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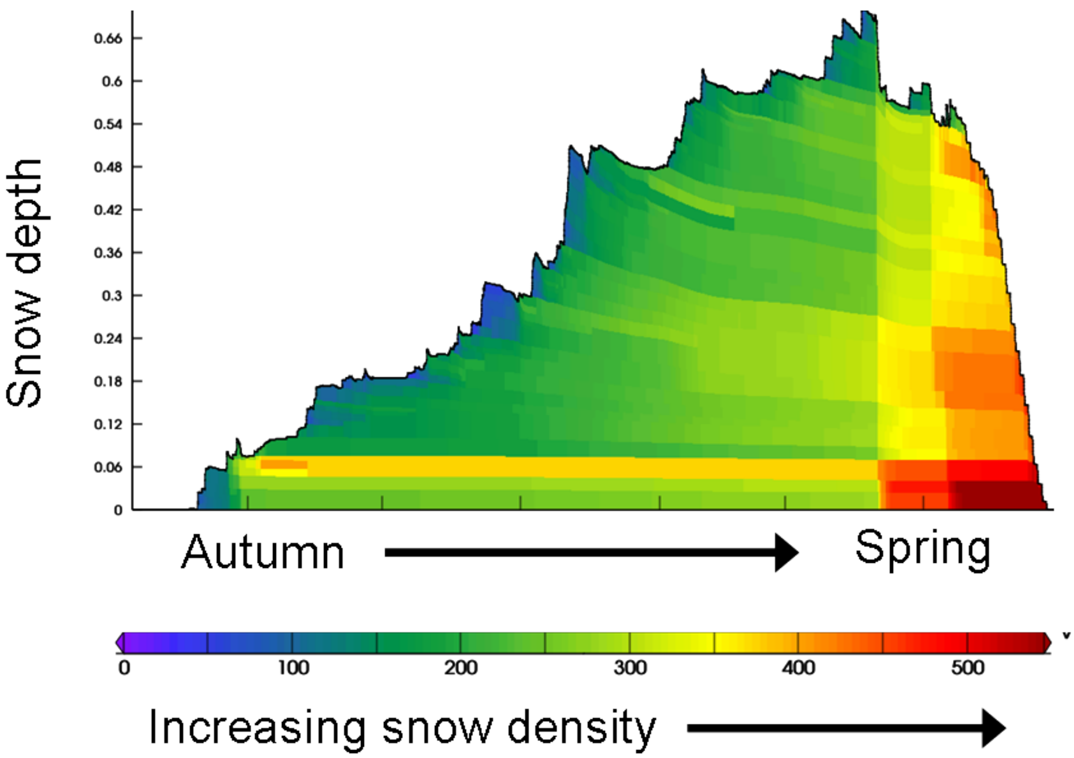
Snow modeling using SURFEX with the CROCUS snow scheme

Dagrun Vikhamar-Schuler, Karsten Müller and Torill Engen-Skaugen



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Abstract

We have used the SURFEX land surface model with the CROCUS snow scheme to model the snowpack stratigraphy at locations of weather stations in Norway. To evaluate the results we used available snow depth and snow profile measurements. Forcing data were compared by evaluating the modeled snow depth. This comparison showed highest sensitivity to the temperature and precipitation datasets. Best estimates of the snow depth are obtained when the model is forced with observations of temperature and precipitation. The experiments also show that observations of the other input parameters may be replaced by NWP data (UM-4 km forecasts) without increasing the errors notably. Particularily, the postprocessed HIRLAM-8 km temperature forecasts produce interesting results, due to the high spatial resolution (0.5 km). Alternative precipitation datasets (postprocessed UM-4 km forecasts and HARMONIE forecasts) did not improve the modeled snow depth notably. These findings make it possible to run the model at locations of weather stations equipped with limited number of sensors, e.g. precipitation stations.
Modeled and measured snow/ground temperatures were compared at the Filefjell-Kyrkjestølane station, showing promising results. A thorough evaluation of the modeled snowpack layers and their physical properties should be a topic for future work, when more snow profiles will be available.

Keywords

Snow avalanche, snow depth, snow model, CROCUS, SURFEX, NWP, observations.

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Chapter 1

Introduction

1.1 The R&D project on snow avalanches

The study presented in this report is carried out within the R&D project "Avalanche danger and senorge.no". The project is coordinated by NVE[1] and has five partners (NVE, met.no[2], NGI[3], NPRA[4] and NNRA[5]). The project is planned for three years (2010-2012). The overall aims of the project are testing and developing methods to establish a regional avalanche forecasting system. The avalanche danger level will be set by international standards based on avalanche, weather and snow data. The R&D project is described in several documents found at this webpage: http://www.nve.no/no/Flom-og-skred/Skred/FoU—skred/FoU-prosjekt-Snoskredfare-og-senorge/. The project is organised in eight subprojects, and the snow simulations presented in this report is one of them.

1.2 Aim and motivation of the snow simulations

The aim of this work is modeling of snow profiles which in turn will support the avalanche experts to determine the danger level for a region. The snow profiles show detailed information about the layer stratigraphy of the snowpack. Each layer is described by physical properties such as density, temperature, grain size, grain type and liquid water content. Snow profiles also show the historical development of a snowpack during a winter season, from the accumulation period to the melting period, which gives additional information about the risk for snow avalanches.

Snow models are used for avalanche forecasting in France and Switzerland, but in different ways. The two most advanced snow models developed for avalanche forecasting are CROCUS and SNOWPACK. CROCUS is developed by MétéoFrance (Brun et al., 1992, 1989). For more information see Section 2. SNOWPACK is developed by WSL Institute for Snow and Avalanche Research (SLF) in Switzerland (Bartelt and Lehning, 2002; Lehning et al., 1999, 2002a,b). In areas with less dense station network (snow and weather observations) there is greater need for models in general. Switzerland has a denser station network than France, while Norway has a quite sparse station network compared to these two countries.

In Switzerland snow models are used if no manual observations are available (Christine Pielmeier, SLF, Switzerland, pers. comm., 2011), otherwise snow observations are extensively used in the operational avalanche warning. Snow models are also applied for estimating fresh snow depth at the stations (Lehning et al., 1999). The models replace precipitation measurements in the high mountains by measureing new snow depth and converting it to SWE (snow water equivalents) by modelling the density and settling. Precipitation is difficult to measure directly under windy and subfreezing conditions. Here snow depth measurements combind with modeled snowpack properties gives more accurate estimates.

[1]Norwegian Water Resources and Energy Directorate
[2]Norwegian Meteorological Institute
[3]Norwegian Geotechnical Institute
[4]Norwegian Public Roads Administration
[5]Norwegian National Rail Administration

In France representative snow profiles for areas with homogeneous climate zones are modeled by CROCUS on a daily basis. Snow profiles for six different expositions and different elevation ranges within each climate zone are simulated and evaluated by the avalanche forecaster. An expert module called MEPRA is used to evaluate the large amount of simulated snow profiles and to compile a report that the forecaster use in the daily avalanche bulletin production.

Evaluation of the snow models, CROCUS and SNOWPACK, as a tool for establishing a new operational avalanche warning system in Norway, is quite interesting. The sparse station network (snow and weather observations) in Norway makes the modeling approach more feasible compared to the Swiss observation-based approach. The results presented in the present report is one step in this validation procedure. The results presented in the present report is one step in this evaluation procedure.

Results of a sensitivity study of the forcing data by running the SURFEX land surface model using the CROCUS snow scheme is presented. A sensitivity study of the forcing data will assess the different weather data sets (observations, weather prognoses), and identify which data sets are most suited for state-of-the art snowpack modeling. The model has been run for selected locations of weather stations in Norway (1D runs). Evaluation of the modeling results is performed using observed snow depth, snow temperature data and available snow profiles.

The report is organized in six chapters, starting with this introduction. The SURFEX model and the CROCUS snow scheme are described in Chapter 2. The applied datasets and a summary of the modeling results are presented in Chapter 3 and Chapter 4, respectively. Discussion and outlook are included in a last chapter before the concluding remarks. Results for all stations are included in three appendices B, C and D.

Chapter 2

The SURFEX model and the CROCUS snow scheme

The CROCUS model was developed by MétéoFrance for snow avalanche warning purposes in the early 1990's (Brun et al., 1992, 1989). It has been run operationally by MeteoFrance for snow avalanche warning and it is part of the SCM chain (SAFRAN-CROCUS-MEPRA), see Figure 2.1. SAFRAN is the meteorological analysis system, which based on various data sets (snow observations, weather observations, numerical weather prediction (NWP) data), interpolates into hourly data of the input parameters needed by CROCUS (Durand et al., 1999). The output parameters from SAFRAN are computed for climatologically homogeneous zones, and not for regular grid cells. For every zone, CROCUS is run to model the evolution of the snowpack. Hence, the result represents the average snowpack of this zone. Furthermore, the output from CROCUS are interpreted by the expert model MEPRA. MEPRA computes two stability indices (natural and accidental) and proposes a risk level for every zone on a 6 level scale.

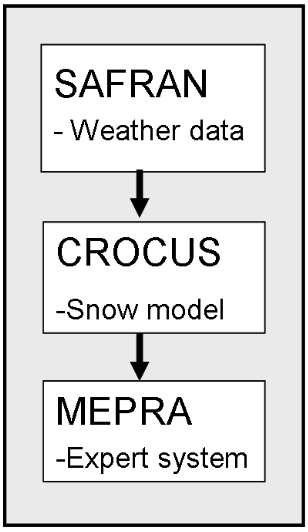


Figure 2.1: The SAFRAN-CROCUS-MEPRA chain.

Recently the CROCUS model was included as a snow scheme within the SURFEX model (v. 5) (Brun et al., 2011; Vionnet et al., 2011). SURFEX (SURFace EXternalisée) is a land surface model, also developed by MétéoFrance (LeMoigne, 2009a,b). The integration of CROCUS into SURFEX, SURFEX itself and postprocessing routines are continuously upgraded and a stable release of SURFEX (v. 7) is planned (Eric Brun and Samuel Morin, MétéoFrance, pers. comm., April 2011). SURFEX can be run stand-alone (offline mode) or in a coupled system with atmospheric models e.g with HARMONIE using AROME physics (inline mode). In addition to CROCUS, two other snow schemes (ISBA-FR and ISBA-ES) are available in SURFEX. ISBA-FR models the snowpack as a single layer, while ISBA-ES models the snowpack with three layers. CROCUS is the most advanced snow scheme, and the snowpack is modeled with up to 50 layers. These three snow schemes were compared in Boone and Etchevers (2001). They found in 2001 that the CROCUS snow scheme is about five times more computer demanding to run compared to the simple one layer ISBA-FR snow scheme.

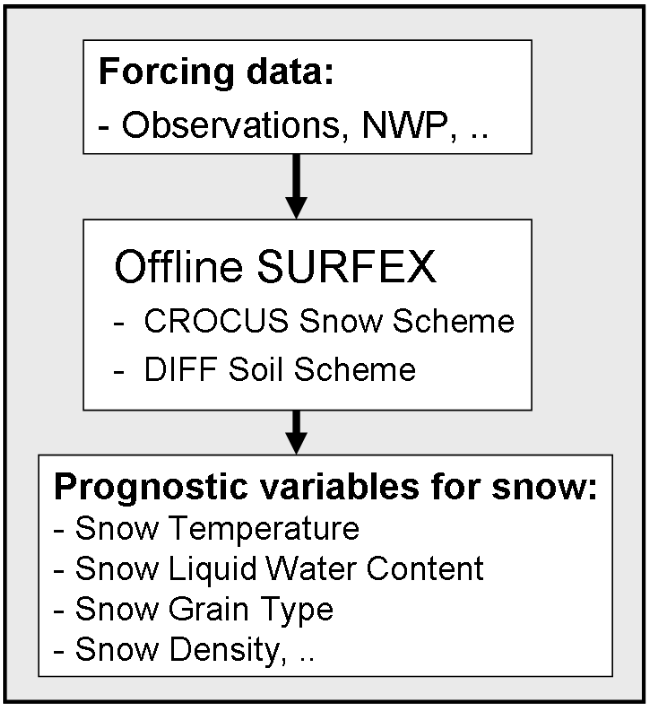


Figure 2.2: Simple visualization of input and output of the SURFEX land surface model. Included are also the snow and soil schemes used in the presented analysis.

In this report we have run SURFEX in offline mode, using the CROCUS snow scheme in combination with the DIFF soil scheme (Figure 2.2). The DIFF soil scheme included in SURFEX is a diffusive approach for modeling soil layers and soil properties. We have run SURFEX for single points (1D runs) at locations of selected weather stations. SURFEX requires a number of forcing data (Table 2.1). Output from our setup of the SURFEX model were NetCDF files with prognostic variables from the CROCUS snow scheme and the DIFF soil scheme. The stratigraphy of the snowpack is modeled using a one-dimensional finite-element grid, and each snow layer is described by the thickness, temperature, dry density, liquid water content and grain types. Each layer represents a snowfall event. An example of model output is shown in Figure 2.3. The NetCDF output file was postprocessed with the Snowtools toolbox (Morin and Willemet, 2010). This toolbox contains a collection of Python scripts for manipulation and plotting CROCUS output. More information is also found in Section 4.3.1.

Variable	Unit	Description	KDVH symbols
ZS	m	Surface orography	
LON	deg	longitude	
LAT	deg	latitude	
TA	K	air temperature	TA
QA	Kg/Kg	air specific humidity	UU*
WIND	m/s	wind speed	FF
DIR SW	W/m2	downward direct shortwave radiation	QE
SCA SW	W/m2	downward diffuse shortwave radiation	
LW	W/m2	downward longwave radiation	QL
PS	Pa	surface pressure	PO
RAIN	Kg/m2/s	rainfall rate	RR1*
SNOW	Kg/m2/s	snowfall rate	RR1*
CO2	NB	CO2 concentration	
DIR	deg	wind direction	DD

Table 2.1: Forcing data required by SURFEX (LeMoigne, 2009a). Symbols from the KDVH met.no climate database for observations are used in the plots in this report. *Specific humidity was computed from observed relative humidity (UU) (Rogers and Yau, 1989). Snowfall and rainfall rate was computed from hourly observed precipitation (RR1) using a threshold temperature of 273.65 K (0.5 °C). For short-term prognoses from UM and HARMONIE we summed convective and large-scale precipitation for each of the precipitation types, rain and snow. More technical details are described in Appendix A.

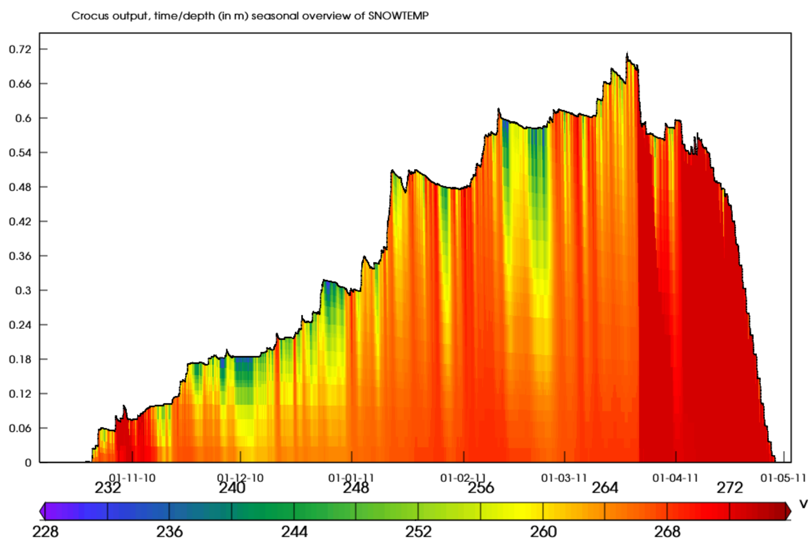


Figure 2.3: Example of model output of snow temperature from the SURFEX model run with the CROCUS snow scheme, and postprocessed with the Snowtools toolbox (Morin and Willemet, 2010). The colour represents the snow temperature (K), where blue represents low temperatures and red represents higher temperatures. This example is from the Grotli met-station during the winter season 2009/2010. Maximum snow depth was approximately 0.70 m before the snow melt began in April.

Chapter 3

Dataset

Different weather data sets are available at met.no. These are observations from weather stations, prognoses from different NWP models and postprocessed prognoses. The best available weather forecasts are broadcasted at http://www.yr.no/, which is the weather forecast portal of met.no. Our sensitivity study aims to identify the best state-of-the-art datasets for snow modeling. Therefore, we have applied a selection of these datasets.

3.1 Observations

Currently met.no operates approximately 630 weather stations located within the Norwegian mainland. Most of the stations are located in the valley bottoms and close to populated areas (Figure 3.1). Approximately 220 of these stations are synoptic stations. Some of these stations are manual stations and some are automatic stations. They vary widely with respect to observational sensors and temporal resolution of the measurements.

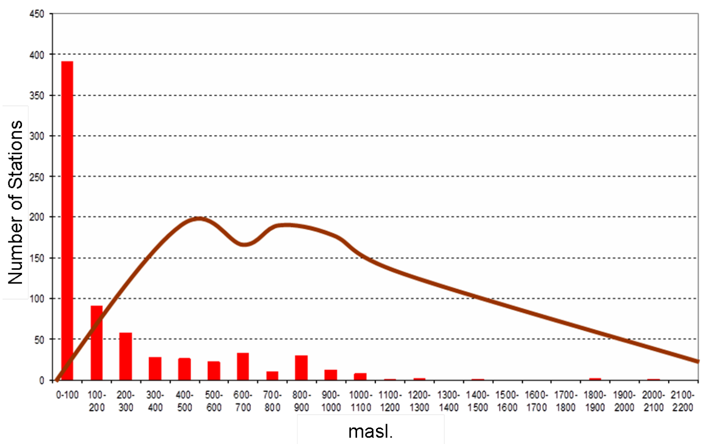
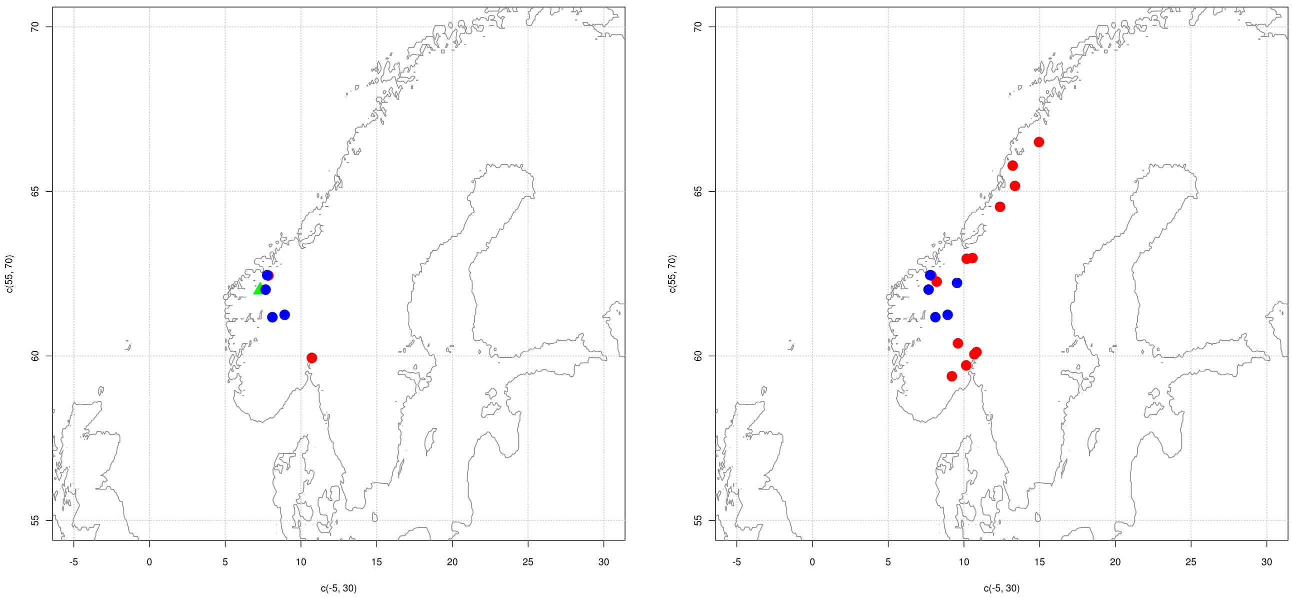


Figure 3.1: Altitude distribution of Norway (derived from 1 km × 1 km digital terrain model) and the distribution of the elevation of the met.no weather stations (Tveito et al., 2008, p. 66). Few stations are located in the mountains, while most of the stations are located below 100 masl.

We first wanted to select all met.no stations instrumented with sensors which with hourly timesteps measure all the input parameters used by SURFEX (see Table 2.1). However, no weather station fulfills these requirements because radiation measurements generally are lacking on all stations. Excluding radiation measurement only six stations meet these criteria (see Figure 3.2a). Therefore, we included weather stations from both NVE and NGI. NGI has a weather station located at Fonnbu avalanche research station. This station meets the criteria required by the SURFEX model, including radiation measurements. NVE has a weather station at Filefjell-Kyrkjestølane which measures all required parameters. Since 2010 met.no also installed a weather station at the same site, and observations from this station was included in this study. The NVE station is a very attractive research station because it also includes snow observations (snow depth, snow water equivalent and intra-snowpack temperature measurements), soil observations (soil temperatures at different heights, soil moisture) and ground water observations.

To obtain a wider dataset, we had to losen the strength of the criteria. In a second step, we therefore selected all stations in the met.no observation network that observe precipitation, temperature and snow depth on hourly basis. This resulted in 19 stations (Figure 3.2b). Metadata for all the stations are included in Table 3.1.



(a) (b)

Figure 3.2: a: Stations used in experiments A-J, b: Stations used in experiment K (Experiments are described in section 4). Blue circles are stations located above 800 masl. Red circles are located below 800 masl. The green triangle symbol is the NGI Fonnbu research station.

3.2 Short-term prognoses

met.no is running several numerical weather prediction models: HIRLAM (HIRLAM, 2009), UM (Davies et al., 2005) and HARMONIE (HARMONIE, 2009). Both HIRLAM and UM run operationally, while HARMONIE is in an experimental research mode. The models are run for different domains, and Figure 3.3 shows the domains of the model runs used in this report.

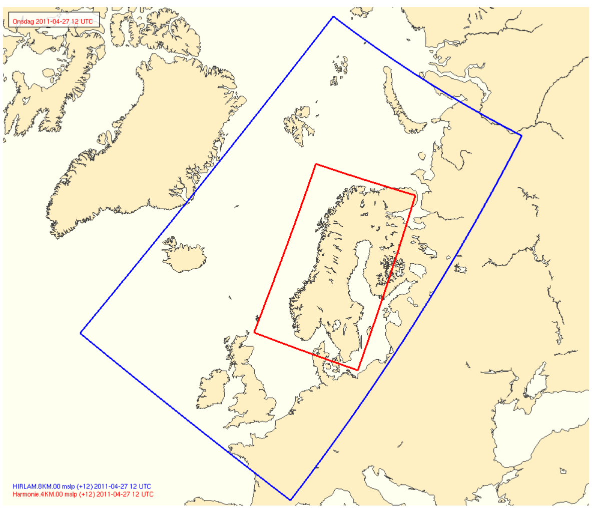


Figure 3.3: Domains of the HIRLAM-8 km (blue), HARMONIE-4 km (red) and UM-4 km (red) model runs used in this report.

Number	Name	Elevation (masl.)	Lat	Lon
4460	HAKADAL JERNBANESTASJON	170	60.1	10.8
15890	GROTLI III*	872	62.0	7.7
18500	BJØRNHOLT	360	60.0	10.6
24710	GULSVIK II	142	60.3	9.6
32060	GVARV - NES	93	59.3	9.2
61410	MANNEN*	1294	62.4	7.7
61420	MARSTEIN*	67	62.4	7.8
61630	BJORLI	579	62.2	8.2
67280	SOKNEDAL	299	62.9	10.1
67560	KOTSØY	127	62.9	10.5
73550	GARTLAND	95	64.5	12.3
77230	MOSJØEN LUFTHAVN	72	65.7	13.2
77425	MAJAVATN V	319	65.1	13.3
79764	HJARTÅSEN	251	66.4	14.9
23550	BEITOSTØLEN II*	965	61.2	8.9
27010	KONNERUD	193	59.7	10.1
54710	FILEFJELL - KYRKJESTØLANE*	956	61.1	8.1
9310	HJERKINN II	1012	62.2	9.5
18700	BLINDERN*	94	59.9	10.7
NA	FONNBU (NGI)*	957	61.9	7.3

Table 3.1: Metadata for the stations: Station number (met.no), name, elevation, latitude and longitude. *Stations used in the experiments A-J (Experiments are described in section 4).

3.2.1 UM-4 km

The Unified Model (UM) from the UK Met Office (http://www.metoffice.gov.uk/) is run operationally at met.no since 2004. For this study we used the short-term prognoses with 4 km spatial resolution. An archive of UM prognoses that satisfy the criteria of the forcing data of SURFEX is readily available at met.no since 2008. Forecasts are produced four times a day (00, 06, 12 and 18), but only the 00 and 12 forecasts are archived. Hourly output is available.

To make a continuous hourly dataset we used the forecast lengths +3, +4, +5, +6, +7, +8, +9, +10, +11, +12, +13, +14 h from the 00 and the 12 forecasts. Of the operational NWP models running at met.no today, the UM model verifies best with respect to precipitation forecasts (Morten Køltzow, met.no, pers. comm. May 2011). The UM model seems to capture well the intensity of the observed heavy rainfall events. Therefore, forecasts from the UM-4 km model is the default model for precipitation and clouds broadcasted at http://www.yr.no/.

3.2.2 Postprocessed UM-4 km precipitation

To better represent the inherent uncertainty, the UM-4 km precipitation forecasts are postprocessed, and also made available at http://www.yr.no. The postprocessing estimates a distribution function in each grid point by employing the surrounding 121 grid points within a 44 km $\times$ 44 km domain (Morten Køltzow, met.no, pers. comm. May 2011). The precipitation forecast in each grid cell is displayed as a range between the 20 percentile and 80 percentile of this distribution function. The median is also archived, and we used the median value in our study as it on average verifies better than the raw UM-4 km precipitation forecasts. This postprocessing is aimed to account for uncertainties related to predictability of convective precipitation on a very local scale (Roberts and Lean, 2008; Wahl, 2010).

3.2.3 HARMONIE-4 km precipitation

The HARMONIE model is run in an experimental research mode at met.no[1]. For this study we used the short-term precipitation prognoses with 4 km spatial resolution from the HARMONIE model run with ALARO physics (Wang et al., 2011). We wanted to test the performance of the precipitation forecasts from HARMONIE with those from the UM model. Verification results show that the UM model often predicts more precipitation than the forecasts from the HARMONIE model (Mariken Homleid, met.no, Norway, pers. comm., 2011). However, verification of precipitation by use of observations is challenging because of the uncertainties related to undercatchment of rain/snow by the rain gauges. In mountainous areas and other windexposed locations precipitation is difficult to measure because an uncertain amount of precipitation falls outside of the gauge (Førland et al., 1996). The problem is larger for snowfall than for rainfall, and it also varies with the rain gauge type. Still up to 50% of the precipitation may fall as snow.

An archive of HARMONIE prognoses that satisfies the criteria of the forcing data of SURFEX is available at met.no since September 2010. The archived forecasts are available four times a day, from 00, 06, 12 and 18, with an hourly output. The data are archived and used in the same way as described for the UM-4 km dataset (section 3.2.1).

3.2.4 Postprocessed Hirlam-8 km temperature

To obtain the best available weather forecasts for the public, the HIRLAM-8 km temperature prognoses are postprocessed. These postprocessed temperature forecasts are broadcasted at the weather forecast portal (http://www.yr.no/). The postprocessing includes improved correction for elevations, point-based correction using observations and Kalman filter techniques (Homleid, 1995) and finally spatial correction using simple kriging (Morten Køltzow, met.no, pers. comm. May 2011). The correction accounts for local topography and temperature inversions not captured in the model, by employing a 0.5 km digital elevation model (orography grid mesh).

Two temperature datasets of 0.5 km spatial resolution are archived: A) elevation-corrected temperature data set and B) elevation-corrected and Kalman-filtered temperature data set. In our study we used data set A.

[1]May 2011: met.no is changing the domains and the resolution of HARMONIE into 2.5 km and 5.5 km.

Chapter 4

Sensitivity study of forcing data

The experiments carried out in this study are described in Section 4.1. Modeling results are evaluated using observed snow depth (Section 4.2), and observations of the physical snow properties of the snowpack (Section 4.3). The data used are described in Section 3.

4.1 Experiments

A sensitivity study of the various forcing data was carried out in order to examine the impact on the snowpack modeling. Questions raised were: Which parameters are most sensitive for the snowpack modeling? Which data provides the best results?

To answer these questions we carried out a first set of experiments A-G (Figure 4.1) based on observations and UM short-term prognoses (Section 3). We expect best snow modeling results to be obtained using observations from a weather station. However, by replacing parameters one by one with UM prognoses, the impact of the single forcing data on the results will be visible. Due to lack of radiation measurements, radiation has not been analysed. The experiments A-G have been carried out for six met.no weather stations (Grotli, Marstein, Filefjell, Blindern, Mannen, Beitostølen) in addition to the NGI-research station Fonnbu close to Stryn (Figure 3.2a). No other met.no stations observe all input parameters required by the SURFEX model on hourly timesteps. **Results from the experiments A-G are summarized in Section 4.2.1 and illustrated with plots from the Grotli station. The resulting plots for all stations are moved to the Appendix B.**

Results from the first set of experiments generally showed that snow depth modeling was most sensible to the precipitation and temperature data sets. Therefore, a second set of experiments H-J was carried out aiming to compare alternative precipitation and temperature data sets available at met.no (Figure 4.2). **Results from the experiments H-J are summarized in Section 4.2.2 and illustrated with plots from the Grotli and Marstein stations. Resulting plots from all the stations are moved to the Appendix C.**

Finally a last experiment K was carried out on 18 weather stations in Norway (Figure 3.2b). All met.no stations that at least observe precipitation and temperature at hourly timesteps, in addition to daily snow depth were selected. Forcing data was created by using all observations at the stations and replacing all missing parameters with UM prognoses. Results from this experiment is presented in Section 4.2.3.

WEATHER station: Observations

○ NWP: UM prognoses

EXPERIMENT	A	B	C	D	E	F	G
Short- and longwave radiation	○	○	○	○	○	○	○
Precipitation		○					○
Air temperature			○				○
Wind dir. + speed				○			○
Surface pressure					○		○
Air humidity						○	○

Figure 4.1: First set of experiments A-G carried out with the forcing data. Example: Experiment A includes observations except radiation which is derived from NWP data (UM prognoses).

WEATHER station: Observations

○ NWP: HARMONIE prognoses

○ NWP: UM prognoses

■ yr.no

EXPERIMENT	H	I	J
Short- and longwave radiation	○	○	○
Precipitation		■	○
Air temperature	■		
Wind dir. + speed			
Surface pressure			
Air humidity			

Figure 4.2: Second set of experiments H-J carried out with the forcing data. Example: Experiment H is equal to experiment C, except that the temperature is the postprocessed HIRLAM-8 km data set.

4.2 Snow depth

Snow depth observations were used to evaluate the modeling results. All the stations in Figure 3.2 observe snow depth daily or hourly. Except from snow depth observations at the weather station and visual snow-covered area observations around the weather station, no other snow observations (e.g. temperature, density, liquid water content, grain types) are carried out routinely by met.no.

4.2.1 Experiments A-G

The sensitivity study was carried out for the seven stations Grotli, Filefjell, Blindern, Mannen, Marstein, Beitostølen and NGI-Fonnbu research station (Figure 3.2a). For the stations Grotli and Fonnbu, the experiments were carried out for the three winter seasons 2008/2009, 2009/2010 and 2010/2011. Some of the weather stations were recently installed or upgraded by met.no: Beitostølen (August 2010), Filefjell-Kyrkjestølane (September 2010), Mannen (March 2010) and Marstein (February 2010). For these stations, the experiments are therefore only carried out for the winter season 2010/2011. The UM data archive, which starts in 2008, limits the number of years to perform experiments.

Results from the Grotli station for the winter season 2009/2010 are shown in Figure 4.3 (same as Figure B.2). This figure illustrates the main results of the experiments A-G. **Resulting plots for all the other stations are included in Appendix B**. The station Mannen was later removed from the study because the precipitation gauge was out of order during most of the winter season 2010/11.

Grotli station: The three winter seasons generally show the same results (Figure B.1 - B.3). When temperature or precipitation observations are replaced with UM forecasts, the snow depth is greatly overestimated. When replacing the other parameters (air humidity, wind speed, wind direction, surface pressure), the change in modeled snow depth is minor. The UM model tends to overestimate the precipitation. In addition the UM model topography is located about 300 m above the true surface topography, which also may lead to overestimated precipitation or wrong phase (snow vs. rain) of the precipitation (Table 4.1). The snow melt season is very well modelled for both seasons: 2008/2009 and 2009/2010.

Beitostølen station: The snow depth for the winter season 2010/2011 is modelled with some overestimation of the snow depth for all the experiments (Figure B.4).

Marstein station: The station is located in a very narrow valley at 67 masl., surrounded by mountains. This local topography is not resolved by the UM-4 km model. Hence the forcasts are valid for the mountains and not the valley bottom. The effect is clearly seen when temperature and precipitation observations are replaced with forecasts from the UM model (lowermost plots in Figure B.5). However, during February 2011 the observed snow depth decreases rapidly, while the modeled snow depth only shows a small decrease. This incident exhibits a sustained offset between modelled and observed snow depth during the melting period. The reason for this discrepancy is not obvious. Observed temperatures were well below zero, indicating no snow melt, and no precipitation was observed. Wind erosion on the snow surface is therefore most likely the cause for the rapid decrease in snow depth.

Blindern station: The snow depth for the winter season 2010/2011 is modelled in good agreement with observed values (see Figure B.6). The snow depth is only overestimated in the experiment where observed precipitation is replaced with prognoses from the UM model. The topography of the UM model is at this location at the same level as the true surface topography (Table 4.1).

Fonnbu station: This station is located in a windy, snowrich mountainous area at the northwestern part of South-Norway. Generally, during 2008/2009 and 2010/2011 the CROCUS model underestimates the snow depth, except when observed precipitation is replaced with precipitation from the UM forcasts (Figure B.7 -Figure B.9). The winter 2009/2010 was a special year with exceptionally little snow in this area. For this year the model overestimates the snow depth. Generally two problems are recognised at this station: a) Snowfall events are often modeled too small. This could be related to too high density of the modeled new snow and also underestimated precipitation observed by the rain gauges[1] b) Settling and removal of snow after a snowfall event is too conservative. Observations show that the wind occasionally removes most of the snow shortly after the snowfall, and this is not captured by the CROCUS model. An example of these problems is seen during the large snowfall event in February 2010/2011. Both the snowfall and the following settling of the snowpack including the erosion are not modelled correctly.

Filefjell-Kyrkjestølane station: Snow depth is modeled quite well for this station until the beginning of March (Figure B.10). After this period the snow is underestimated, leading to too early snow melt. This happens for the experiments A-D, where observed radiation, surface pressure, air humidity and wind are replaced with UM data. When observed precipitation is replaced with UM data, the period from the beginning of March, including the entire snow melt period, is very well modeled. Contrary, during the accumulation season the snow depth is slightly overestimated, due to large amounts in the precipitation forecasts. The results for the Filefjell station is therefore different from the results for the Fonnbu station. It is possibly related to different weather and snow conditions at the eastern and the western parts of the mountains in South Norway.

Experiment G: A clear overestimation of the snow depth is recognised when using solely UM forecasts as forcing data (Figure B.11). Only the snow accumulation period is included in the plots.

	Orography (masl.)				
Station	**True elev.**	**Raw UM**	**Postprocessed HIRLAM temp.**	**Postprocessed UM prec.**	**HARMONIE**
Grotli	872	1149	876	1219	1116
Beitostølen	965	912	952	961	932
Marstein	67	952	244	983	880
Blindern	94	95	97	148	121
Filefjell	956	1170	961	1279	1183
Fonnbu	957				

Table 4.1: Orography information for the stations: Station name and true surface elevation (masl.) for the weather stations. Furthermor, model elevation from 1) the raw UM-4 km forecasts, 2) the postprocessed HIRLAM-8 km temperature forecasts, 3) the postprocessed UM-4 km precipitation forecasts and 4) the HARMONIE-4 km forecasts.

Summary exp. A-G: Snow depth modeling is most sensitive to precipitation and temperature[a]. An evaluation of alternative temperature and precipitation datasets available at met.no were therefore carried out. This evaluation is presented in the next section.

[a]Due to lack of radiation measurements, radiation has not been analysed.

[1]No correction is made for undercatchment of the precipitation gauges.

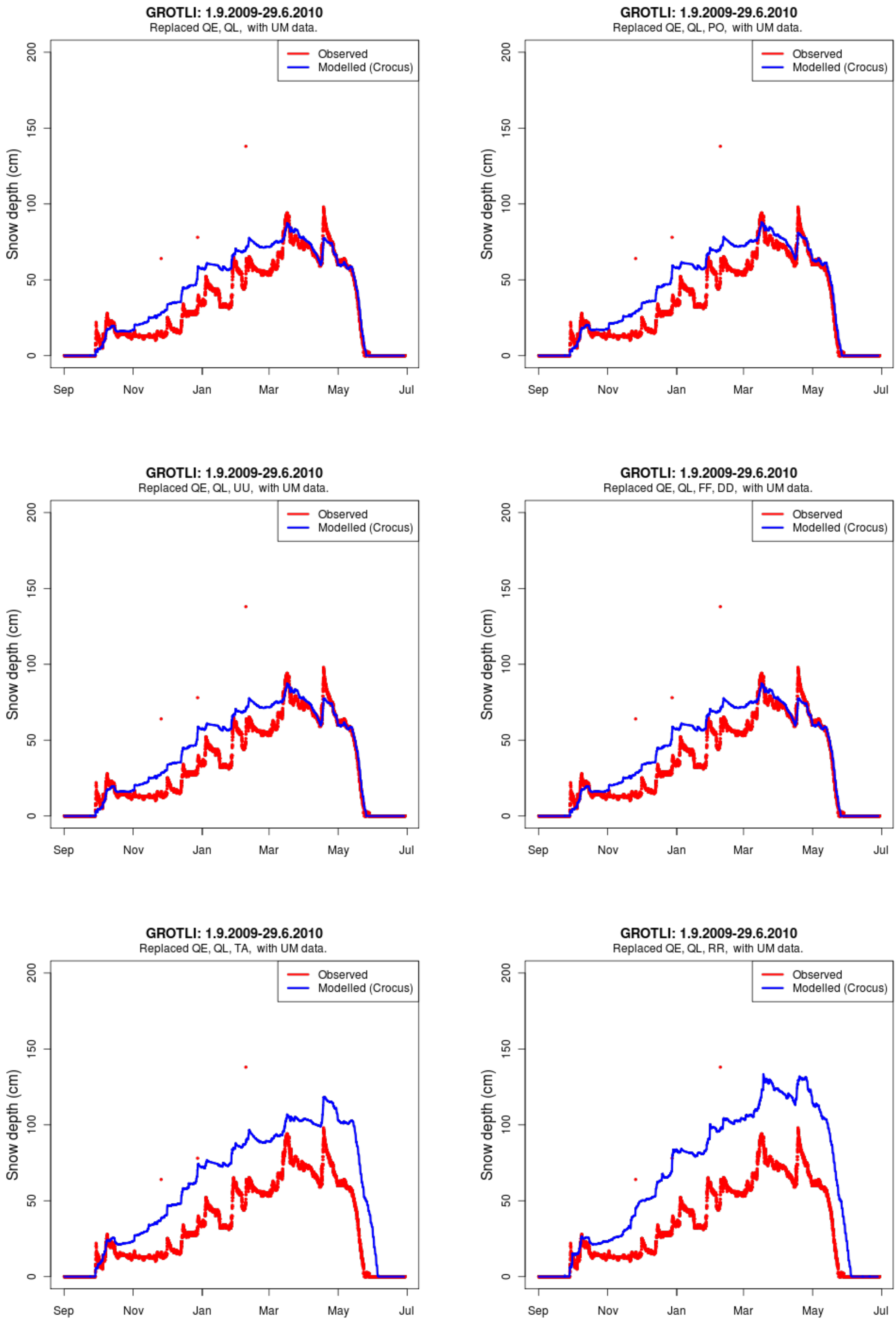


Figure 4.3: Modeled and observed snow depth at Grotli for the winter 2009/2010, corresponding to experiments A-F (top left to bottom right). Forcing data are observations except the parameters marked in the plots. QE = Short-wave radiation, QL = Long-wave radiation, UU = specific air humidity, FF/DD = wind speed/direction, TA = air temperature and RR = precipitation.

4.2.2 Experiments H-J

In this section we evaluate alternative NWP data for temperature and precipitation, and their impact on the modeling results. This is organised in experiments H-J:

H: Postprocessed HIRLAM-8 km temperature forecasts (Section 3.2.4).

I: Postprocessed UM-4 km precipitation forecasts (Section 3.2.2).

J: Harmonie-4 km precipitation forecasts (Section 3.2.3).

The experiments are carried out for the five weather stations located at Grotli, Marstein, Beitostølen, Filefjell-Kyrkjestølane and Blindern. The precipitation gauge was out of order at the station Mannen, and these experiments are therefore not carried out for this station. The experiments H-J have also not been carried out for the Fonnbu station.

Experiment H: Postprocessed HIRLAM-8 km temperature

Experiment H is identical to experiment C, except for the temperature forcing data. The snow depth modeling is improved using the postprocessed HIRLAM-8 km temperature forecasts, as compared to experiment C (raw UM-4 km temperature forecasts). The high spatial resolution (0.5 km) of the postprocessed HIRLAM-8 km temperature includes better representation of the local topography leading to improved temperature estimates in e.g. narrow valleys. This is clearly seen at the Marstein weather station (Figure 4.4). The station is located at 67 masl., while the raw UM model forecasts the temperature at an elevation corresponding to the mountain area (952 masl.) (see Table 4.1). By using the postprocessed HIRLAM-8 km temperature data, the temperature is modeled at 244 masl., and therefore modeled snow depth is closer to observed snow depth. Another example of improved modeling is shown in Figure 4.5.

For some stations the results are almost unchanged, when the raw UM-4 km temperature forecasts are replaced with the postprocessed HIRLAM-8 km temperature dataset. These stations are located in smooth terrain with no abrupt changes (e.g. Beitostølen).

Experiment I: Postprocessed UM-4 km precipitation

Experiment I is identical to experiment B, except for the precipitation forcing data. Using postprocessed UM-4 km precipitation does not improve the snow depth modeling as compared to the raw UM-4 km dataset. The experiments show that the results are relatively unchanged or slightly deteriorated. This is illustrated in Figures 4.6 and 4.7 for Grotli and Marstein, respectively. For the station Marstein, which is located in a narrow valley bottom (67 masl), it is clearly seen that both precipitation datasets (raw UM forecasts and postprocessed UM forecasts) produce precipitation at the wrong elevation (around 900 masl.). This is due to the topography in the atmospheric model, which is represented as very coarse and smooth.

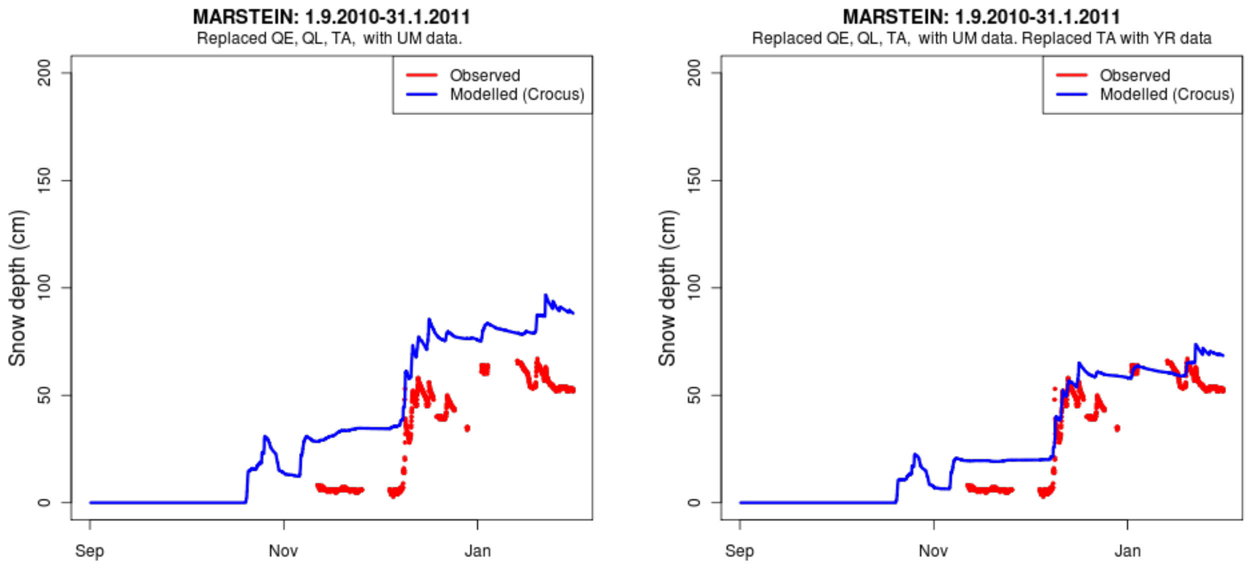
For the Beitostølen station, snow depth is heavily overestimated (Figure C.6). This station is located close to a water (and weather) divide between the eastern and the western parts of the mountains in South Norway. The filtering technique used in the postprocessing of the UM-4 km precipitation may have included both these areas for Beitostølen. Therefore, the forecasts at this station may have been overestimated.

Experiment J: HARMONIE precipitation

Experiment J is identical to experiment B, except for the precipitation forcing data. By replacing precipitation forecasts from the UM-4 km model with precipitation forecasts from the HARMONIE 4 km model when running the SURFEX model (using the CROCUS snow scheme), notably less snow is modeled for the two stations Grotli and Filefjell-Kyrkjestølane (Figure 4.8 and 4.9). These results correspond with the verification analysis for HARMONIE precipitation, showing less precipitation in the HARMONIE forecasts than in the UM forecasts (Mariken Homleid, met.no, Norway, pers. comm., 2011).

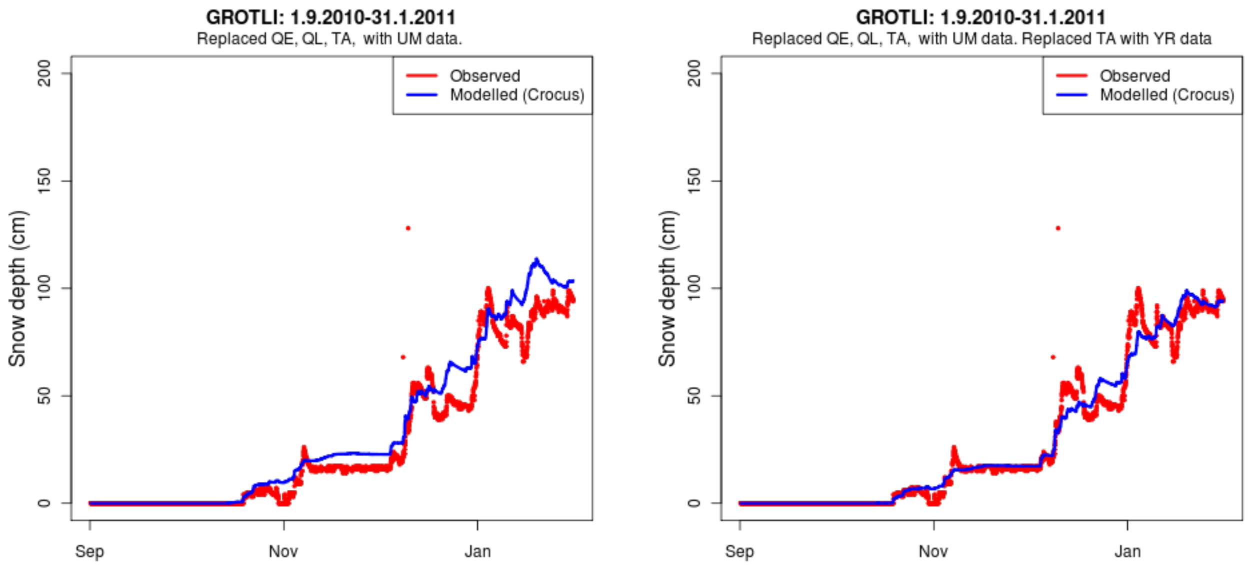
Summary exp. H-J:

The modeled snow depth is generally improved using postprocessed HIRLAM-8 km temperature forecasts (experiment H) compared to UM-4 km temperature forecasts (experiment C). This is due to the high spatial resolution (0.5 km) of this dataset. Alternative precipitation datasets did not improve the snow depth modeling drastically. Compared to the raw UM-4 km precipitation forecast (experiment B), no improvement is observed using the postprocessed UM-4 km precipitation forecasts (the median) (experiment I). The results are in some cases even deteriorated. Using the HARMONIE 4 km precipitation forecasts (experiment J) result in reduced snow depth as compared to the UM-4 km precipitation forecasts (experiment B) and an underestimation with regard to the observed snow depth.



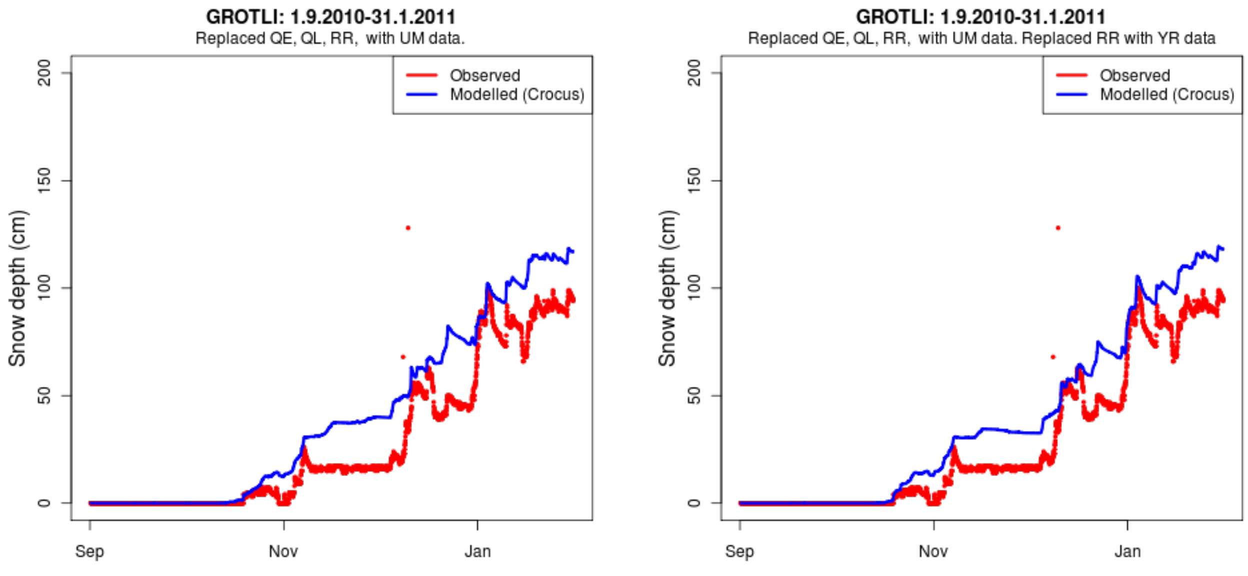
(a) (b)

Figure 4.4: Modeled and observed snow depth for Marstein. Temperature from a) raw UM-4 km forecasts (Exp. C) and b) postprocessed HIRLAM-8 km forecasts (Exp. H).



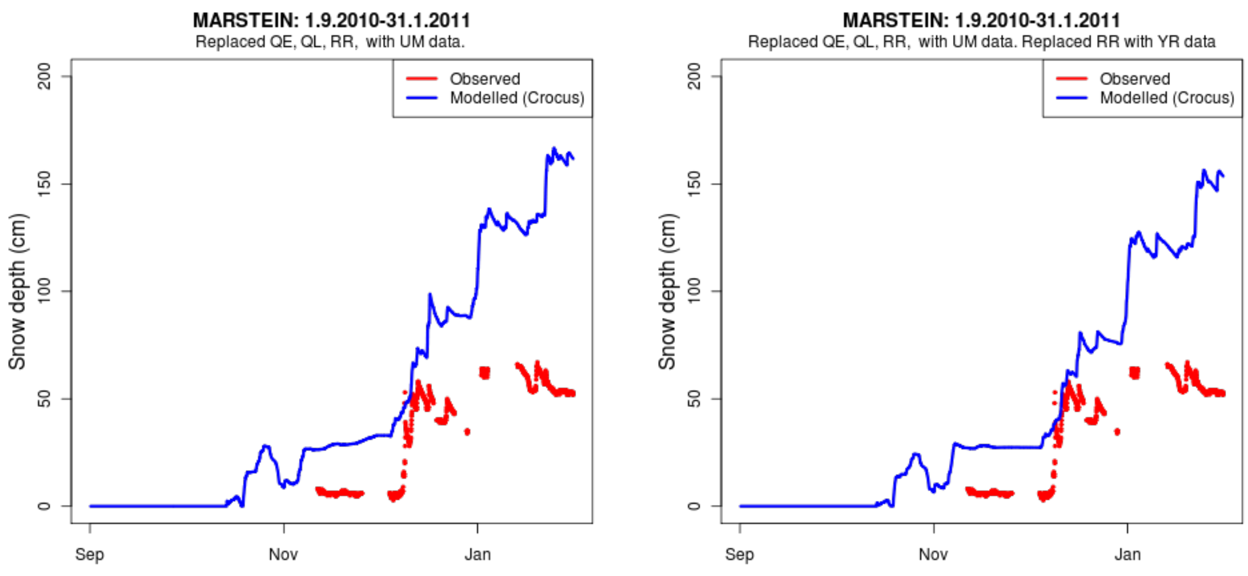
(a) (b)

Figure 4.5: Modeled and observed snow depth for Grotli. Temperature from a) raw UM-4 km forecasts (Exp. C) and b) postprocessed HIRLAM-8 km forecasts (Exp. H).



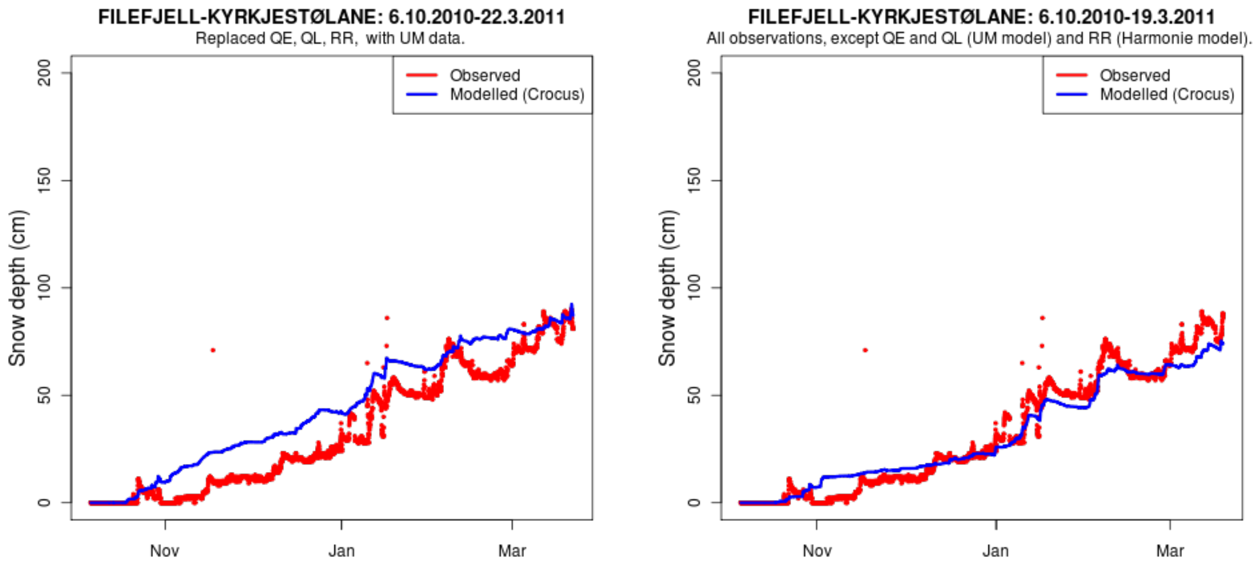
(a) (b)

Figure 4.6: Modeled and observed snow depth for Grotli. Precipitation from a) raw UM-4 km forecasts (Exp. B) and b) postprocessed UM-4 km data (Exp. I).



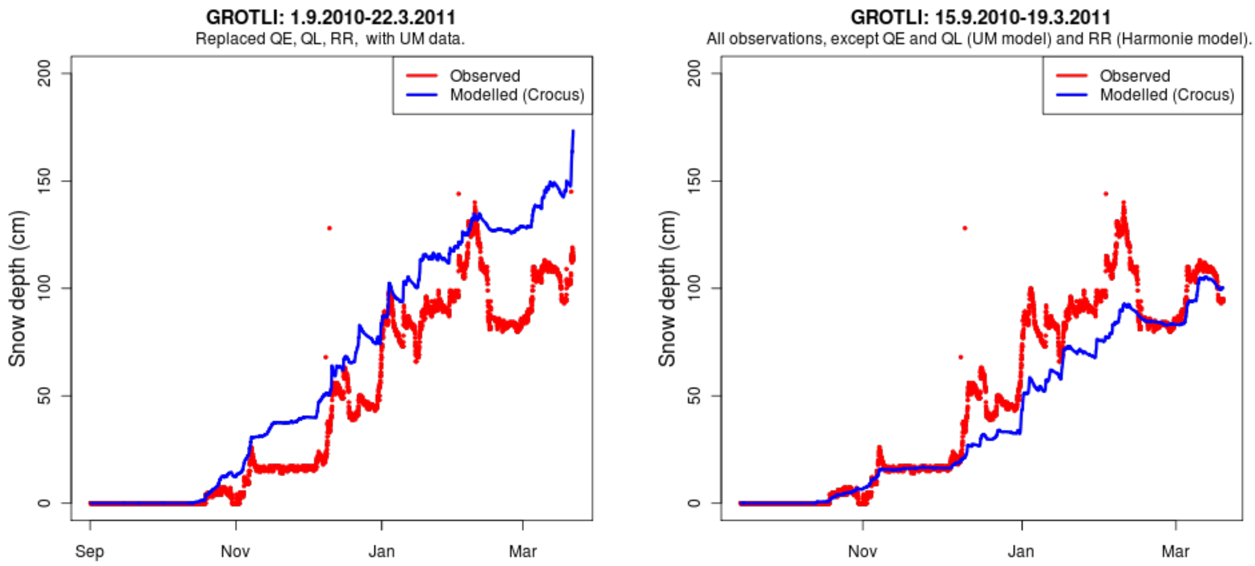
(a) (b)

Figure 4.7: Modeled and observed snow depth for Marstein. Precipitation from a) raw UM-4 km forecasts (Exp. B) and b) postprocessed UM-4 km forecasts (Exp. I).



(a) (b)

Figure 4.8: Modeled and observed snow depth for Filefjell-Kyrkjestølane. Precipitation from a) raw UM-4 km forecasts (Exp. B) and b) HARMONIE-4 km forecasts (Exp. J).



(a) (b)

Figure 4.9: Modeled and observed snow depth for Grotli. Precipitation from a) raw UM-4 km forecasts (Exp. B) and b) HARMONIE-4 km forecasts (Exp. J).

4.2.3 Experiment K

The last experiment K was carried out on all met.no weather stations that satisfied the following criteria:

- Hourly observations of at least precipitation, temperature and snow depth.

This resulted in 19 weather stations in Norway (Figure 3.2b). The previous experiments A-J showed that precipitation and temperature are most sensitive with respect to snow depth modeling results. Best results from those experiments were obtained using observations. Therefore, we wanted to run SURFEX with the CROCUS snow scheme on many stations using observations of precipitation and temperature, but still replace all other remaining input parameters with NWP data (in this case raw UM-4 km forecasts). For many stations only radiation and surface pressure were replaced. Parameters replaced for the individual station are shown in the plots (Figure 4.10- 4.12).

Overall, the results for the winter season 2010/2011 are very promising, when compared to observed snow depth. However, for most stations, the snow depth is to some degree overestimated. Best results are obtained for the stations Bjorli, Bjørnholt and Hjartåsen. The only station where the snow depth is underestimated is Filefjell-Kyrkjestølane. The station Mannen is exceptional for two reasons: a) precipitation is extracted from UM-4 km forecasts since the precipitation gauge was out of function during most of the winter 2010/2011 and b) the station is extremely wind-exposed leading to increased accumulation and erosion of snow.

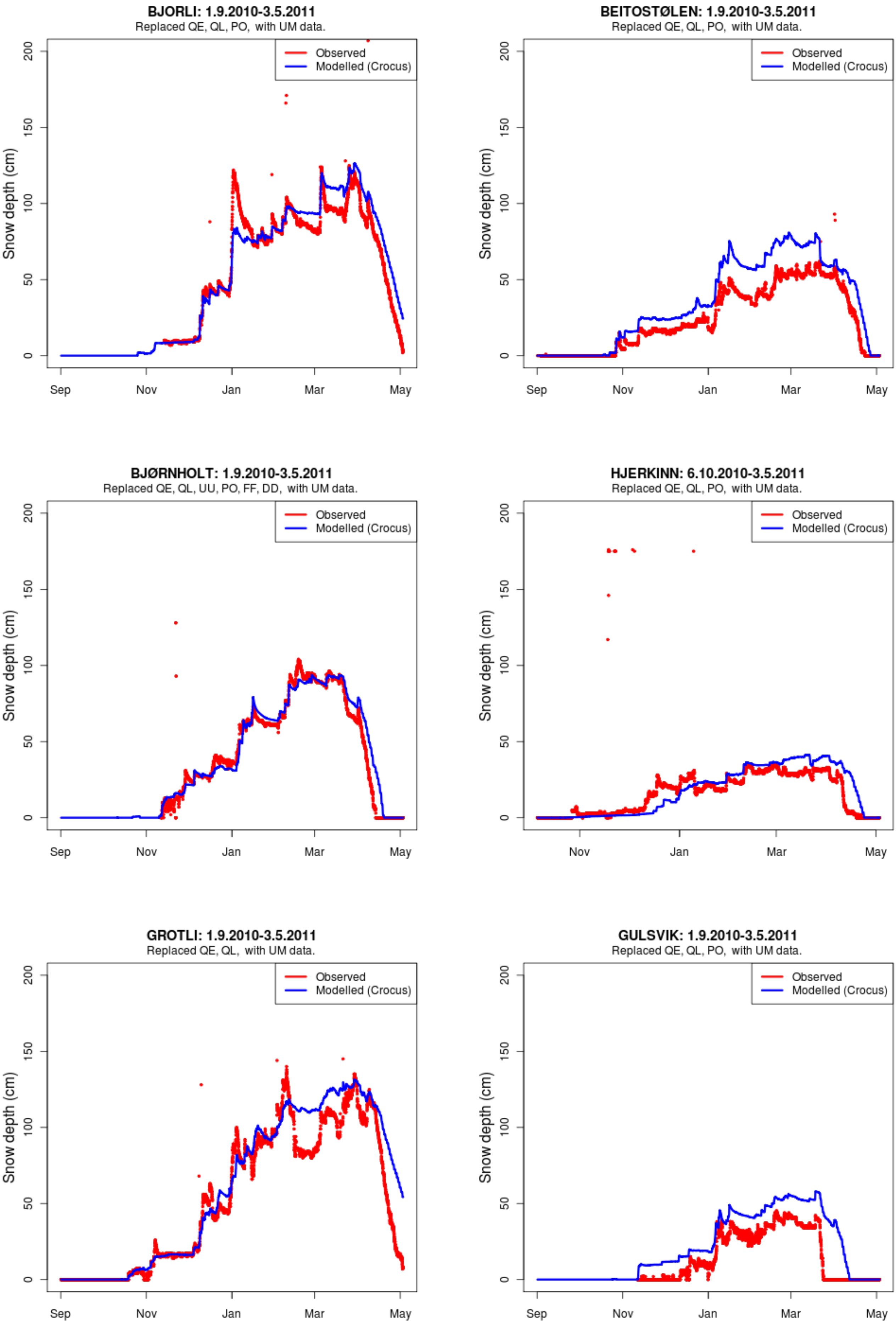


Figure 4.10: Modeled and observed snow depth (exp. K).

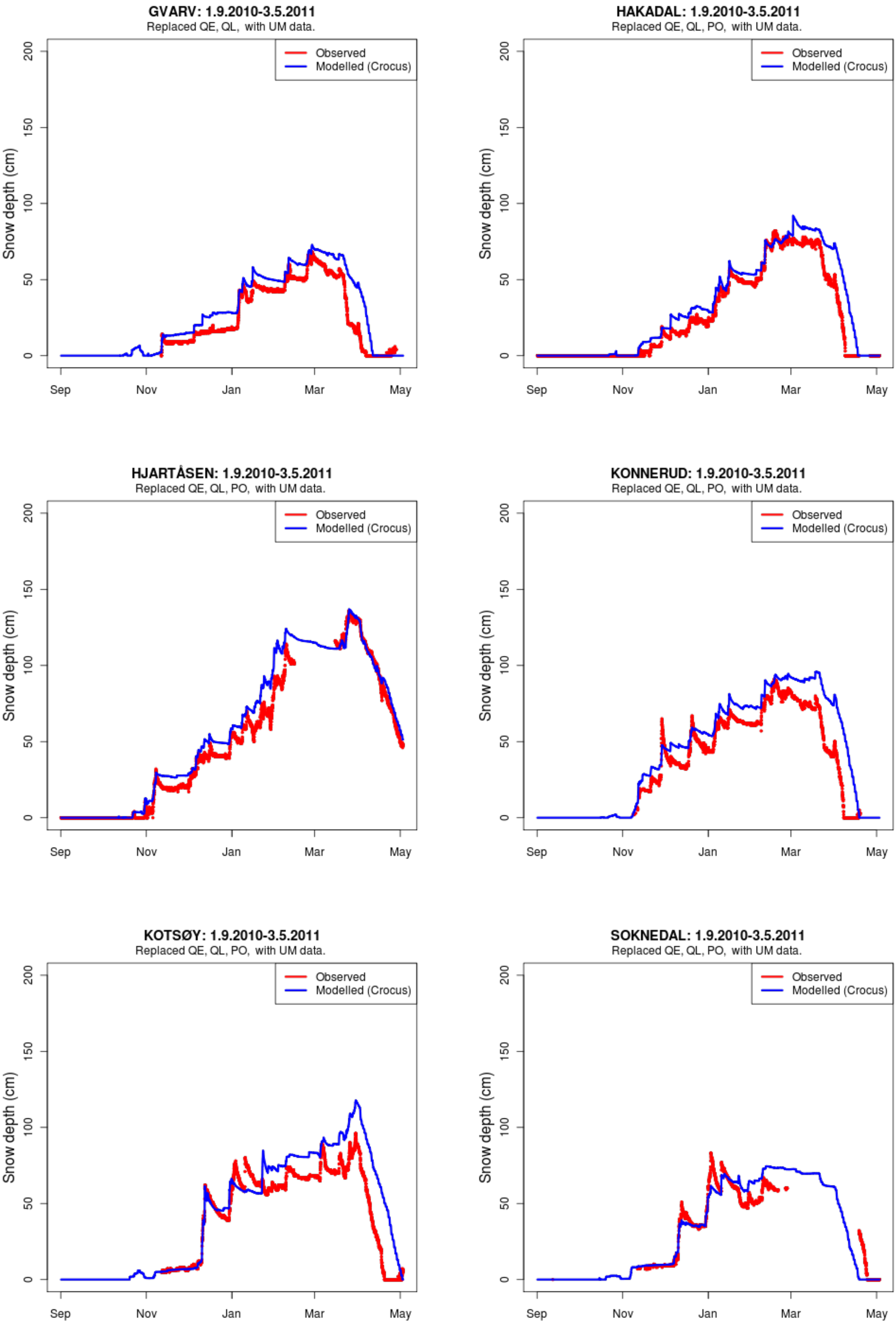


Figure 4.11: Modeled and observed snow depth (exp. K).

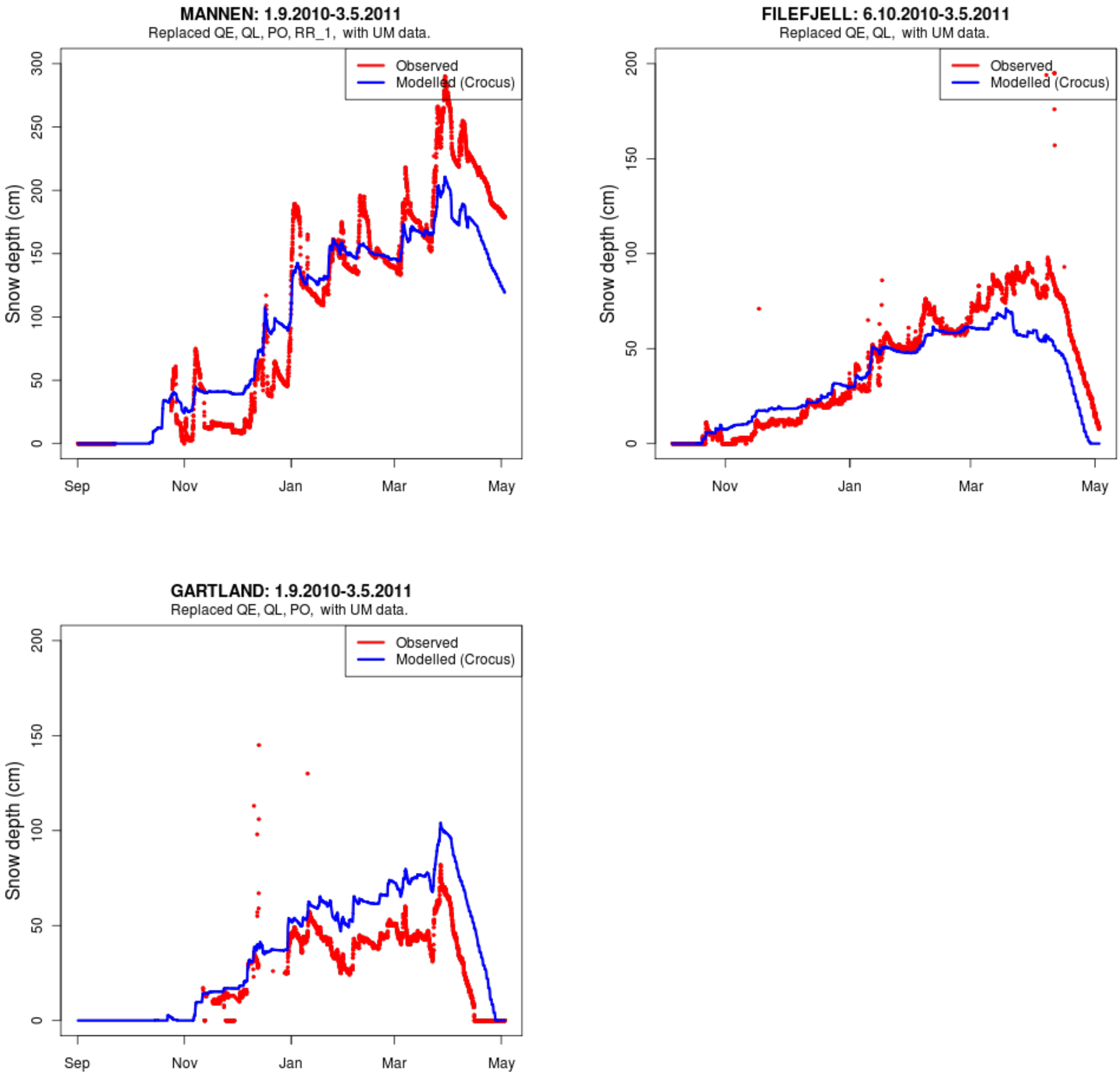


Figure 4.12: Modeled and observed snow depth (exp. K). Note that the station Mannen (1294 masl.) is a very windexposed station.

4.3 Snow pack layers

Although a correctly modeled snow depth is a good indicator of the model performance, it is the knowledge of the internal state of the snowpack, the layering and bonding between individual layers, that is essential to the avalanche forecaster. The physical properties such as density, temperature, grain size and form and liquid water content therefore need to be correctly predicted by the model. Today all these variables are however not regularily observed, except for snow temperature at Filefjell-Kyrkjestølane station and some snow profiles from the stations Fonnbu and Mannen.

We start this section by a brief technical description on how snow profiles were computed from the SURFEX output files (Section 4.3.1). Furthermore, results from a simple visual comparison of modeled and measured snow profiles is presented in Section 4.3.2. The last part (Section 4.3.3) includes a comparison of modeled and observed snow temperature at the Filefjell-Kyrskjestølane station. A more thorough evaluation of the modeled snowpack layers is not included in the analysis presented in this report, and it should be a topic for future work, when a larger number of observed snow profiles will be available.

4.3.1 Postprocessing of the SURFEX model output

The output from SURFEX (run with the CROCUS snow scheme) are NetCDF files containing prognostic and diagnostic variables. Among the prognostic variables are snow properties for every single layers: e.g. snow density, snow water equivalent, snow temperature. For our analysis we wanted to compute snow profiles. For this purpose we applied the toolbox Snowtools, which is a collection of Python scripts that manipulate the NetCDF output files from SURFEX, when it is run with the CROCUS snow scheme (Morin and Willemet, 2010). These tools are continuously updated and extended for new functions (Samuel Morin, MétéoFrance, France, pers. comm., March 2011). Two of the functions in the Snowtools toolbox are shown in Figure 4.13: 1) plots of individual snow profiles and 2) plots showing the seasonal overview of single snow parameters.

The plot showing individual snow profiles follows the CAAML-standard (Canadian Avalanche Association Markup Language), which is an XML standard for point snow profile information (http://caaml.org/). The symbols for grain types follows the international standard for snow classification (Fierz et al., 2009).

The plot showing the seasonal overview of the snowpack is produced for several snow parameters, e.g.:

- Density (kg/m^3) ("SNOWRO").
- Snow temperature (K) ("SNOWTEMP").
- Liquid water content ($\%$) ("SNOWLIQ").
- Snow grain type.

Example plots for snow temperature, snow density and liquid water content are shown in Figure 4.14.

For every experiment A-K plots showing the seasonal overview for all variables have been produced. However, there are too many plots available to be included in this report. Instead, we focus on presenting those plots were we have observations to evaluate the snow parameters. This evaluation is presented in the next two sections 4.3.2 and 4.3.3.

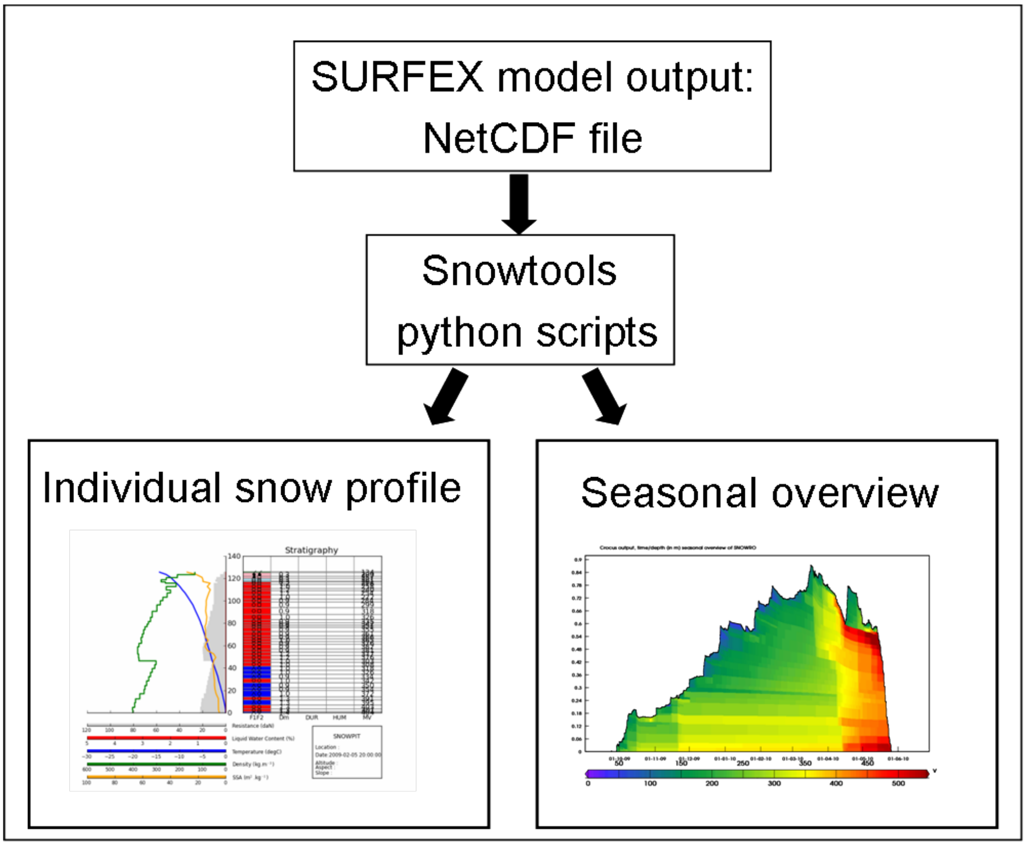
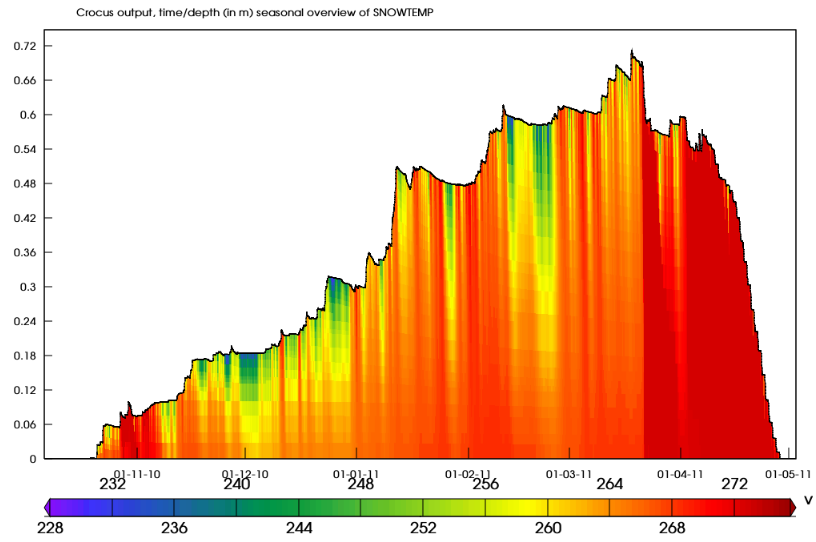
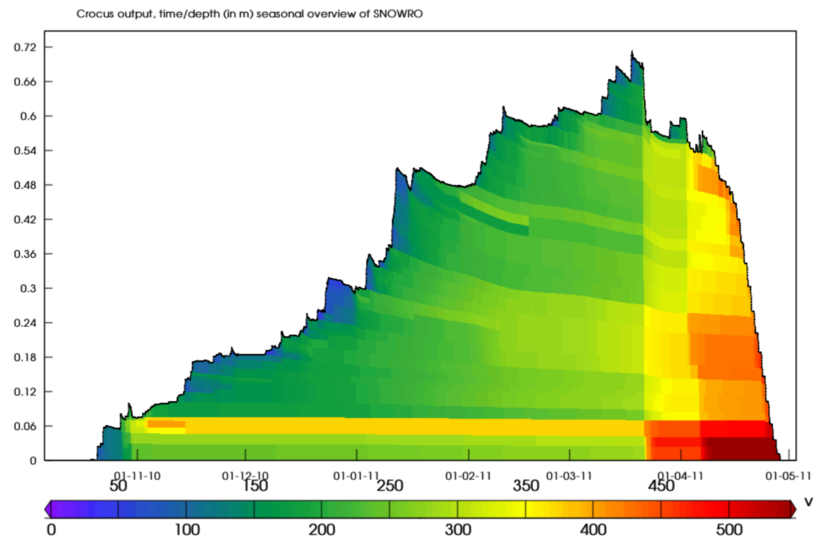


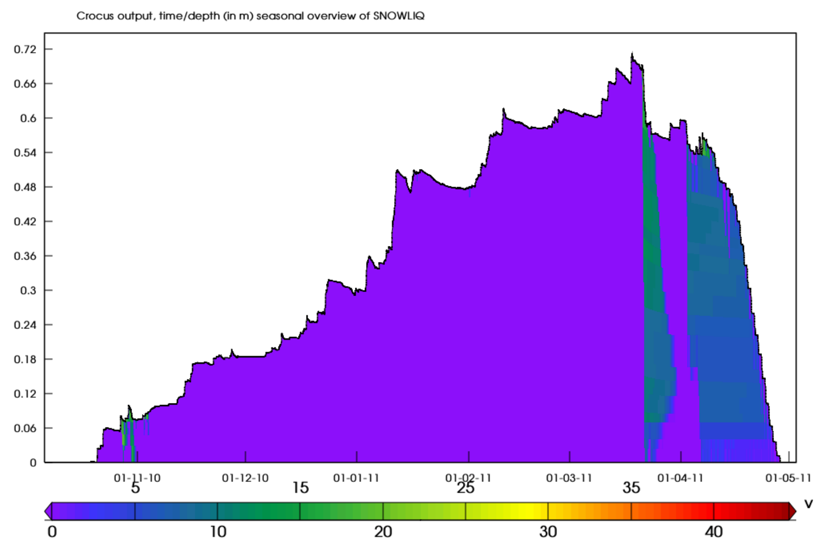
Figure 4.13: Illustration of two of the functions within the Snowtools toolbox (Morin and Willemet, 2010): plots of individual snow profiles (left) and plots showing the seasonal overview (right). The left figure shows the snow stratigraphy at a given timestep. A diagram is shown together with tabular values. The diagram shows various snow properties (resistance, liquid water content, temperature, density) for every modeled snow layer. The tabular values show density and grain type symbols. The right figure shows a seasonal evolution of the snowpack for different snow properties. In the given plot the color represents the snow density where blue represents low densities and red represents higher densities. The x-axis shows the time evolution, and the y-axis shows the snow depth.



(a)



(b)



(c)

Figure 4.14: Example of seasonal snow profiles from Filefjell-Kyrkjestølane met-station 2010/2011 for a) snow temperature ("SNOWTEMP" in Kelvin), b) snow density ("SNOWRO" in kg/m^3) and c) liquid water content ("SNOWLIQ" in %). The NetCDF output files from the SURFEX model run with the CROCUS snow scheme are postprocessed with the Snowtools Python scripts (Morin and Willemet, 2010).

4.3.2 Modeled and observed snow profiles

For validation of the physical properties of the snow, field measurements of snow profiles are necessary. Snow profile measurements are currently not routinely observed by any institution[2] in Norway. NGI provided observed snow profiles from Fonnbu research station for the winter season 2008/2009. The dates of the available snow profiles from Fonnbu are marked in Figure 4.15. The snow profiles were delivered as image files (jpg) from the Snow Pilot software (http://snowpilot.org/)(see Figures 4.16a and 4.17a). Snow Pilot is a program for plotting snow profile observations from the field. Having only image files available, a statistical comparison to modeled snow pack estimates is difficult to perform (see Figures 4.16b and 4.17b). A simple visual comparison of the modeled and the measured snow profiles for two selected dates are therefore presented below. 26 February 2009 represents a mid-winter situation with dry snow (Figure 4.16), while the 11 April 2009 represents a melt event at the start of the snow melt season (Figure 4.17). The two remaining dates shown in Figure 4.15 are included in Appendix D (Figures D.2 and D.3).

A comparison of the modeled and observed snow profile from 26 February 2009 (Figure 4.16) shows that new snow, melt forms and degrading particles for this situation are modeled correctly. The snow depth is underestimated. There is a cold bias of the modeled snow temperature in the top layers of the snowpack (approximately the upper 50 cm). The snow density is generally modeled too low (up to 100 kg/m^3 lower). Both the observed and the modeled snow profiles show no liquid water content throughout the profile. For the 11 April 2009 (Figure 4.17) we see that temperature of the entire snowpack is around 0°C. Liquid water content is here modeled with up to 1% above 80 cm snow height. The density is also here modeled slightly too low. The modeled resistance profiles match the observed in their general form (except for the 17 January 2009). The shape of the resistance profile gives the forecaster a good indication of the type and thickness of potential avalanches. Several melt crusts were observed in the snow profiles, which are absent in the modeled snow profiles.

A more thorough evaluation of modeled snow properties should be carried out in the future, when a larger number of observed snow profiles are available. The evaluation should include statistical analysis to identify errors and uncertainties. Having only observed snow profiles as image files (jpg) as in this study, makes it difficult to evaluate the modeled snow properties.

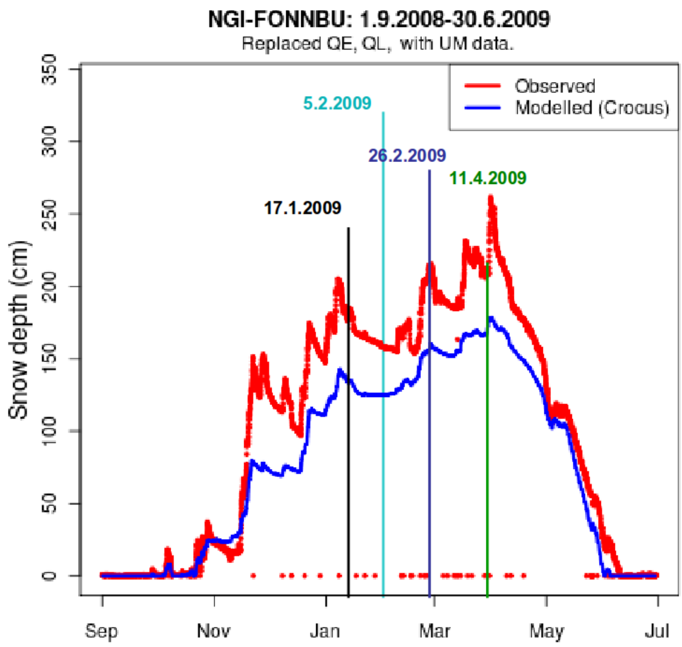
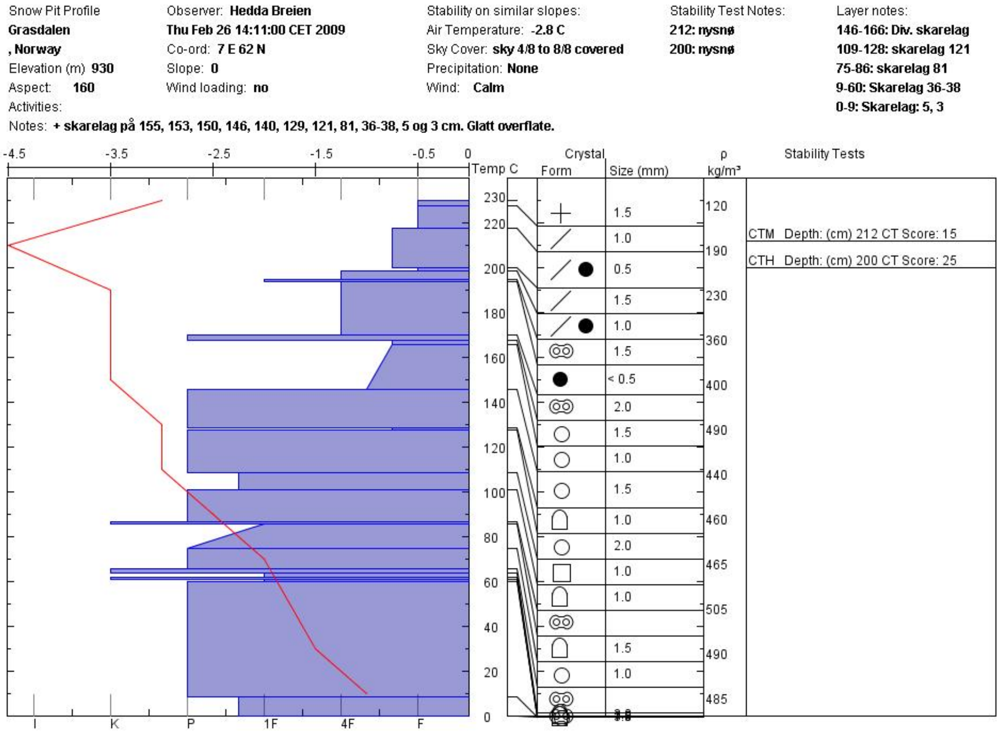
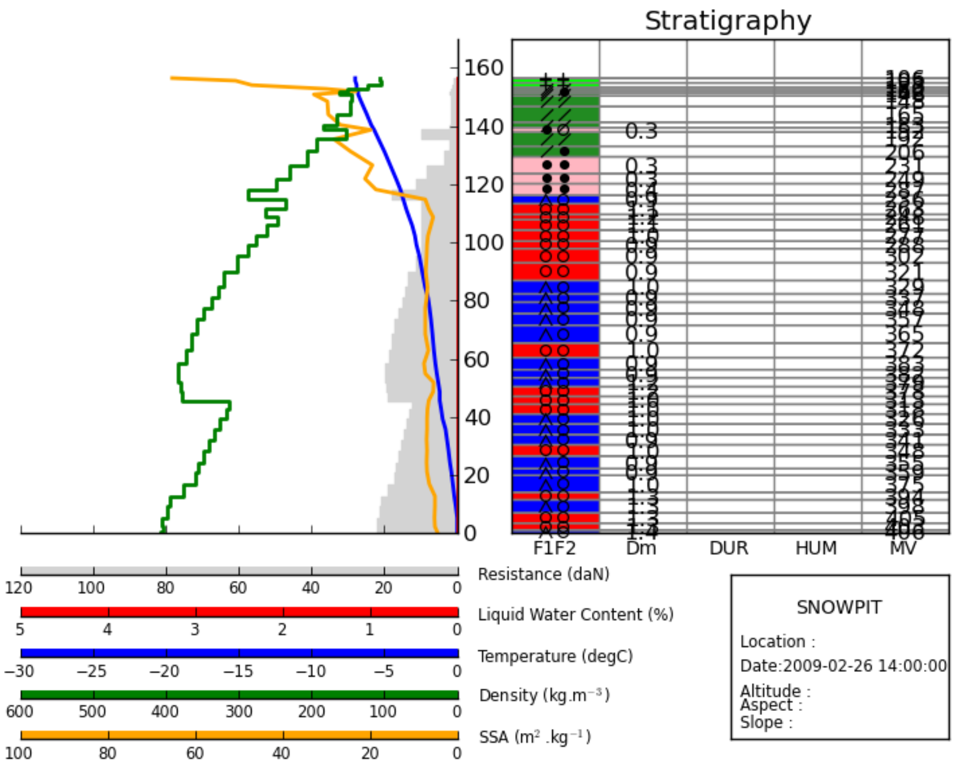


Figure 4.15: Illustration of the dates when NGI has carried out snow profiles at the Fonnbu research station during the winter 2008/2009.

[2]Both NVE and NNRA performed field measurements of snow profiles during the winter 2010/2011 at Filefjell-Kyrkjestølane and Mannen, respectively.

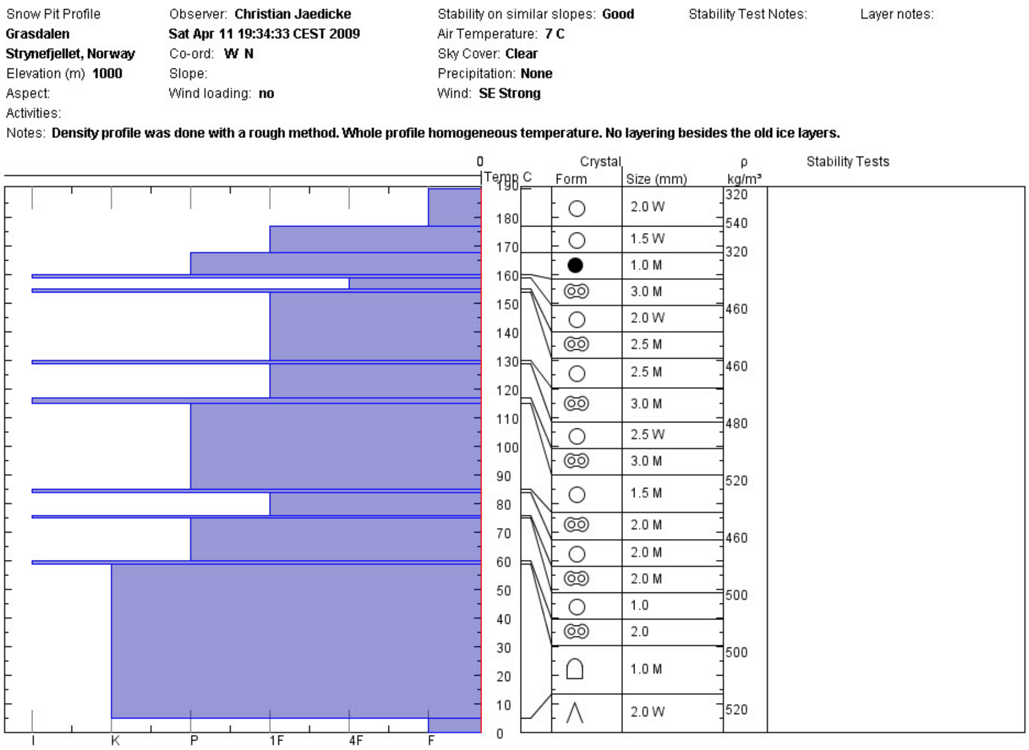


(a) Observed

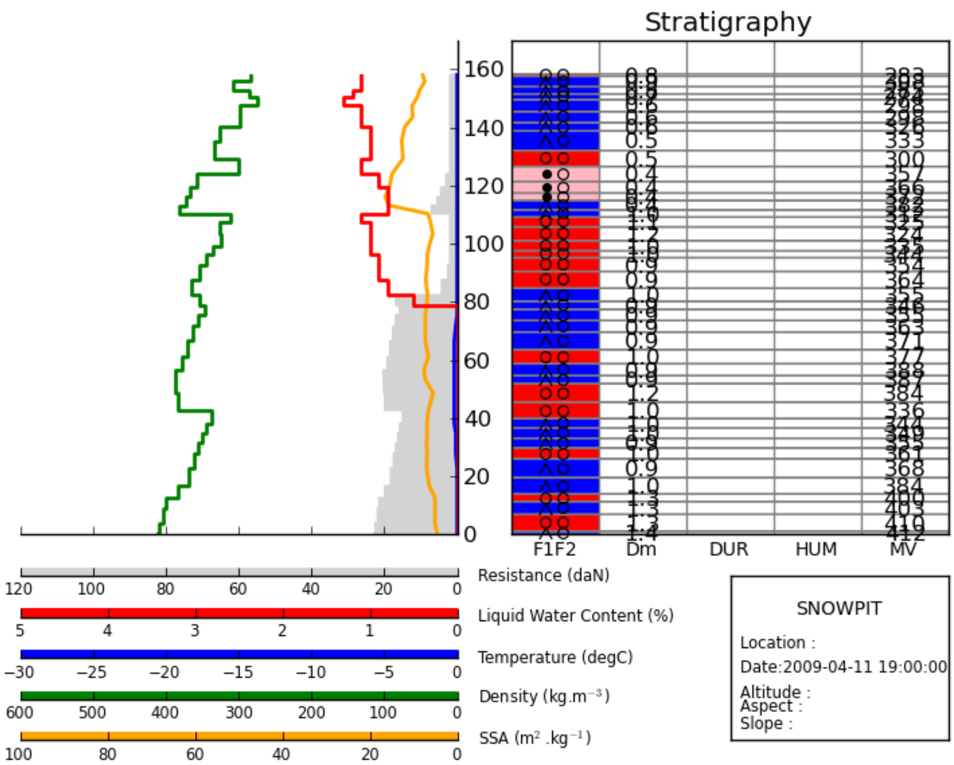


(b) Modeled

Figure 4.16: Snow profile 26 February 2009 at Fonnbu research station: a) Observed (NGI) and b) modeled (CROCUS). The profile illustrates a dry snow situation during mid-winter.



(a) Observed



(b) Modeled

Figure 4.17: Snow profile 11 April 2009 at Fonnbu research station: a) Observed (NGI) and b) modeled (CROCUS). Wet snow situation, representing the start of the snow melt season.

4.3.3 Modeled and observed snow temperature

Snow temperature is measured hourly by NVE at the Filefjell-Kyrskjestølane station since 19 September 2009 at 0 cm (ground surface), 5 cm, 15 cm, 30 cm and 55 cm snow depth. In this study, the snow temperature is evaluated at the Filefjell-Kyrkjestølane station during the winter 2010/2011. Modeled and observed temperature at the snow/ground interface is shown in Figure 4.18. The modeled snowprofile is identical to experiment A at Filefjell (Figure B.10, upper left). This means that the forcing data consist of observations from the weather station (met.no) and only radiation is extracted from NWP data (UM-4 km forecasts). In this case the modelled snow depth is slightly overestimated as compared to observed snow depth. There is also a general cold bias for the modeled ground temperature, but the daily variations are captured by the CROCUS model.

These results are promising, and it would be very interesting to do similar comparisons at other locations and for longer time series. For the time being there are no other stations that observe snow temperature in addition to all the other input parameters required by SURFEX and CROCUS.

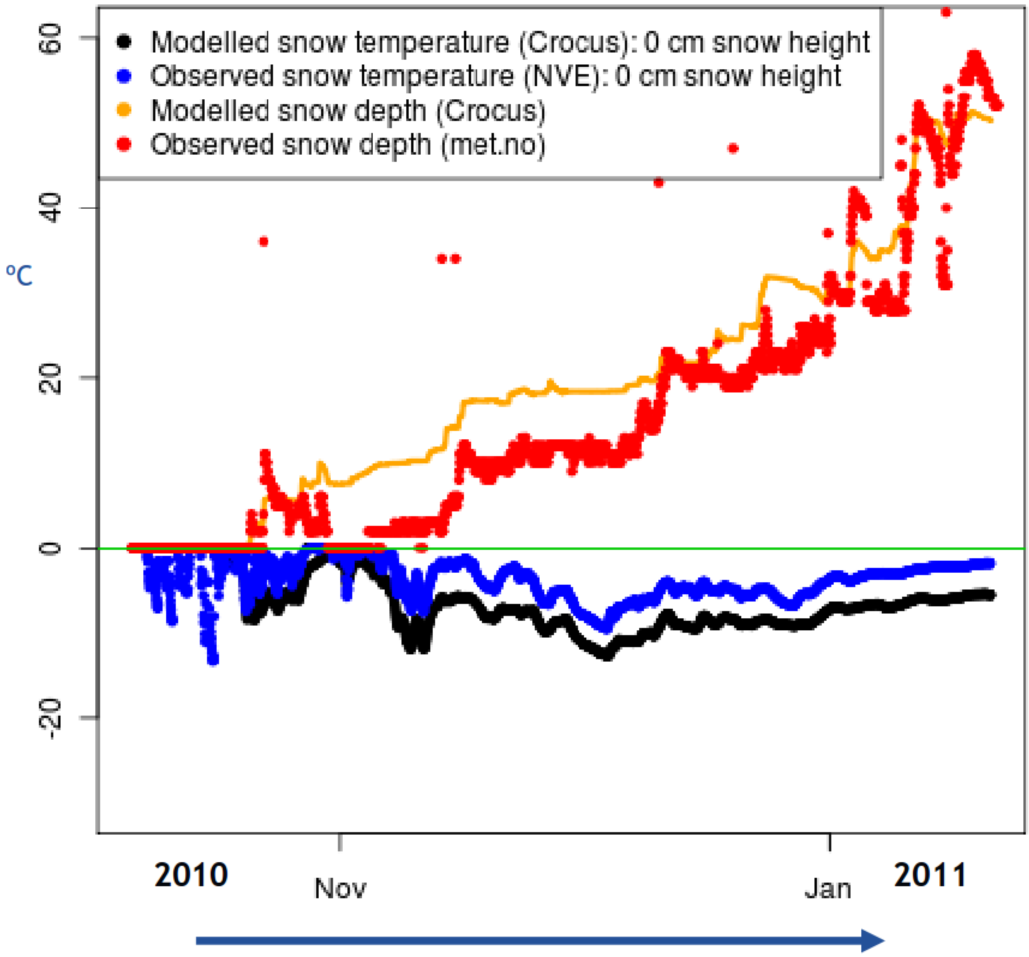


Figure 4.18: Modeled and observed (NVE) ground temperature as well as snow depth at the Filefjell-Kyrkjestølane station 2010/2011.

Chapter 5

Discussion and outlook

5.1 Uncertainties

This section very briefly lists uncertainties and error sources related to the snow modeling results presented in Section 4. There are several factors contributing to errors in snow modeling. These are related to the forcing data and the CROCUS model:

Spatial resolution: Observed snow depth from weather stations are here compared to modeled snow depth at the actual NWP grid point containing the weather stations location. In our experiments we combine observations and forecasts. The spatial resolution of the forecasts varied from 0.5 km $\times$ 0.5 km to 4.0 km $\times$ 4.0 km. A relevant question will then be which point/area is actually beeing modeled? The spatial resolution of the coarsest forcing data used in the modeling defines the modeled area. Still we chose to compare with snow depth observations at specific locations due to the lack of alternative validation data sets. A direct comparison to observed snow profiles is then challenging because the snowpack varies greatly even locally. A modeled snow profile therefore represents the mean snowpack of this area.

Representativity of the terrain: The topography is modeled very coarse and smooth in the atmospheric models as compared to the actual terrain. Steep valleys and mountains are therefore not very well represented. In areas with very rough topography this leads to errors in predicted temperature, precipitation and precipitation phase. This error increases with increasing terrain deviation. Example: When the topography in the atmospheric model is located high above the real terrain, the temperature is modeled too cold and for temperatures around the freezing point, the precipitation may be predicted as snow and not rain. There is no correction for these effects in the NWP data, except for the postprocessed UM-4 km temperature forecasts.

Model inconsistency: Combining observations and forecasts lead to inconsistency in the forcing data, e.g. the UM model may have forecasted precipitation while no precipitation was observed. The use of different data sets is anchored in the practical application of snow avalanche warning. For this purpose we want to identify the best meteorological datasets, leading to the best snow modeling results with offline models.

Forecasts: Verification of the operational forecasts produced at met.no are analyzed annually, see e.g. Bremnes and Homleid (2010). The Harmonie forecasts are not yet included in these annual reports since it is still run in an experimental research mode. However, this is likely to change in near future. Generally, precipitation forecasts are more uncertain than temperature forecasts.

Observations: Uncertainties are also related to instruments and sensors used for observing the different parameters. Particularly, precipitation is challenging to observe correctly, and underestimation of the precipitation is often the result. Precipitation falling as snow is even more difficult to observe than rainfall. We used uncorrected observations of precipitation.

CROCUS model: The CROCUS model aims to capture the physical processes of accumulation and melt of a snowpack. In this report we have not evaluated uncertainties related to the algorithms of the different physical processes. Additionally, wind transported snow is not included in the model, since SURFEX models the snow only at points (one dimensional modeling). Neglecting wind erosion leads to an overestimation of the snow depth after strong snowfall events at windy sites.

5.2 Outlook

Snow models are used in avalanche forecasting both in France and in Switzerland, but in different ways (Section 1.2). In areas with less dense station network (snow and weather observations) there is generally a greater need for models. Switzerland uses Snowpack in an operational mode connected to each of their 108 IMIS weather stations over the Swiss Alps. Measured snow depth at the station in combination with modeled snow settling replaces precipitation measurements which are costly and often inaccurate (Lehning et al., 1999). Snow profiles are used if no manual observations are available from an area (Christine Pielmeier, SLF, Switzerland, pers. comm., 2011).

In France representative snow profiles for areas with homogeneous weather patterns are modeled by CROCUS on a daily basis. Snow profiles for six different expositions and different elevation ranges are simulated and evaluated by the avalanche forecaster. The expert module MEPRA is used to evaluate the large amount of simulated snow profiles and to compile a report that the forecaster uses as one of the tools for producing the daily avalanche bulletin.

The approach used in France is very interesting for Norway since we lack a dense network of field observers and automatic weather stations (AWS). The disadvantage of the French approach is that it is difficult to validate the model output since the snow profiles represent the mean profile for an area, and not for a specific location like a weather station (which is easier to validate). It is necessary to gain lots of experience with the model to judge the reliability of the modeled snow profiles. French avalanche forecasters have years of experience with the CROCUS model. They use the output from the model in situations and regions where e.g. snow observations are lacking. We can build on their forecasting experiences. However, we need to evaluate the model output under Norwegian conditions and eventually adjust model routines. The Swiss approach will be more interesting once the AWS network has been extended substantially. We will setup the model to run in combination with the AWS that provide the required measurements and do so with each station that becomes newly available. At the same time we may run SNOWPACK parallel to SURFEX/CROCUS fed by NWP data and/or observations to investigate the different performance of the two models.

In the short term, we want to introduce the modeled snow profiles in the test-forecasting 2011/2012. Both, for the forecasters to get accustomed to the models and to gain feedback on where they could be useful and what improvements are necessary. We plan to collect detailed snow profiles on a regular basis for a few stations where the models are setup. These stations should represent mountainous areas with different snow conditions: a) mountains of southeastern Norway (e.g. Filefjell weather station), b) mountains of southwestern Norway (e.g. Fonnbu weather station), c) mountains in Northern Norway and d) windexposed stations (e.g. Mannen weather station). The measured snow profiles will give us information on how well the models simulate the internal structure of the snowpack.

Chapter 6

Concluding remarks

In this section we summarize the important findings in our study:

Snow depth:

- Very good estimates of the snow depth are obtained using the CROCUS snow scheme within the SURFEX model.
- Modeled snow depth is most sensitive to the precipitation and the temperature. Using observations from weather stations as forcing data for these parameters provide the best results of modeled snow depth.
- Modeled snow depth is least sensitive to air humidity, surface air pressure and wind (where average wind speeds are low). The results show that NWP data may replace observations of these parameters without significant errors introduced.
  - The sensitivity of modeled snow depth to radiation has not been evaluated in this study, but may be important for certain conditions.
  - At windexposed locations redistribution of snow is an important process. However, the SURFEX model is a one dimensional model and the present version does not account for accumulation and erosion of snow due to wind.
- Modeled snow depth improves using postprocessed HIRLAM-8 km temperature forecasts compared to UM-4 km temperature forecasts. This is due to the high spatial resolution (0.5 km) of the postprocessed dataset.
- No improvement is observed using postprocessed UM-4 km precipitation forecasts (the median), compared to raw UM-4 km precipitation forecasts. The results are in some cases even deteriorated.
- Using the HARMONIE precipitation forecasts result in reduced snow depth as compared to the UM-4 km precipitation forecasts and an underestimation with regard to the observed snow depth. The UM-4 km precipitation forecasts often leads to an overestimation of the snow depth.

Snow layers within the snowpack:

- A simple visual comparison of observed and modeled snow profiles was carried out for available profiles measured at the Fonnbu research station during the winter 2008/2009. However, a thorough evaluation of the modeled snowpack layers and their physical properties should be a topic for future work, when more observed snow profiles will be available.
- Modeled and measured snow temperatures were compared at the Filefjell-Kyrkjestølane station, showing promising results. There was a cold bias for the ground temperature, but daily variations were reasonably modeled.

Outlook

- Modeling of snow profiles is a very interesting approach for Norway, at least until a dense network of field observers and automatic weather stations (AWS) are established.
- Modeling of snow profiles for point locations (weather stations) or for representative areas should be discussed in future work. It is recommended to consider the French model where snow profiles are modeled for homogenous climates zones.
- Terrain effects may be modeled by e.g. modifying the forcing data for representative terrain slopes and expositions for an area.
- Modeled snow profiles should be introduced to the test-forecasting of regional avalanches (another subproject). The forecasters will get accustomed to the models and can give feedback on how the models can be useful and what improvements are necessary.

It should be underlined that these findings are based on results from a limited number of weather stations. Results may be different with a larger number of fully equipped weather stations representing a larger variety of climatological- and snow- conditions of Norwegian mountains.

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A number of people and institutions have contributed to this work. Particularily we would like to express our gratitude to the reserach group CEN (Centre d'étude de la neige) at MétéoFrance headed by Pierre Etchevers. Special thanks to Eric Brun and Samuel Morin, MétéoFrance/CNRS, CNRM–GAME, for sharing the CROCUS code, the Snowtools toolbox and discussing technical and scientific problems.

Thanks to Kalle Kronholm at NGI for providing the snow profiles from Fonnbu research station.

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Appendix A

Technical details

This appendix includes technical information about the forcing data and settings in SURFEX. Table A.1 describes how the precipitation phase was determined depending on the forcing data. Table A.2 includes information about the NWP data and the settings in one of the SURFEX input files (myforc.f90). Different datasets were used from HARMONIE and UM prognoses for air temperature, wind speed, wind direction and specific air humidity.

Forcing data	
Observations	Rain: $Temperature \geq 0.5$℃ Snow: $Temperature < 0.5$℃
NWP data (Harmonie, UM)	Precipitation phase and amount of rain and/or snow (mm), were derived directly from the prognoses from the NWP models. Total precipitation for each phase was the sum of convective and large-scale precipitation.

Table A.1: Precipitation phase was determined differently depending on the forcing data. A threshold value for temperature was used for the observations, while the NWP models produces prognoses for both precipitation type (convective and large-scale precipitation), precipitation phase (rain/snow) and precipitation amount (mm).

NWP model		
UM	Temperature prognoses Specific air humidity Wind speed and direction	2 m 2 m 10 m
HARMONIE	Temperature prognoses Specific air humidity Wind speed and direction	30 m (lowest model level) 30 m (lowest model level) 30 m (lowest model level)

Table A.2: Settings in the SURFEX parameter file myforc.f90. We used different datasets from the UM and the HARMONIE model. All other input parameters represent ground surface level for both models.

Appendix B

Results from experiments A-G

This appendix presents results from the sensitivity study for the stations:

- Grotli 2008/2009
- Grotli 2009/2010
- Grotli 2010/2011
- Beitostølen 2010/2011
- Marstein 2010/2011
- Blindern 2010/2011
- Fonnbu research station (NGI) 2008/2009
- Fonnbu research station (NGI) 2009/2010
- Fonnbu research station (NGI) 2010/2011
- Filefjell-Kyrkjestølane 2010/2011

The results are presented in the Figures B.1- B.9. Each Figure includes one station and one winter season. The last plot (Figure B.11) shows a clear overestimation of the snow depth when using solely UM forecasts as forcing data.

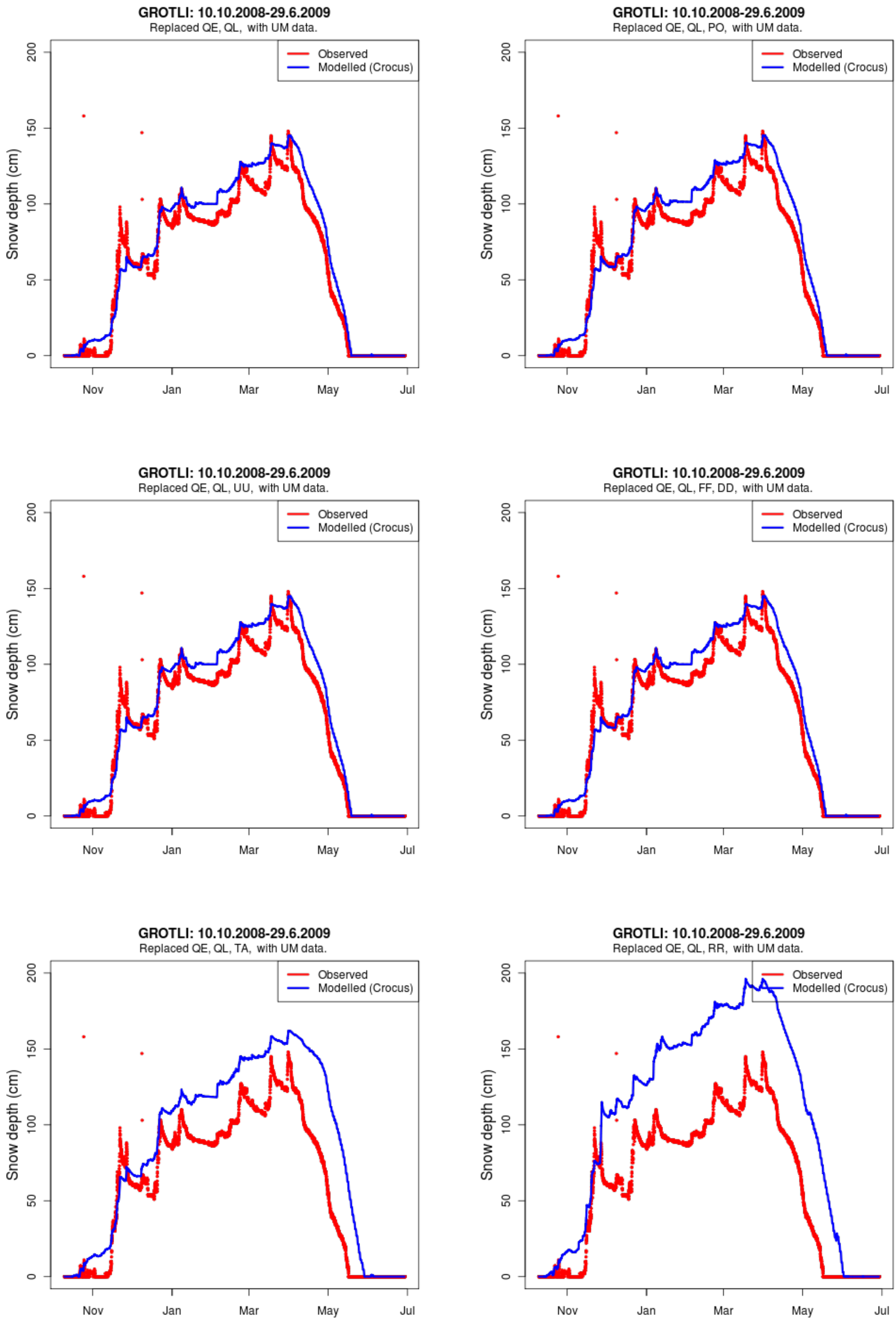


Figure B.1: Modeled and observed snow depth at Grotli for the winter 2008/2009, corresponding to experiments A-F (top left to bottom right). Forcing data are observations except the parameters marked in the plots. QE = Short-wave radiation, QL = Long-wave radiation, UU = specific air humidity, FF/DD = wind speed/direction, TA = air temperature and RR = precipitation.

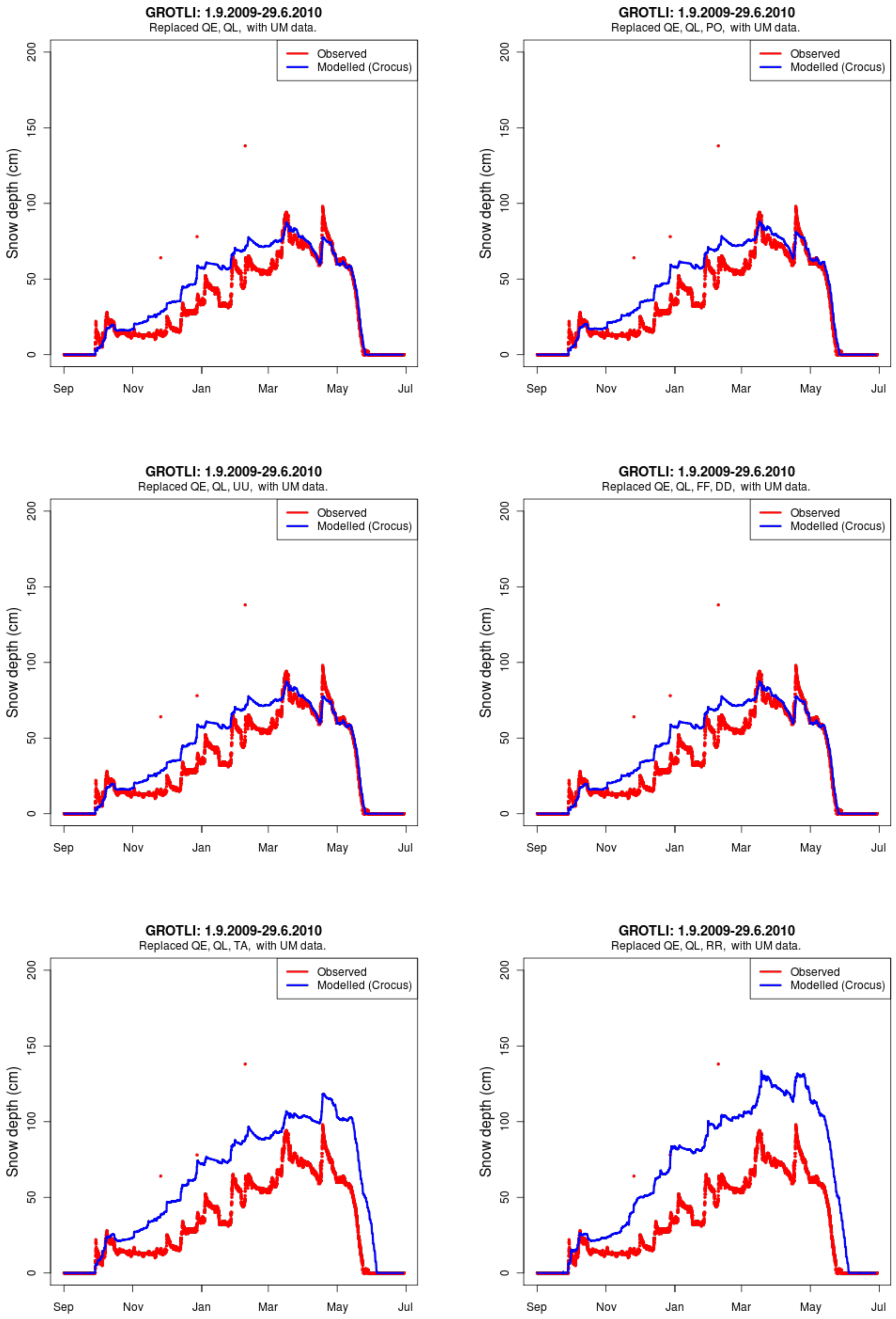


Figure B.2: Modeled and observed snow depth at Grotli for the winter 2009/2010, corresponding to experiments A-F (top left to bottom right). Forcing data are observations except the parameters marked in the plots. QE = Short-wave radiation, QL = Long-wave radiation, UU = specific air humidity, FF/DD = wind speed/direction, TA= air temperature and RR = precipitation.

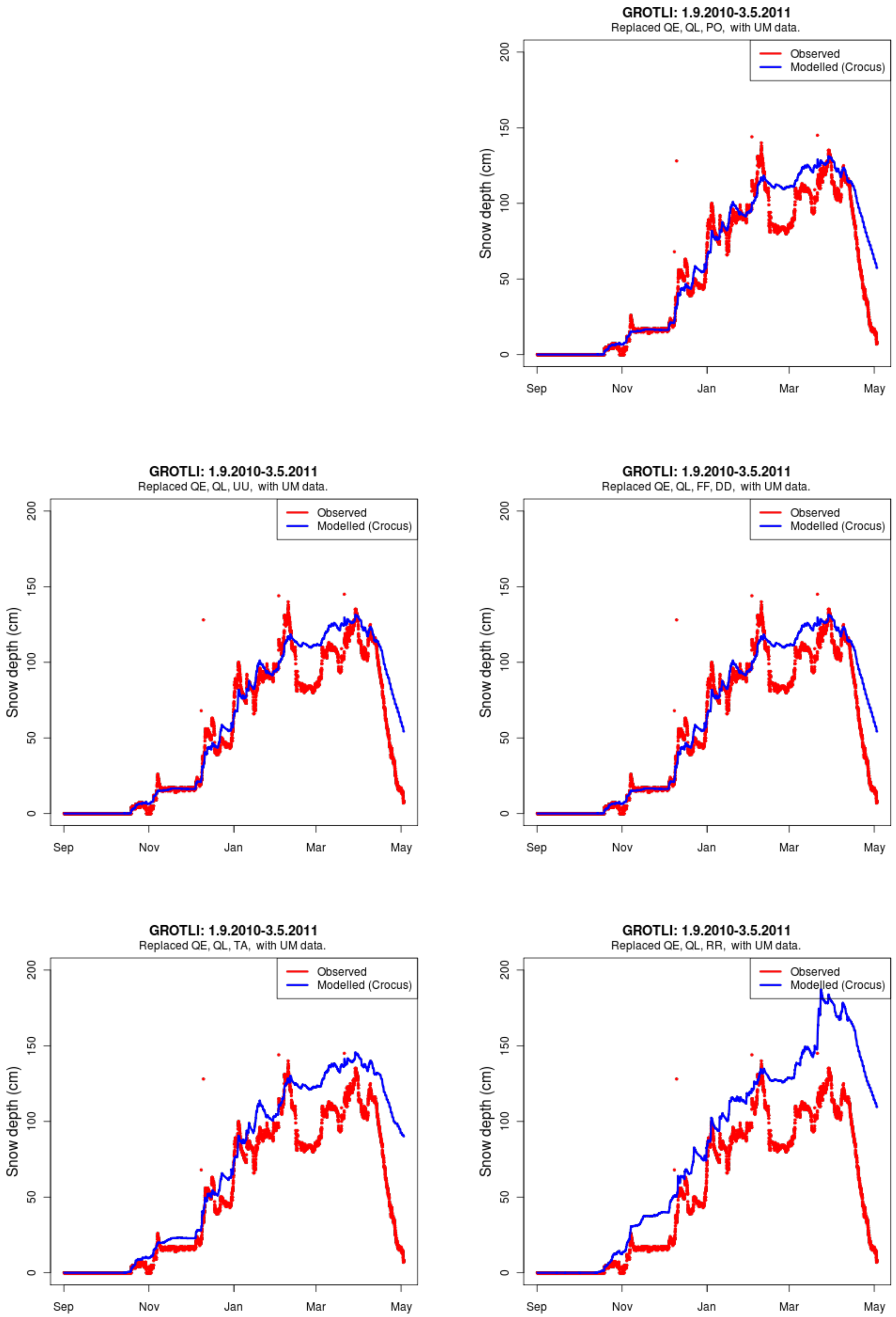


Figure B.3: Modeled and observed snow depth at Grotli for the winter 2010/2011, corresponding to experiments B-F (top left to bottom right). Forcing data are observations except the parameters marked in the plots. QE = Short-wave radiation, QL = Long-wave radiation, UU = specific air humidity, FF/DD = wind speed/direction, TA = air temperature and RR = precipitation.

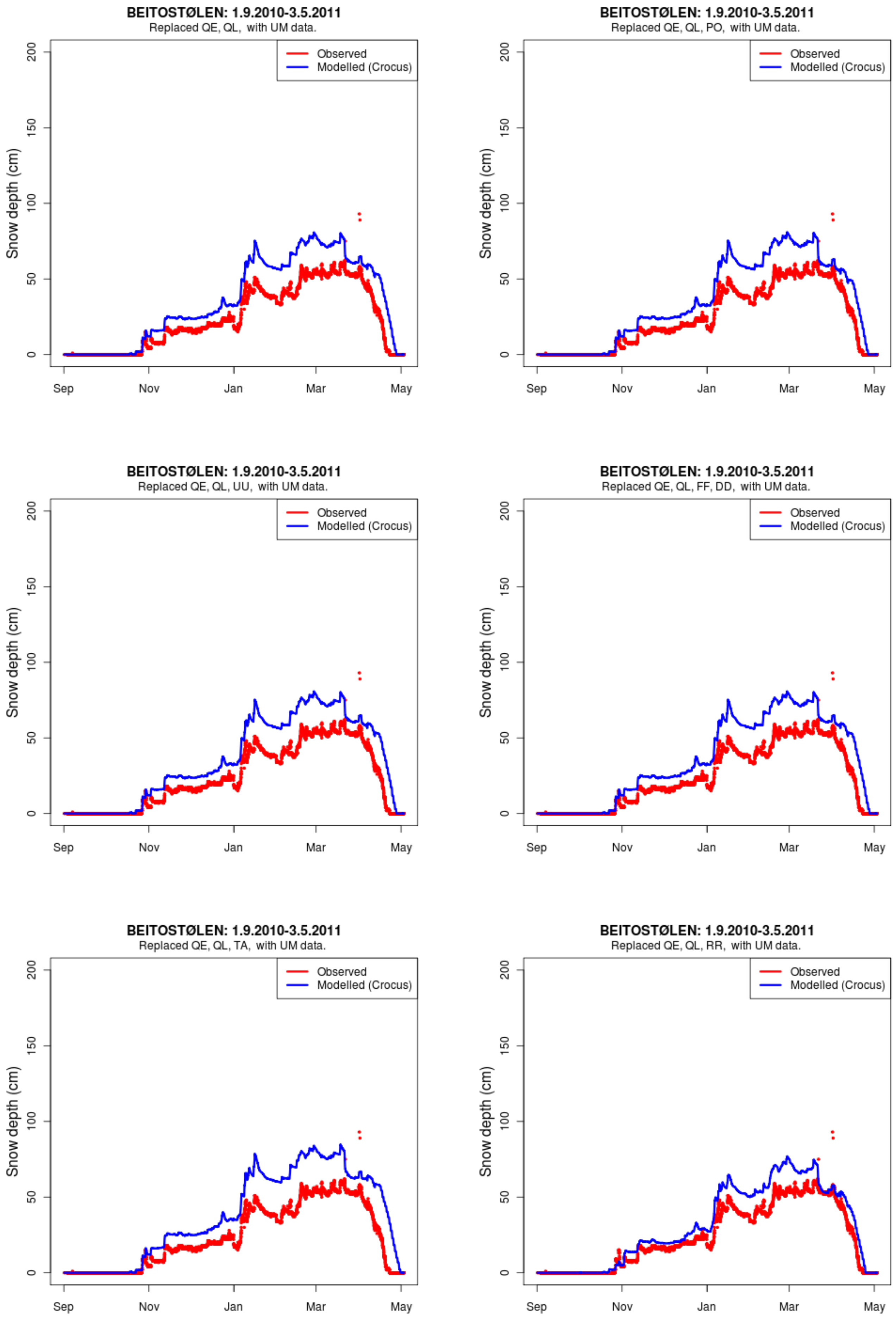


Figure B.4: Modeled and observed snow depth at Beitostølen for the winter 2010/2011, corresponding to experiments A-F (top left to bottom right). Forcing data are observations except the parameters marked in the plots. QE = Short-wave radiation, QL = Long-wave radiation, UU = specific air humidity, FF/DD = wind speed/direction, TA= air temperature and RR = precipitation.

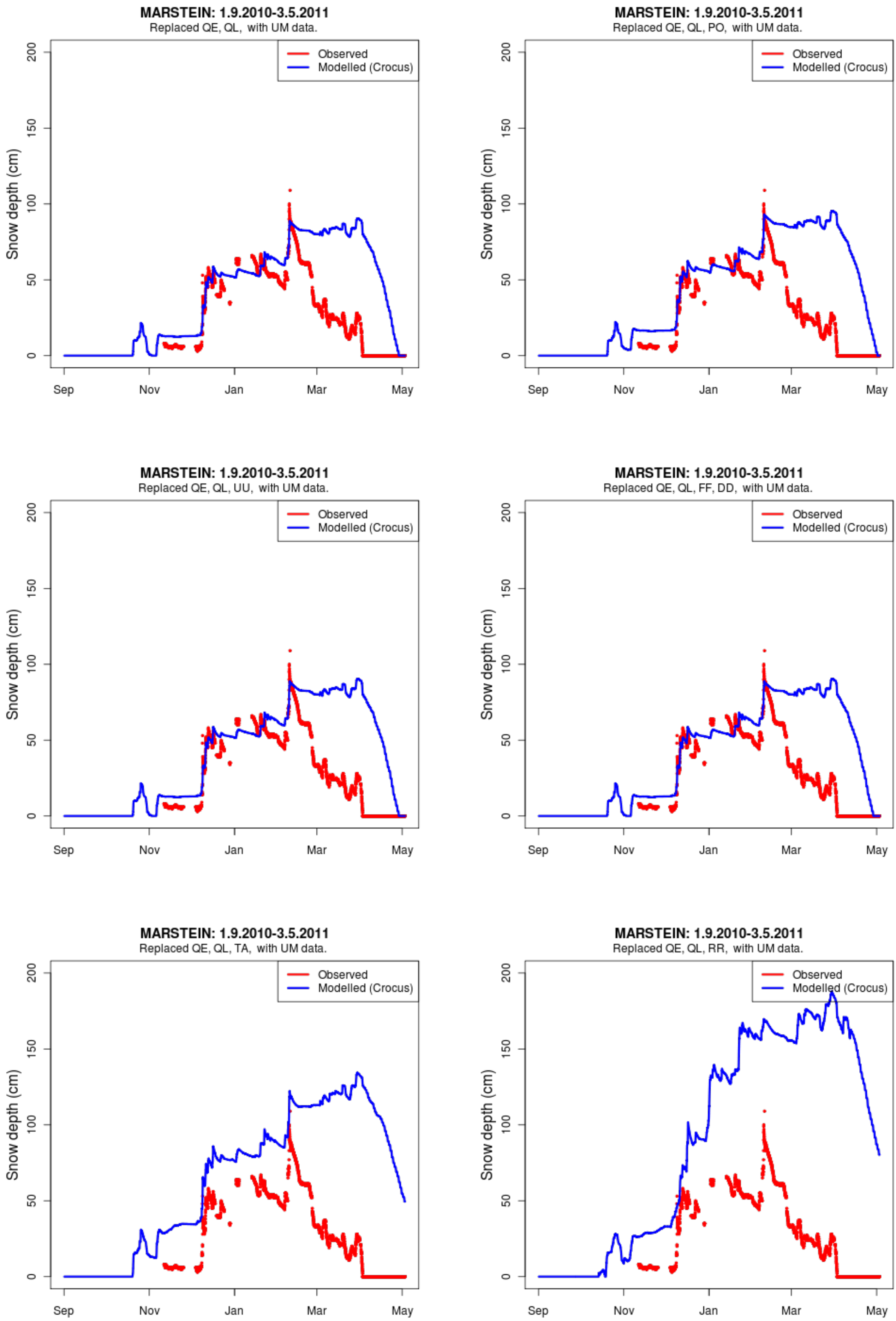


Figure B.5: Modeled and observed snow depth at Marstein for the winter 2010/2011, corresponding to experiments A-F (top left to bottom right). Forcing data are observations except the parameters marked in the plots. QE = Short-wave radiation, QL = Long-wave radiation, UU = specific air humidity, FF/DD = wind speed/direction, TA = air temperature and RR = precipitation.

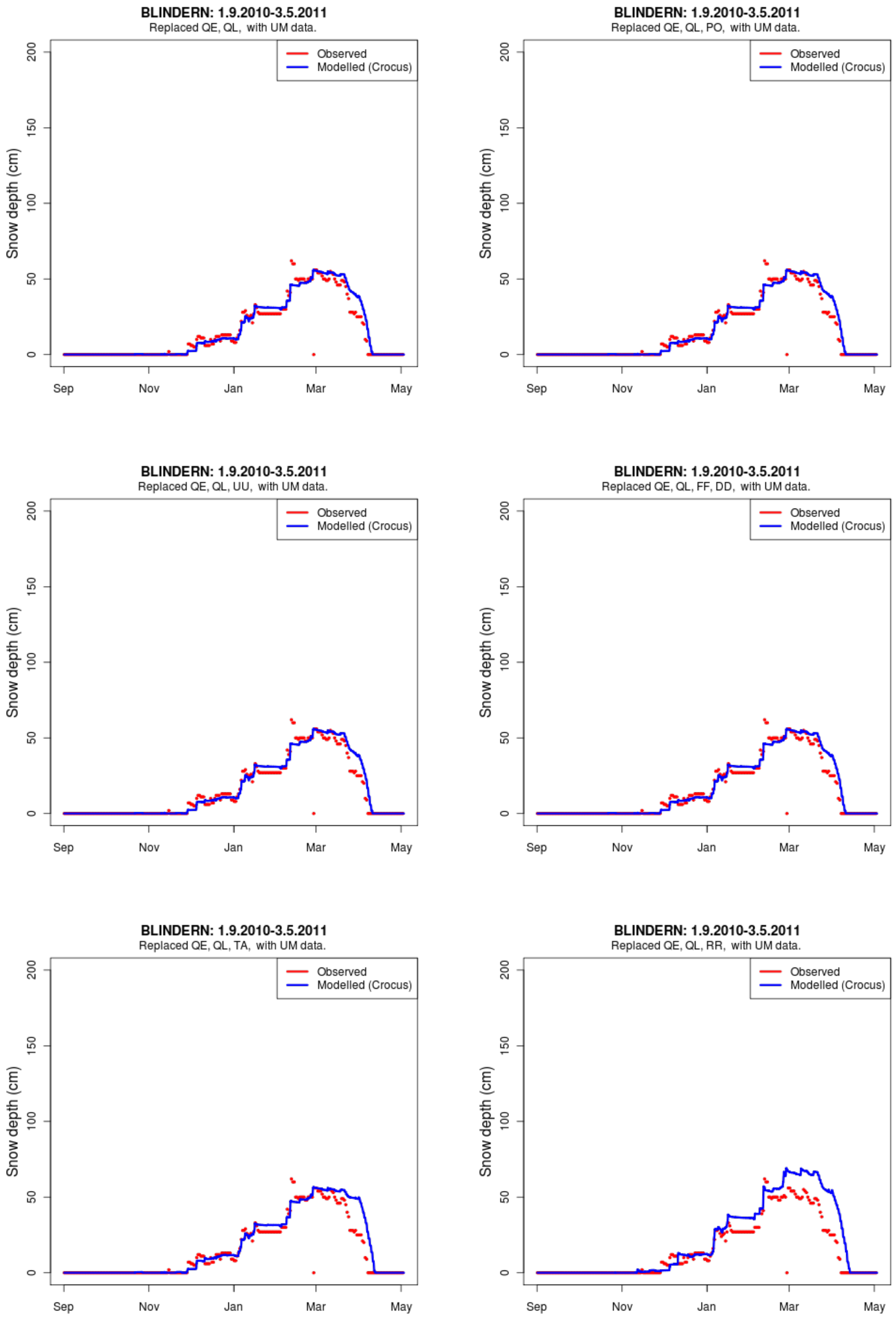


Figure B.6: Modeled and observed snow depth at Blindern for the winter 2010/2011, corresponding to experiments A-F (top left to bottom right). Forcing data are observations except the parameters marked in the plots. QE = Short-wave radiation, QL = Long-wave radiation, UU = specific air humidity, FF/DD = wind speed/direction, TA = air temperature and RR = precipitation.

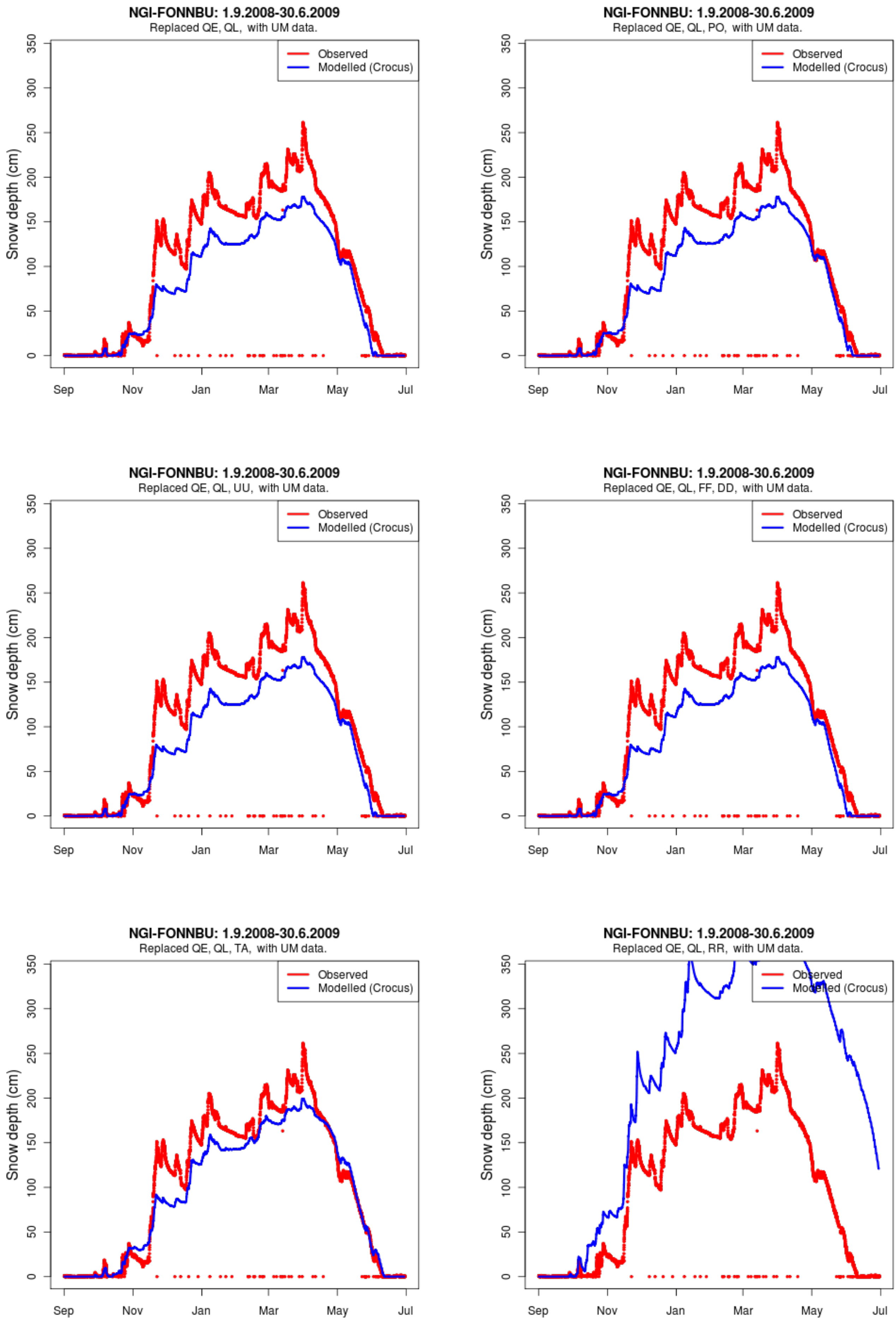


Figure B.7: Modeled and observed snow depth at Fonnbu research station (NGI) for the winter 2008/2009, corresponding to experiments A-F (top left to bottom right). Forcing data are observations except the parameters marked in the plots. QE = Short-wave radiation, QL = Long-wave radiation, UU = specific air humidity, FF/DD = wind speed/direction, TA= air temperature and RR = precipitation.

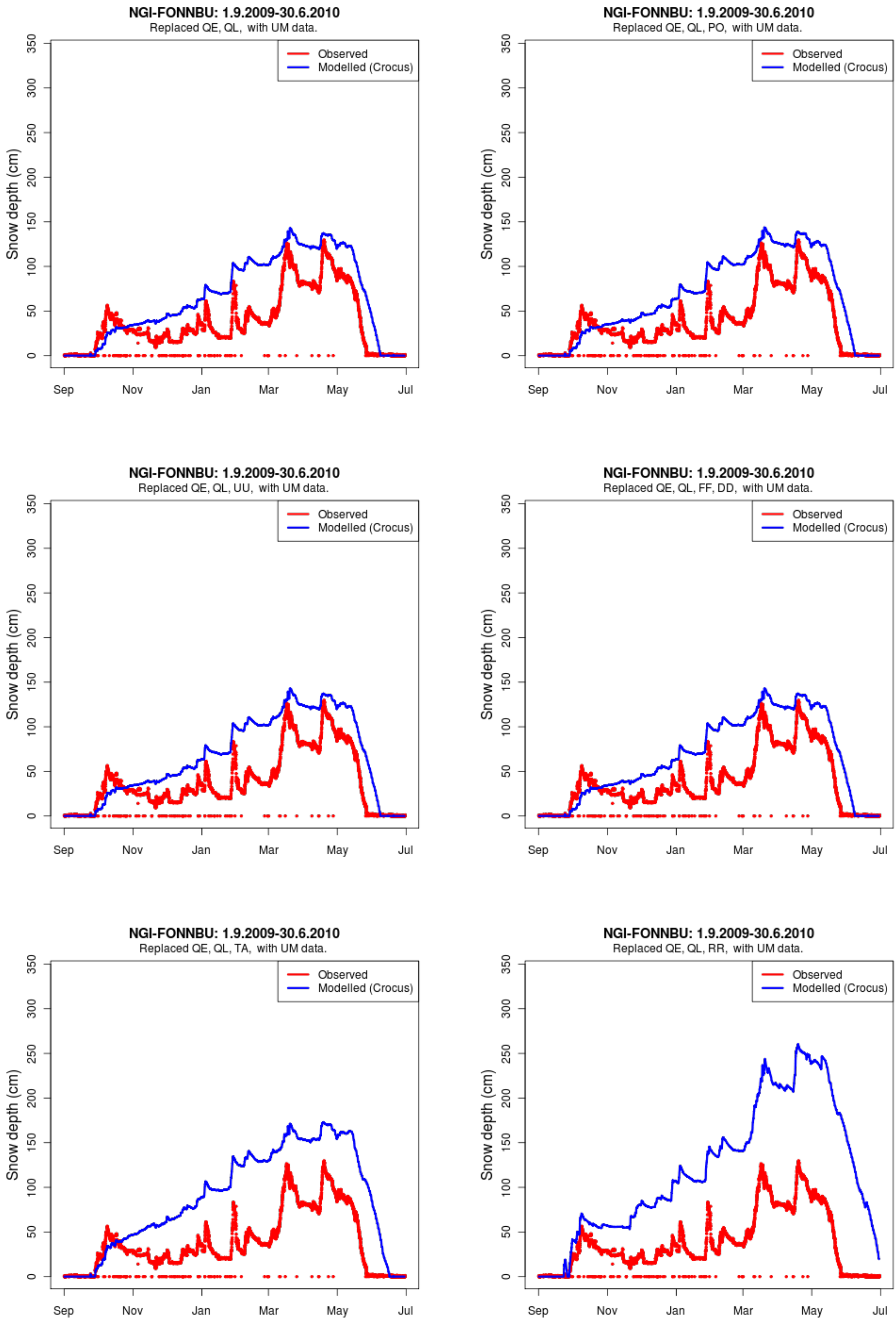


Figure B.8: Modeled and observed snow depth at Fonnbu research station (NGI) for the winter 2009/2010, corresponding to experiments A-F (top left to bottom right). Forcing data are observations except the parameters marked in the plots. QE = Short-wave radiation, QL = Long-wave radiation, UU = specific air humidity, FF/DD = wind speed/direction, TA= air temperature and RR = precipitation.

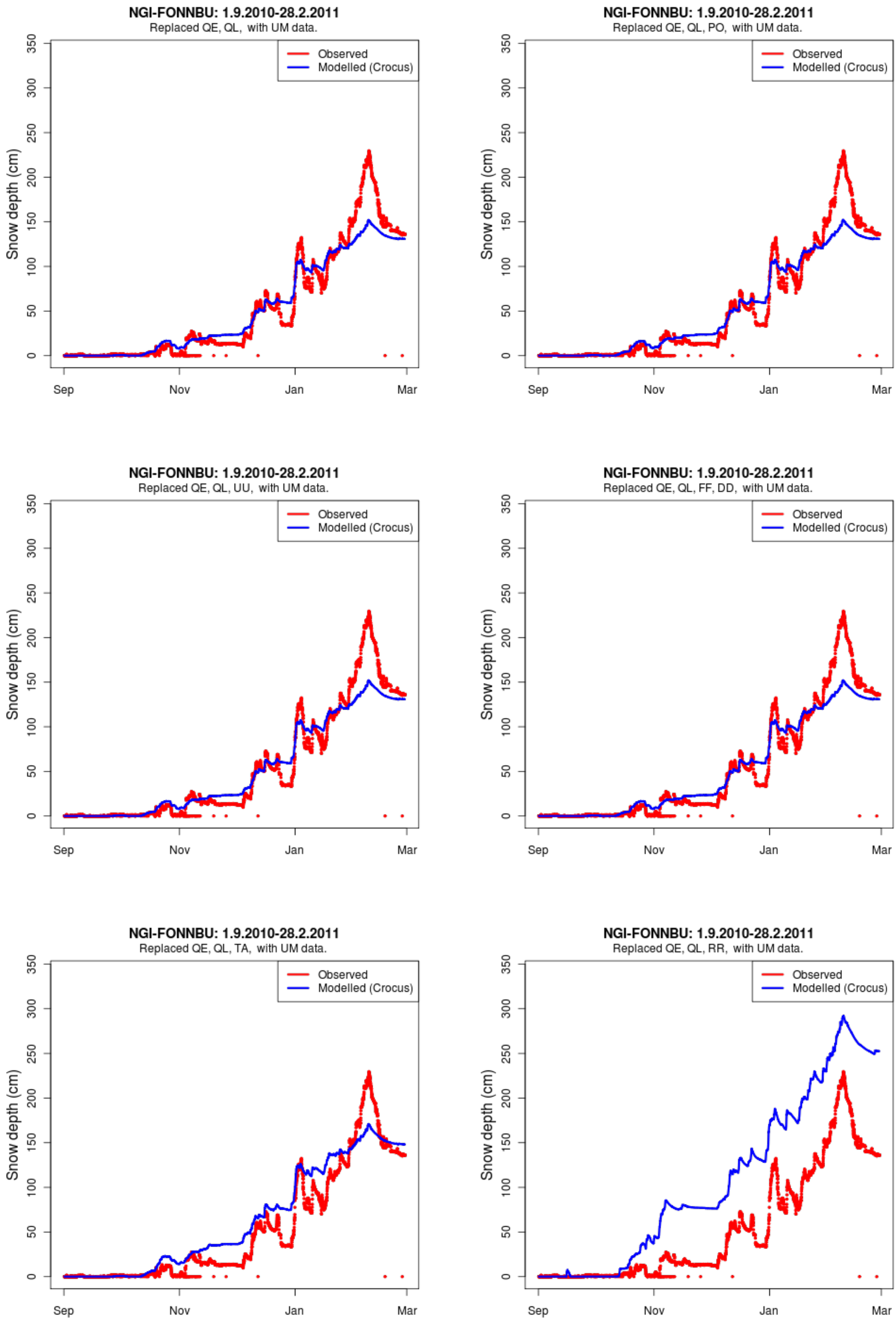


Figure B.9: Modeled and observed snow depth at Fonnbu research station (NGI) for the winter 2010/2011, corresponding to experiments A-F (top left to bottom right). Forcing data are observations except the parameters marked in the plots. QE = Short-wave radiation, QL = Long-wave radiation, UU = specific air humidity, FF/DD = wind speed/direction, TA= air temperature and RR = precipitation.

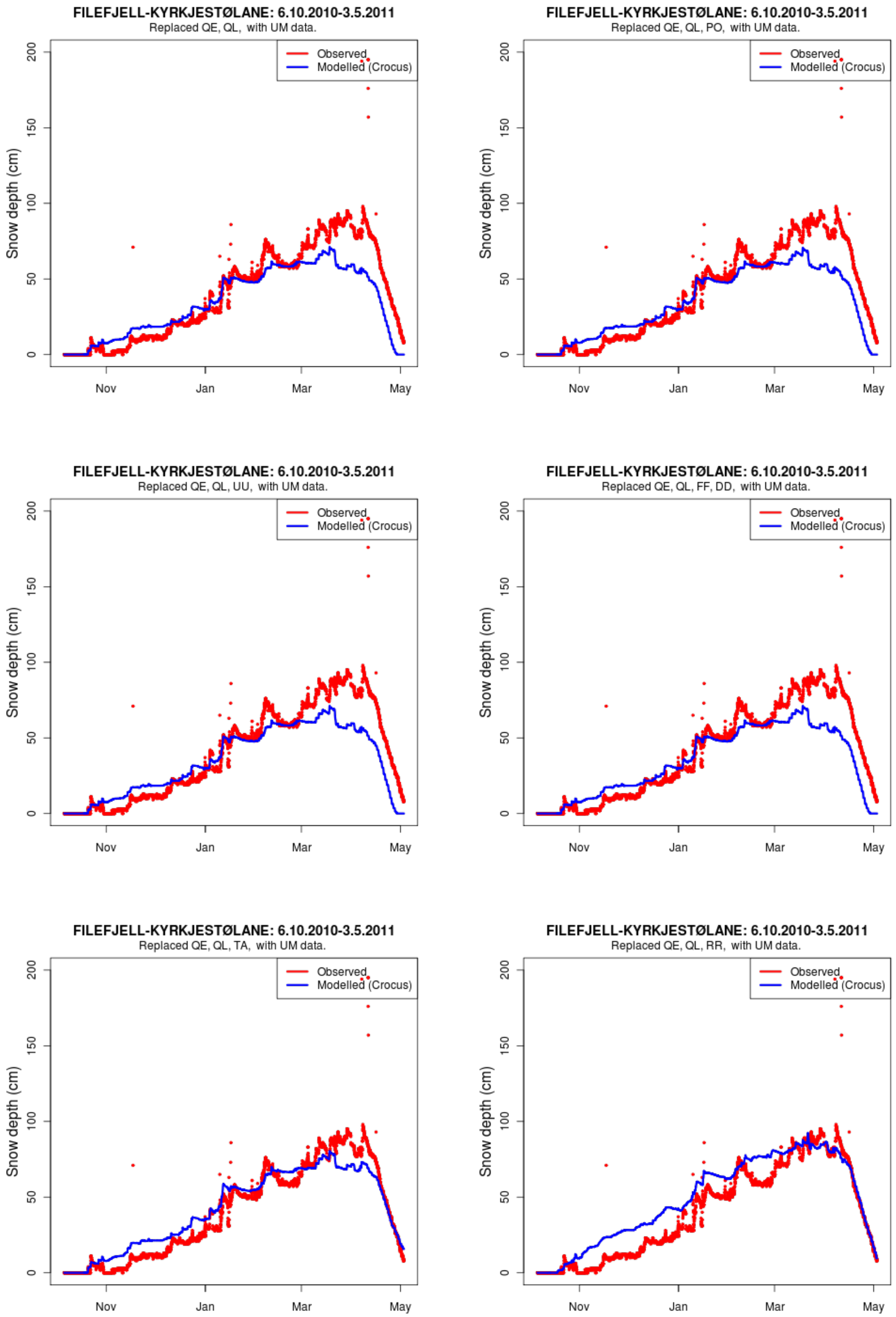


Figure B.10: Modeled and observed snow depth at Filefjell-Kyrkjestølane for the winter 2010/2011 corresponding to experiments A-F (top left to bottom right). Forcing data are observations except the parameters marked in the plots. QE = Short-wave radiation, QL = Long-wave radiation, UU = specific air humidity, FF/DD = wind speed/direction, TA= air temperature and RR = precipitation.

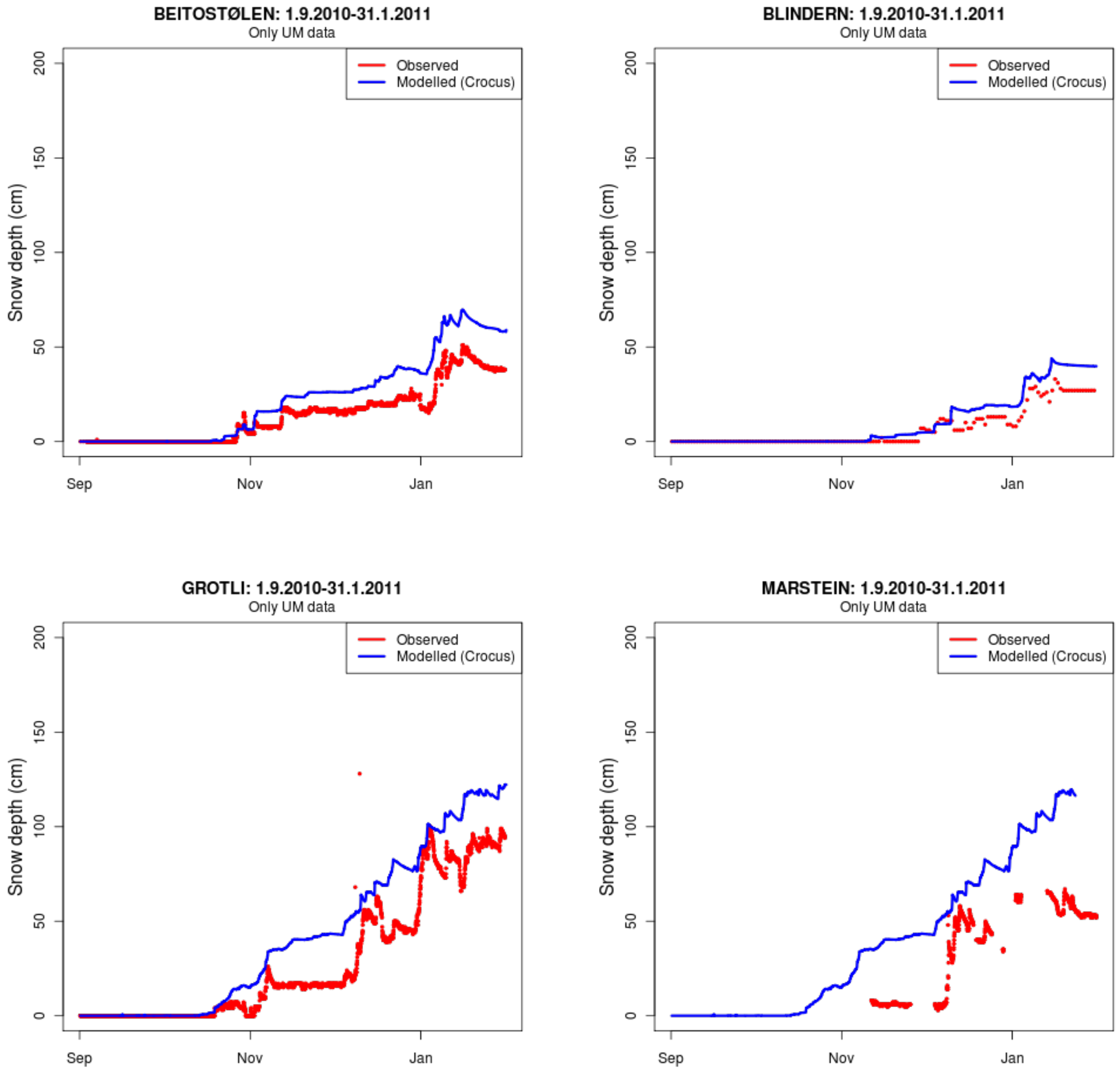


Figure B.11: Modeled and observed snow depth using raw UM forecasts for all inputparameters for the winter 2010/2011 (Eperiment G.

Appendix C

Results from experiments H-J

This appendix presents results from the comparison of alternative temperature and precipitation datasets available at met.no. Temperature and precipitation from the raw UM-4 km forecasts are replaced with these datasets when running the SURFEX model with the CROCUS snow scheme. This is organized in experiments H-J:

H: Postprocessed HIRLAM-8 km temperature forecasts (Section 3.2.4, C.1).

I: Postprocessed UM-4 km precipitation forecasts (Section 3.2.2, C.2).

J: Harmonie-4 km precipitation forecasts (Section 3.2.3, C.3).

C.1 Experiment H: Postprocessed HIRLAM-8 km temperature

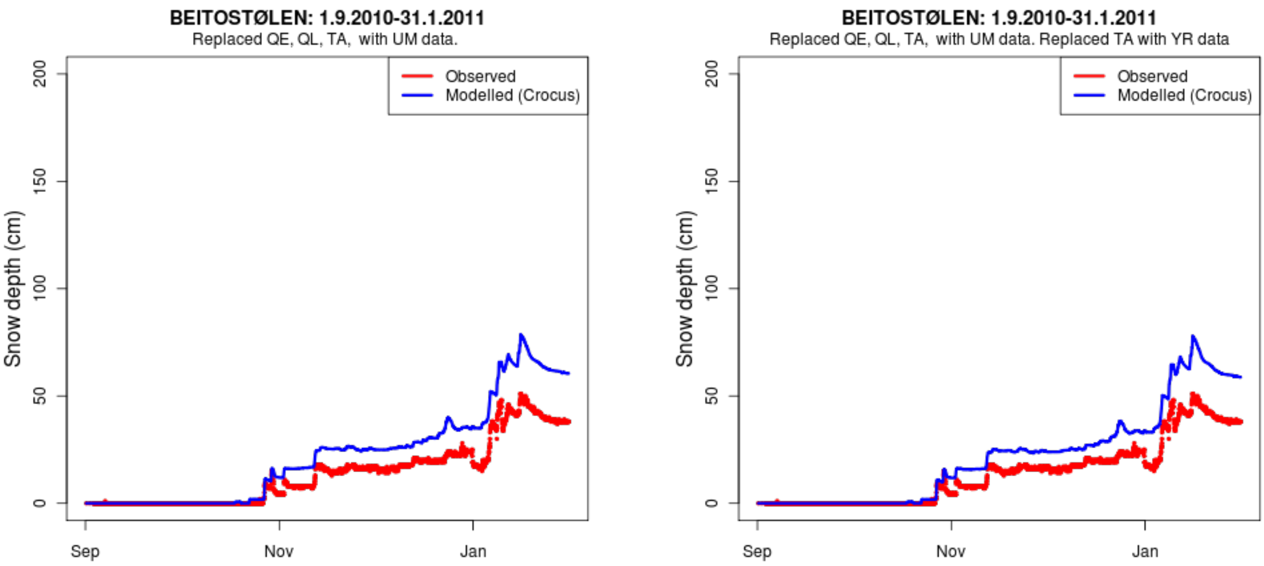


Figure C.1: Modeled and observed snow depth for Beitostølen (exp. H). Temperature from A) the raw UM model and B) postprocessed HIRLAM-8 km data.

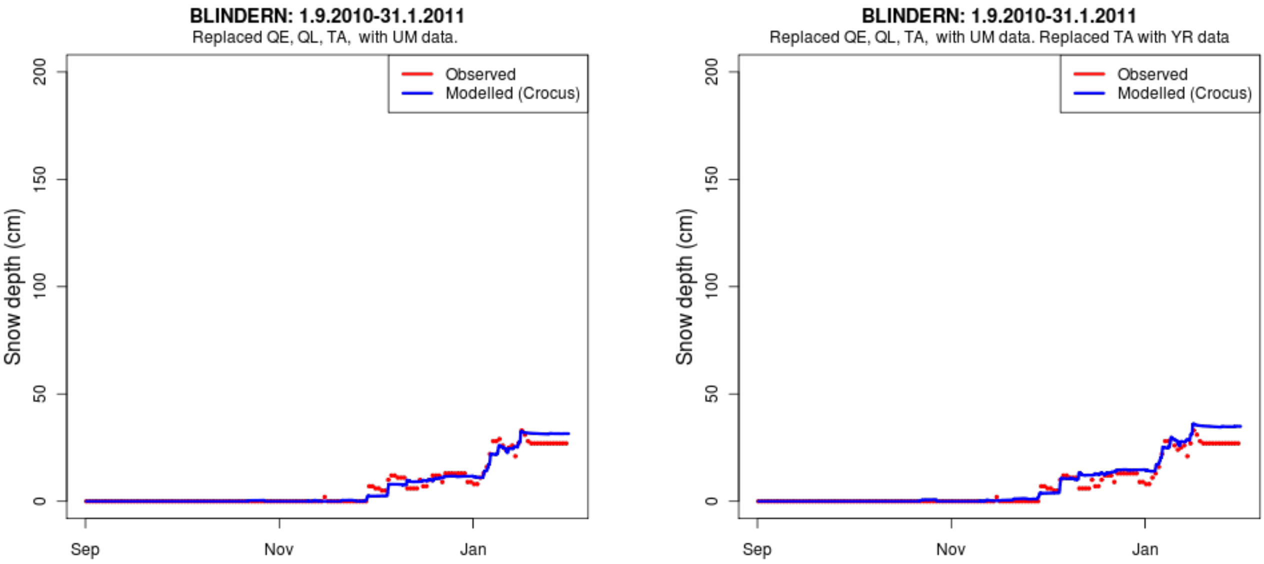


Figure C.2: Modeled and observed snow depth for Blindern (exp. H). Temperature from A) the raw UM model and B) postprocessed HIRLAM-8 km data.

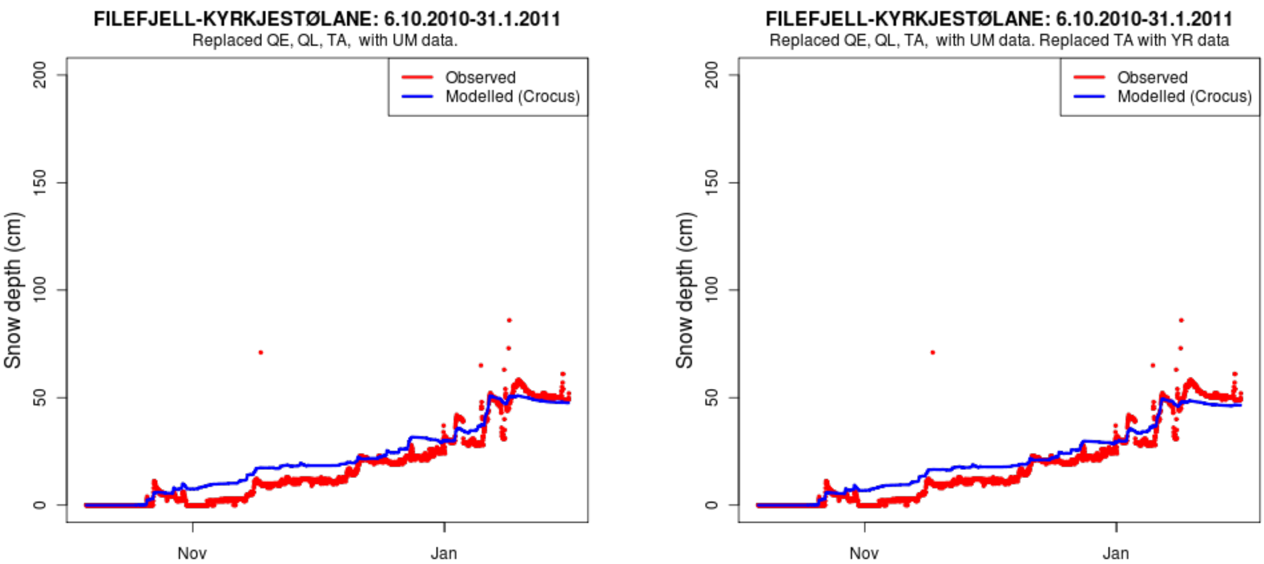


Figure C.3: Modeled and observed snow depth for Filefjell-Kyrkjestølane (exp. H). Temperature from A) raw the UM model and B) postprocessed HIRLAM-8 km data.

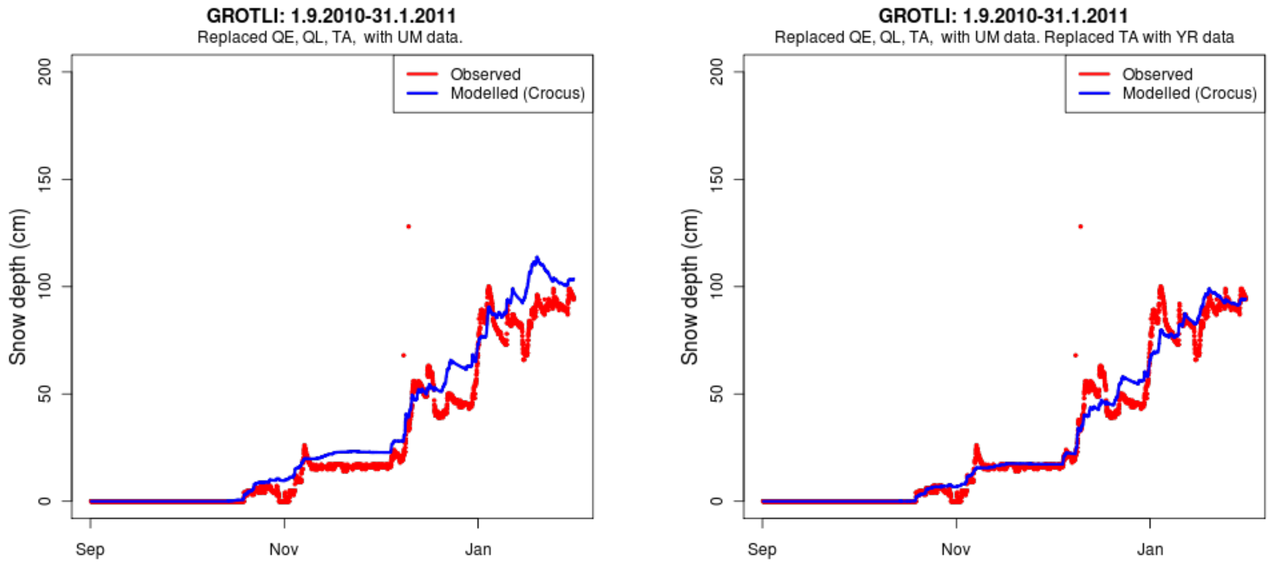


Figure C.4: Modeled and observed snow depth for Grotli (exp. H). Temperature from A) the raw UM model and B) postprocessed HIRLAM-8 km data.

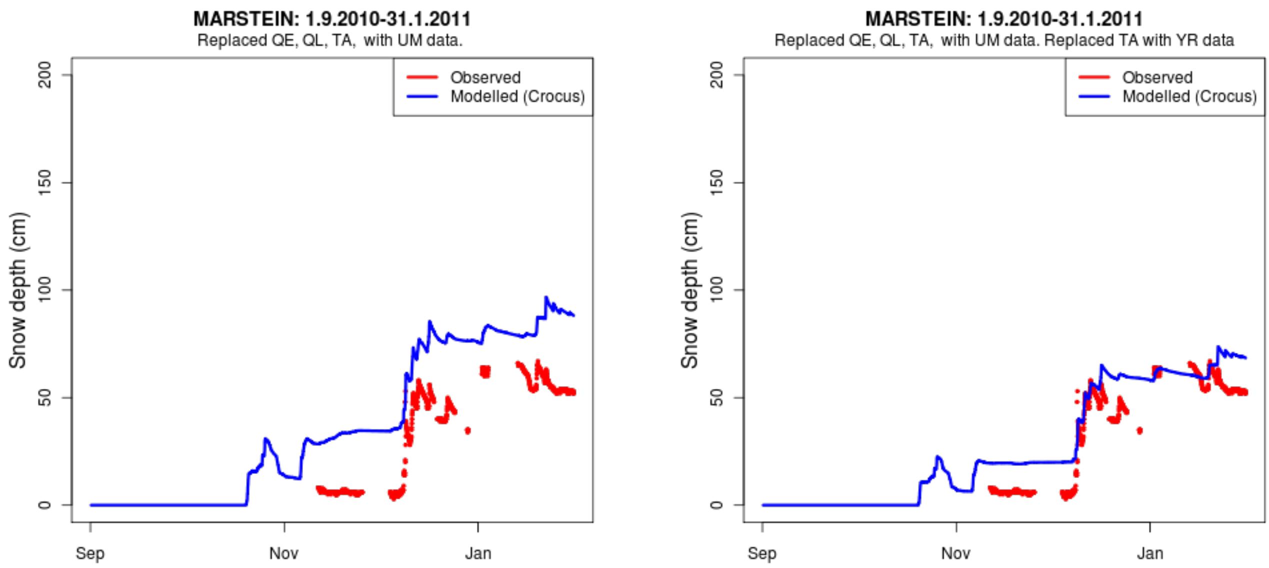


Figure C.5: Modeled and observed snow depth for Marstein (exp. H). Temperature from A) the raw UM model and B) postprocessed HIRLAM-8 km data.

C.2 Experiment I: Postprocessed UM-4 km precipitation

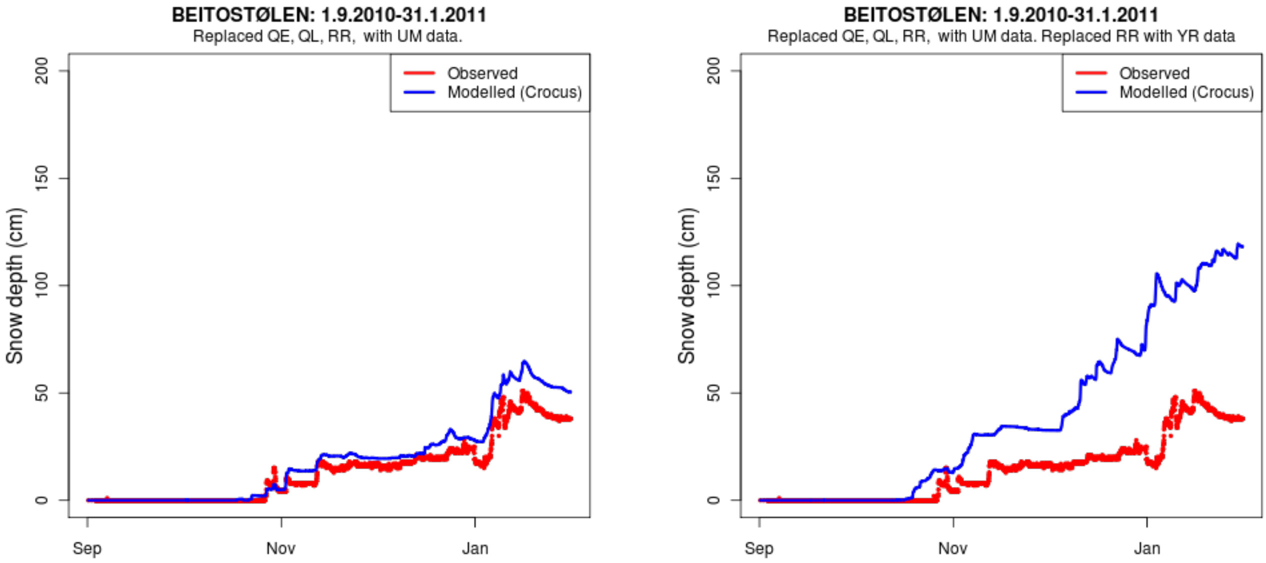


Figure C.6: Modeled and observed snow depth for Beitostølen (exp. I). Precipitation from A) the raw UM model and B) postprocessed UM-4 km data.

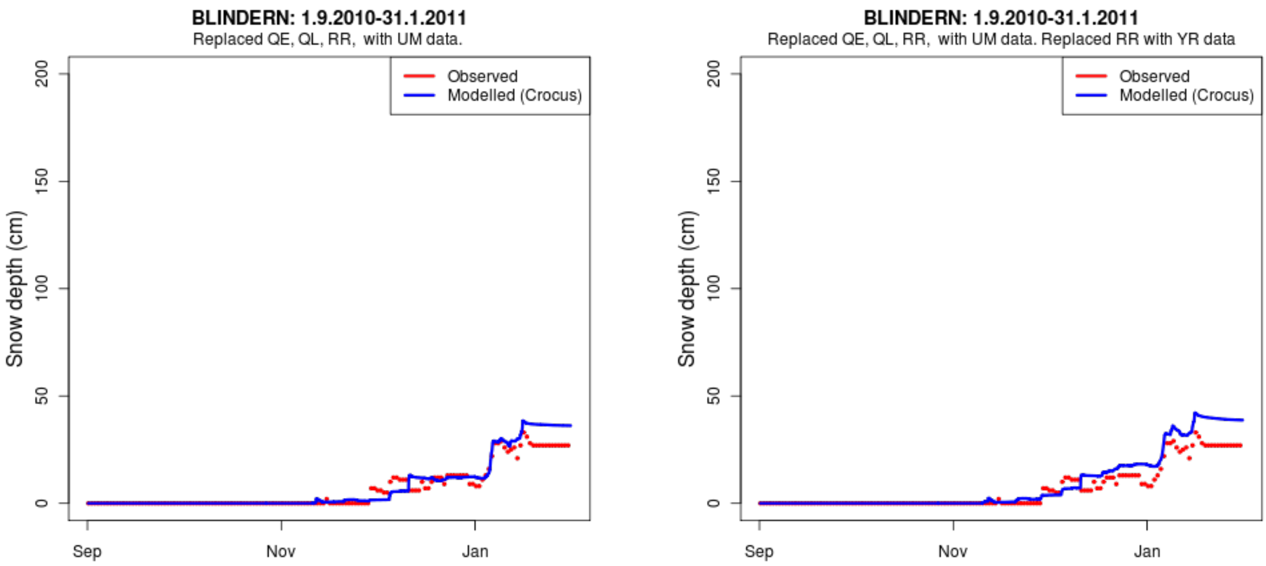


Figure C.7: Modeled and observed snow depth for Blindern (exp. I). Precipitation from A) the raw UM model and B) postprocessed UM-4 km data.

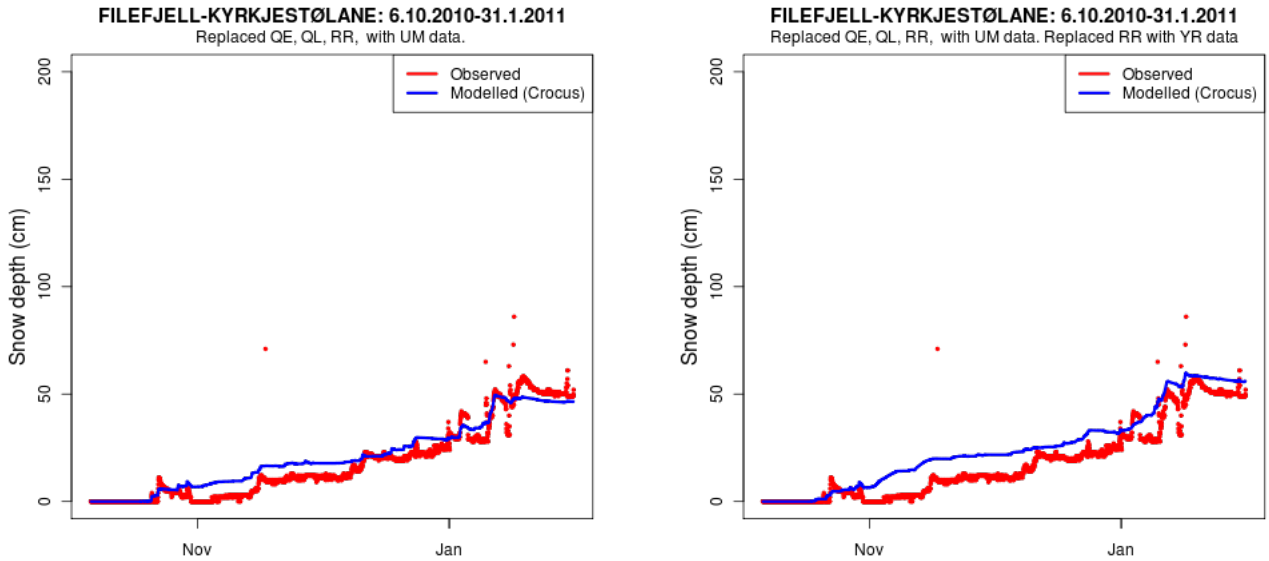


Figure C.8: Modeled and observed snow depth for Filefjell-Kyrkjestølane (exp. I). Precipitation from A) the raw UM model and B) postprocessed UM-4 km data.

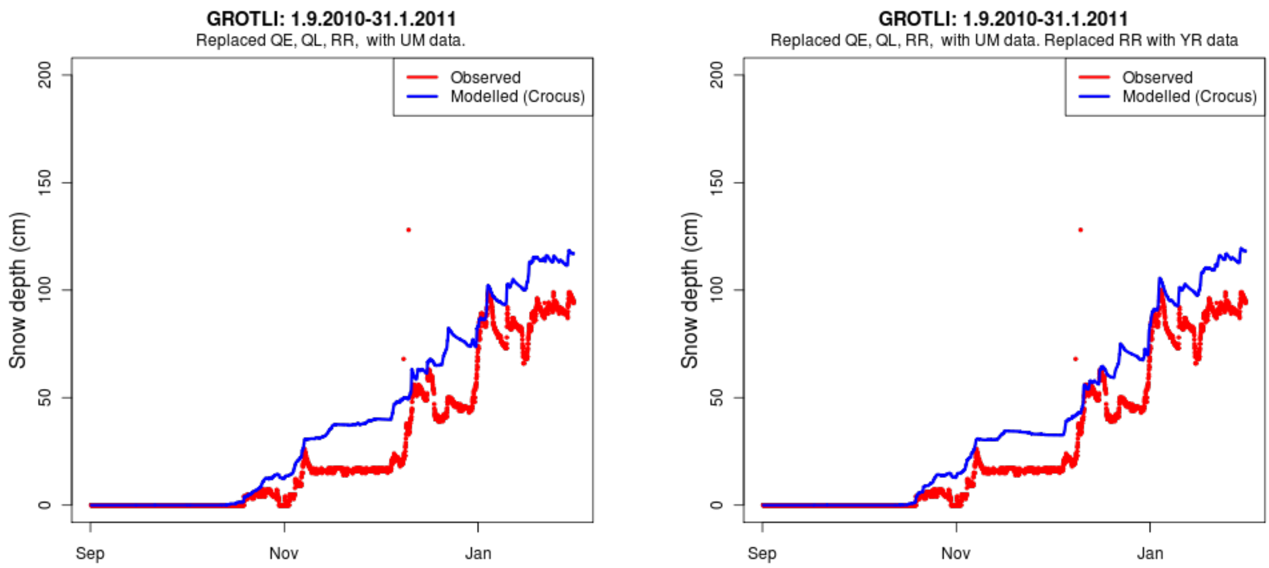
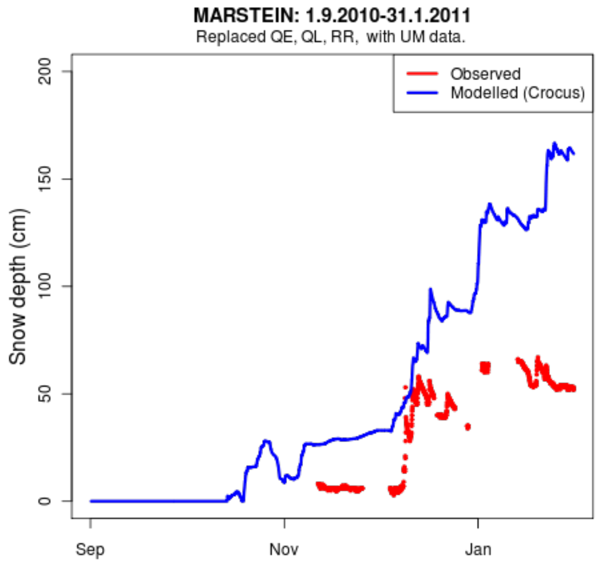


Figure C.9: Modeled and observed snow depth for Grotli (exp. I). Precipitation from A) the raw UM model and B) postprocessed UM-4 km data.



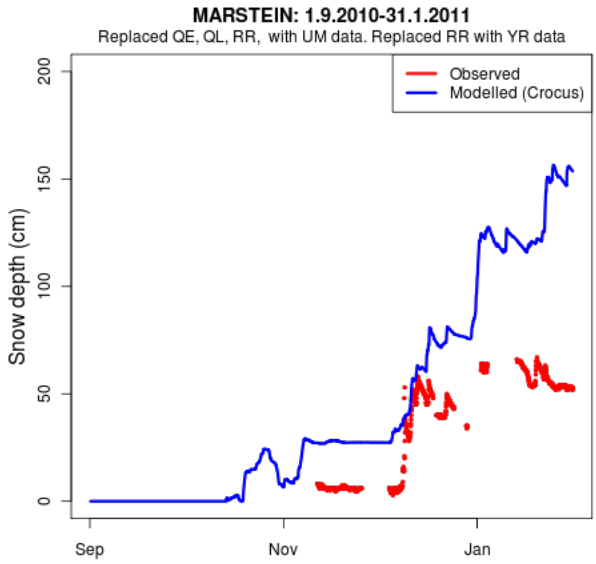


Figure C.10: Modeled and observed snow depth for Marstein (exp. I). Precipitation from A) the raw UM model and B) postprocessed UM-4 km data.

C.3 Experiment J: HARMONIE precipitation

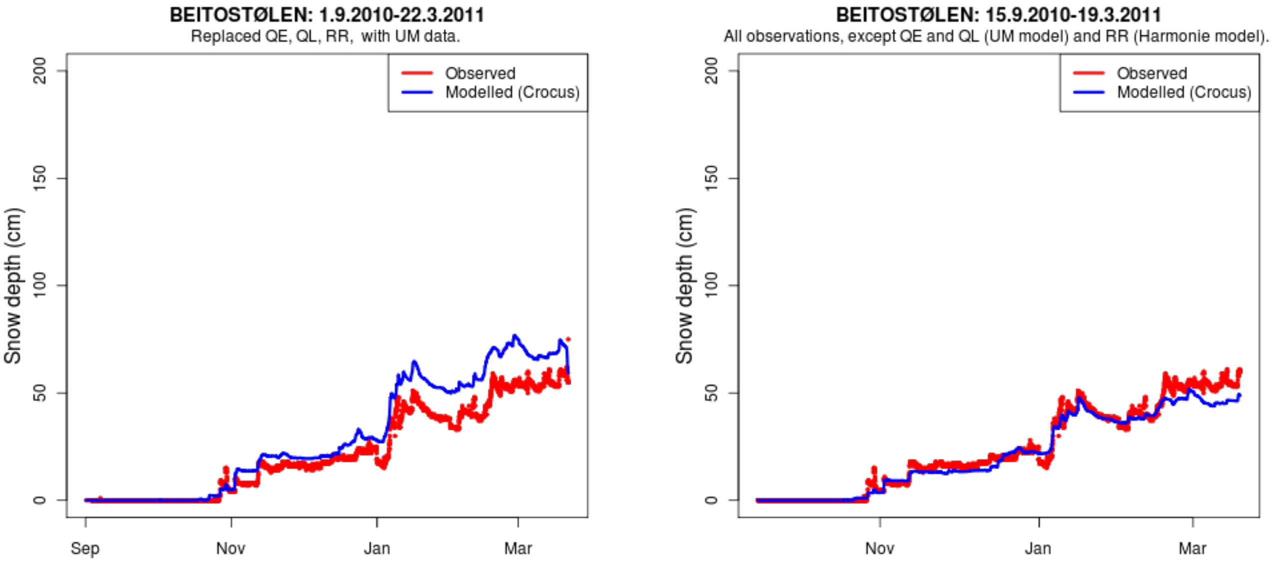


Figure C.11: Modeled and observed snow depth for Beitostølen (exp. J). Precipitation from A) the UM model and B) the HARMONIE model.

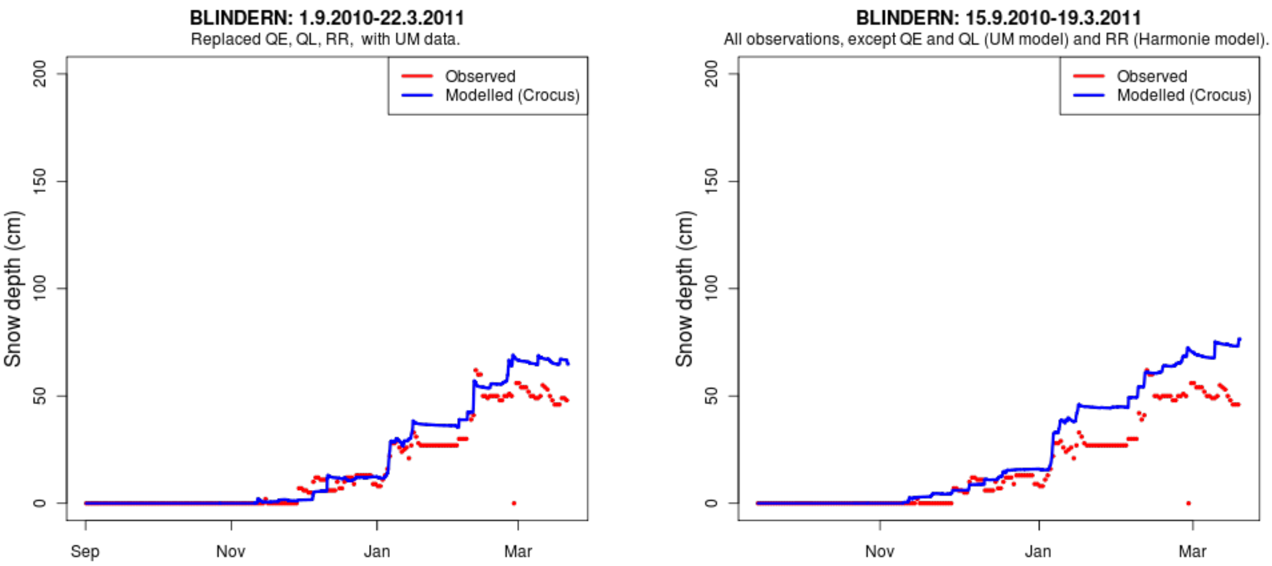


Figure C.12: Modeled and observed snow depth for Blindern (exp. J). Precipitation from A) the UM model and B) the HARMONIE model.

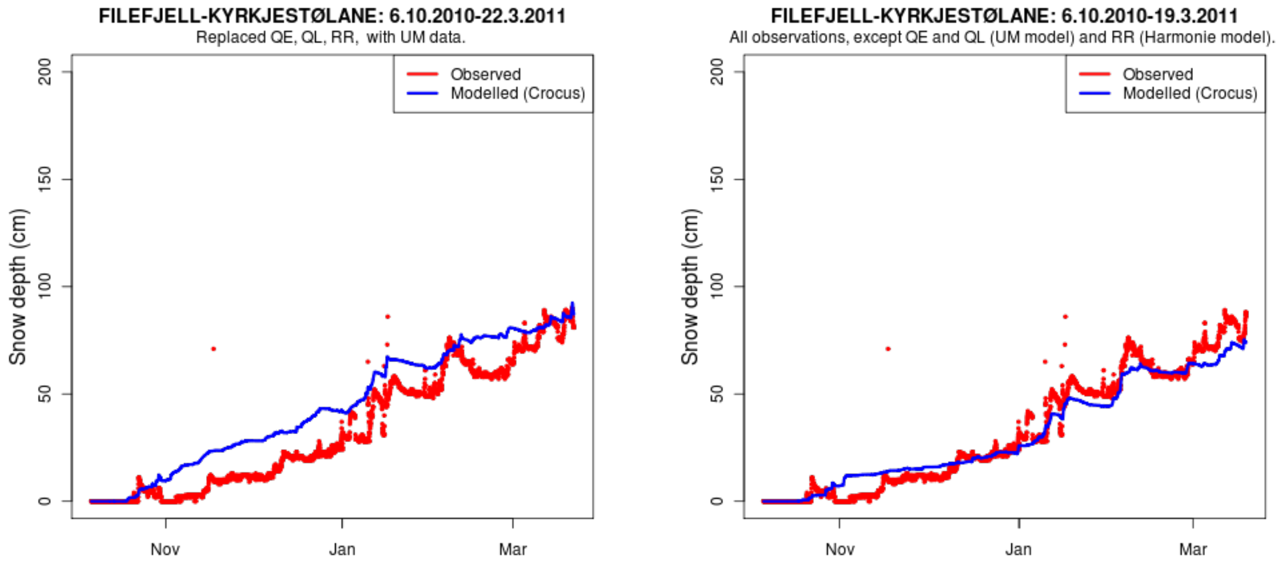


Figure C.13: Modeled and observed snow depth for Filefjell-Kyrkjestølane (exp. J). Precipitation from A) the UM model and B) the HARMONIE model.

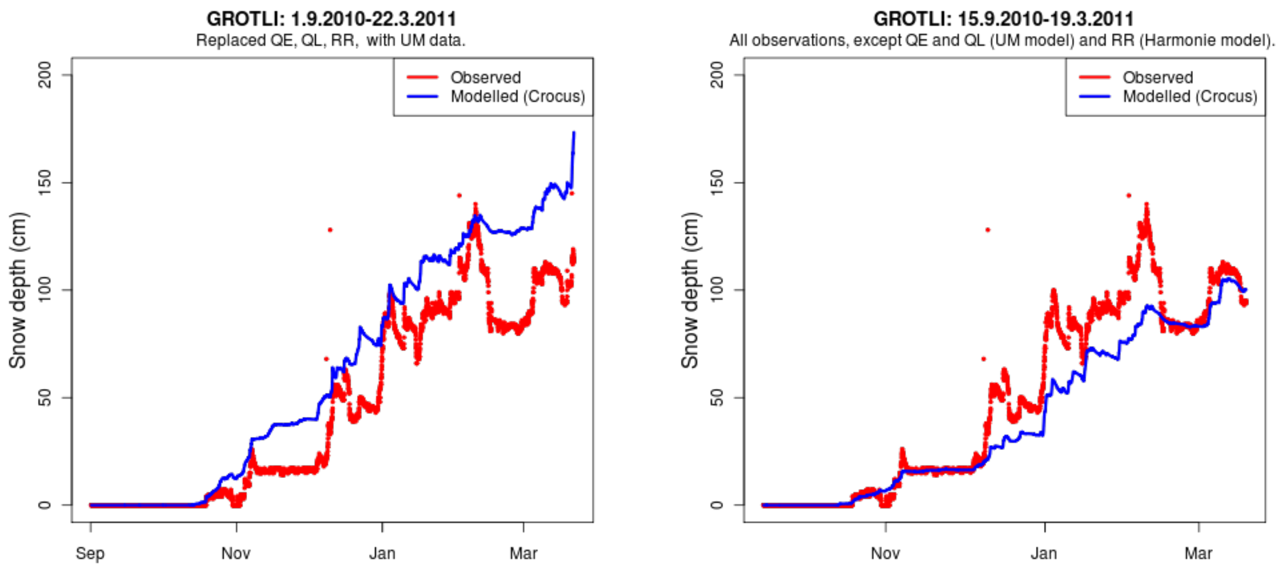


Figure C.14: Modeled and observed snow depth for Grotli (exp. J). Precipitation from A) the UM model and B) the HARMONIE model.

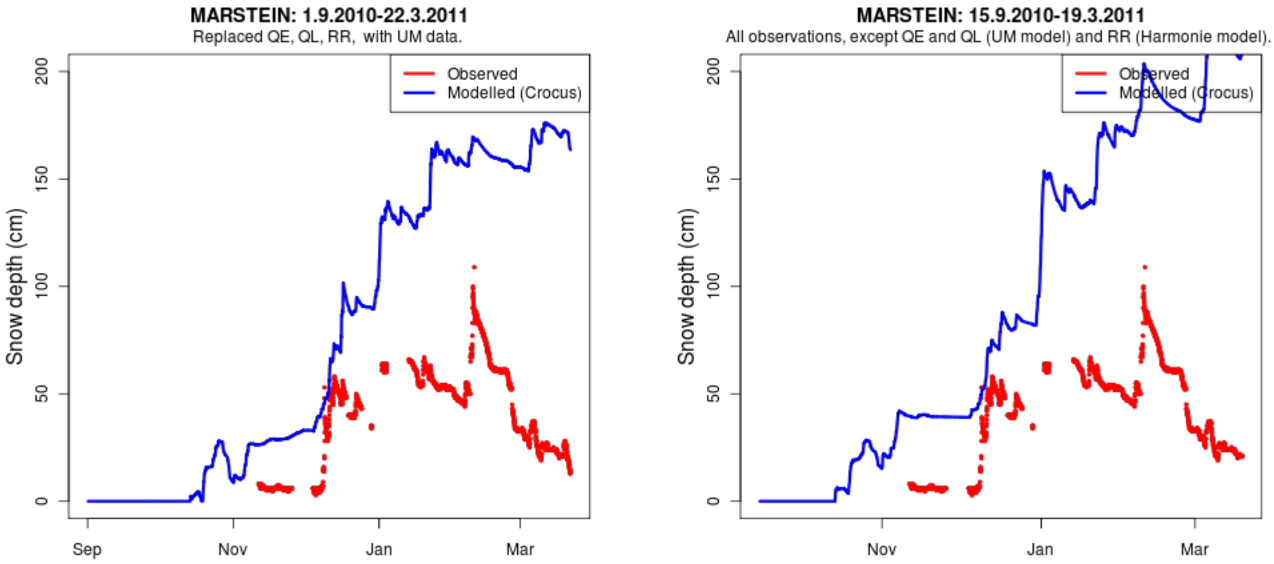


Figure C.15: Modeled and observed snow depth for Marstein (exp. J). Precipitation from A) the UM model and B) the HARMONIE model.

Appendix D

Snow profiles

This appendix includes observed and modeled snow profiles from Fonnbu research station during the winter 2008/2009. The actual dates are shown in Figure D.1. A mid-winter situation with dry snow (26 February 2009) and a situation representing the start of the snow melt season (11 April 2009) has been presented in Section 4.3.2. The two remaining dates (17 January 2009 and 5 February 2009) are included in this appendix (Figures D.2 and D.3). The observed profiles are image files provided by NGI (output from the Snow Pilot software). The modeled profiles are image files produced using the Snowtools toolbox (Morin and Willemet, 2010).

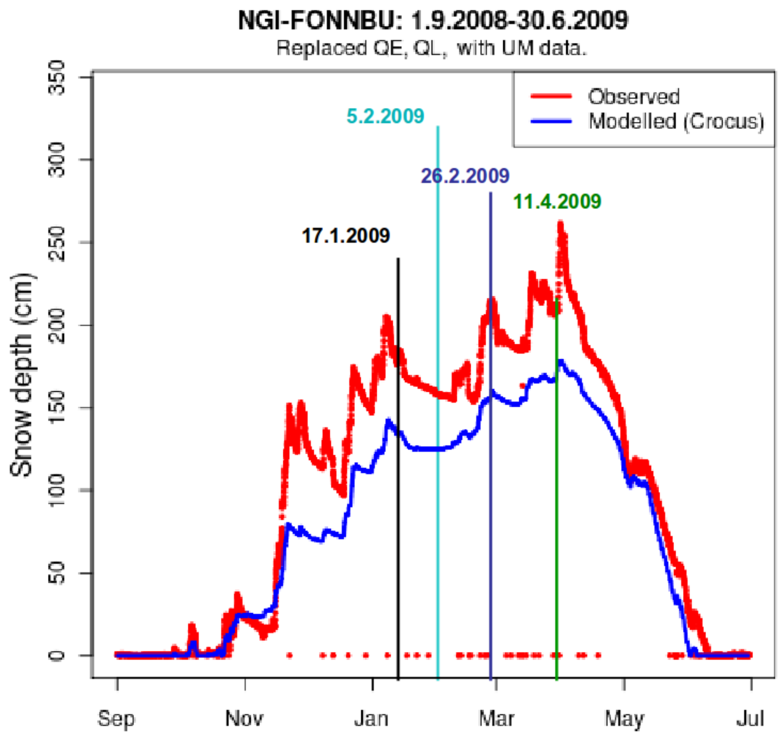
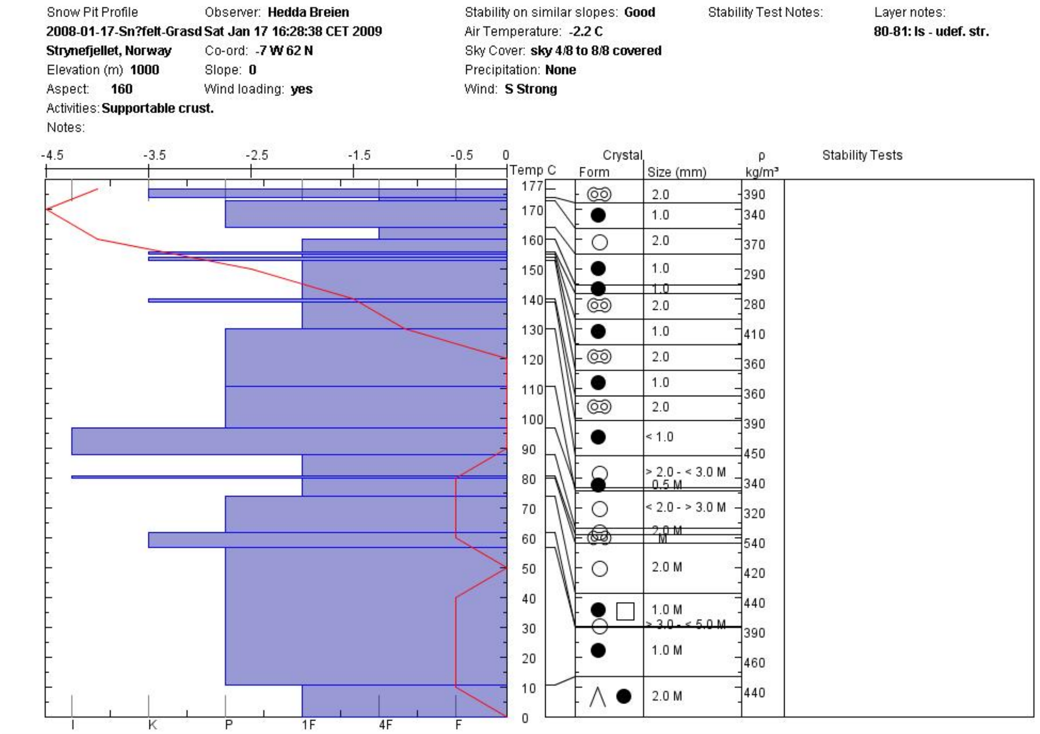
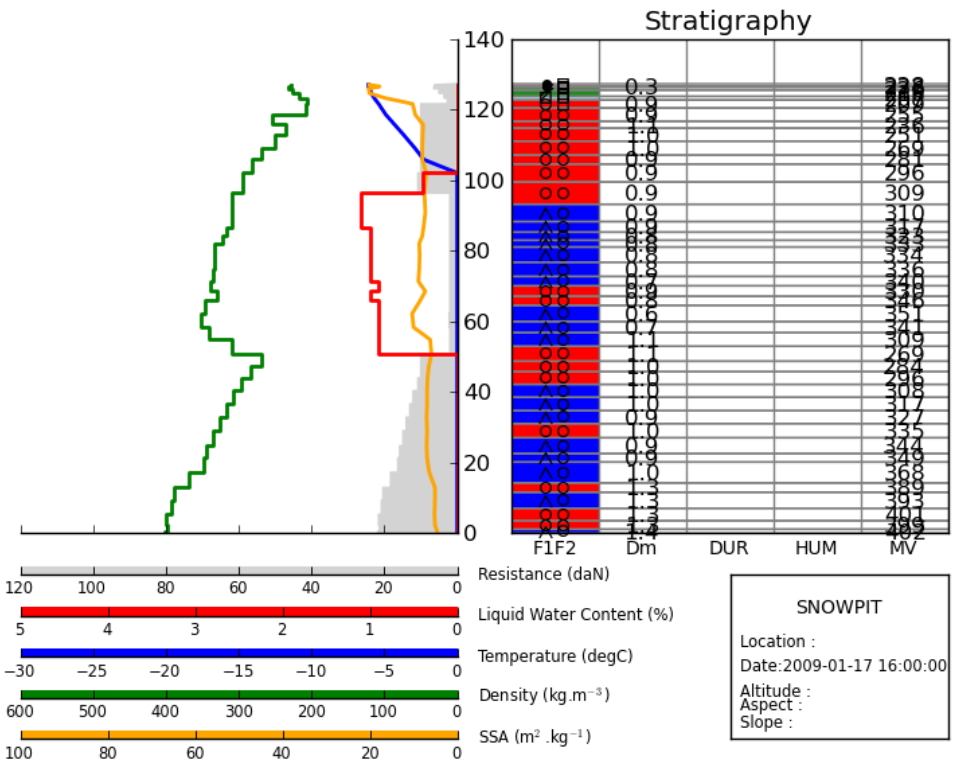


Figure D.1: Illustration of the dates when NGI has carried out snow profiles in the field during the winter 2008/2009.

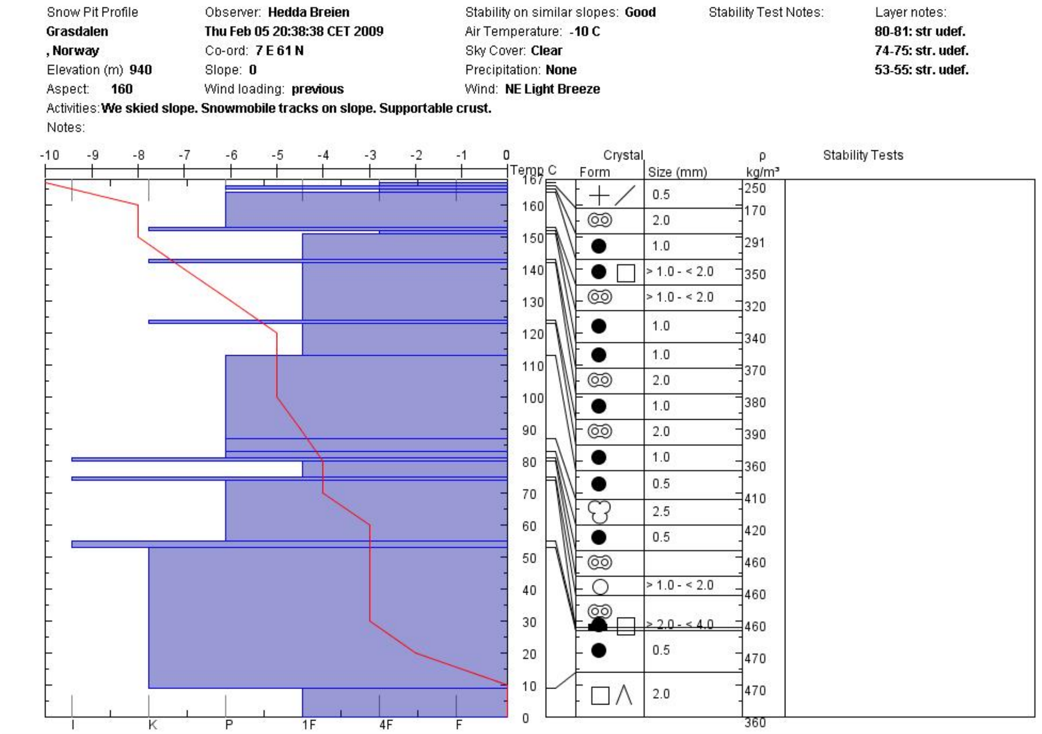


(a) Observed

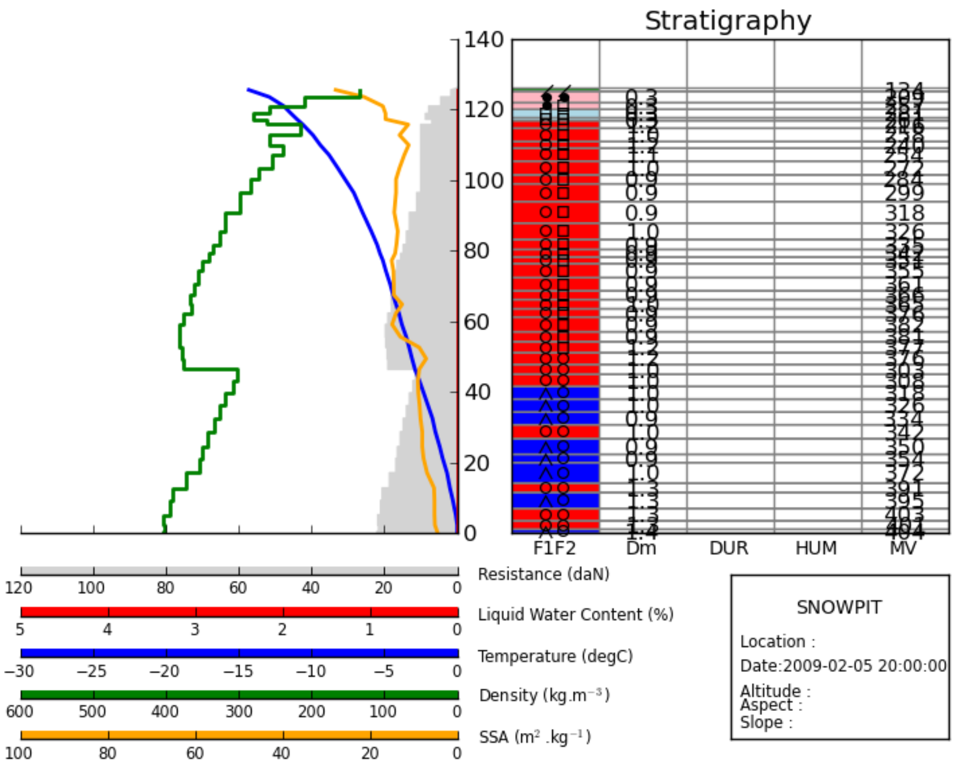


(b) Modeled

Figure D.2: Snow profile 17 January 2009 at Fonnbu research station: a) Observed (NGI) and b) modeled (CROCUS).



(a) Observed



(b) Modeled

Figure D.3: Snow profile 5 February 2009 at Fonnbu research station: a) Observed (NGI) and b) modeled (CROCUS).