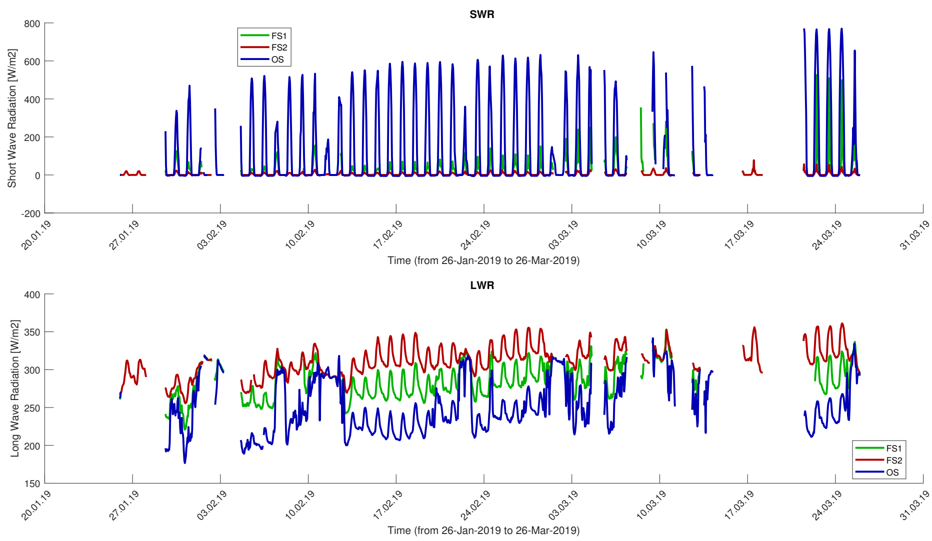


Figure 3.10: Aggregated (1hr) of SWR and LWR during the campaign, from 26.01.2019 to 26.03.2019.

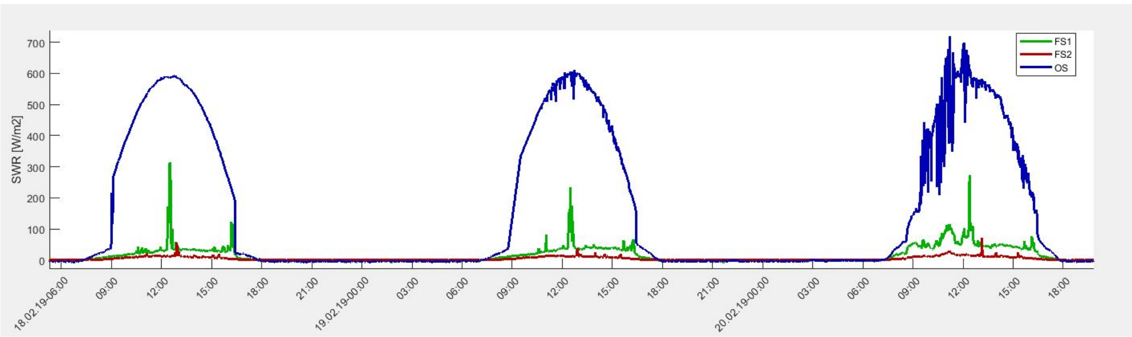


Figure 3.11: Observed non-aggregated data of SWR during a 3 day period, with 2 consecutive days of clear skies followed by a day of overcast.

3.3 Input Data for FSM 2.0

FSM 2.0, needs specific site characteristics and meteorological driving variables (weather) in order to produce output parameters such as SWE. FSM 2.0 also needs site characteristics such as geographical location, CC, MCH, LAI and SVF which was gathered through different methods which will also be covered in below sections.

3.3.1 Forest Characteristics

Leaf Area Index (LAI) was calculated with the help of hemispherical photos taken at the sites. An upward looking fish-eye camera with a 180° field of view was placed on a plate at the exact spot of the LWR and SWR sensor, enabling to capture the canopy effects. On the plate, a compass and a leveling instrument was also mounted to ensure correct level and direction of the photos. Since the camera was manually focused with aperture and ISO, every shooting consisted of three pictures

(a) Hemispherical Photo of FS1

(b) Binarized Hemispherical Photo of FS1

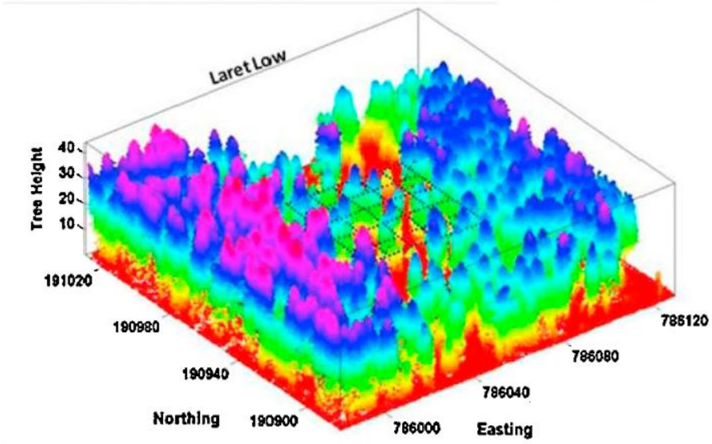
Figure 3.12: Hemispherical Photos

with different exposure settings. This gives a selection to chose the best fitted picture in the processing. Hemisfer, developed by Schleppi P., and Thimonier A., among others at Swiss Federal Institute for Forest, Snow and Landscape Research WSL (WSL), was used to process the hemispherical photos into binary images that ultimately calculates the LAI [18], [19]. Hemisfer is designed to estimate the LAI from the light transmission in hemispherical photos. It calculates LAI based on six different methods from the binarized picture in Figure 3.12(b). The following six LAI calculation methods are used by Hemisfer:

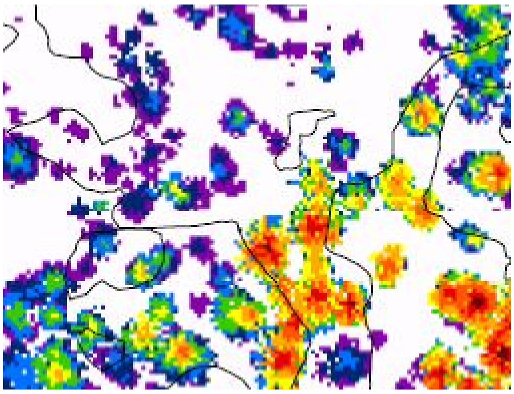
- Miller (1967)
- Miller (1967) as implemented in the Li-Cor LAI-2000
- Lang (1987)
- Norman and Campbell (1989)
- Thimonier et al. (2010)
- Gonsamo et al. (2018)

In this thesis, an average value of all six results was calculated and used as LAI input for FSM 2.0.

Sky View Fraction (SVF) was calculated based on the binarized images from Hemisfer. Canopy Closure (CC) and Mean Canopy Height (MCH) was both derived and calculated from Airborne Light Detecting and Ranging data (LiDAR) point clouds taken from helicopter flights over the sites with a *Reigl LMS Q560 Sensor* in September 2010. The sensor emits a laser signal towards the ground and a reflected part of the signal will come back to the sensor. With this information a terrain model of the site, a digital surface model and canopy height model can be created [20]. The LiDAR data from 2010 is the newest to this date. Growth of trees has not been able to be accounted for. However a validation of existing trees matching the maps was done before the data was used. The validation eliminates usage of trees that do not longer exist at the sites.



(a) A digitalized image made from 276 points of raw LiDAR data in Laret. [20].



(b) 2D map of the area of FS1 created from LiDAR Data. Notice that the forest ground is white, and that tree peaks are orange-red, opposite color-code of figure (a).

Figure 3.13: Digitalization of LiDAR Data

3.3.2 Meteorological Data

FSM 2.0 needs meteorological driving data from the local site in order to run. Hourly meteorological driving data was collected from the SwissMetNet station *DAV2* (automatic meteorological stations run by MeteoSwiss) located nearby Davos. Corrections on the precipitation rate and the air temperature were made to the data from *DAV2* in order to compensate for its slightly higher altitude and south location of the Wolfgang pass. The field sites are located north of the Wolfgang pass at an altitude of 1507m.a.s.l while weather station *DAV2* is located at 1590m.a.s.l. The Wolfgang pass has orographic influence, meaning that air mass is forced to move from a lower altitude (field site) to a higher elevation quickly without losing any thermodynamic heat allowing the air to be cooled down and raise the air humidity rapidly and create clouds, and under right conditions also precipitation. Corrections factors determined through previous similar work conducted in the area to 1.25 (gain) for the field sites in Laret [21].

Following meteorological data was extracted for the time period at hourly resolution and used as input to FSM 2.0:

- Incoming SWR (W/m^2)
- Incoming LWR (W/m^2)
- Snowfall Rate (kg/m^2/s)
- Rainfall Rate (kg/m^2/s)
- Air Temperature (Kelvin)
- Relative Humidity (%)
- Wind Speed (m/s)
- Surface Air Pressure (Pa)

Using meteorological data from Davos stationary weather station provides consistent data, without data gaps, which would be the case the OS station was used to provide the meteorological input data for the model. The Open Site station had frequent data gaps due to snowfall and ice build up on its sensors, this made the Davos weather station more suited to provide driving meteorological data for the entire season. Unfortunately the permanent weather station in Laret, marked M in Figure 3.1, was not able to provide meteorological data for this season.

4

Results and Discussion

4.1 Observed Data

There are significant differences in the observed sub-canopy micro-meteorological data for Forest Site 1 and 2. This confirms that the local forest heterogeneity has a substantial impact on the micro climate, arguing for snow models to take this complexity into account. An example of the significant differences between locations is seen in Figure 4.1 where sub-canopy incoming shortwave radiation is plotted on a day with clear skies. FS1, the gap site is shown in green, which in contrast to the dense site, FS2, in red, receives significantly more SWR. When the solar angle of the sun stands directly above the canopy gap, the sub-canopy incoming SWR is drastically increased, this is seen as the spikes of the green line. Some of these spikes are therefore reaching the Open site stations levels (plotted in blue). The top graph in Figure 4.1 presents discrepancy in LWR between sites. The difference in LWR is only about 40W/m^2 compared to SWR magnitude of roughly 700W/m^2 at the maximum point, about 17 times the magnitude. The accumulated LWR for the two forest sites are significantly different, which is ultimately what effects the snow melting. Tree canopies are heated by the incoming SWR during the day, and emits LWR constantly, also during night time. A day with high levels of incoming SWR results in warmer trees and more LWR emitted during night. Because of the cloud absence during clear sky conditions, the incoming LWR from the atmosphere is minimized, which leaves the trees as the main source of emitted LWR. Hence why the dense site in red receives the highest LWR. Despite the close proximity of the forest sites, as seen in the map of Laret (Fig. 3.2), they are experiencing very different sub-canopy radiation.

During overcast conditions and variable cloud cover, sub-canopy incoming LWR are fairly the same for the two forest sites, see top graph of Figure 4.2. The OS has a large dip in LWR during midday when the clouds temporarily separate exposing the blue sky which has lower radiating temperature than clouds, creating this temporarily dip as seen in top graph in Figure 4.2. Despite the similar sub-canopy incoming LWR during overcast conditions for the forest sites, their site characteristics clearly affects the sub-canopy incoming SWR as seen in bottom graph of Figure 4.2.

The observed sub-canopy meteorological data evidently shows discrepancies between the dense and gap site. These findings confirm the importance of accounting for local canopy characteristics in forest snow models.

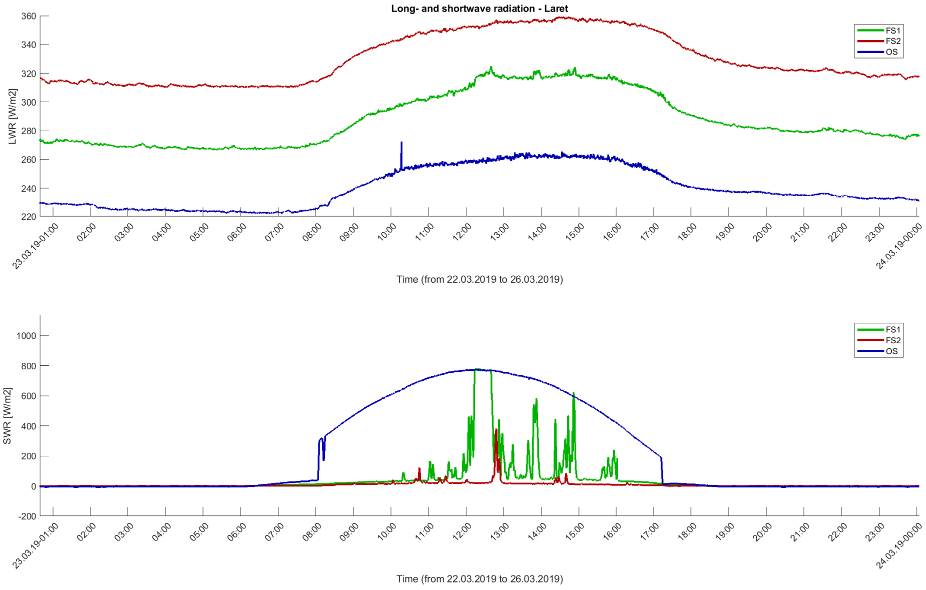


Figure 4.1: Observed data of sub-canopy incoming longwave radiation (top graph) and sub-canopy incoming shortwave radiation (bottom graph), for all three data acquisition sites during a day with **clear sky conditions**, 2019-03-23.

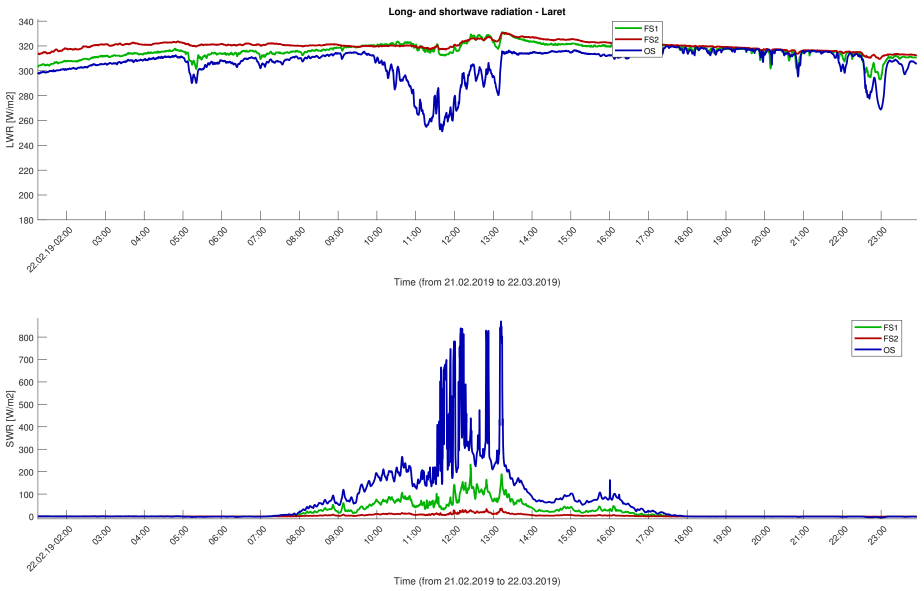


Figure 4.2: Observed data of sub-canopy incoming longwave radiation (top graph) and sub-canopy incoming shortwave radiation (bottom graph), for all three data acquisition sites (OS, FS1, FS2) during a day with **overcast conditions and variable cloud cover**, 2019-02-22.

4.2 FSM 2.0 Performance

Two versions of FSM 2.0 are used in the assessment of its performance. Version 1 (v.1) is the original default version of FSM 2.0 where only canopy characteristics of LAI and MCH are used as input. The other canopy characteristics that FSM 2.0 needs, SVF and CC is derived within FSM from the given LAI. Because LAI is derived from hemispherical photos its value will always be over 0 (only hemispherical photos taken in large open site areas can be completely free of canopy and therefore value of 0). Because LAI is over 0, the radius considered to calculate MCH has to be large enough to include trees. A small radius of 2m from the LiDAR point cloud maps could potentially not see any trees, this does not work in the default mode. A radius of 10m is therefore used in the calculation of MCH for v.1. The default model is based on established equations and parameterization used for large scale modelling by the landscape modelling community to derive these other canopy characteristics. Community Land Model (CLM), the Canadian Land Surface Scheme (CLASS), and the Interaction Soil-Biosphere-Atmosphere (ISBA) are all established land surface models which are used within the snow modelling predictions FSM 2.0 [12].

The other version, v.3, is an attempt to include local scale differences. Nothing is changed in the calculations within FSM 2.0, but an alternative parameterization is done externally for all canopy characteristics. LAI is calculated the same way as in v.1, CC is calculated based on LiDAR cloud point maps of 5m radius, and SVF is also calculated externally, derived from the hemispherical photos. Because of this, MCH is decoupled from LAI which means that a smaller, more local radius of 5m, can be used, which is done in version 3.

Both versions assume all SWR radiation from the atmosphere to be diffuse, which means that FSM 2.0 will take SVF as a constant transmission factor of the canopy, τ_c, independent of the solar angle, see Equation 2.4. But because the driving meteorological data (SWR inlcuded) is taken from an open site weather station, FSM output will have smooth curve following the solar angle, despite using a constant transmission factor.

Performance of FSM 2.0 is presented as an assessment of the entire campaign between 2019-01-26 and 2019-03-26 for v.1 and v.3. FSM outputs have then been extracted for specific days, assessing its performance across weather and forest sites.

The statistical measures used to assess the performance of FSM 2.0 are Root Square Mean Error and Pearsons Correlation Covariance.

$$\text{Root mean squared error, RMSE } = \sqrt{\frac{1}{n}\sum_{t=1}^{n} e_t^2} \tag{4.1}$$

$$\text{Pearson's Correlation Covariance}, cov_{x,y} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{n-1} \tag{4.2}$$

4.2.1 Longwave Radiation

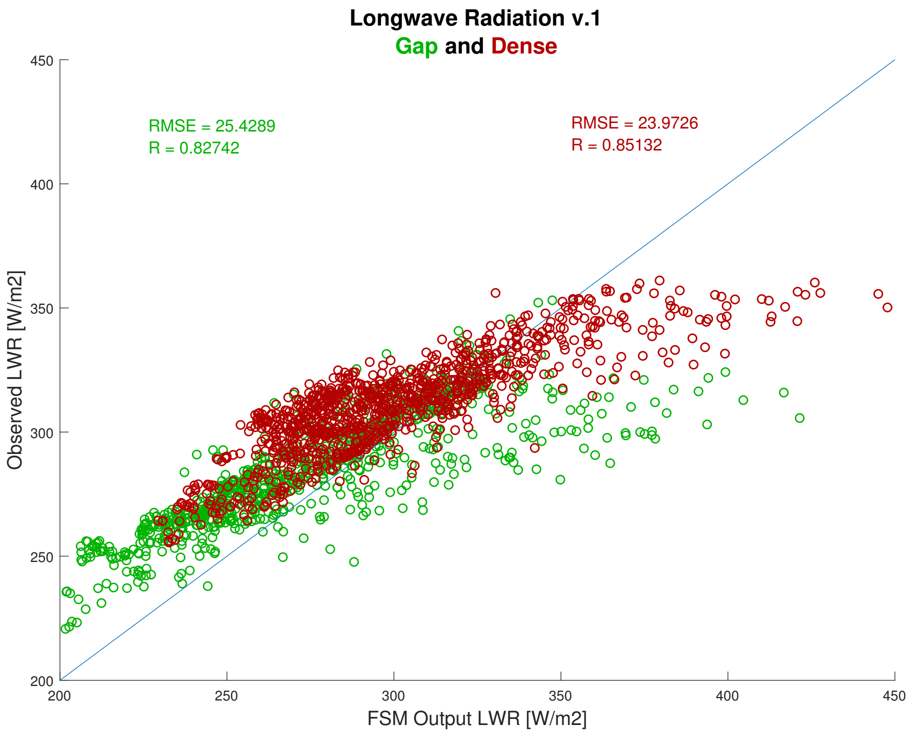
FSM 2.0 results of sub-canopy incoming LWR is fairly consistent with the observed data as shown in Figure 4.3. However, v.3 shows a better prediction than v.1 with RMSE of only 15.3 compared to v.1 RMS error of 23.9 for the dense site. This is probably an effect of more detailed description of the canopy characteristics in v.3.

4.2.2 Shortwave Radiation

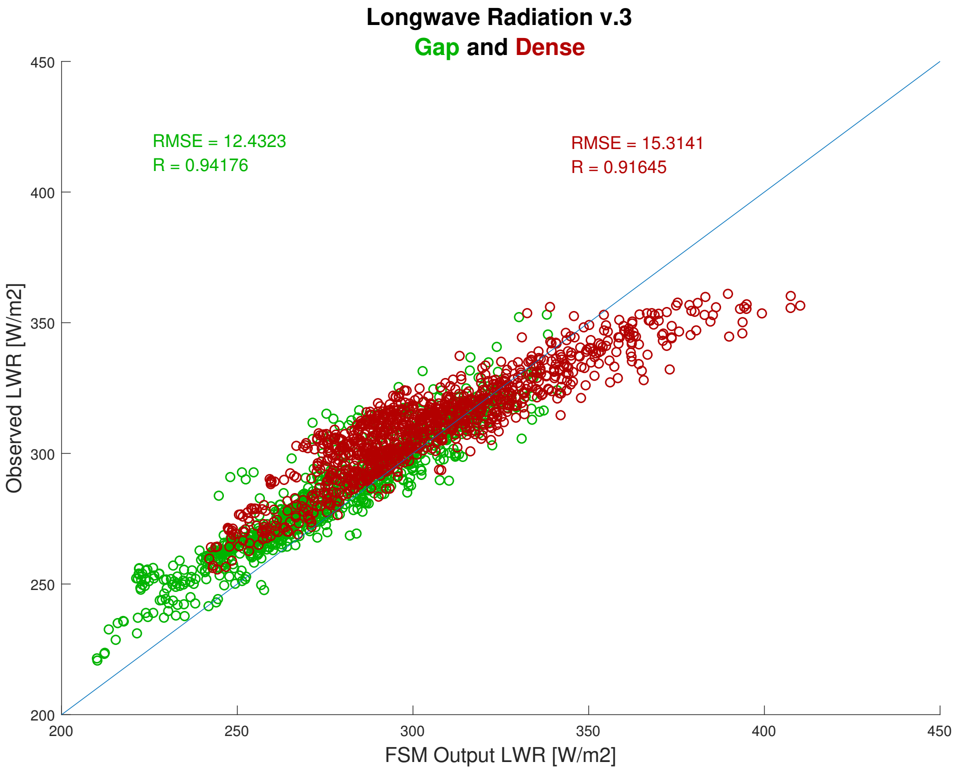
In Figure 4.4, it is clear that both versions have most difficulties to predict sub-canopy incoming SWR for the gap site. Given the spatial variability in the green points on the far right, it seems as both v.1 and v.3 are overestimating sub-canopy incoming SWR. Version 3 is slightly better at predicting in the gap site. However, v.3 performs substantially better in predicting the same meteorological variable for the dense site. The RMSE is only 6.3 compared to the gap site error of 79.1. Again, despite over-estimations at the gap site for both versions, v.3 outperforms v.1.

4.2.3 Air Temperature

Version 3 is also performing better at predicting sub-canopy air temperature, as seen in Figure 4.5. This can be expected knowing its performance for the radiations. LWR, SWR and THF are the three most influencing fluxes in the Snow Energy Equation (Eq. 2.1), and air temperature is a driving variable in the sensible energy equation (Eq. 2.6) of turbulent heat fluxes, which suggest that using the v.3 over the default version will give better predictions of SWE and ultimately snow melt date.

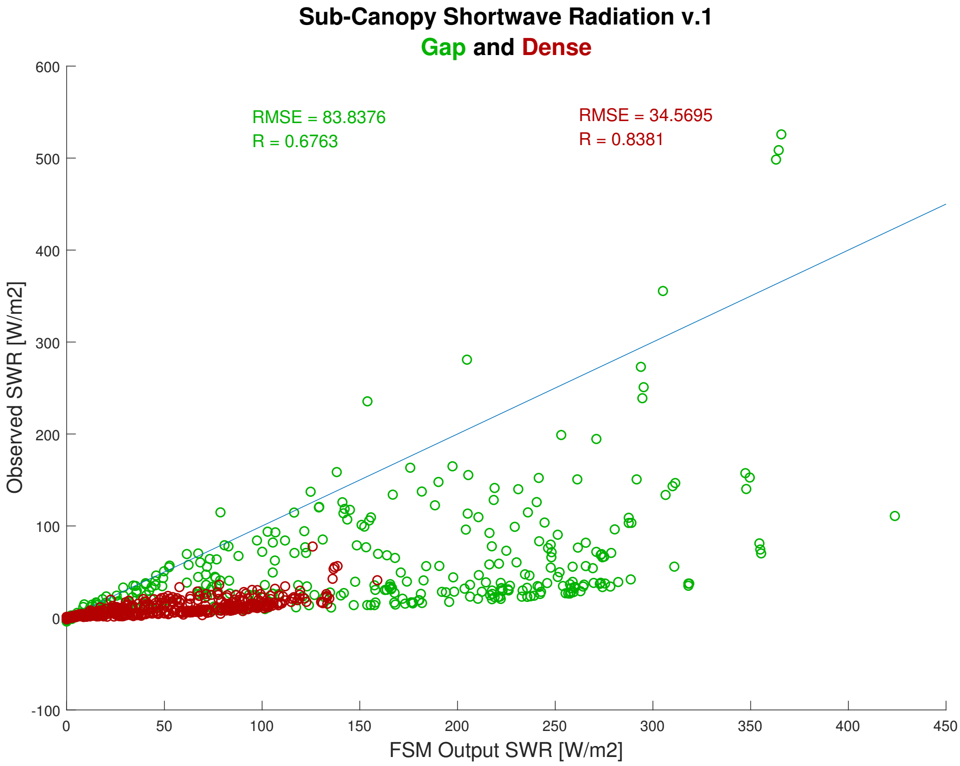


(a) Version 1

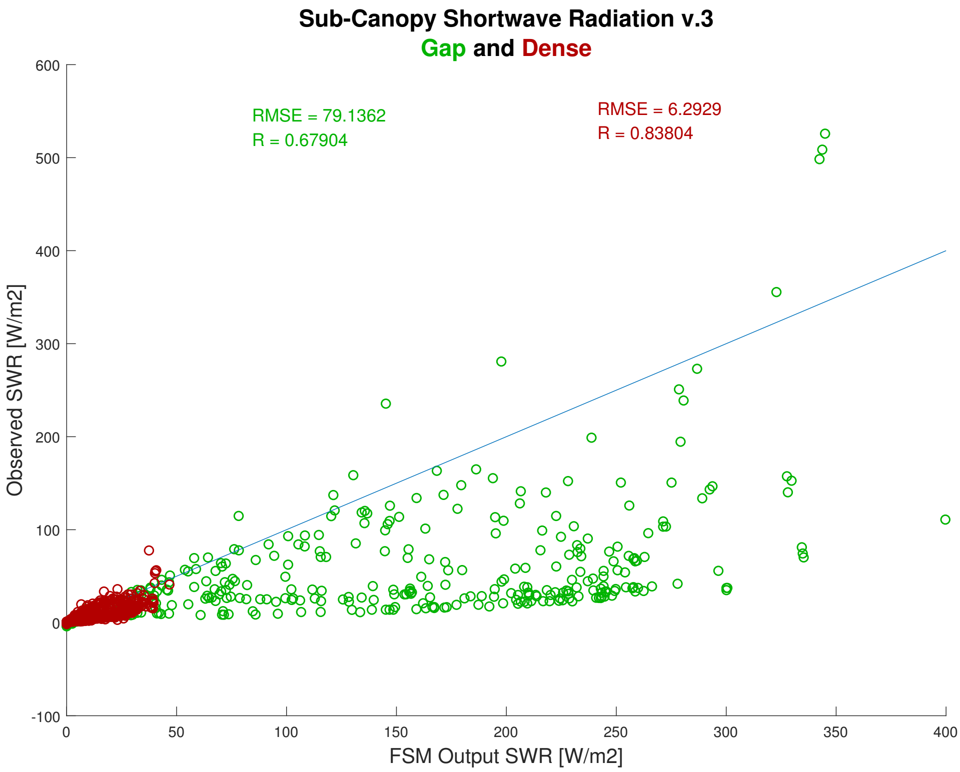


(b) Version 3

Figure 4.3: Version comparison of FSM 2.0 performance of LWR_{sci} for forest site 1 and 2. Each point represents aggregated values of 1 hour.

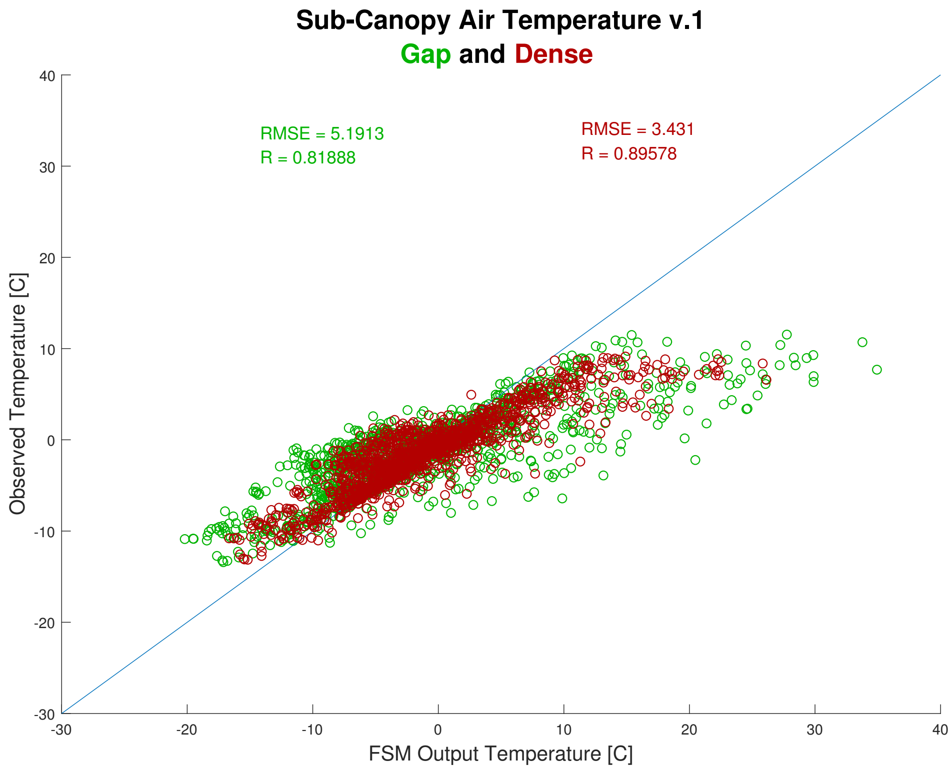


(a) Version 1

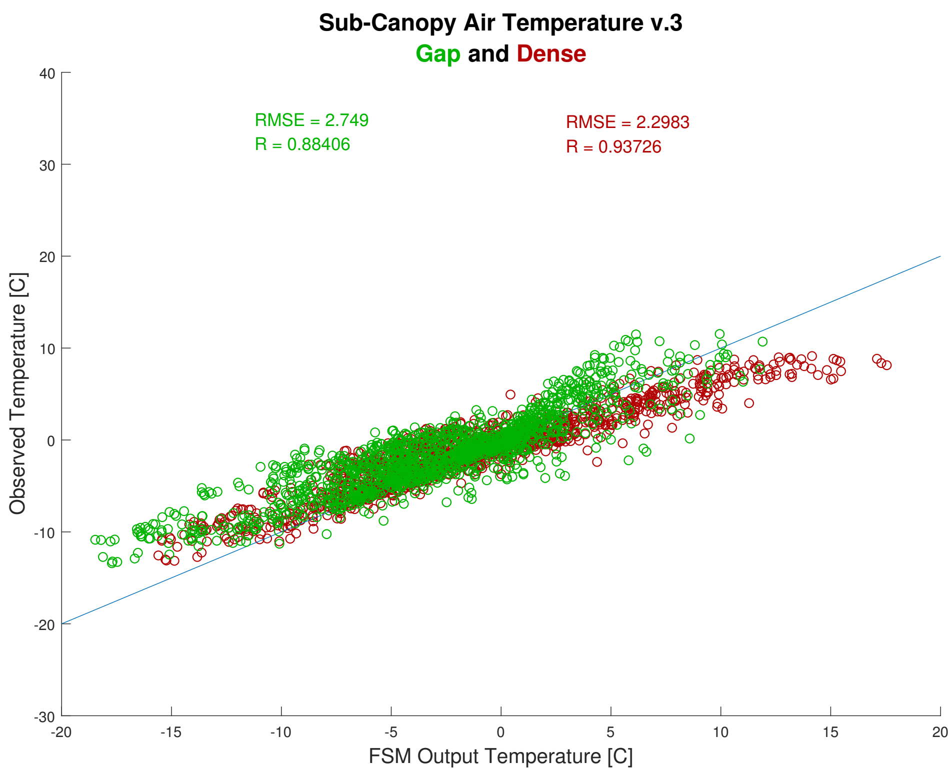


(b) Version 3

Figure 4.4: Version comparison of FSM 2.0 performance of SWR_{sci} for forest site 1 and 2. Each point represents aggregated values of 1 hour.



(a) Version 1



(b) Version 3

Figure 4.5: Version comparison of FSM 2.0 performance of AT_{sci} for forest site 1 and 2. Each point represents aggregated values of 1 hour.

RMSE Performance of FSM 2.0				
Meteo variables	**Version 1**		**Version 3**	
	FS1	FS2	FS1	FS2
LWRsci	25,5	23,9	12,4	15,3
SWRsci	83,5	34,4	79,1	6,3
ATsc	5,3	3,4	2,7	2,3

Table 4.1: Summary of the two FSM 2.0 versions' performances.

4.3 FSM 2.0 Performance Across Weather Conditions

As seen in Table 4.1, v.3 outperforms v.1 in all categories comparing the Root Mean Square Error. The following section will investigate the two versions performances, at the gap and dense site, during specific weather: clear sky and overcast conditions.

Figure 4.6 is an extraction of v.1 and v.3 outputs of sub-canopy incoming LWR for a day with clear sky conditions and a day with overcast conditions. The outputs of FSM 2.0 v.3 are impressive in both weather scenarios, with maximum differences of roughly just 15 and 45W/m^2. An overestimation of sub-canopy incoming LWR means that the model is overestimating the canopy temperature, see Equation 2.5. Since canopy temperature is unknown for the model and calculated by simultaneously solving the energy balance equation at each time interval it could be that the method used in FSM 2.0 (1-layer canopy) might not be accurate enough. This is a possible improvement area, where a several-layer canopy calculation in FSM 2.0 might give a better estimated canopy temperature, or substituting canopy temperature to air temperature like previous research have shown can be sufficient [16].

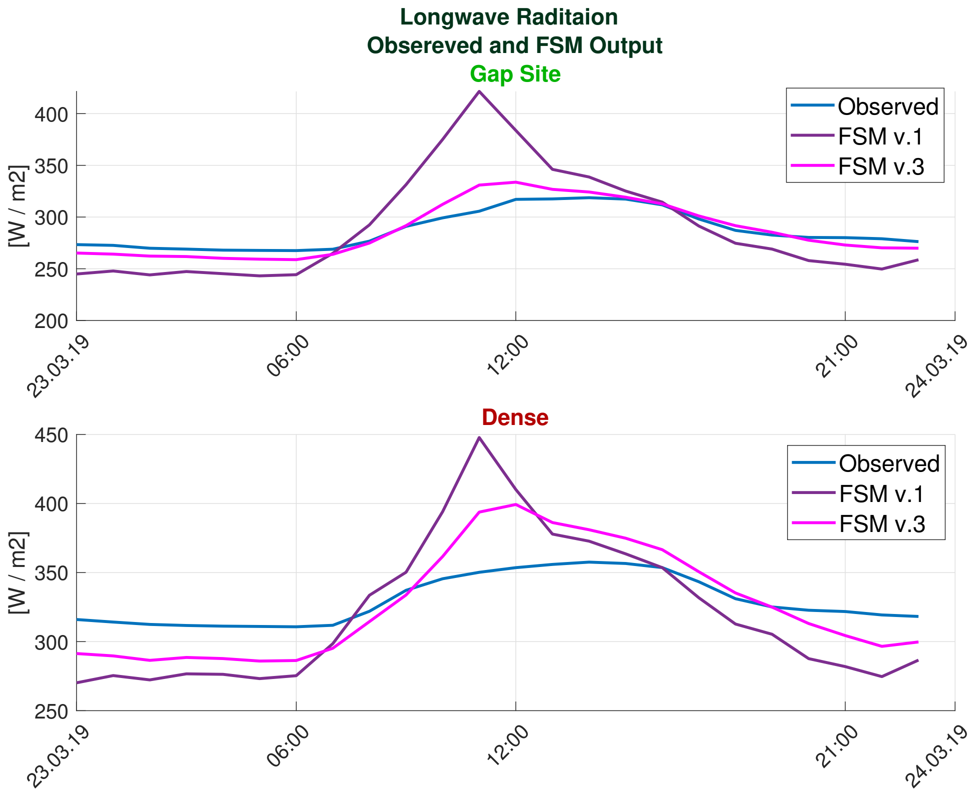
For sub-canopy incoming shortwave radiation v.3 performs noticeably better at the dense site, compared to the the gap site. This is true for both clear sky and overcast conditions see Figure 4.7. The peak is underestimated by both v.1 and v.3 during clear sky conditions for the gap site with approximately 150W/m^2. For the dense site the versions performs vastly different. V.3 predicts the peak within 10W/m^2 while v.1 overestimates it with about 75W/m^2.

The accumulated sub-canopy SWR for an entire day is overestimated by both versions. Basically the area underneath FSM outputs in v.1 (purple) and v.3 (pink) are greater than the area underneath the observed data (blue). This is further visualized for v.3 in a bar chart in Figure 4.8 which also shows the accumulated LWR predictions for v.3.

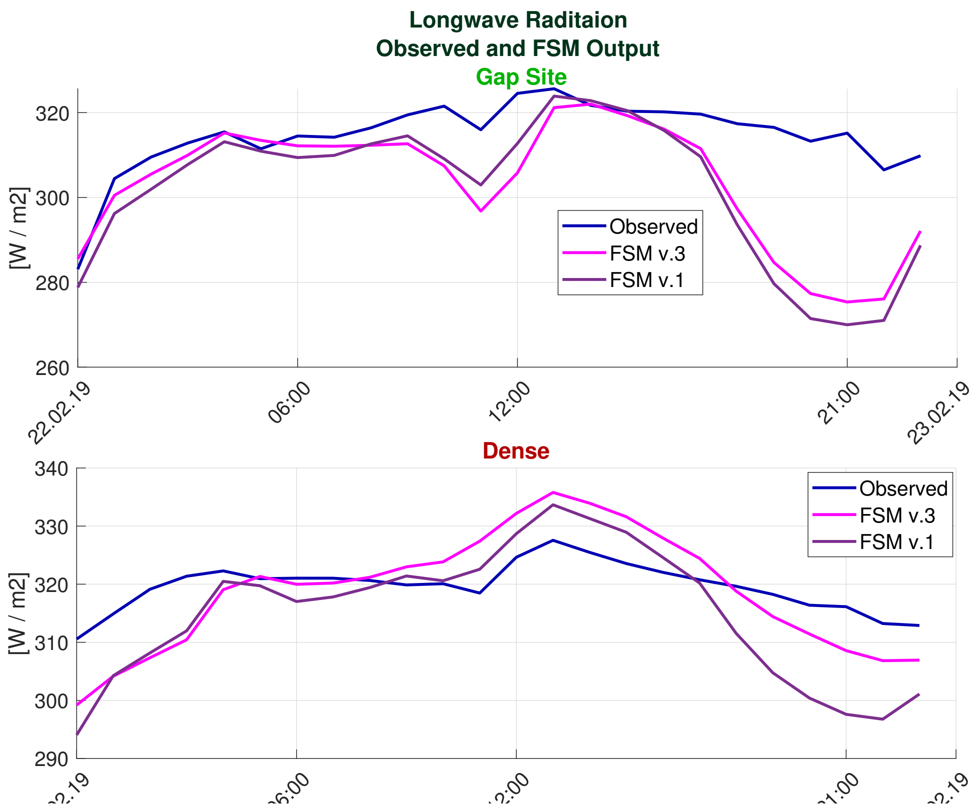
The accumulated overestimation for both versions is due to the assumption of constant τ_c. Potential improvement to the model would be to assign different transmission factors to the hemispherical photos which would be taken into consideration in LAI. Alternatively find a replacement for LAI.

From Figure 4.8 (a) it is evident that the best performing version, v.3, is overestimating the total radiation during clear sky conditions for the gap site. The consequence of this is that FSM 2.0 v.3 overestimates the energy released to the snow cover in the snow energy balance. The excess energy will stimulate phase change of the snow, that is snow melting, which ultimately leads to an underestimation of current SWE and an earlier snow melt date. But v.3 is predicting total radiation in the dense site very well which would assume that the SWE and snow melt date for this site will be quite accurate.

The overestimation made by both versions, of peak temperature in Figure 4.9 (a) during clear sky conditions is a great example of how local parameters for the input data makes an important difference in the predicted output. Version 1 predicts that during clear sky conditions in late March the sub-canopy air temperature will reach 35°C right before noon, while the truth is that the sub-canopy air temperature reaches its peak of 10°C shortly after noon. Version 3 is also predicting the peak to be slightly before noon, however, instead of predicting an outrageous temperature of 35°C it estimates the peak to be approximately 11°C. Version 1 is performing better during overcast conditions, which could stem from the local canopy parameters of CC, MCH and SVF not having such a big affect in cloudy conditions since the incoming SWR will be less. Interestingly, v. 3 underestimates the sub-canopy temperature for the gap site during overcast conditions. This could be the result of the underestimation at midday in incoming LWR as seen in Figure 4.6 (b) for the gap site.

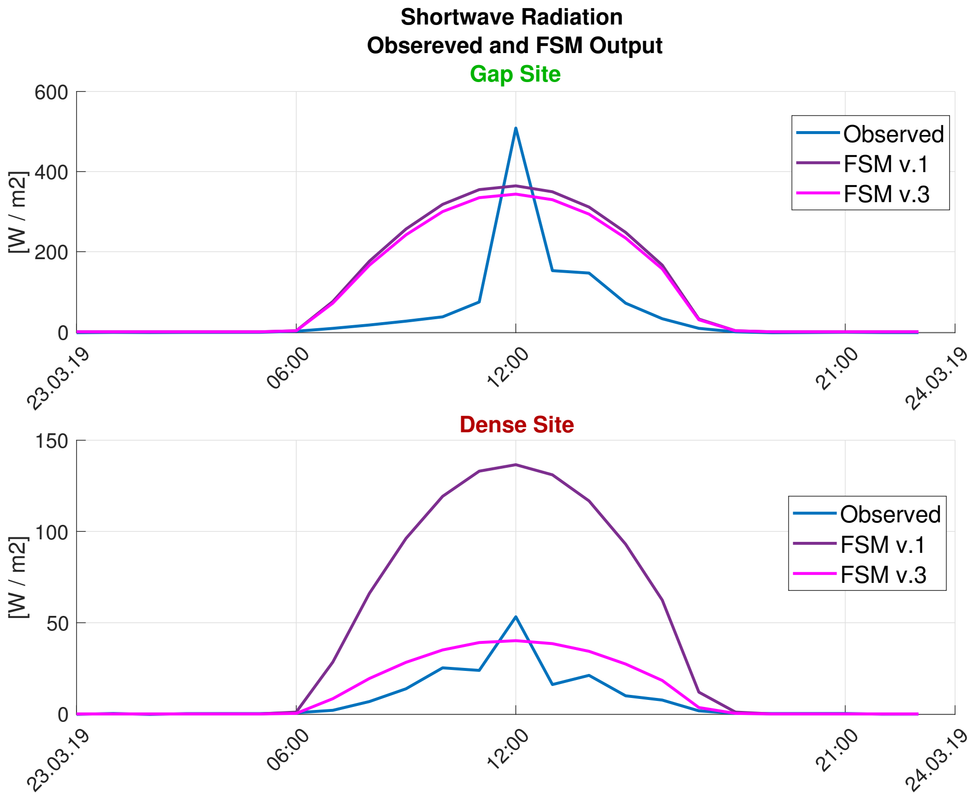


(a) LWRsci for **clear sky conditions** - 20190323

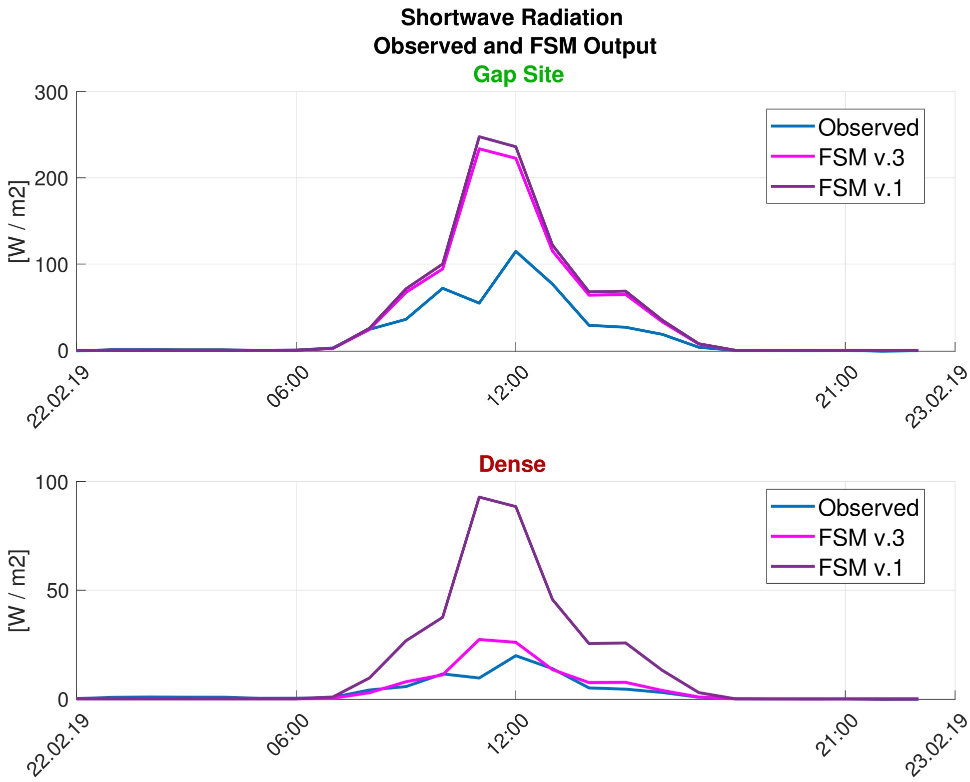


(b) LWRsci for **overcast conditions and variable cloud cover** - 20190222

Figure 4.6: LWRsci for a clear sky day (a) and a day with overcast conditions (b). Comparing observation to FSM 2.0 v.3 output.

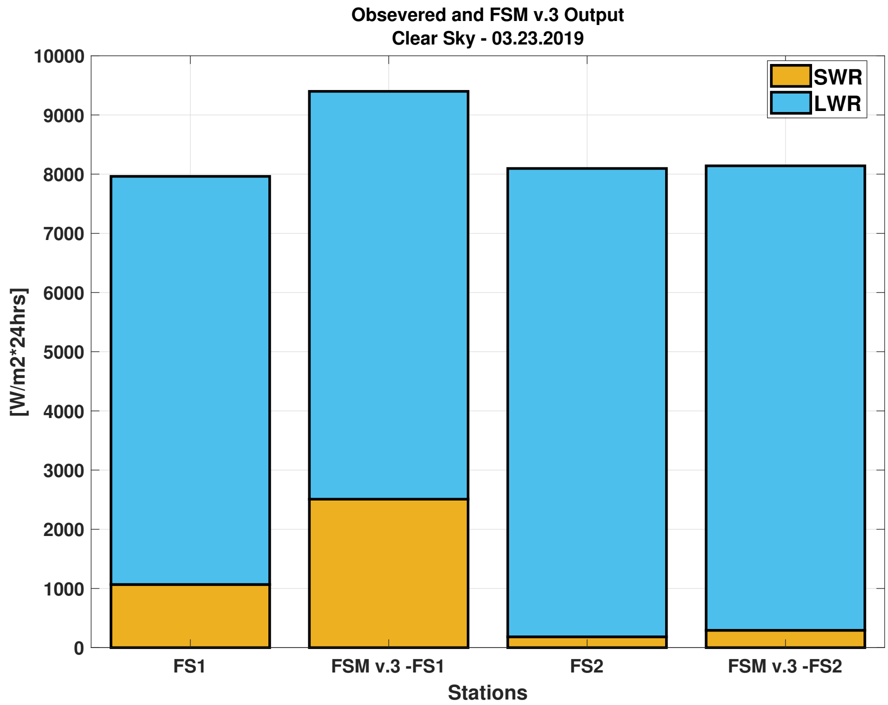


(a) SWRsci for **clear sky conditions** - 20190323

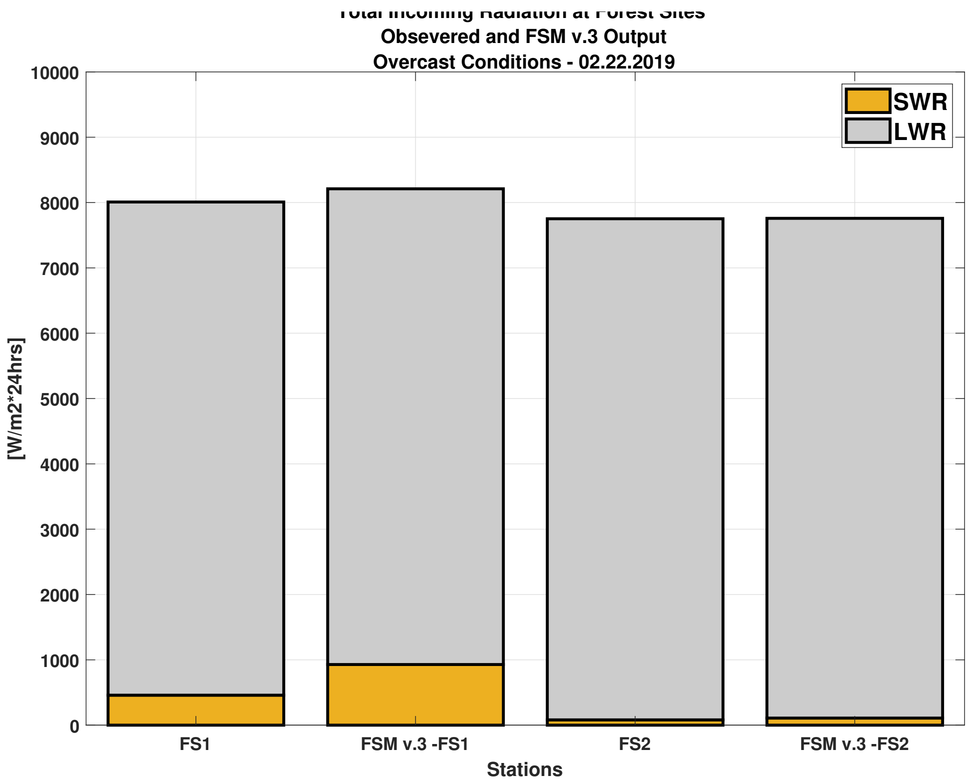


(b) SWRsci for **overcast conditions and variable cloud cover** - 20190222

Figure 4.7: SWRsci for a clear sky day (a) and a day with overcast conditions (b). Comparing observation to FSM 2.0 v.3 output.

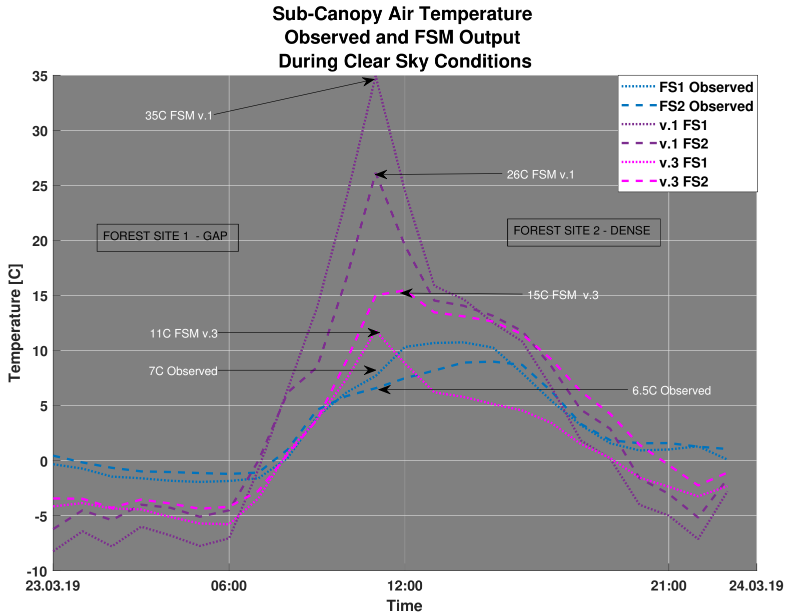


(a) Accumulated (total) sub-canopy radiation for **clear sky conditions** - 20190323. Showing observed and FSM 2.0 v.3 predictions

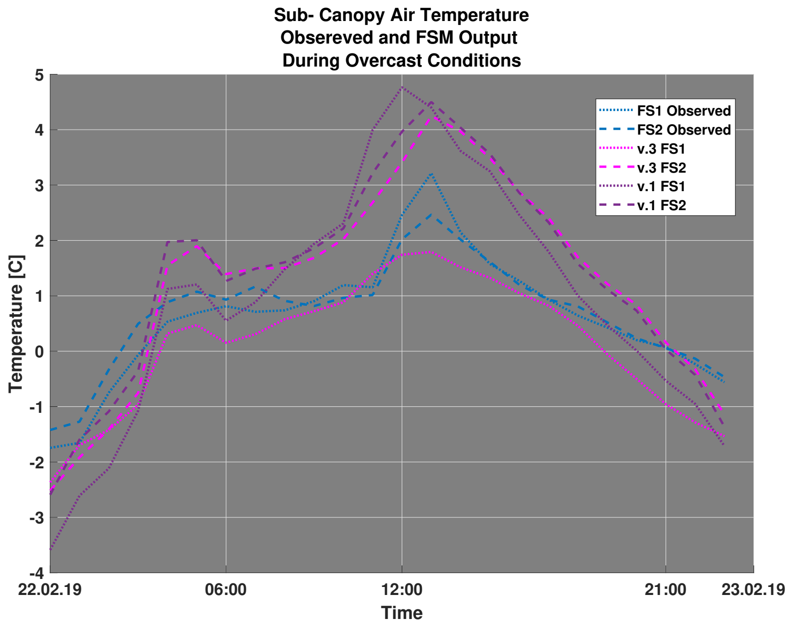


(b) Accumulated (total) sub-canopy radiation for **overcast conditions and variable cloud cover** - 20190222. Showing observed and FSM 2.0 v.3 predictions.

Figure 4.8: Total sub-canopy incoming radiation during 24hrs of clear sky conditions (a) and during overcast conditions (b). Observations and v.3 output.



(a) Observed and version outputs of Sub-canopy air temperature during **clear sky** - 20190323



(b) Sub-canopy air temperature during **overcast conditions and variable cloud cover** - 20190222

Figure 4.9: Sub-canopy air temperature output from both version 1 and 3 plotted with the observed data for the same time. (a) Clear sky conditions (b) Overcast conditions.

5 Conclusion

It is proven that two forest sites in close proximity have crucially different sub-canopy micro-meteorological climates. Implementing local canopy characteristics have a positive effect on micro-meteorological sub-canopy climate predictions for the snow model, as version 3 with these local parameters used in the input data continually outperforms the default version 1. Furthermore, results of version 3 prove that incoming sub-canopy shortwave radiation can be considered diffused in FSM 2.0, and still predict micro-meteorological data fairly well. However, this is the most difficult sub-canopy meteorological variable for FSM 2.0 to predict. Particularly so in forest canopy gap where the direct incoming shortwave radiation has a strong impact. A multi-layer canopy approach in the calculations of temperature canopy within FSM 2.0 could be a solution to predictions of sub-canopy incoming SWR. Another solution could be to improve SVF, which is used as the transmission factor of the canopy affecting the fraction of SWR going through the canopy. SVF is derived from the binarized hemispherical photos which could be taken at a higher resolution. A third solution could be to implement the direct SWR for the most vital periods: during solar noon. However, since diffused SWR is already overestimating the total SWR, adding direct SWR might contribute to better peak predictions but an overall worse prediction. Lastly, if different transmission factors could be attached to the hemispherical photos, dependent on the solar path, the incoming sub-canopy SWR might be improved. This would require implementation of solar path for each specific site for each hour and day throughout the campaign, which would make the model even more complex.

5.1 Further Research

Using several stations in more sites would increase the possibility to assess the model in locations that are in between dense and a canopy gap. Analyzing data from a broad variety of forest canopies could potentially show correlations between canopy characteristics and sub-canopy climate that could be implemented to the canopy characteristics that FSM 2.0 estimates in version 1.

Measuring the snow surface temperature could improve the Turbulent Heat Flux as the gradient between the surface and air temperature is a driving factor of the sensible heat flux. This thesis project was limited to one Infrared sensor measuring the snow surface temperature, at the gap site. The data collected from this was very noisy, suggesting that testing and calibrating such sensor should be done carefully and well in advance to the field work season.

Lastly, two obvious limitations to this thesis is the dated LiDAR cloud points from 2010 and using meteorological input data from Davos weather station. Old LiDAR data will affect the accuracy of canopy characteristics derived from this data. However, all LiDAR data was validated before use, meaning that trees that do not exists anymore, due to logging or natural incidences, is eliminated from the LiDAR data. Despite this, it has not been able to consider the growth of the trees. Using meteorological data from a weather station in Davos, meant that precipitation and air temperature had to be corrected. Weather can be very local, such as cloud variability. If future research were to use meteorological data from a weather station closer to the field sites, like the new permanent meteorological station in Laret, seen in the map as M in Figure 3.1, then FSM 2.0 would have more accurate weather information of the field sites, and therefore likely to improve its outputs.

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