The Cryosphere Discuss., https://doi.org/10.5194/tc-2017-220
Manuscript under review for journal The Cryosphere
Discussion started: 3 November 2017

Forcing the SURFEX/Crocus snow model with combined hourly meteorological forecasts and gridded observations in southern Norway

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Abstract. In Norway, thirty percent of the annual precipitation falls as snow. Knowledge of the snow reservoir is therefore important for energy production and water resource management. The land surface model SURFEX with the detailed snowpack scheme Crocus (SURFEX/Crocus) has been run with a grid spacing of approximately 1 km over an area in southern Norway for two years (01 September 2014 - 31 August 2016), using two different forcing data sets: 1) hourly meteorological forecasts from the operational weather forecast model AROME MetCoOp (2.5 km grid spacing), and 2) gridded hourly observations of temperature and precipitation (1 km grid spacing) in combination with the meteorological forecasts from AROME MetCoOp. We present an evaluation of the modeled snow depth and snow cover, as compared to point observations of snow depth and to MODIS satellite images of the snow-covered area. The evaluation focuses on snow accumulation and snow melt. The results are promising. Both experiments are capable of simulating the snow pack over the two winter seasons, but there is an overestimation of snow depth when using only meteorological forecasts from AROME MetCoOp, although the snow-covered area throughout the melt season is better represented by this experiment. The errors, when using AROME MetCoOp as forcing, accumulate over the snow season, showing that assimilation of snow depth observations into SURFEX/Crocus might be necessary when using only meteorological forecasts as forcing. When using gridded observations, the simulation of snow depth is significantly improved, which shows that using a combination of gridded observations and meteorological forecasts to force a snowpack model is very useful and can give better results than only using meteorological forecasts. There is however an underestimation of snow ablation in both experiments. This is mainly due to the absence of wind-induced erosion of snow in the SURFEX/Crocus model, underestimated snow melt and biases in the forcing data.

1 Introduction

Snow is a key element in the hydrological cycle and in Arctic areas. Seasonal snow covers large areas of the Northern Hemisphere. In these areas the snow cover extent in spring has reduced more rapidly the past 40 years than over the past 90 years (Brown and Robinson, 2011). Generally, the size of the area covered by snow is decreasing, and the period with snow-covered ground is reducing. Information about changes in the seasonal variation and the amounts of snow are important for many societal applications and for Arctic ecosystem changes. An overview of changes in snow and impacts due to these changes, is provided by (Bokhorst et al., 2016). As an example, in Norway, 30% of the precipitation falls as snow (Saloranta, 2012), and knowledge of the snow conditions is of high importance for local flood prediction, hydropower production planning, snow avalanche prediction for the mountains, traffic flow and management, tourism, and mobility and food access for mammals living in the snow.

For these purposes, a wide range of empirically and physically based snow models have been developed and reported in literature (see e.g. Magnusson et al. (2015)). Several snow model intercomparison projects have also been performed, e.g. by Essery et al. (2013). Models differ in several ways e.g. the parameterization and simplification of snow processes, the spatial and temporal resolution or the need for input data of various weather elements. Physical parameterization of the snow processes is the main focus regarding the physically based models, while the empirically based models generally include more statistics to capture the physical snow processes. The need for input data is therefore usually also larger and more detailed for physically based models than for the empirically based models. Empirical models also often need calibration.

In Norway, hydropower production companies and the national flood forecasting service use snow models operationally for estimating the snow distribution and runoff in the various drainage areas. Historically, the HBV model (Bergstrøm, 1976; Sælthun, 1996) is extensively used in the operational production chains. However, the snow routine in the HBV model is an empirical degree day model, using daily values of temperature and precipitation (Sælthun, 1996). Atmospheric models used in the operational weather forecasting are presently evolving fast, by including more detailed models of land surface processes such as snow and soil. SURFEX (Surface Externaliseé) (Masson et al., 2013) is an example of a land surface model, which can be run both inline the atmospheric weather forecast model AROME MetCoOp (Müller et al., 2017), or offline as a stand-alone model. At the Norwegian Meteorological Institute (MET Norway), the AROME MetCoOp model is run operationally to provide short-term weather forecasts covering large parts of the Nordic region (Müller et al., 2017). In this study we are evaluating the performance of the SURFEX model, using the Crocus snow scheme (Vionnet et al., 2011) for Norwegian snow conditions. We selected a west-east transect in a mountainous area of South Norway as the study area. Experiments were performed by applying two different data sets from the winters 2014/2015 and 2015/1016 as forcing to the SURFEX/Crocus model: 1) Predictions from the AROME MetCoOp model (Müller et al., 2017) with a grid spacing of 2.5 km and 2) Gridded observations of precipitation and temperature (GridObs) with a grid spacing of 1 km (Lussana et al., 2017). Both data sets have 1 hourly temporal resolution, and are discussed in detail in section 2.2. The aim was to compare and combine different gridded forcing data sets as input to the SURFEX/Crocus model and validate the computed accumulated snow amounts and snow melt pattern in both Norwegian mountains and lowlands. The simulations were run without any assimilation of snow observations. The results may be used for future development of a system for daily snow mapping.

2 Model and data sets

2.1 The SURFEX/Crocus model

The model used in this study is the detailed snowpack model Crocus (Brun et al., 1992; Vionnet et al., 2011) coupled with the ISBA land surface model within the SURFEX (Surface Externaliseé) interface (Masson et al., 2013). The soil scheme used is ISBA-DIF (Boone et al., 2000; Habets et al., 2003), which uses a multi-layer approach. The snowpack scheme Crocus

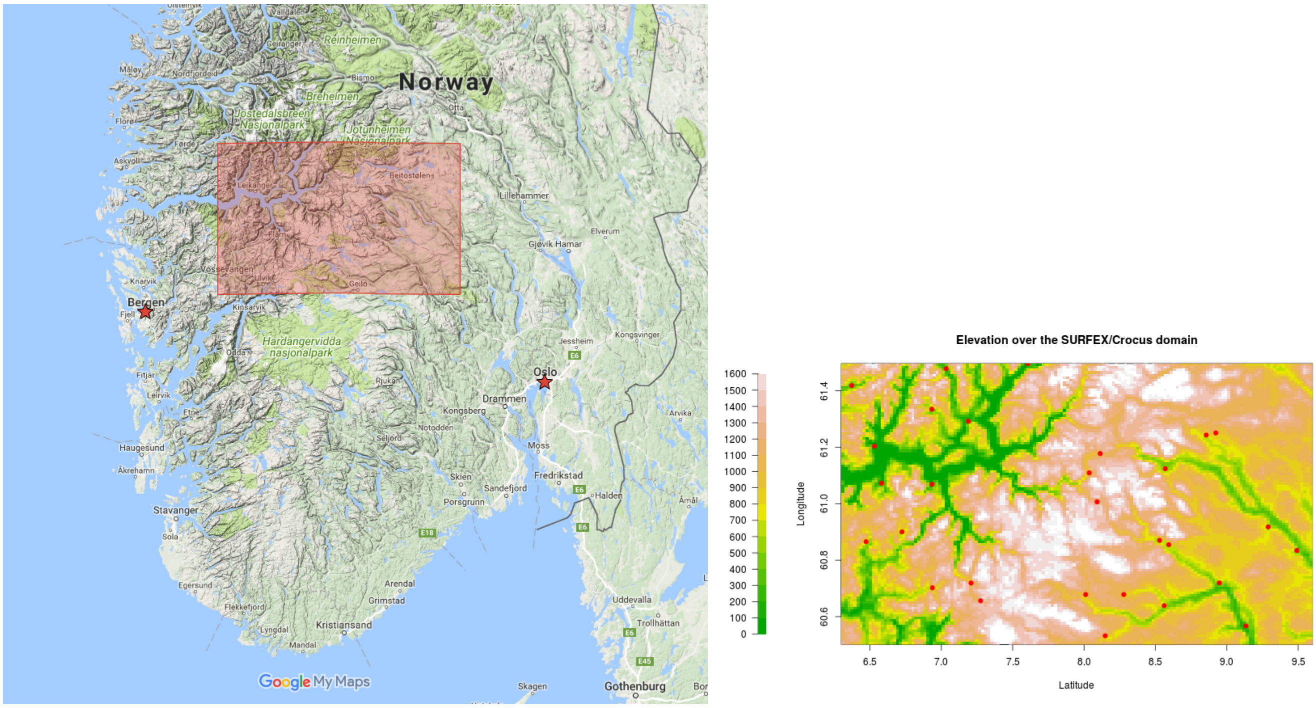

Figure 1. Map showing the domain over which the SURFEX/Crocus model was run on the left (map data: Google), with on the right a map showing the elevation over the SURFEX/Crocus model domain, and the locations of the 30 observations used in this paper (indicated by red dots).

models the physical properties of up to 50 dynamic layers within the snowpack, as well as the underlying ground. Once the snowpack reaches a threshold of 1 kg/m² SWE, the fractional snow cover fraction over a grid point is assumed to be 1. The SURFEX/Crocus model can be run in stand-alone (or offline) mode, or fully coupled to an atmospheric model.

For this study, the SURFEX/Crocus model was used in an offline mode (not fully coupled to an atmospheric model), on a 0.01°grid (approximately 1 km), with a 5 minute internal time step and output every hour. The transport of snow by wind is not simulated. The SURFEX/Crocus model was run for two winter seasons: from 1 September 2014 until 31 August 2016. Figure 1 shows the domain over which the model was run, and the elevation over the model domain. This domain covers elevations from 0 masl. along fjords up to the highest mountain in Norway (2468 masl.). Therefore, the area includes different vegetation zones, ranging from high mountains above the tree line, sparsely forested and densely forested areas.

2.2 Forcing data sets

The SURFEX/Crocus model requires atmospheric forcing. For this study, we have used two different sets of forcing data. Table 1 shows an overview of which variables the SURFEX/Crocus model requires and the different sources used in the two experiments: 1) AROME-Crocus and; 2) GridObs-Crocus. AROME-Crocus uses only (hourly) data from the AROME

	AROME-Crocus	**GridObs-Crocus**
Air temperature [K]	AROME-MetCoOp	Gridded observations
Specific humidity [kg/kg]	AROME-MetCoOp	AROME-MetCoOp
Wind speed [m/s]	AROME-MetCoOp	AROME-MetCoOp
Wind direction [degrees]	AROME-MetCoOp	AROME-MetCoOp
Incoming direct shortwave radiation [W/m²]	AROME-MetCoOp	AROME-MetCoOp
Incoming longwave radiation [W/m²]	AROME-MetCoOp	AROME-MetCoOp
Surface pressure [Pa]	AROME-MetCoOp	AROME-MetCoOp
Rainfall rate [kg/m²/s]	AROME-MetCoOp	Gridded observations
Snowfall rate [kg/m²/s]	AROME-MetCoOp	Gridded observations

Table 1. Description of the forcing data sets used in the two experiments: 1) AROME-Crocus; and 2) GridObs-Crocus.

MetCoOp model (described below in section 2.2.1) while GridObs-Crocus uses a combination of gridded observations of precipitation and temperature (both on a 1 hourly temporal resolution), described in section 2.2.2, and AROME MetCoOp data.

2.2.1 Numerical weather forecasts (AROME-MetCoOp)

AROME MetCoOp is a high-resolution, non-hydrostatic, convective-scale weather prediction model operated by a bilateral cooperative effort [Meteorological Cooperation on Operational Numerical Weather Prediction (MetCoOp)] between the Norwegian Meteorological Institute and the Swedish Meteorological and Hydrological Institute (Müller et al., 2017), operational since March 2014. The core of the model is based on the convection-permitting Applications of Research to Operations at Mesoscale (AROME) model developed by Météo-France (Seity et al., 2011). It has been modified and updated to suit advanced high-resolution weather forecasts over the Nordic regions, see Müller et al. (2017) for details. The horizontal resolution is 2.5 km and the domain covers the Nordic countries. The atmosphere is divided into 65 vertical layers, with the first layer at approximately 12.5 m height. Atmosphere–surface interactions and surface–soil processes are described by SURFEX (Masson et al. 2013). The fluxes computed by SURFEX at the atmosphere–surface interface serve as the lower boundary conditions for the atmospheric part of the model. All surface processes are treated as one-dimensional vertical processes.

AROME MetCoOp operates with a 3-hourly update cycling, where initial fields of atmospheric and land surface variables are corrected with observations through data assimilation. At every main cycle (0000, 0600, 1200, and 1800 UTC) a 66-h forecast is produced. Forcing for our study is taken from the 4 main cycles, with successive 3-8h lead time (0-8h lead time for the 0000 UTC cycle) forecasts combined into a forcing file for each day. The 2.5 km forecasts were further interpolated to 1 km spatial resolution using bilinear interpolation, in order to combine the meteorological forecasts with the gridded observations (with a spatial resolution of 1 km) and to run the SURFEX/Crocus model with 1 km grid spacing.

2.2.2 Gridded observations (GridObs)

In an earlier study by Vikhamar-Schuler et al. (2011) , it was shown that snow modeling with the SURFEX/Crocus model has highest sensitivity to the temperature and precipitation input datasets. Best results were obtained when the model was forced with observations of temperature and precipitation, while replacing other input parameters with meteorological forecast data did not increase errors notably. In the study by Vikhamar-Schuler et al. (2011) the SURFEX/Crocus model was run in 1D mode for observation points, and observations from weather stations could be used directly. This is not possible when running the SURFEX/Crocus model on a 2D domain.

However, hourly gridded observations of temperature and precipitation are available on a 1 km grid over Norway (Lussana et al., 2016, 2017). This dataset uses all measurements available in MET Norway's Climate database (eKlima, 2017). The station distribution is uneven, with more stations in the southern part of Norway and a sparser network in the north and in the mountains. The gridded dataset uses a spatial interpolation procedure based on Bayesian concepts and relying on observations only. This procedure is based on statistical interpolation: the classical Optimal Interpolation (OI) scheme has been modified taking into account a scale-separation approach. Three-dimensional correlation functions are used to account for the orographic distribution of observing stations. The interpolation method is described in more detail in Uboldi et al. (2008) and Lussana et al. (2009).

The resulting gridded temperature dataset can be regarded as an unbiased estimate of the true temperature both at grid points and at station locations. Only for the most extreme negative values (temperatures below -30 °Celsius) there is a systematic warm bias of about 1 °Celsius (Lussana et al., 2016, 2017). There are not as many stations measuring hourly precipitation as there are daily ones. The hourly gridded observations of precipitation have therefore been corrected by using the denser network of daily precipitation measurements, in such a way that the sum of hourly precipitation over a 24 hour period matches the daily observed precipitation for each grid point. Lussana et al. (2017) found that the precision of the estimates (at grid points) is about ±20% for precipitation, but there is a systematic underestimation of precipitation in data-sparse areas and for intense precipitation.

SURFEX/Crocus requires a separate snowfall and rainfall rate, which has been derived from the hourly total precipitation by using a threshold temperature of +0.5 ° Celsius (using the gridded observations of temperature available on the same grid). This threshold temperature is commonly used for hydrological purposes in Norway (see for example Skaugen (1998)).

2.3 Validation data set

We use two different data sets to validate the results from both experiments: point observations of snow depth and snow cover maps derived from MODIS satellite images.

2.3.1 Snow depth observations

Thirty observations of snow depth have been selected for use in verification of the model results (see Fig. 1). Nearly all stations (25 out of 30) are official meteorological stations run by the Norwegian Meteorological Institute, while a few stations are

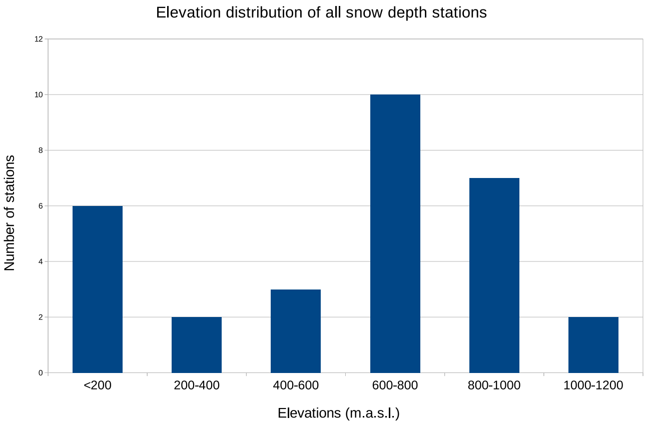

Figure 2. Distribution of elevation for all stations used in this study.

owned by other institutions (municipalities, energy producing companies and Bane Nor, the state-owned company responsible for the Norwegian national railway infrastructure). Data from all stations is freely available from the climate database of the Norwegian Meteorological Institute (eKlima, 2017). All stations measure snow depth, nearly all (29 out of 30) measure precipitation, and 9 stations also measure air temperature. The stations were selected based on the availability of high quality snow depth observations between 1 September 2014 and 31 August 2016. The locations of the stations are reasonably well distributed over the domain (see Fig. 1) and their elevations range between 14 and 1162 meters above sea level. Figure 2 shows the elevation distribution of all stations used in this study.

In order to compare the observations with the results from the SURFEX/Crocus experiments, the nearest locations to the observations have been derived from the model grid. Daily snow depth observations taken at 06 UTC have been used for direct comparison to snow depth from the SURFEX/Crocus simulations. The observations were also used to calculate the start, length and end of the snow season, to compare against model results. The length of the snow season is defined as the number of days with more than 5 cm snow during a year. The 5 cm threshold was also used by Vionnet et al. (2016), although they used continuous snow on the ground as an additional condition. The start of the snow season is defined as the first day with more than 5 cm of snow, and the end of the snow season as the day after the last day with more than 5 cm of snow.

2.3.2 MODIS snow cover images

MODIS (Moderate Resolution Imaging Spectroradiometer; http://modis.gsfc.nasa.gov/) snow cover images (Hall and Riggs (2007); Klein and Stroeve (2002)) with a resolution of 500 m are available for the melt season of the 2014-2015 winter. The same method as described in Lussana et al. (2017) was used: the MODIS images were converted to snow-covered area (SCA) on a scale from 0-100% coverage using a method based on the Norwegian linear reflectance to snow cover algorithm (NLR) (Solberg et al., 2006). The input to the NLR algorithm is the normalized difference snow index signal (NDSI- signal) (Salomonson and Appel, 2004). When cloud cover is present, there is no information on the snow-covered area.

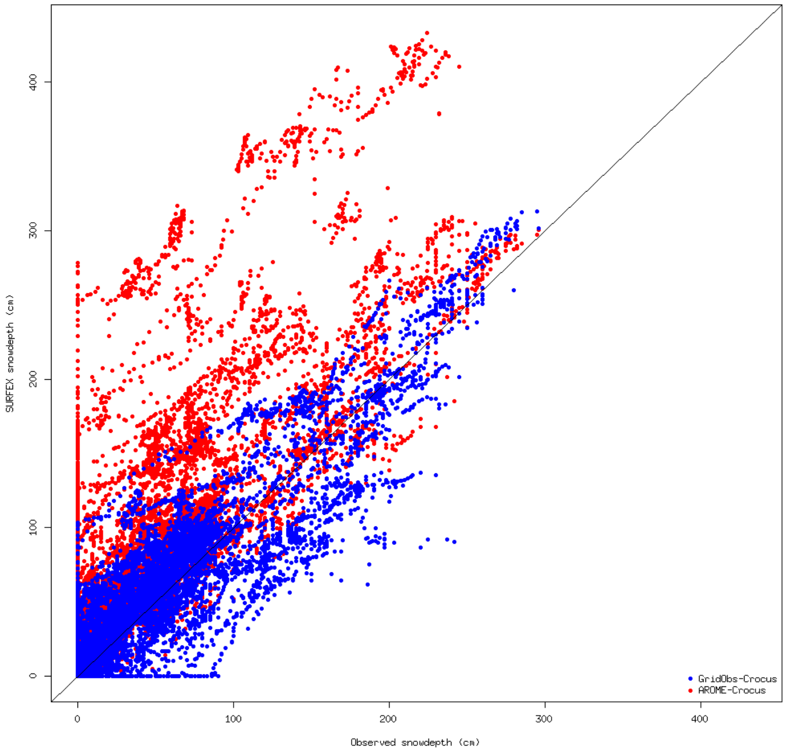

Figure 3. Scatter plot of daily observed and simulated snow depth (cm) for GridObs-Crocus (in blue) and AROME-Crocus (in red) for all weather stations, from 01 September 2014 to 31 August 2016.

The MODIS images were used for visual comparison of the snow melt pattern from satellite images and from both SURFEX/Crocus experiments. For this purpose, four dates with cloud free conditions were selected throughout the melt season: 15 March 2015, 20 April 2015, 15 May 2015 and 04 July 2015.

3 Results

3.1 Snow depth

A scatter plot of daily observed and modeled snow depth for both experiments is shown in Fig. 3. The plot includes simulations for the two winter seasons 2014/15 and 2015/16. GridObs-Crocus is in good agreement with the observations, while AROME-Crocus shows significant overestimation of snow depth. In order to show the performance of both experiments over the full range of station altitudes, Fig. 4 shows snow depth plots for 6 locations: 2 located below 400 m, 2 located between 500 and 900 m, and 2 above 900 m (which for Norway means they are located above the tree line). Consistent with Fig. 3, Fig. 4 shows that

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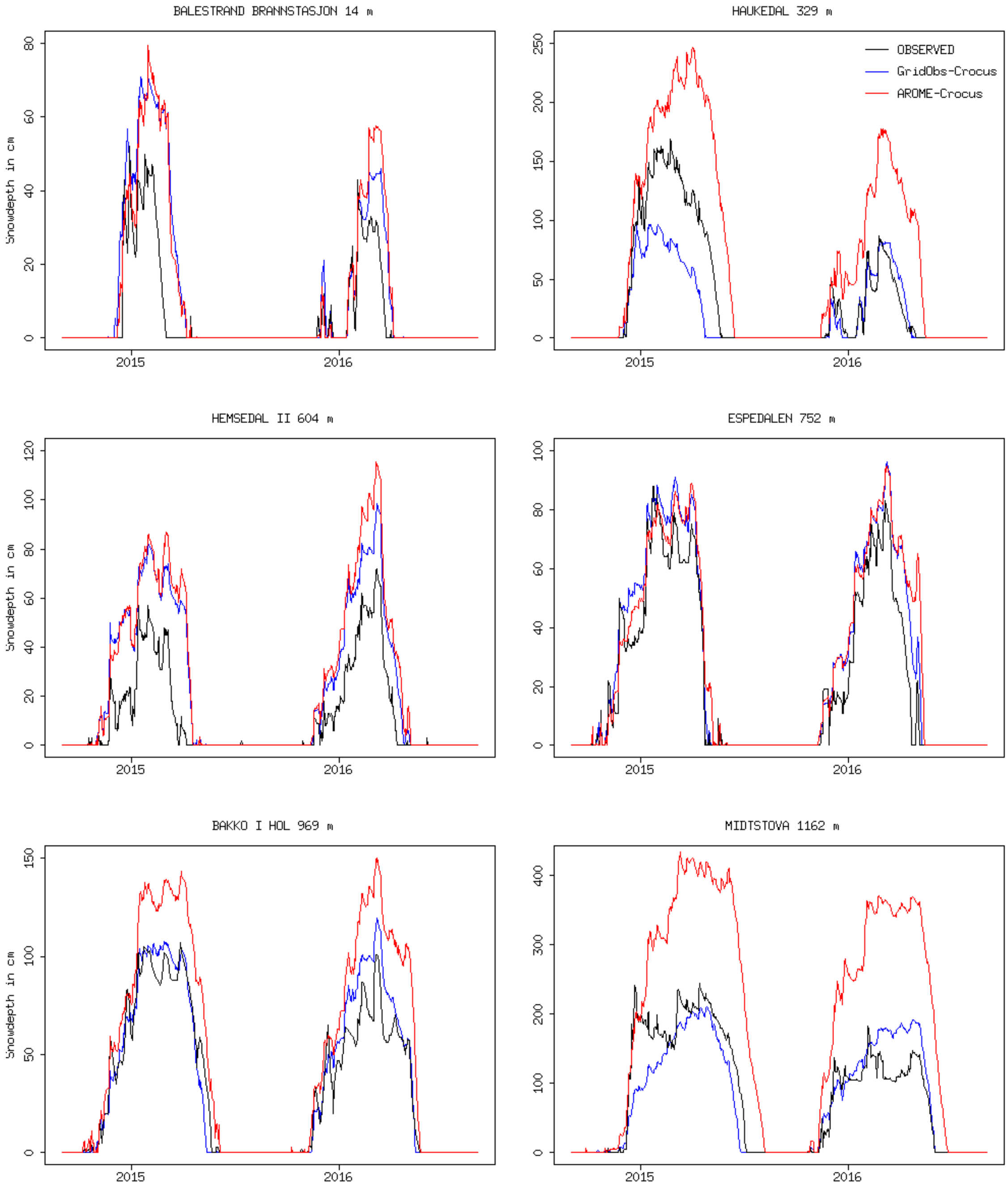

Figure 4. Observed and simulated snow depth (cm) at the location of six weather stations during the two winter seasons 2014-2016 (01 September 2014 - 31 August 2016) : 1) GridObs-Crocus (blue); 2) AROME-Crocus (red) and 3) observations (black).

AROME-Crocus overestimates the snow depth for all altitudes, and has more snow compared to GridObs-Crocus. This overestimation is especially strong for high altitude stations (situated above 900 m). The snow depth from GridObs-Crocus is closer to the observed snow depth, but at times underestimates the snow depth (most notably for the first winter season at Haukedal (329 masl.) and Midtstova(1162 masl.)). Episodes where the snow depth decreases during the winter season (apart from snow melt in spring) are not always well captured by the SURFEX/Crocus experiments, and this issue is partly responsible for the overestimation of snow depth.

The results for Hemsedal II (604 masl., see Fig. 4) are of particular interest, as this is the only station measuring snow depth but not precipitation (and therefore not part of the gridded observation dataset used as input for GridObs-Crocus). GridObs-Crocus overestimates the snow depth at Hemsedal II, but not to the same extent as AROME-Crocus does. GridObs-Crocus matches the observed pattern of increases and decreases more closely than AROME-Crocus.

The strong overestimation at Midtstova (see Fig. 4) by AROME-Crocus can be explained by the fact that Midtstova is located in an area with systematic and relatively large overestimation of precipitation in AROME-MetCoOp. In addition, AROME-MetCoOp underestimates the temperature by about 2 degrees in this area during winter. This can be seen in verification reports of the AROME MetCoOp model, for example in Homleid and Tveter (2016). The underestimation of the temperature at Midtstova leads to even more of the already overestimated model precipitation falling as snow instead of rain. Midtstova is also a high-mountain station, which is very exposed to strong wind. Redistribution of snow due to wind is not captured in the SURFEX/Crocus model. GridObs-Crocus shows much more realistic results for Midtstova.

Table 2 summarizes the bias over all stations for the two winter seasons (01 September 2014 - 31 August 2015 and 01 September 2015 - 31 August 2016). The bias was calculated as the mean of the differences between simulated and observed snow depth, and only for the days where there is snow present in the observations or at least one of the experiments. GridObs-Crocus shows a significantly smaller bias (4 and 9 cm) compared to AROME-Crocus (42 and 41 cm). The maximum observed snow depth is on average 112 cm for 2014-2015 and 88 cm for 2015-2016. GridObs-Crocus shows a very small bias (0 and 9 cm respectively), while AROME-Crocus overestimates the mean maximum snow depth by 43-45 cm.

As snow depth accumulates over the winter season, a missed (or under/over estimated) snow event can influence the remainder of the season. It can therefore be useful to look at daily snow depth variations instead, as was also done by Quéno et al. (2016) and Schirmer and Jamieson (2015). Figure 5 shows the categorical frequency distribution of the daily change in snow depth for six accumulation categories, five decrease categories and one category centered around zero accumulation, on a logarithmic scale. The observed snow depth is measured in centimeter units, this is why there are no observations in the -0.5,0,5 cm category. The first two accumulation categories (up to 10 cm) are overestimated in both GridObs-Crocus and AROME-Crocus. The strongest observed increase category (>40 cm) as well as the strongest decrease category (< -20 cm) are strongly underestimated in both SURFEX/Crocus experiments.

SURFEX/Crocus does not allow for either the transport of blowing snow or wind-induced ablation, which can be a large contributor to strong decreases in snow depth. Figure 4 showed that episodes of a decrease in snow depth (not including the snow melt at the end of the season) were not always captured well by the models, and it could be that blowing snow is the

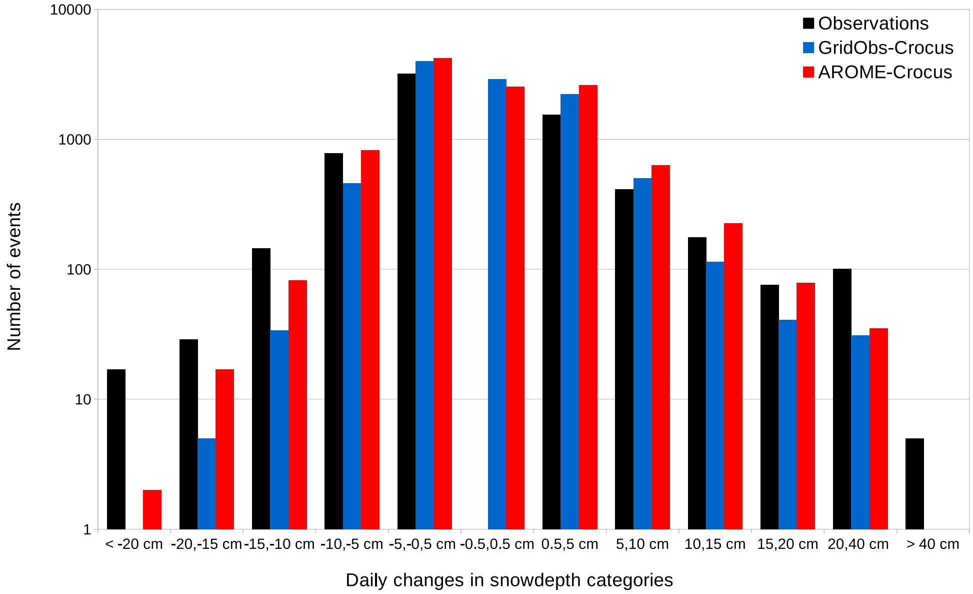

Figure 5. Categorical frequency distribution of daily changes in snow depth for observations (in black), GridObs-Crocus (in blue) and AROME-Crocus (in red), for all stations during 01 September 2014 - 31 August 2016. The y axis is on a logarithmic scale.

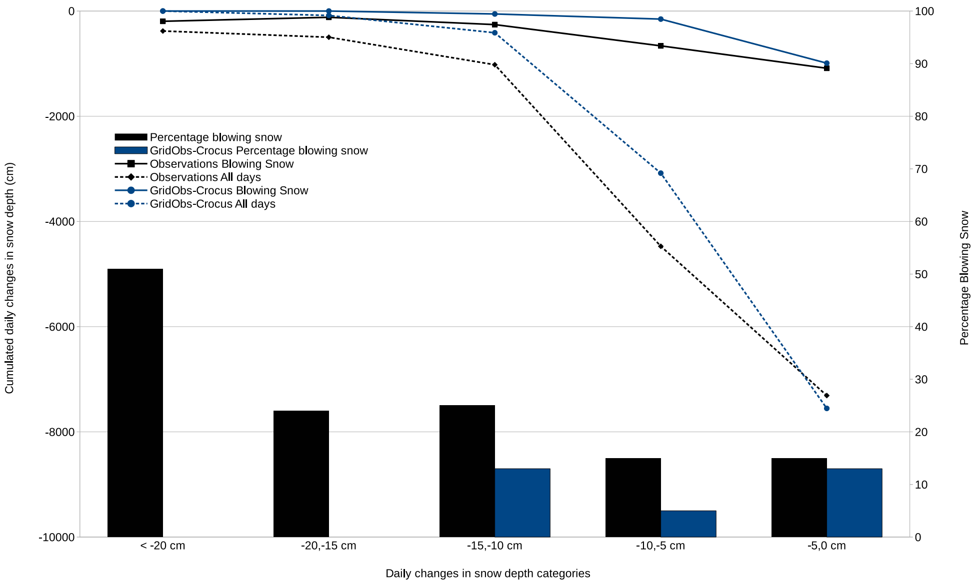

Figure 6. Cumulated daily change in snow depth for observations (in black), GridObs-Crocus (in blue) for all stations during 01 September 2014 - 31 August 2016, for blowing snow days (solid lines) and all days with decreasing snow depth (dashed lines). The columns show the percentage of snow loss that is caused by blowing snow, for observations (black) and GridObs-Crocus (blue).

	2014-2015	2015-2016
Bias snow depth GridObs-Crocus (cm)	4	9
Bias snow depth AROME-Crocus (cm)	42	41
Mean length snow season (observed, days)	151	137
Bias length snow season GridObs-Crocus (days)	10	8
Bias length snow season AROME-Crocus (days)	33	18
Average date start of snow season (observed)	15 November	15 November
Bias start snow season GridObs-Crocus (days)	-2	2
Bias start snow season AROME-Crocus (days)	-10	0
Average date end of snow season (observed)	02 May	25 April
Bias end snow season GridObs-Crocus (days)	-3	2
Bias end snow season AROME-Crocus (days)	17	11
Average date max snow (observed)	30 January	22 February
Bias average date max snow GridObs-Crocus (days)	13	13
Bias average date max snow AROME-Crocus (days)	26	10
Average max snow (observed, cm)	112	88
Bias max snow GridObs-Crocus (cm)	0	9
Bias max snow AROME-Crocus (cm)	43	45

Table 2. Bias in snow depth, length of snow season (defined as number of days with more than 5 cm snow depth), start of snow season (defined as first day with more than 5 cm snow), end of snow season (defined as the day after the last day with more than 5 cm snow), the date for the maximum snow depth and the maximum snow depth. The two snow seasons run from 01 September 2014 to 31 August 2016. A negative bias in days means a too early date for the start/end/max snow, and a positive bias in days means a later date compared to observations.

cause of this. Following Quéno et al. (2016), two diagnostics have been applied to look into this issue: blowing snow days and melting snow days. Blowing snow days are defined as days during which the wind speed during the past 24 hours (between 06 and 06 UTC, as this is when snow depth measurements are made) exceeds 8 m/s, while the snow surface temperature is below 0 °Celsius (since only dry snow can be blown away). The temperature of the snow surface is taken from SURFEX output for 12 UTC each day. The wind speed is taken from AROME-MetCoOp, which is used as forcing in both SURFEX/Crocus experiments. The wind threshold of 8 m/s for dry snow transport is taken from Li and Pomeroy (1997). Figure 6 shows the cumulated amount of the daily changes in snow depth for 5 categories of decreasing snow depth for blowing snow days and for all days where the snow depth decreases, for observations and for GridObs-Crocus, as well as the percentage of snow depth loss due to blowing snow. The cumulated amount of snow decrease is underestimated for nearly all categories. For the strongest decreasing rate (more than 20 cm), the observations indicate that 51% of the decrease in snow is caused by blowing snow. This category is not represented by GridObs-Crocus. For GridObs-Crocus, blowing snow days only contribute to the smallest decrease categories. In total (over all categories), blowing snow days contribute to 17% of the cumulated decrease in

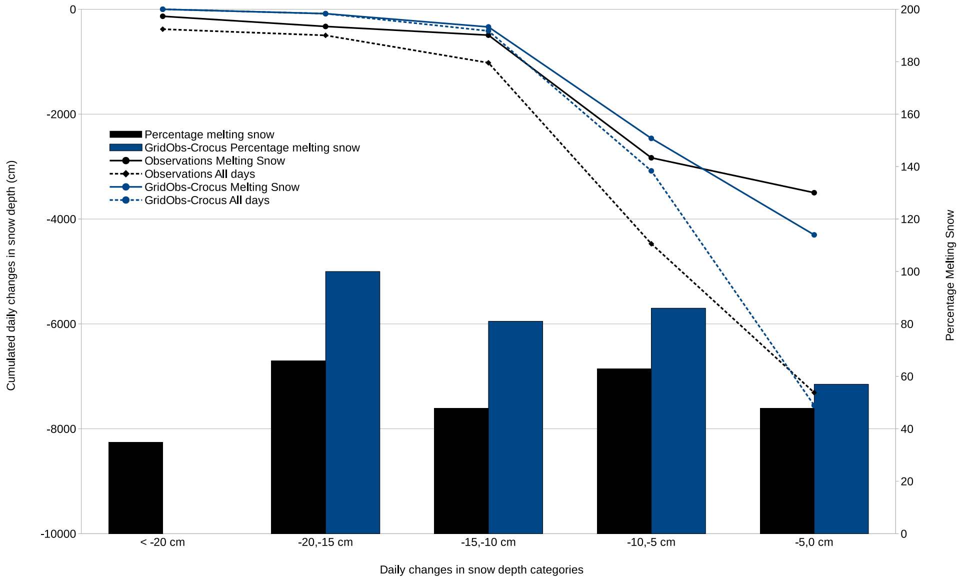

Figure 7. Cumulated daily changes in snow depth for observations (in black), GridObs-Crocus (in blue) for all stations during 01 September 2014 - 31 August 2016, for melting snow days (solid lines) and all days with decreasing snow depth (dashed lines). The columns show the percentage of snow loss that is caused by melting snow, for observations (black) and GridObs-Crocus (blue).

snow depth in the observations, while this amounts to 10% in GridObs-Crocus.

Melting snow days are defined as days where the surface temperature of the snow is at or above 0 °Celsius. Figure 7 is similar to Fig. 6, but for melting snow days. For GridObs-Crocus, melting snow is the main responsible factor contributing to a decrease in snow depth. The largest decrease category is not represented by GridObs-Crocus, but for the other categories, melting snow is responsible for 57 - 100% of the decrease in snow depth. This is not surprising as SURFEX/Crocus does not represent blowing snow, so decrease in snow depth is caused by either snow melt or other processes such as snow compaction. The cumulated daily changes in snow depth for melting snow days as well as all days with a decrease in snow depth are underestimated by GridObs-Crocus for all categories except the smallest one (less than 5 cm loss in snow depth). This shows there is a general underestimation of snow ablation, as well as an underestimation of snow melt in GridObs-Crocus. The same goes for AROME-Crocus (not shown).

3.2 Characteristics of the snow season

Table 2 shows statistics for the two snow seasons 2014/2015 and 2015/2016. The length of the snow season is defined as the number of days with more than 5 cm snow during a year. For GridObs-Crocus, the length of the snow season is overestimated by 8-10 days (see table 2), while AROME-Crocus has a bias of 18-33 days. The same positive bias was found by Vionnet et al. (2016). One possible explanation of this bias is the fact that the SURFEX/Crocus model assumes a uniform snow cover from the moment snow is present on the ground, and therefore shows less variability in snow cover compared to observations.

In observations, there is often a period where the snow cover fluctuates - for example thinning to below 5 cm after the first snow has fallen and before a continuous snow cover has been established for the winter season. The start of the snow season is defined as the first day with more than 5 cm of snow, and the end of the snow season as the day after the last day with more than 5 cm of snow. A negative bias in the start of the snow season means a too early start, while a positive bias means a too late start of the snow season. GridObs-Crocus has a bias of only two days (negative for the first winter and positive for the second winter) for the start of the snow season, while the snow season starts up to 10 days too early in AROME-Crocus during the first year (the second year has a bias of zero days). The season ends on average in late April or early May. In GridObs-Crocus, the season ends 3 days early during the first year, and 2 days late during the second year. In AROME-Crocus, the season ends 11-17 days too late. The observed maximum snow depth occurs on average at the end of January during the first year, and late February in the second year. Both experiments show a later date for the maximum snow depth.

Figure 8 show the distribution of the bias in the start and end of the snow season, as well as the date of maximum snow depth, for all 30 stations and for two winter seasons. Most stations show a bias near zero (between -5 and +5 days) for the start of the snow season. In AROME-Crocus, the snow season often starts too early. The bias for the end of the snow season shows more variability and an even clearer difference between the two models: GridObs-Crocus ends the snow season too early while AROME-Crocus ends the season too late. The bias for the date of the maximum snow depth of the season is mostly around zero for most stations and both models, but there are some outliers especially towards the strong positive bias. This is due to stations like for example Midtstova in Fig. 4, where the maximum observed snow depth occurs rather early in the season, while both experiments show a maximum much later in the season.

3.3 Snow-cover pattern

Figure 9 shows the spatial pattern of snow cover over the SURFEX/Crocus domain compared to MODIS data over the same area. The snow covered area is shown at different dates throughout the snow melt season: 15 March, 20 April, 15 May and 04 July 2015. On 15 March 2015, nearly the whole area is covered with snow. The only exceptions are areas right besides the fjords (white areas) in the west (well captured by both experiments), and at the bottom of valleys in the east (not captured by the SURFEX/Crocus experiments). On 20 April 2015, the snow has clearly started to melt in the valleys to the east. This is captured well by AROME-Crocus, while GridObs-Crocus shows too little snow around the valleys in the southeast of the domain. By 15 May 2015, a lot of snow had disappeared in the eastern part of the domain, while the western part has not changed much from the previous month. The average date for the end of the snow season for the 2014-2015 season was 02 May 2015 (see table 2), but the dates of the end of the snow season for individual stations range from 18 February until 05 July. Again, AROME-Crocus captures the snow cover pattern better than GridObs-Crocus. By 04 July 2015, the snow cover is limited to areas with higher elevation. AROME-Crocus captures the spatial pattern of snow cover very well. In GridObs-Crocus, nearly all snow has melted now, and the snow-covered area is underestimated. Earlier it was shown (in Fig. 8) that GridObs-Crocus has a negative bias (too late) for the end of the snow season for the 30 snow depth stations, while AROME-Crocus has a positive bias (too early).

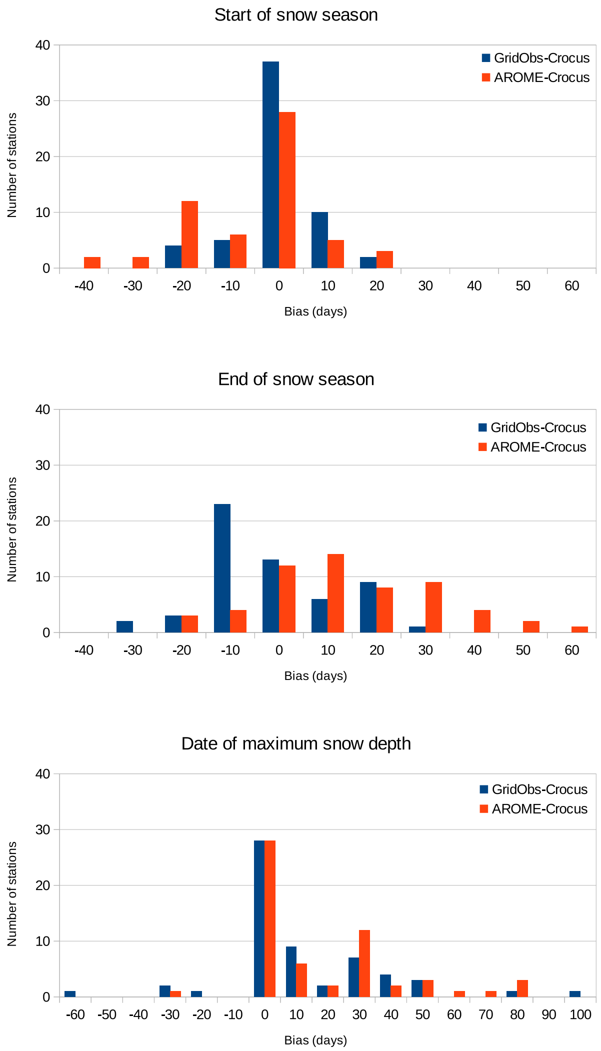

Figure 8. Distribution of the bias in start of snow season (top), end of snow season (middle) and date of maximum snow depth (bottom), for all 30 stations and for 2 winter seasons.

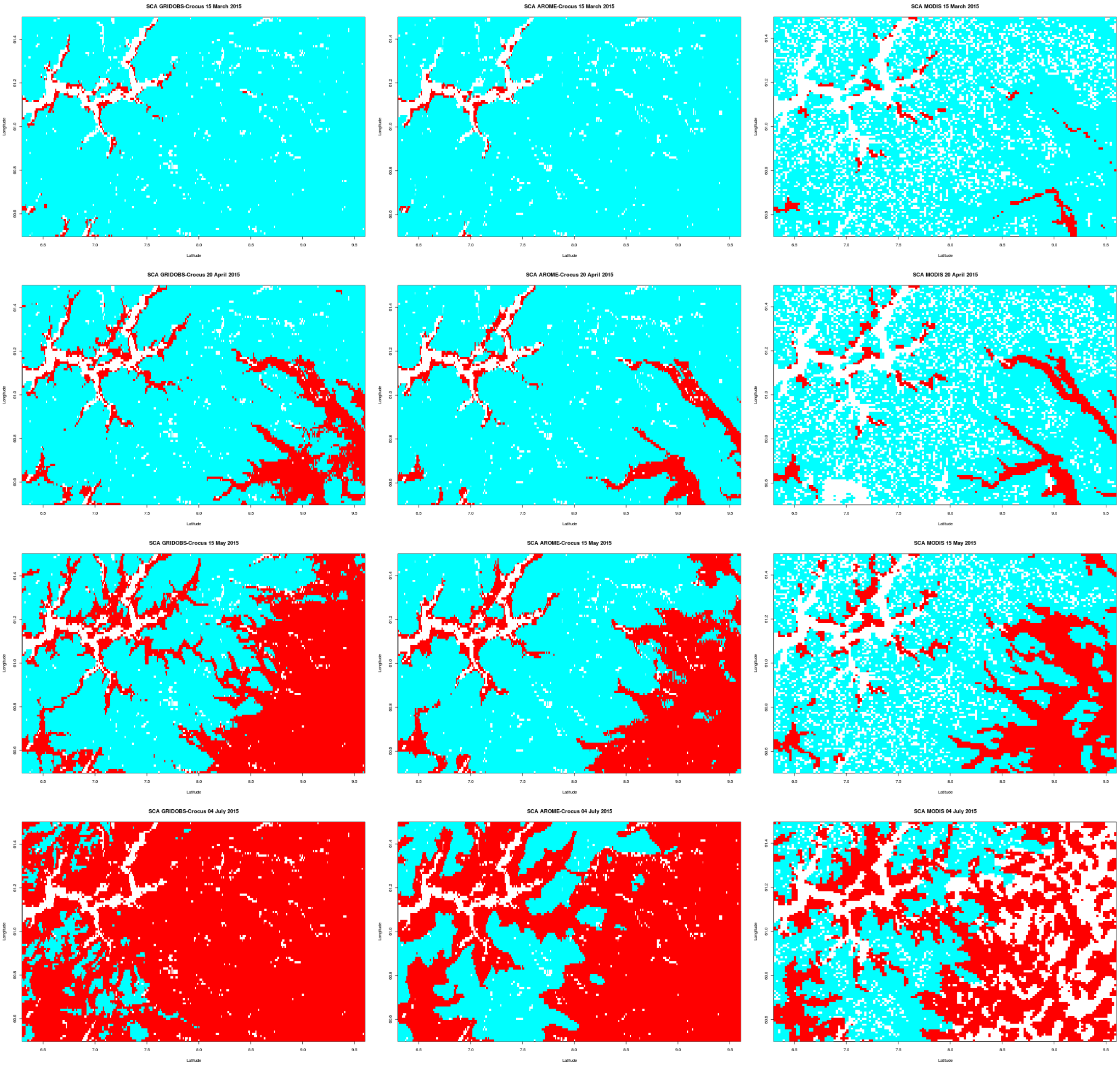

Figure 9. Snow covered area (where cyan is snow, red is no snow, and white is missing data or water surfaces) for GridObs-Crocus (left column), AROME-Crocus (middle column) and from MODIS satellite images (right column), for (rows from top to bottom): 15 March 2015, 20 April 2015, 15 May 2015 and 04 July 2015.

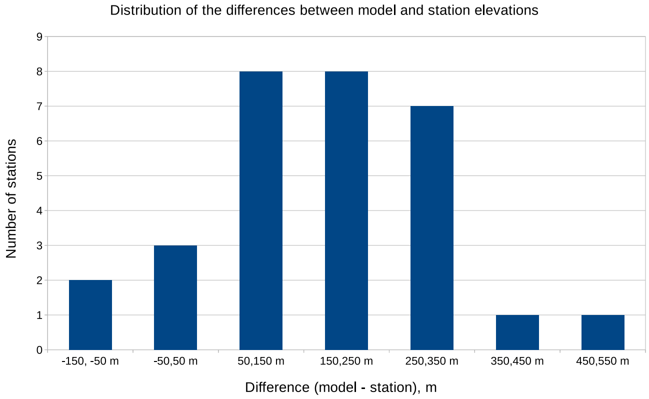

Figure 10. Differences between station elevation and the height of the station in the SURFEX/Crocus model.

4 Discussion

The results are promising; both experiments are capable of simulating the snow pack over the two winter seasons. There is however an overestimation of snow depth in the AROME-Crocus experiment (when using only meteorological forecasts from AROME MetCoOp), although the snow-covered area throughout the melt season is better represented by this experiment. The errors in AROME-Crocus accumulate over the snow season, showing that assimilation of snow depth observations into SURFEX/Crocus might be necessary when using only meteorological forecasts as forcing. When using gridded observations, the simulation of snow depth is significantly improved, which shows that using a combination of gridded observations and meteorological forecasts to force a snowpack model is very useful and can give better results than only using meteorological forecasts. There is an underestimation of snow ablation in both experiments, which is due to a combination of the absence of wind-induced erosion of snow and underestimation of snow melt in SURFEX/Crocus, and biases in the forcing data. The quality of the model validation, forcing data set and snowpack model are further discussed below.

4.1 Quality of the model validation

Nearly all (29) of the 30 stations that measure snow depth also measure precipitation, which means the observed precipitation from these stations are used in the gridded observations dataset used to force GridObs-Crocus. Only 9 out of the 30 stations also measure temperature. Although precipitation is not directly related to snow depth, and temperature also plays an important role, it could still be argued that the GridObs-Crocus results are best in the locations of the observations that are included in the gridded dataset used to force SURFEX/crocus.

The orography used in the SURFEX/Crocus experiments has a resolution of 1 km. Because of this, there are differences between the actual station height and the average height used for the center of the 1 km grid cell in SURFEX/Crocus. Figure 10 shows the distribution of those differences for all 30 stations. The average bias is 180 m. Most stations are placed at higher elevations in the model as compared to their actual elevation, but it should also be kept in mind that a grid point

The Cryosphere Discuss., https://doi.org/10.5194/tc-2017-220
Manuscript under review for journal The Cryosphere
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in SURFEX/Crocus describes a larger area (and range of elevation) compared to the actual observations. Especially in the mountainous region in the west of the domain (see Fig. 1), with high mountains (with steep slopes) and deep valleys, there are very large differences in height within a distance range of 1 km. An average bias of 180 m is therefore acceptable, but of course this can mean that an observation location might not be representative for the grid point it represents in SURFEX/Crocus.

4.2 Quality of the forcing data sets

Raleigh et al. (2015) showed that snow simulations are more sensitive to biases in forcing data than random errors, and that precipitation bias is the most important factor. There is a negative bias in the gridded precipitation used in GridObs-Crocus (Lussana et al., 2017), especially for data-sparse areas and for intense precipitation. Missing episodes of intense snowfall would explain part of the underestimation of the snow depth in GridObs-Crocus. There are plans to improve the gridded observations of precipitation by adjusting the solid precipitation to account for the wind undercatch, and by post-processing of the predicted precipitation fields to adjust for bias (Lussana et al., 2017). AROME-MetCoOp is known to overestimate the occurrence of precipitation events of less than 10 mm (Müller et al., 2017), and Fig. 5 showed that AROME-Crocus overestimated daily changes in snow depth up to 15 cm.

Another uncertainty lies in the use of a fixed threshold temperature of 0.5 °Celsius to distinguish between rainfall and snowfall in GridObs-Crocus. This simplification could result in some actual snow events characterized as rainfall, and to a lesser extent the other way around.

Sauter and Obleitner (2015) investigated the sensitivity of SURFEX/Crocus snowpack modeling on Svalbard (Arctic Norway) to input parameters, and found that for higher elevations (in the accumulation zone), precipitation and radiation are the key factors in the evolution of the snowpack and contribute most to the model uncertainty. At lower elevations, precipitation was less important but factors such as wind speed or surface roughness increased in importance. Quéno et al. (2017) used satellite products of incoming solar and longwave radiation to force the SURFEX/Crocus model, however they concluded that improved meteorological forcing does not always lead to more accurate snowpack simulations, due to error compensations within the atmospheric forcing and the snowpack model.

4.3 Quality of the snowpack model

The SURFEX/Crocus model assumed a uniform snow cover when SWE reaches the relatively low threshold of 1 kg/m². The SURFEX/Crocus model was originally developed for use in high alpine regions, where there is not a lot of vegetation. In those areas, the assumption of the uniform snow cover is realistic, but for areas covered with forest and closer to sea level this could lead to an overestimation of the snow cover. This in turn would lead to an overestimation of the snow depth, which would be expected in both experiments. AROME-Crocus does show an overestimation of snow depth. This is not the case for GridObs-Crocus, but this is partly due to the negative bias of the gridded observations of precipitation used as forcing.

The SURFEX/Crocus model grid is a collection of independent grid points with no transport of snow or other variables between grid points. It is therefore not possible to simulate the redistribution of snow by wind. It can be argued that with a resolution of approximately 1 km, the drifting snow would anyway be redistributed within the area of a grid point and not transported to neighboring grid points. Vionnet et al. (2014) showed that for explicit simulation of wind-induced snow transport a spatial resolution of less than 50 meters is required. This is currently not a feasible option for snowpack simulations over larger domains. There is an option in the SURFEX/Crocus model to calculate the rate of sublimation in case of snowdrift, which results in a loss of snow. In this study this option was not used. Using this option might improve the results of the AROME-Crocus experiment, but further decrease of the snow cover in GridObs-Crocus would not improve the snow simulations as it would increase the underestimation of snow depth and snow cover.

Figure 5 showed that both SURFEX/Crocus experiments underestimate the melting of snow, further supplemented by Fig. 7 for the GridObs-Crocus experiment. Underestimated melting was also found by Quéno et al. (2016, 2017) and Vionnet et al. (2016), and complementary studies are needed to investigate the cause of this issue.

Lafaysse et al. (2017) developed an ensemble snowpack model using SURFEX/Crocus called ESCROC (Ensemble System Crocus) to address modeling errors. They found that by using optimal members they were able to more than half of simulation errors, and those ensembles have a significantly better predictive power than the classical deterministic approach. For future work, it would be interesting to use ESCROC and investigate the effect of different physical settings of SURFEX/Crocus. In addition, since November 2016, AROME-MetCoOp is run as an ensemble with 10 members, called MEPS (MetCoOp Ensemble Prediction System). This means that an ensemble of meteorological forcing is another possible direction for future work. Vernay et al. (2015) used the 35 members of the ensemble prediction system based on the French NWP model ARPEGE as forcing to the SURFEX/Crocus model. The results indicated that accounting for the uncertainty in meteorological forecast significantly improves the skill and the usefulness of the model chain.

5 Conclusions

In this study we analyze the effect of using gridded observations of temperature and precipitation (the two most important variables for snow modeling) to force the snowpack model SURFEX/Crocus, compared to using forcing from numerical weather predictions only. Two years of model simulations were used (01 September 2014 - 31 August 2016). The two experiments (AROME-Crocus using only meteorological weather forecasts from AROME-MetCoOp as forcing, and GridObs-Crocus using gridded observations of temperature and precipitation combined with meteorological forecasts from AROME-MetCoOp) were validated against snow depth observations and against MODIS images of snow-covered area. The main findings are as follows:

- Forcing SURFEX/Crocus with gridded observations of temperature and precipitation significantly improves the simulated snow depth. This shows that using a combination of gridded observations and meteorological forecasts as forcing to SURFEX/Crocus can give better results than only using meteorological forecasts. When using purely AROME-MetCoOp forcing data, the snow depth is strongly overestimated, which was also shown by Quéno et al. (2016) and Vionnet et al. (2016).
- While using only weather forecasts from AROME-MetCoOp as forcing for SURFEX/Crocus resulted in an overestimating of the snow depth for individual stations, this experiment (AROME-Crocus) better represented the spatial pattern

of snow cover. Using gridded observations of temperature and precipitations as forcing for the SURFEX/Crocus model resulted in a snow cover that melted away too fast by the end of the season.

- Snow melt is underestimated in both experiments. This appears to be an issue with the SURFEX/Crocus model, and needs to be further investigated.
- Blowing snow (which is not simulated by SURFEX/Crocus) contributes to 17% of all decreases in snow depth, and to 50% of the strongest decreases of more than 20 cm of snow depth loss in a day.

For future work, it would be interesting to run the SURFEX/Crocus model with the option for sublimation in case of snowdrift. In addition, the dataset of gridded observations, and specifically the gridded precipitation is under development. It would be interesting to repeat this experiment using the new dataset which adjusts the solid precipitation to account for the wind undercatch and post-processes the predicted precipitation fields to adjust for the negative bias. Using the ensemble snowpack model ESCROC, and/or an ensemble of meteorological forcing would be an another interesting topic for future work.

The findings in this study have improved our understanding of regional snow modeling in Norway, which is important for not only water resource planning and flood forecasting, but also for impact studies related to climate change and winter climate. The results may also be used for future development of a system for daily snow mapping in Norway.

Data availability. Snow depth and meteorological variables from the stations used in this study are freely available through eklima.met.no (eKlima, 2017). AROME-MetCoOp forecasts are available through http://thredds.met.no/thredds/metno.html. The gridded dataset of temperature and precipitation is available at http://thredds.met.no/thredds/catalog/metusers/senorge2/seNorge2/archive/catalog.html. Hourly temperature and precipitation data is available from 2010 up to the present day. For daily temperature and precipitation data, the archive goes back to 1957 and can be downloaded at http://doi.org/10.5281/zenodo.845733. The data are also shown on the web-portals senorge.no and xgeo.no (both in Norwegian only). The SURFEX-Crocus simulations for both experiments can be made available for research purposes by contacting the authors.

Competing interests. The authors declare that they have no conflict of interest.

Acknowledgements. The authors are grateful for the funding of this study by the research council of Norway through the project "Better SNOW models for prediction of natural hazards and HydropOWer applications" (SNOWHOW), led by Thomas Skaugen at the Norwegian Water Resources and Energy Directorate (NVE). We would like to thank our fellow participants in the SNOWHOW project for invaluable help and discussions: Thomas Skaugen, Tuomo Saloranta (NVE), Karsten Müller (NVE), Kjetil Melvold (NVE) and Sjur Kolberg (SINTEF). In addition, we would like to thank Tuomo Saloranta for providing the processed MODIS images, and Cristian Lussana (MET Norway) for help and discussions.

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