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 forecasts from the operational weather forecast model AROME MetCoOp (2.5 km grid spacing) including post-processed temperature (500 m grid spacing) and wind variables, 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 30 point observations of snow depth and to MODIS satellite images of the snow-covered area. The evaluation focuses on snow accumulation and snow melt. Both experiments are capable of simulating the snow pack over the two winter seasons, but there is an overestimation of snow depth when using meteorological forecasts from AROME MetCoOp (with a bias of 42 cm and RMSE of 68 cm), 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. When using gridded observations, the simulation of snow depth is significantly improved (the bias for this experiment is 6 cm and RMSE 28 cm), 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 mainly using meteorological forecasts. There is however an underestimation of snow ablation in both experiments. This is generally 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. Seasonal snow covers large areas of the Northern Hemisphere and the Arctic. 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; Brown et al., 2017). The largest declines in snow cover extent and duration are observed in Arctic coastal areas, e.g. in Scandinavia (Rasmus et al., 2015; Brown et al., 2017). In Norway there is a general trend towards a later start and an earlier end of the snow season, although there are large annual variabilities (Hanssen-Bauer et al., 2015, 2017). Trends in snow depth may vary with elevation, as observed for some Norwegian regions (Skaugen et al., 2012; Dyrrdal et al., 2013).

Information about seasonal changes in snow duration and amounts 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).

In Norway 30% of the annual precipitation falls as snow (Saloranta, 2012). Observations show that changes in the winter climate the past 50 years, and particularly since 2000, give more warming events and rainfall events during winter (Vikhamar-Schuler et al., 2016; Kivinen et al., 2017). This, in turn, affects the internal snow structure giving e.g. more wet snow conditions and ground-ice layering (Johansson et al., 2011; Vikhamar-Schuler et al., 2013). Updated information on the daily local snow conditions in mountainous and lowland areas is very useful for many applications, notably local flood prediction, hydropower production planning, snow avalanche prediction, tourism and traffic flow management. Typical information needed for these applications are daily snow forecasts (for the next days), but depending on the application, also knowledge on the snow conditions for the past winter(s), last month(s), last week(s), past 3 days and yesterday.

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. Etchevers et al. (2004) and 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 describe the physical snow processes. The need for input data is therefore usually larger and more detailed for physically based models than for the empirically based models. Empirical models often need calibration.

In Norway, both the national operational flood forecasting and hydropower companies use the HBV model, which includes an empirical degree day model for snow simulations (Bergstrøm, 1976; Sælthun, 1996; Ruan and Langsholt, 2017). Snow maps are also produced operationally on a daily basis and published at www.seNorge.no and www.xgeo.no (Saloranta, 2016), and these maps are used by the national snow avalanche service (Barfod et al., 2013; Engeset, 2013). Both these applications use gridded daily observations of temperature and precipitation (Mohr, 2008; Lussana et al., 2018a). Gridded observations for hydrological applications including producing snow maps are also used in other countries, e.g. in Switzerland (Foppa et al., 2007, www.slf.ch) and Sweden (www.smhi.se).

Another type of forcing data for snow models are numerical weather forecasts (NWP) from atmospheric models. NWP data provide simulations for many parameters, on an hourly scale. This type of data therefore represents different information compared to gridded daily observations of temperature and precipitation. Using sub-daily (e.g. hourly) data in snow modeling may contribute to improved snow melt (e.g. in spring with freezing nights and melting snow during daytime) and improved snow accumulation simulations (rainfall/snowfall). Complex physically-based snow models, which simulate both the surface energy balance and the heat flow through the snowpack, usually require many weather elements as input. SnowPack (Bartelt and Lehning, 2002; Lehning et al., 2002), SURFEX/ISBA/Crocus (Vionnet et al., 2012), JULES (Best et al., 2011) and FSM (Essery, 2015) are examples of snow or land-surface models, which also simulate the internal structure of the snowpack. SnowPack and Crocus are used in the operational snow avalanche service in Switzerland and France, respectively (Fierz et al., 2013; Lafaysse et al., 2017). Many studies show how high resolution NWP data are very valuable in driving these snow models, see e.g. Bellaire et al. (2011, 2013); Horton et al. (2015); Vionnet et al. (2016); Quéno et al. (2016). NWP data have also been used as driving data in hydrometeorological models (Carrera et al., 2010, e.g.).

For a point location in the Columbia Mountains, Western Canada, Bellaire et al. (2011, 2013) used 15 km resolution weather forecasts from the NWP model GEM to force the SnowPack model. This study was later extended to a gridded area in the same region by Horton et al. (2015) who forced the SnowPack model using 2.5 km resolution NWP data from the GEM-LAM model. The use of NWP data as precipitation forcing for snow models was analysed and discussed by (Schirmer and Jamieson, 2015). They compared two NWP datasets (GEM: 15 km and GEM-LAM: 2.5 km spatial resolution) over complex mountainous terrain during winter time, and found that the highest resolution dataset performed best in terms of precipitation forecasts. Bernier et al. (2011) used a downscaling technique to account for local terrain effects on the surface temperatures not resolved by the low-resolution NWP model. With higher spatial resolution of the NWP models, the orographic precipitation is better reproduced. In the French Alps, high-resolution forecasts (2.5 km) from the AROME NWP model were used to drive Crocus (Vionnet et al., 2016). A similar study using the same AROME NWP model was carried out for the French and the Spanish Pyrenees by Quéno et al. (2016). Both these studies showed that high-resolution NWP data represents a very useful and promising data source for snow models to produce snow maps of high quality. However, the authors point out some limitations of using only NWP data. Terrain effects are not well enough accounted for on a kilometric scale, whereas future development of sub-kilometric scale NWP data might improve e.g. terrain effects on the incoming solar radiation. Combining NWP data with other data sources (e.g. observations, radar) might improve the forcing data, particularly the precipitation fields. Redistribution of snow due to wind is another difficult issue in mountainous areas. Running snow models with ensemble based forecasts is a promising method to account for these uncertainties (Vernay et al., 2015b; Lafaysse et al., 2017).

Weather forecasting models are presently evolving fast, and they include more and more detailed parametrization of land surface processes connected to snow and soil. SURFEX (Surface Externaliseé) (Masson et al., 2013) is an example of a land surface model, which can be run both inline as part of an atmospheric weather forecast model, for example 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 evaluate the performance of the SURFEX model, using the Crocus snow scheme (Vionnet et al., 2012) for Norwegian snow conditions. SURFEX/Crocus has not previously been run in a gridded stand alone version for regions in Norway (as a 2D study). However, the model has earlier been tested for single points (1D study) with observations from weather stations and NWP data (Vikhamar-Schuler et al., 2011). Our study is carried out as part of several research projects within hydropower and flood forecasting. The domain was chosen to cover mountains in southern Norway and to include a cross-section from west to east that crosses the watershed in this region. This domain includes catchment areas that are of high interest to hydropower companies.

The aim of our study is to test the performance and the benefit of different gridded forcing datasets as input to the SURFEX/Crocus model, and validate the simulated snow amounts and snow melt pattern in the selected domain. The originality of our work is linked to the unique combination of using both raw weather predictions, post-processed weather predictions and gridded observations. Our simulations were run without any assimilation of snow observations. 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 with a grid spacing of 2.5 km (Müller et al., 2017), of which both the temperature and the wind data were improved by post-processing algorithms, and 2) Gridded observations of precipitation and temperature (GridObs) with a grid spacing of 1 km (Lussana et al., 2018b, a). Both data sets have hourly temporal resolution, and are discussed in detail in section 2.3.

Although AROME-SURFEX/Crocus has previously been used over the French Alps and the Pyrenees (Vionnet et al., 2016; Quéno et al., 2016), neither of our two datasets described above have been used as forcing for SURFEX/Crocus for Norwegian mountains and lowland regions before. Additionally, the climate in South-Norway is different from the Alps and the Pyrenees. A west-east transect crossing the mountain chain comprises a climatic transect from maritime, alpine to more continental climate. Snow conditions and stratigraphy vary regionally as outlined by e.g. (Sturm et al., 1995), who defined six snow classes, of which at least two classes are inside our domain (maritime and alpine). The SURFEX/Crocus snow model may therefore perform differently in individual regions. Our study contributes to a development which can produce new supplementary snow information (including snow stratigraphy) and thereby may contribute to the development of a future system for daily snow mapping, different from the seNorge and the HBV model. The performance of the SURFEX/Crocus model is compared with three other snow models including the seNorge model in a separate study by Skaugen et al. (2017).

2 Model setup 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., 2012) 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. In this study, the soil has 14 layers. A force-restore method with 3 layers for hydrology was used for soil discretization and physics within ISBA-DIF. The HSWD (Harmonized World Soil Database) 1 km resolution database for soil texture (FAO/IIASA/ISRIC/ISS-CAS/JRC, 2012) was used for the soil properties. The snowpack scheme Crocus models the physical properties of 50 dynamic layers within the snowpack, as well as the underlying ground. Once the snowpack reaches a threshold of 1 kg m^{-2} 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. These dates were chosen because the hydrological year starts on 1 September, and at that time there is normally no snow in the mountains. In this study, we start a new simulation on 1 September, with no snow present, and with default values for soil properties, for both 2014/2015 and 2015/2016.

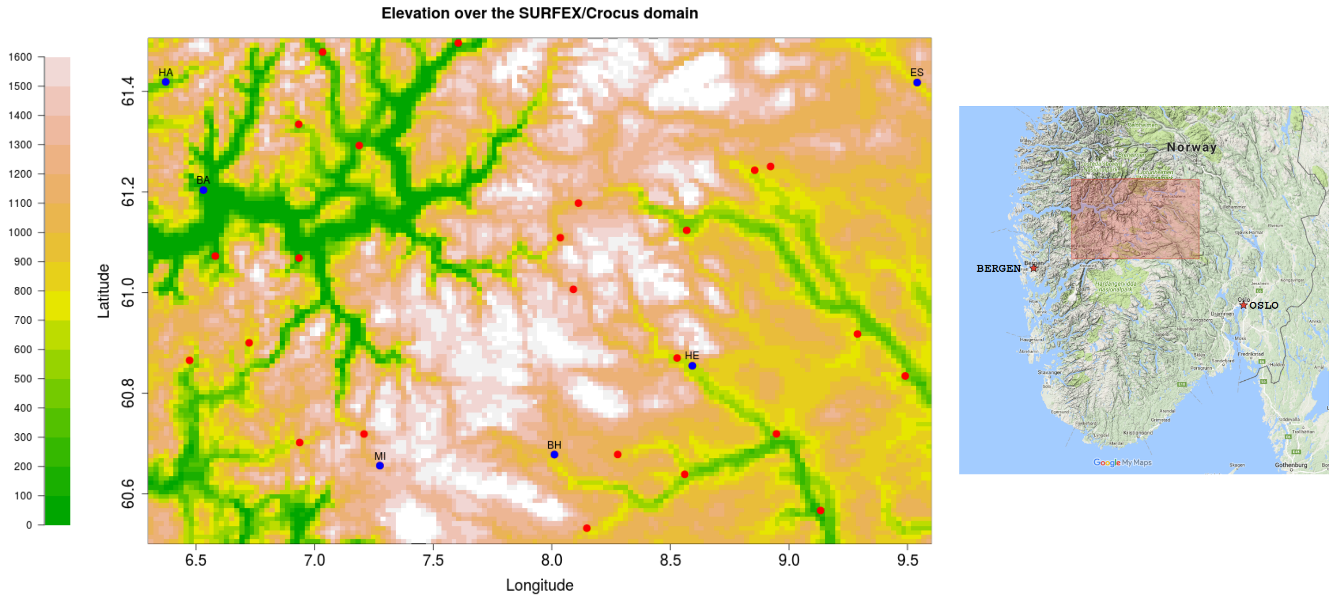

Figure 1. Map showing the domain over which the SURFEX/Crocus model was run on the right (map data: Google), with on the left a map showing the elevation over the SURFEX/Crocus model domain, and the locations of the 30 observations used in this paper (indicated by blue and red dots). The blue dots indicate the 6 stations used in Fig. 4: BA = Balestrand Brannstasjon, HA = Haukedal, HE = Hemsedal II, ES = Espedalen, BH = Bakko i Hol and MI = Midtstova.

2.2 The study area

Figure 1 shows the domain over which the SURFEX/Crocus model was run, and the elevation over the model domain. The domain covers nearly 20.000 km^{-2} (111 x 175 km), and contains 100 x 330 grid points. As mentioned in the introduction, the study area was chosen to cover the mountains in southern Norway and to include a cross-section from west to east that crosses the watershed in this region, as well as to include several catchment areas that are of interest to hydropower companies. The 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. This makes it a challenging area for snow modeling.

Due to the watershed and the prevailing weather patterns, there is a large gradient in precipitation amount over the domain. The far western parts of the domain receive on average around 1500 mm of precipitation during a winter season, while the eastern parts only receive 100-300 mm (Hanssen-Bauer et al., 2015). The western part of the domain has a maritime climate while the eastern part has a more inland climate, which means the average temperature during winter is higher at the western part of the domain (around or just below 0 °Celsius), compared to the eastern side (around -10 °Celsius) (Hanssen-Bauer et al., 2015). This means the gradient in average snowfall amount is not as large as the gradient in precipitation amount, but the western part of the domain still receives significantly more snow than the eastern part (Hanssen-Bauer et al., 2015).

	AROME-Crocus	GridObs-Crocus
Air temperature [K]	AROME-MetCoOp post-processed	Gridded observations
Specific humidity [kg kg^{-1}]	AROME-MetCoOp	AROME-MetCoOp
Wind speed [m s^{-1}]	AROME-MetCoOp post-processed	AROME-MetCoOp
Wind direction [degrees]	AROME-MetCoOp post-processed	AROME-MetCoOp
Incoming direct shortwave radiation [W m^{-2}]	AROME-MetCoOp	AROME-MetCoOp
Incoming longwave radiation [W m^{-2}]	AROME-MetCoOp	AROME-MetCoOp
Surface pressure [Pa]	AROME-MetCoOp	AROME-MetCoOp
Rainfall rate [kg m^{-2} s^{-1}]	AROME-MetCoOp	Gridded observations
Snowfall rate [kg m^{-2} s^{-1}]	AROME-MetCoOp	Gridded observations

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

2.3 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 (hourly) data from the AROME MetCoOp model (described below in section 2.3.1) while GridObs-Crocus uses a combination of gridded observations of precipitation and temperature (both on a 1 hourly temporal resolution), described in section 2.3.2, and AROME MetCoOp data.

2.3.1 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 grid spacing is 2.5 km and the domain covers the Nordic countries. The atmosphere is divided into 65 vertical levels, with the first level 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 atmosphere within AROME MetCoOp. 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, and 3-5h lead time for the 1800 UTC cycle) forecasts combined into a forcing file for each day. These lead times were chosen to avoid the first hours of a cycle when the model might have spin-up issues, and to make use of all available cycles with the shortest possible lead time (model error increases with lead time, see for example Homleid and Tveter (2016)).

The AROME-MetCoOp temperature used to force SURFEX/Crocus has a grid spacing of 500 m. This is a post-processed variable that uses a Kalman filter correction at observation stations (Homleid, 1995), which is then interpolated horizontally using decreasing weights with increasing distance from the station. The temperature is further corrected with a height correction which also takes into account vertical temperature profiles in inversion situations in winter time. The wind speed from AROME-MetCoOp has also been statistically post-processed to represent the maximum wind speed during the last hour. In addition, correction factors are applied to the wind speed depending on wind direction and on the region. The variables from the AROME-MetCoOp 2.5 km forecasts were 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.

2.3.2 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. 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 hourly precipitation values have been obtained by using a two-step procedure. First, the spatial interpolation method described by Lussana et al. (2018a) has been applied independently to daily and hourly precipitation totals. Second, the daily precipitation totals have been disaggregated on an hourly time basis with a procedure similar to the one described by Vormoor and Skaugen (2013). The two-step procedure has been implemented so that the final hourly product can benefit from the more accurate daily quantitative estimates that are based on a denser network of stations, if compared to the hourly ones. The hourly temperature values have been obtained by means of the method described by Lussana et al. (2018b), while the hourly temperature dataset is described and evaluated in Lussana et al. (2016).

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, 2018b). For precipitation, Lussana et al. (2018a) 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.

The number of stations that are included in the gridded dataset is not constant (new stations are added, sometimes stations are closed down). The numbers of stations within the SURFEX/Crocus domain are: 20-30 stations for hourly precipitation, 90-100 stations for daily precipitation and 70-100 stations for temperature. Stations just outside the domain are included in this estimate as they are used in the interpolation and are therefore part of the gridded dataset used in this study.

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)).

2.4 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.

2.4.1 Snow depth observations

Thirty observations of snow depth have been selected for use in verification of the model results (see Fig. 1 for their locations within the domain). Nearly all stations (25 out of 30) are official meteorological stations run by the Norwegian Meteorological Institute, while a few stations are 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. The elevation of the grid points in the SURFEX domain is also shown in Fig. 2, which shows a typical issue with the location of weather stations, particularly in the Norwegian mountains: there are many stations located at low elevations (at the bottom of valleys), and very few stations at high elevations.

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. In a domain with deep valleys and high mountains, it is difficult to match the exact elevation of the weather stations with the nearest grid point in the SURFEX/Crocus experiments. As there were only 30 stations with high quality snow depth observations in the domain, it was decided not to filter out stations based on these height differences. This issue is discussed in more detail in section 4.1 in the Discussion chapter.

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

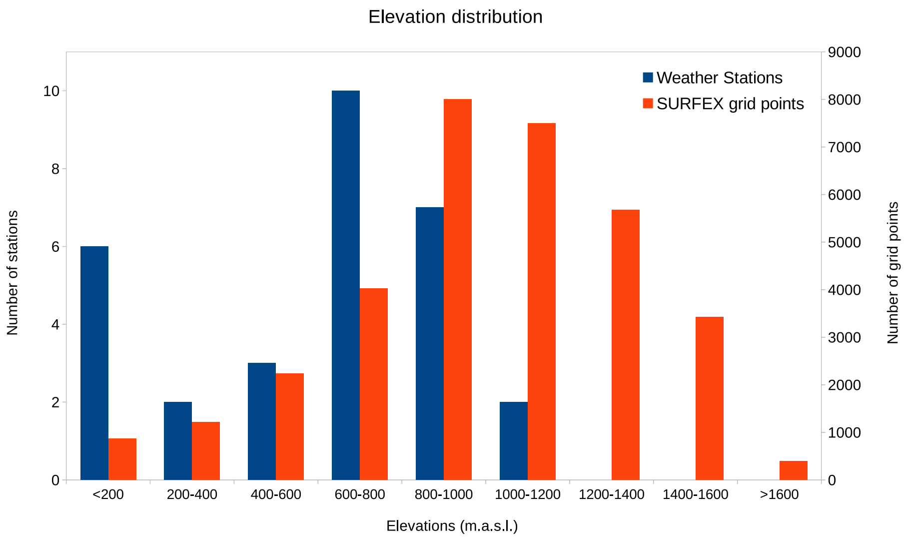

Figure 2. Distribution of elevation for all weather stations used in this study (in blue, on left axis), and of the grid points in the SURFEX domain (in red, on right axis).

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.

2.4.2 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. (2018a) 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.

The MODIS images were used for visual and quantitative 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.

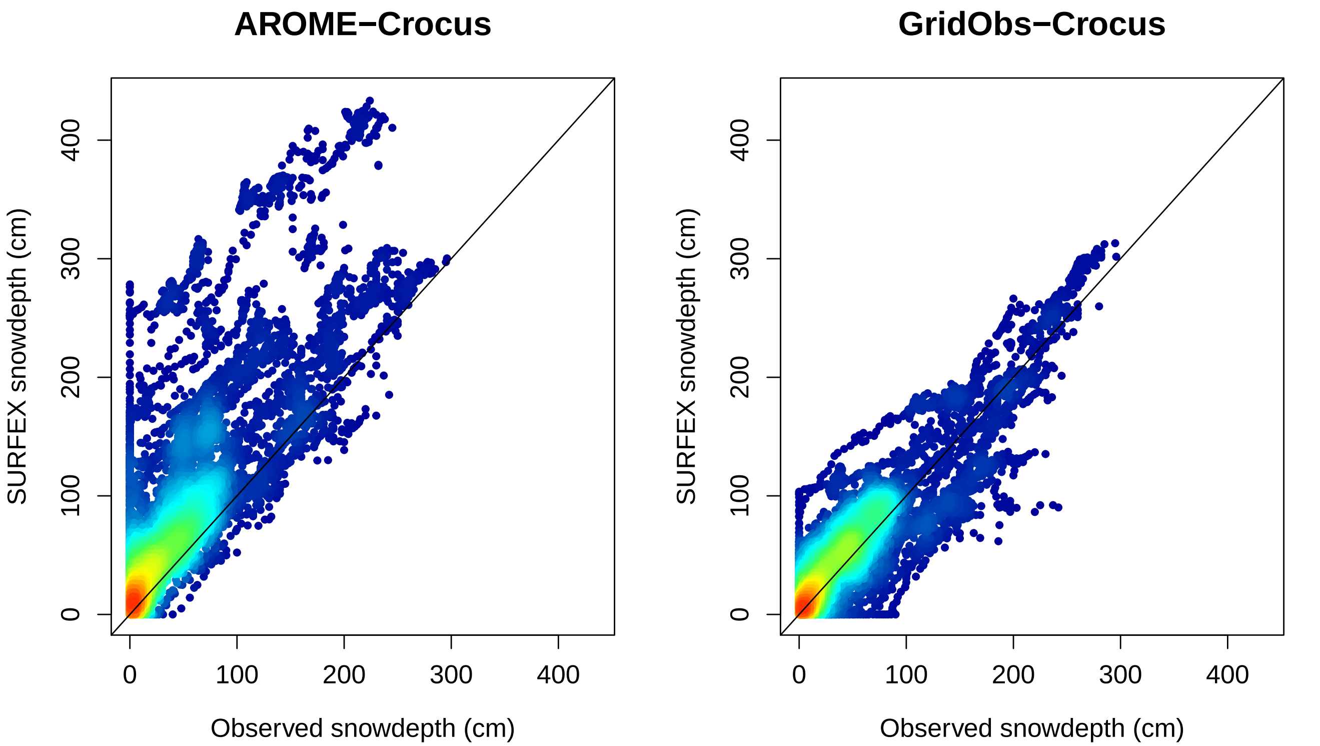

Figure 3. Scatter density plot of daily observed and simulated snow depth (cm) for AROME-Crocus (left) and for GridObs-Crocus (right) for all weather stations, from 01 September 2014 to 31 August 2016. The density ranges from low in blue to high in red.

3 Results

3.1 Snow depth

A density scatter plot of daily observed and simulated snow depth for both experiments and the two winter seasons 2014/15 and 2015/16 is shown in Fig. 3. Only data points where either the simulated or the observed snow depth is larger than 0 cm are taken into account. GridObs-Crocus is in reasonably good agreement with the observations (although there are cases of over- and underestimation of around 100 cm), while AROME-Crocus shows significant overestimation of snow depth (in some cases more than 250 cm). To investigate the snow depth at individual stations over the full range of station altitudes in more detail, 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 in Norway means they are located above the tree line). For the location of these 6 stations within the domain, see Fig. 1 in which they are indicated with blue dots. Consistent with Fig. 3, Fig. 4 shows that 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

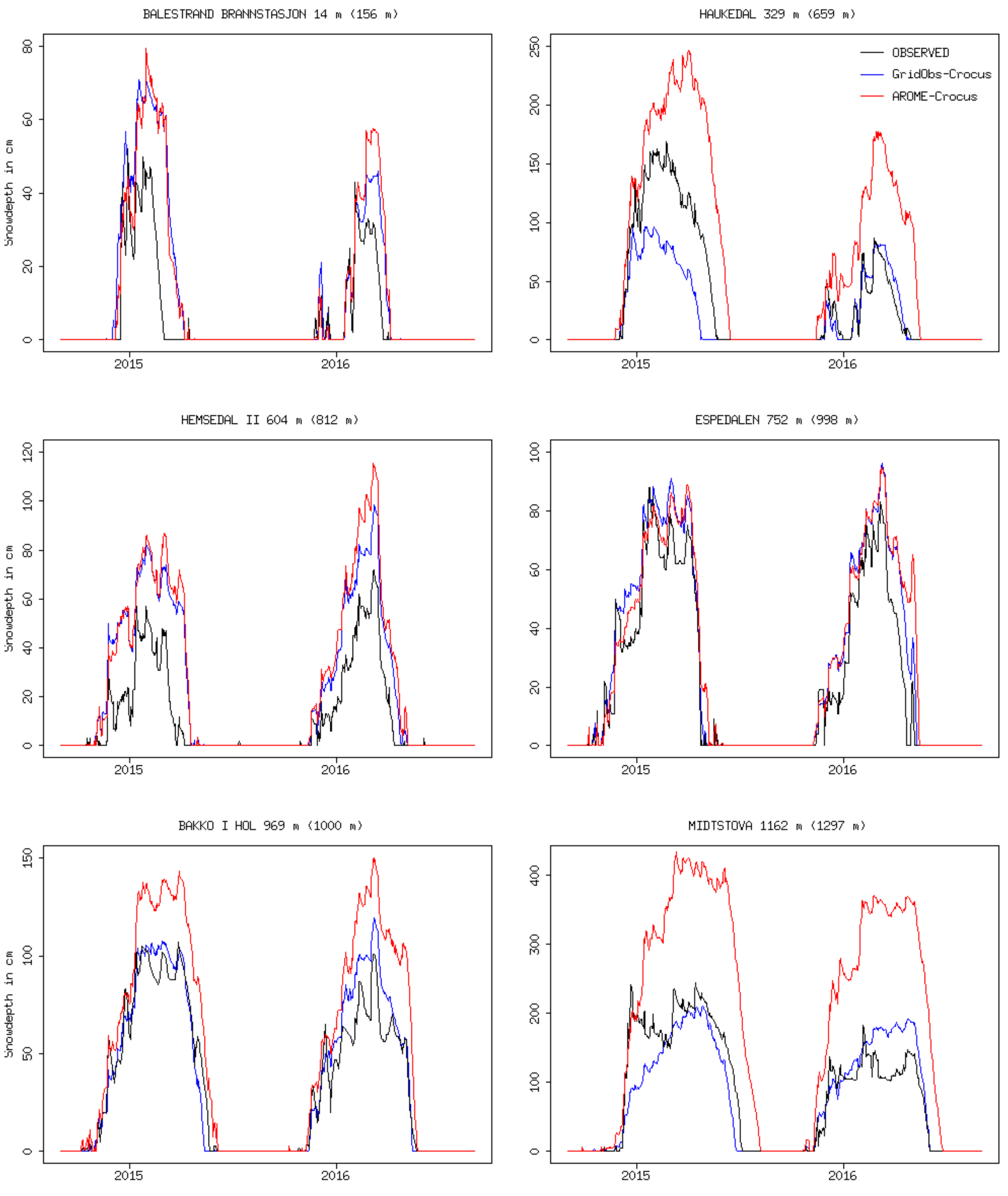

Figure 4. Observed and simulated snow depth (cm) at the location of six weather stations during the two winter seasons 2014-2016 (01 September 2014 - 31 August 2016) : 1) GridObs-Crocus (blue); 2) AROME-Crocus (red) and 3) observations (black). The elevation (in masl.) of the station is indicated above each plot, with in parentheses the elevation of the grid point in SURFEX/Crocus. The location of the 6 stations within the domain is indicated by blue dots in Fig. 1.

at times underestimates the snow depth (most notably for the first winter season at Haukedal (329 masl.) and Midtstova (1162 masl.)). Episodes when 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. The bias in snow depth at Hemsedal II for the two seasons combined is 25 cm for GridObs-Crocus (RMSE: 27 cm) and 30 cm for AROME-Crocus (RMSE: 33 cm). When compared to the bias (6 cm for GridObs-Crocus and 42 cm for AROME-Crocus) and RMSE (28 cm for GridObs-Crocus and 68 cm for AROME-Crocus) for all stations for the two seasons combined, it shows that Hemsedal II performs better than most stations in AROME-Crocus. For GridObs-Crocus, the bias at Hemsedal II is larger than for most other stations, while the RMSE is slightly better. The fact that GridObs-Crocus still outperforms AROME-Crocus even at a station that is not part of the gridded observation dataset is interesting.

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). In the forcing data for Midtstova we find a bias of -1.5 degrees for AROME-Crocus, compared to -0.8 degrees for GridObs-Crocus. This bias is larger than the overall bias for all nine stations measuring temperature: -0.5 degree for AROME-Crocus and -0.2 degree for GridObs-Crocus. During the snow accumulation season the temperature at Midtstova is mostly well below freezing level. There are a few episodes each winter with temperatures just above zero, where the underestimated temperature in AROME-MetCoOp means the precipitation during those episodes comes as snow instead of rain, but these do not add up to large amounts. 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, although there is an underestimation during the first part of the 2014-2015 winter. From 27 October 2014 until 26 January 2015, the precipitation sensor at Midtstova was out of order, and the forcing from GridObs-Crocus for Midtstova will therefore be represented by interpolated values from surrounding stations, which might explain the underestimation.

An evaluation of the precipitation forcing data for AROME-Crocus and GridObs-Crocus for the six stations from Fig. 4 reveals that while the rainfall amount is often quite similar in the two experiments, the largest differences are found in the snowfall amount. AROME-Crocus consistently shows a larger amount of snowfall (accumulated over a year) compared to GridObs-Crocus, often about twice as much. The differences are largest for the stations located in the western part of the domain. As described in section 2.2, this region receives the highest amounts of winter precipitation in our study area.

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-

	2014-2015			2015-2016		
	Observed	GridObs Bias	AROME Bias	Observed	GridObs Bias	AROME Bias
Snow depth (cm)	-	+4	+42	-	+9	+41
Length snow season (days)	151	+11	+34	137	+8	+18
Date start of snow season (days)	15 November	-2	-10	15 November	+2	0
Date end of snow season (days)	02 May	-3	+17	25 April	+2	+11
Date max snow (days)	30 January	+13	+26	22 February	+13	+10
Max snow (cm)	112	0	+43	88	+9	+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. GridObs-Crocus is abbreviated to GridObs and AROME-Crocus to AROME.

RMSE	2014-2015		2015-2016	
	GridObs	AROME	GridObs	AROME
Snow depth (cm)	29	68	27	68
Length snow season (days)	25	44	21	28
Date start of snow season (days)	10	18	5	8
Date end of snow season (days)	15	26	12	17
Date max snow (days)	31	38	24	17
Max snow (cm)	30	68	28	70

Table 3. RMSE for snow depth, length of snow season, start of snow season, end of snow season, 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. GridObs-Crocus is abbreviated to GridObs and AROME-Crocus to AROME.

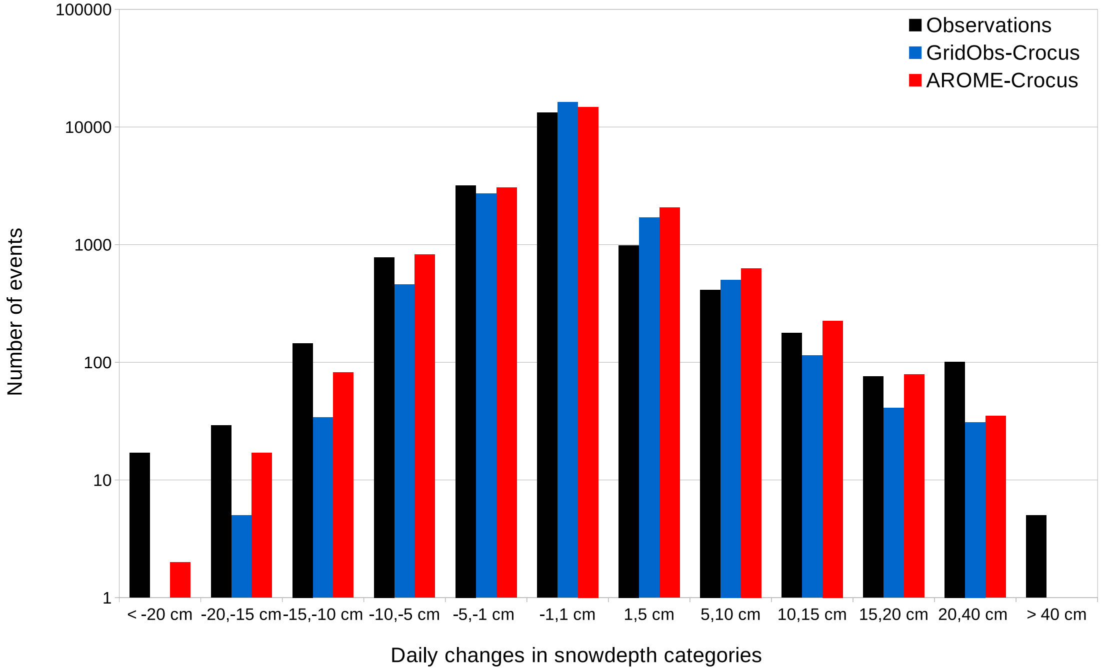

Figure 5. Categorical frequency distribution of daily changes in snow depth for observations (in black), GridObs-Crocus (in blue) and AROME-Crocus (in red), for all stations during 01 September 2014 - 31 August 2016. The y axis is on a logarithmic scale.

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. Table 3 summarizes the RMSE over all stations for the two winter seasons. The RMSE values are significantly larger for AROME-Crocus (compared to GridObs-Crocus) for nearly all variables, except for the date of maximum snow depth for 2015-2016.

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 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 in stand-alone mode does not account for wind-induced snow redistribution, 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 cause of

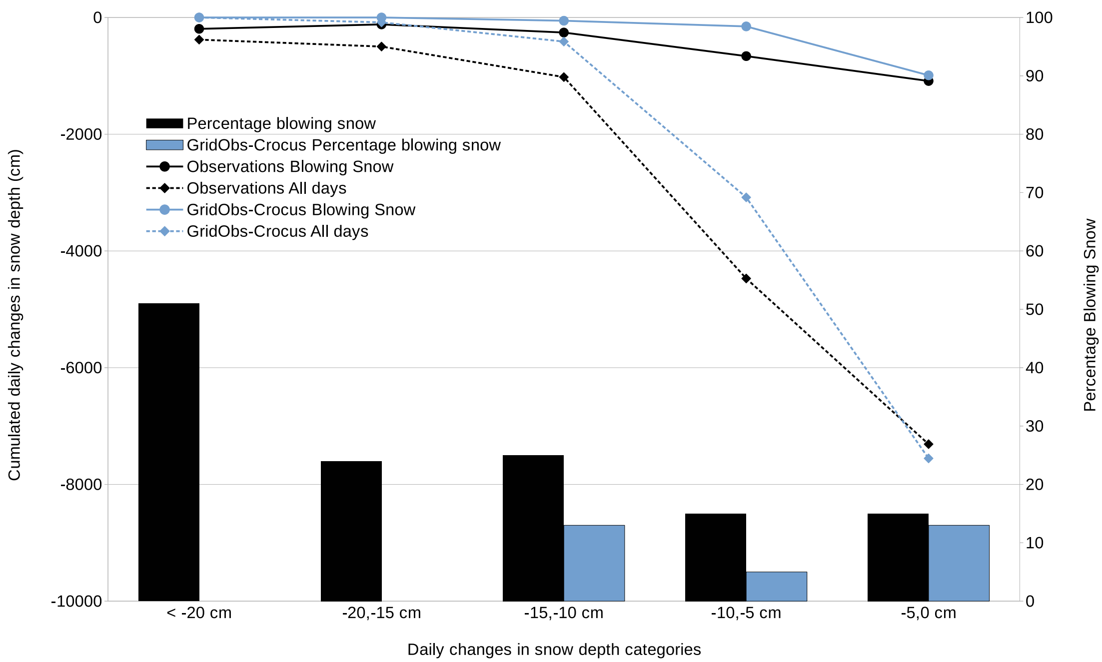

Figure 6. Cumulated daily change in snow depth for observations (in black), GridObs-Crocus (in blue) for all stations during 01 September 2014 - 31 August 2016, for blowing snow days (solid lines) and all days with decreasing snow depth (dashed lines). The columns show the percentage of snow loss that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

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 (at a height of 10 m) during the past 24 hours (between 06 and 06 UTC, as this is when snow depth measurements are made) exceeds 8 m s^{-1}, 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 the SURFEX/Crocus 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 modeled wind speed is used because only 6 out of 30 stations used in this study observe wind speed. When comparing the forecasted maximum wind speed from AROME-MetCoOp with the observed maximum wind speed from these 6 stations, we find a slight overestimation by AROME-MetCoOp (a bias of 0.3 m/s). Blowing snow days and non-blowing snow days are correctly identified in 94% of all days, with a hit rate of 0.86 and a false alarm rate of 0.04. This shows that the modeled wind speed can be used to determine blowing snow days. The wind threshold of 8 m s^{-1} 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

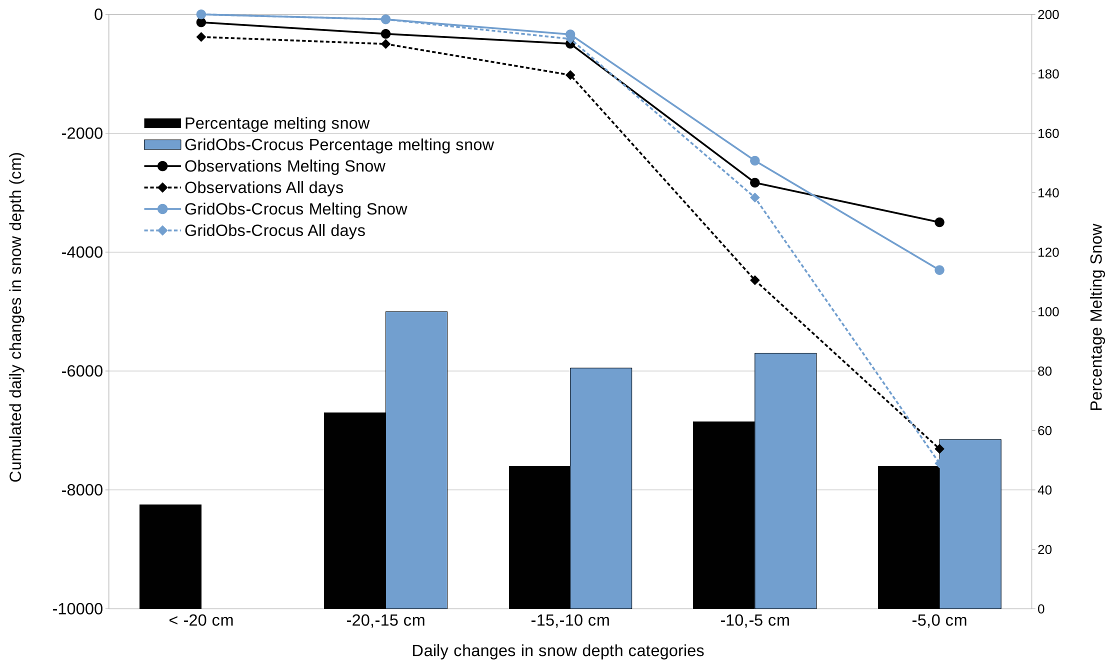

Figure 7. Cumulated daily changes in snow depth for observations (in black), GridObs-Crocus (in blue) for all stations during 01 September 2014 - 31 August 2016, for melting snow days (solid lines) and all days with decreasing snow depth (dashed lines). The columns show the percentage of snow loss that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

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

Melting snow days are defined as days when the surface temperature of the snow is 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).

SURFEX/Crocus does have an option to run with sublimation in case of snowdrift. This option has been tested for two stations from Fig. 4: Midtstova and Hemsedal II. In this experiment, SURFEX/Crocus was run twice in 1D mode for these 2

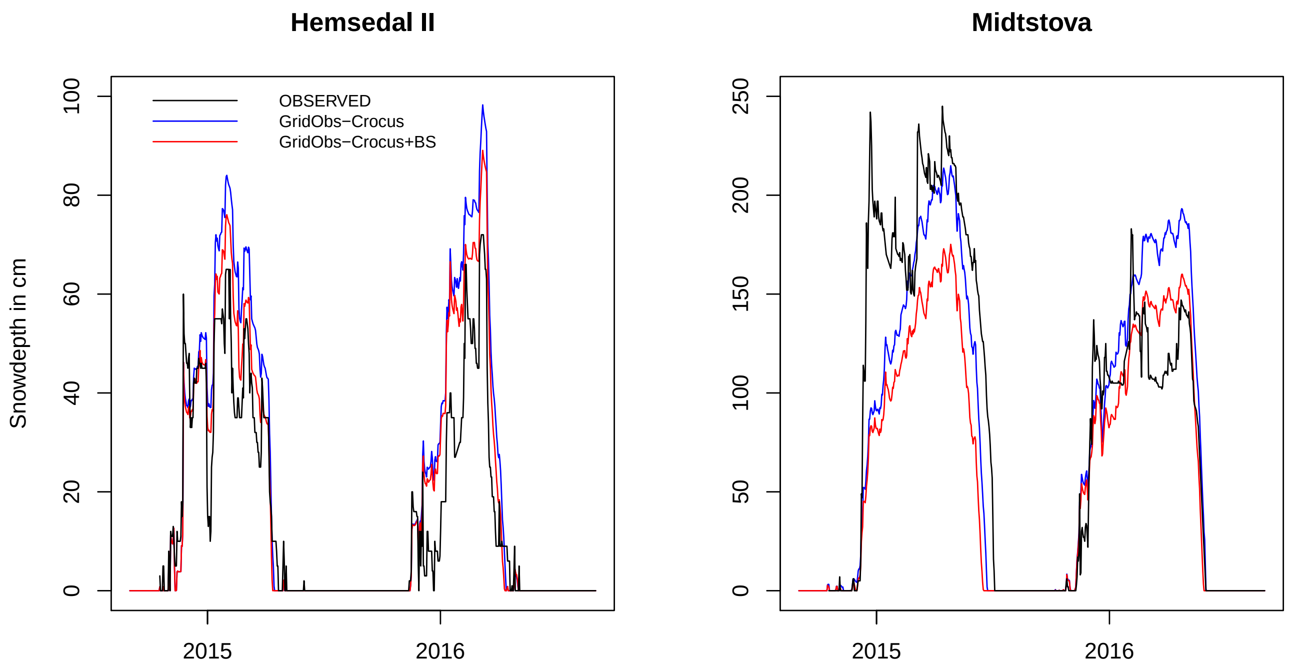

Figure 8. Observed and simulated snow depth (cm) at the location of Hemsedal II and Midtstova during the two winter seasons 2014-2016 (01 September 2014 - 31 August 2016) : 1) GridObs-Crocus 1D experiment (blue); 2) GridObs-Crocus+BS 1D experiment with sublimation loss during blowing snow events (red) and 3) observations (black).

locations: one experiment with identical settings as GridObs-Crocus, and one nearly identical with the exception of the option for sublimation in case of snowdrift (GridObs-Crocus+BS). The results are shown in Fig. 8. For both locations, the snow depth in GridObs-Crocus+BS is decreased, as expected. For Hemsedal II, this reduction is an improvement compared to the GridObs-experiment, which overestimated the snow depth. The bias in GridObs-Crocus was +16 cm for Hemsedal II, which has improved to +10 cm in GridObs-Crocus+BS. For Midtstova, GridObs-Crocus underestimates the snow depth for most of the two winter seasons (bias: -5 cm), and this underestimation is significantly larger in the GridObs+BS experiment (-28 cm).

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 8-11 days (see table 2), while AROME-Crocus has a bias of 18-34 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

Jaccard Index	GridObs-Crocus	AROME-Crocus
15 March 2015	0.92	0.99
20 April 2015	0.82	0.94
15 May 2015	0.65	0.82
04 July 2015	0.19	0.68

Table 4. Jaccard index for the snow covered areas shown in Fig. 10. A score of 1 means the image perfectly matches the MODIS image, a score of 0 means there is no overlap between the image from the experiment compared to the MODIS image.

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 9 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 10 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

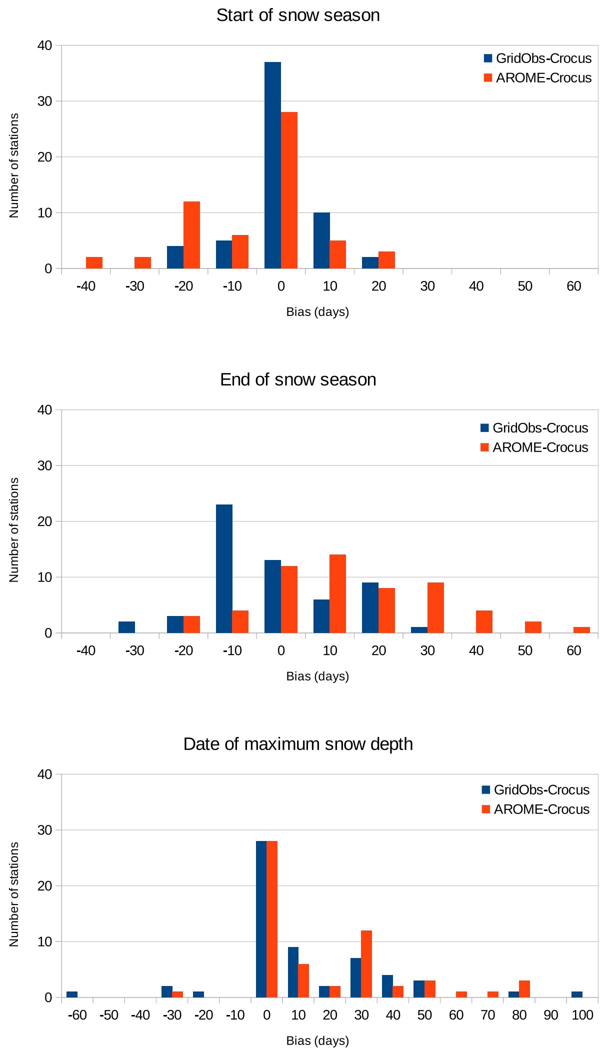

Figure 9. Distribution of the bias in start of snow season (top), end of snow season (middle) and date of maximum snow depth (bottom), for all 30 stations and for 2 winter seasons.

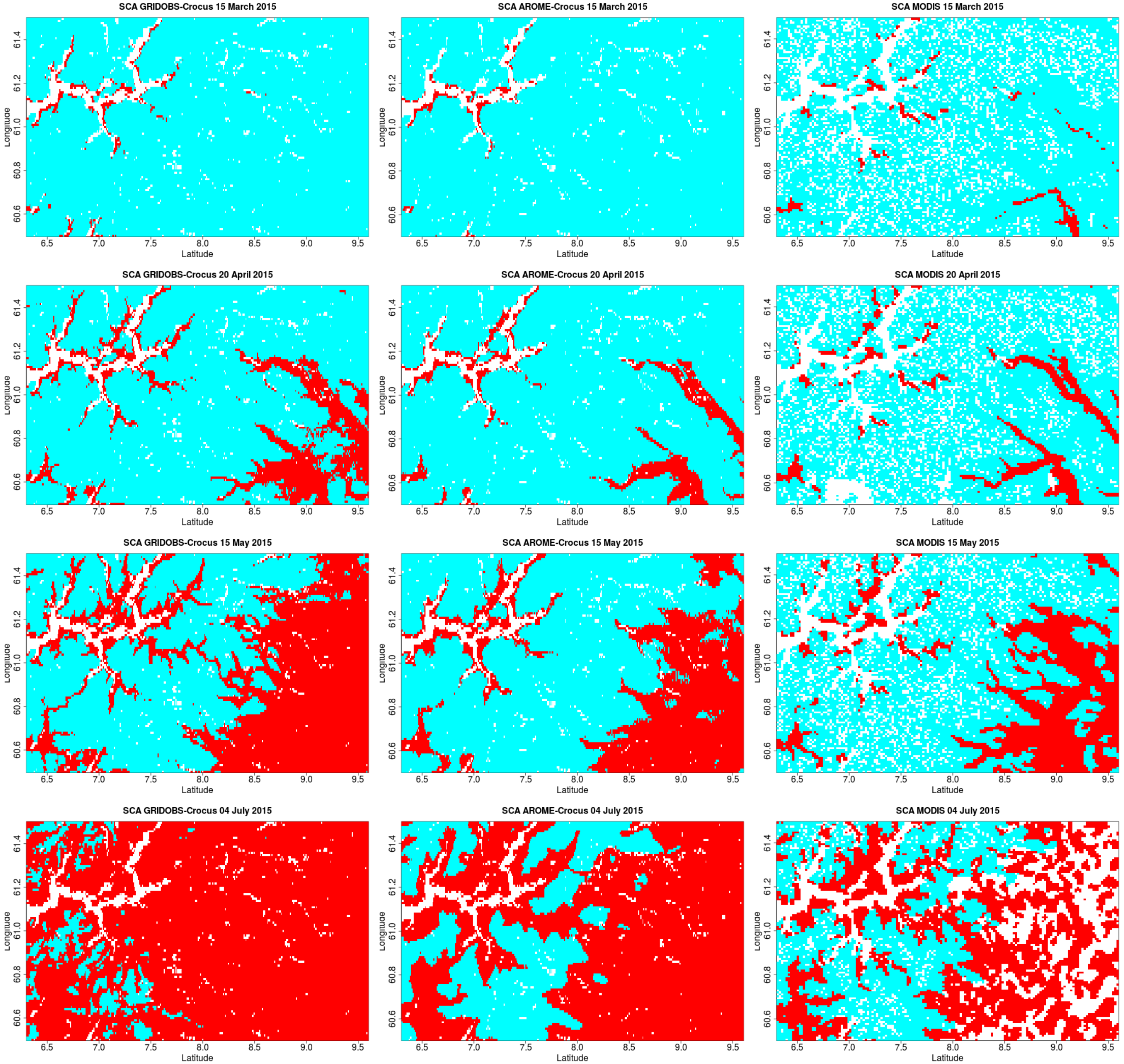

Figure 10. Snow covered area (where cyan is snow, red is no snow, and white is missing data or water surfaces) for GridObs-Crocus (left column), AROME-Crocus (middle column) and from MODIS satellite images (right column), for (rows from top to bottom): 15 March 2015, 20 April 2015, 15 May 2015 and 04 July 2015.

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. 9) 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). As discussed previously, the differences between the snowfall amounts from the two precipitation forcing datasets is largest on the west side of the domain; AROME-Crocus receives about twice as much snow compared to GridObs-Crocus in this region. This explains why the differences between GridObs-Crocus and AROME-Crocus in Fig. 10 are also largest in this area.

Table 4 shows the Jaccard indices for the images from Fig. 10. The Jaccard index was also used by for example Quéno et al. (2016). It is a similarity index applied to the snow cover images which were remapped onto the same grid (which means that the snow cover from the MODIS images used to calculate the Jaccard index has a lower resolution than the one shown in Fig. 10). The Jaccard index is calculated as $J(X,Y) = |X \cap Y|/|X \cup Y|$, where X and Y are the simulated and observed snow cover, respectively. The number of grid points that are snow-covered in both SURFEX/Crocus and in the MODIS image is divided by the total amount of snow-covered grid points (in either SURFEX/Crocus or MODIS). When the Jaccard index equals 1, there is a perfect match between snow-covered grid points, and when the Jaccard index equals 0, there is no match at all. Table 4 shows that AROME-Crocus consistently has higher Jaccard indices compared to GridObs-Crocus. The indices decrease (for both experiments) during the melt season.

4 Discussion

Although both experiments are capable of simulating the snow pack over the two winter seasons, there is an overestimation of snow depth in the AROME-Crocus experiment, even though 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 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.

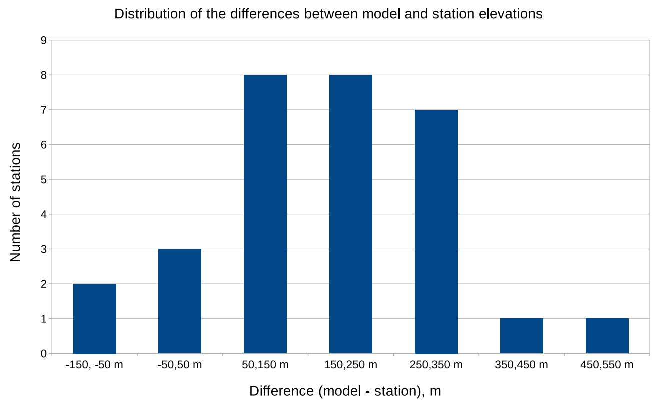

Figure 11. Differences between station elevation and the height of the station in the SURFEX/Crocus model.

4.1 Quality of the model validation

Nearly all (29) of the 30 stations that measure snow depth also measure precipitation (7 measure hourly precipitation, while 22 measure daily 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 only station that was not part of the gridded precipitation dataset is Hemsedal II. The RMSE for GridObs-Crocus at Hemsedal II is 27 cm, about the same as the overall RMSE for all stations for GridObs-Crocus (28 cm). Although this shows that the performance of a station not included in the gridded precipitation dataset is about the same as the performance of stations that are part of this dataset, one station is not enough to draw conclusions about the entire domain.

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 11 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 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. It could be argued that SURFEX grid points with a large height difference compared to the corresponding station should not be used for verification purposes. However, when calculating bias and RMSE values only for the stations with a height difference below 250 m, this did not have a large impact on the results. With a few exceptions, the bias and RMSE are lower when excluding stations with a large height difference, but the differences in overall bias are only ± 3 cm, which does not change any of the conclusions in this study.

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., 2018a), 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., 2018a). 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. An evaluation of the accumulated precipitation from the two forcing datasets showed that while the rainfall amounts are rather similar, the snowfall amount in AROME-Crocus is much larger compared to GridObs-Crocus, especially at the west side of the domain. This suggests that the overestimation of total precipitation in AROME-MetCoOp might be limited to the snowfall amount.

In this study, the forcing data from AROME-MetCoOp is interpolated from the original 2.5 km resolution to the 1 km resolution required by SURFEX/Crocus, apart from the temperature which is a post-processed, terrain-adjusted variable with a resolution of 500 m. The interpolation of AROME-MetCoOp data over a domain with complex topography could lead to differences in elevation (between AROME-MetCoOp and SURFEX/Crocus), which might lead to bias in for example the precipitation. We believe this might affect the AROME-Crocus experiment more than the GridObs-Crocus experiment, since the two experiments use different data sources.

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 m^{-2}. 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, as there is no interaction with vegetation, but for areas covered with forest and closer to sea level this could lead to an overestimation of the snow cover. When the snow cover is overestimated, the albedo will be too high and this will slow down the snow melt at the end of the season. This might explain the underestimated snow melt in both experiments.

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. This option was tested for two stations in his study, using the GridObs-Crocus forcing dataset. As expected, this resulted in a decrease in snow depth and a decrease in season length. As GridObs-Crocus already underestimates the snow depth and snow cover, this is not an improvement.

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 explain more than half of the 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. (2015a) 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 (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 meteorological weather forecasts from AROME-MetCoOp, including a few post-processed variables, 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 (a bias of 6 cm and RMSE of 68 cm). This shows that using a combination of gridded observations and meteorological forecasts as forcing to SURFEX/Crocus can give better results than mainly using meteorological forecasts. When using AROME-MetCoOp forcing data, the snow depth is strongly overestimated (a bias of 42 cm and RMSE of 68 cm), which was also shown by Quéno et al. (2016) and Vionnet et al. (2016).

- The AROME-MetCoOp forcing data provided the best results on representing the spatial snow cover pattern throughout the melt season. Using gridded observations of temperature and precipitation 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 might 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. Using the option in SURFEX/Crocus of running with sublimation in case of snowdrift is not enough to address this issue.

The dataset of gridded observations, and specifically the gridded precipitation is under continuous development. For future work, 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. To investigate the impact of using gridded observations of temperature and precipitation separately, "leave-one-out" experiments could be carried out (two extra experiments where one uses only gridded observations of temperature, and one uses only gridded observations of precipitation, while all other variables come from AROME-MetCoOp). Using the multi-physical ensemble system ESCROC (Ensemble System Crocus), and/or an ensemble of meteorological forcing would be an another interesting topic for future work. Finally, when using AROME-MetCoOp as forcing data for running SURFEX/Crocus at a resolution higher than 2.5 km, terrain adjustment routines should be applied to the generation of forcing data. In this study we accounted for local terrain effects, by using post-processed AROME-MetCoOp temperature and wind, but this could be extended to other variables.

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. Running the SURFEX/Crocus model in gridded version for Norwegian conditions using a combination of data sources (raw and post-processed weather predictions and observations) is very promising. The result from this study is very valuable information which may 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 www.senorge.no and www.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.

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