An evaluation of Norwegian snow maps: simulation results versus observations

Anita Verpe Dyrrdal

ABSTRACT

The snow map service introduced by the Norwegian Meteorological Institute and Norwegian Water Resources and Energy Directorate in 2004 is evaluated at eleven meteorological stations situated in three regions in Norway. The focus is on the start and end of the snow season and the total number of snow days. In addition, accumulated snow depth throughout the winter season, along with snow depth on four selected dates, is examined. In the evaluation, simulations by a precipitation/degree-day snow model are compared to observations. The approach used to calculate snow depth tends to compact the snow too much, resulting in an underestimation of snow depth at most stations. In Region 1 the snow model simulates a shorter snow season than what is observed. In Region 2 the results are ambiguous and correlations between simulations and observations are low. In Region 3, however, the snow model performs very well, and there are no significant differences between simulated and observed snow season. The results confirm that the use of snow simulations in areas outside the observational network is valuable, but there is room for improvement.

Key words | Norway, snow maps, snow model, snow season

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INTRODUCTION

In 2004, a new snow map service was introduced by the Norwegian Meteorological Institute (NMI) and the Norwegian Water Resources and Energy Directorate (NVE), and was made available to the public at www.senorge.no. The new snow maps substituted traditional snow accumulation maps, and they show snow water equivalent (SWE), snowmelt, total runoff, snow state, fresh snow, snow age and snow depth.

The purpose of this study is to evaluate the snow maps described above by comparing them to observations at eleven different meteorological stations in three regions in Norway. Evaluation of the snow maps is important since the maps are accessible to the public and several different organizations are using them as a source. One of the main users is the National Flood Forecasting Service. The snow map system makes it possible to monitor the development of floods and the contributions from snow and precipitation prior to and during the flood (Engeset *et al.* 2004*a*). The maps are also used in preparing for avalanches, in power production, wildlife management, agriculture, tourism, transportation, construction, extreme weather forecasting, consumer analysis and military activities, among others. In addition, climate researchers make use of the snow maps to investigate changes and variability in snow season, energy balance and in determining if climate models of different types provide reasonable results (personal communication from T. Skaugen, 2008). It is very useful to assess the performance of the snow model in different parts of the country, and to determine if it can be applied in areas without observations.

Due to complex topography and the small number of meteorological stations with snow observations in Norway, interpolation is not an option. Gridded simulation of snow is therefore a better way to present past snow conditions.

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It is essential to have a consistent set of maps showing snow conditions in the entire country, and at all times. It is also important to study climate change in the past, and to evaluate if climate models can describe the historical snow variations in all parts of the country. Evaluation of these simulations of the past will be used to improve the snow model and hopefully also improve the forecast. Although snow maps only date to 1971, we have simulated snow data from 1961 which will be the starting year of our comparison with observations.

DATA AND METHODS

Snow accumulation data were analyzed at eleven stations in three different regions of Norway. We had three main requirements for the stations:

1. smooth topography;
2. terrain model height comparable with real station height; and
3. observations should be of good quality and time series should cover the period back to 1970.

These requirements were set in order to minimize differences between real and modelled snow accumulation caused by differences between real and model topography (points (1) and (2)), as well as by observational errors (3). The main reasons for our selection of regions were the flat topography, the quality of the observations and latitudinal representativeness. Figure 1 shows where the eleven stations are located; station names along with some basic information are found in Table 1. We obtained daily snow observations at www.eklima.no, which is a free portal for

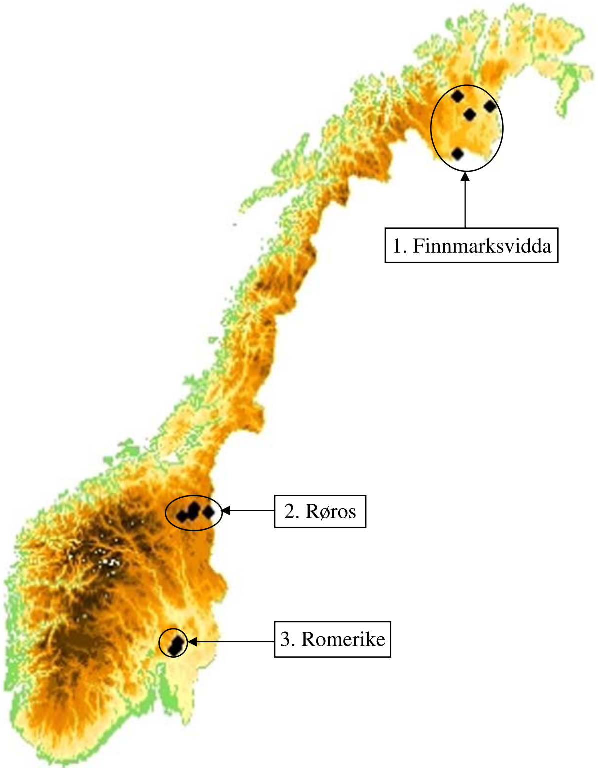

Figure 1 | Map of Norway indicating the eleven stations in the three regions studied.

Table 1 | Names of regions and stations with real station elevation and elevation used in the snow model

Region	Station (period of time series)	Snow model elevation (m)	Real elevation (m)	Elevation difference (m)
1. Finnmarksvidda	1. 93500 Jotkajavre* (1926–2003)	400	389	11
	2. 97350 Cuovddatmohkki (1967–2003)	300	286	14
	3. 97250 Karasjok (1901–2003)	146	130	16
	4. 93900 Sihcajavri (1954–2003)	378	382	4
2. Røros	5. 10400 Røros (1954–2001)	650	628	22
	6. 10600 Aursund* (1957–2003)	690	685	5
	7. 10100 Os i Østerdal* (1900–2003)	700	788	−88
	8. 10900 Vauldalen* (1957–2003)	880	830	50
3. Romerike	9. 4780 Gardermoen (1966–2003)	208	202	6
	10. 4740 Ukkestad* (1957–2003)	160	187	−27
	11. 11120 Eidsvoll–verk* (1957–2003)	180	181	−1

*Precipitation stations where temperature is not observed.

Norwegian meteorological and climate data. Snow depth in centimetres is measured once a day at most precipitation and weather stations. In addition, the precipitation stations report snow cover from 0 to 4 (0 being no snow observed within approximately 1 km radius around the station and 4 being 100% snow cover).

Daily snow simulations presented at www.senorge.no are created using interpolated fields for precipitation and air temperature with 1 × 1 km grid spacing as input in a precipitation/degree-day type model (Engeset *et al.* 2004*a*). This is a point model for each grid cell. A degree-day factor varies according to the time of the year between a minimum value of 2 and a maximum value of 3 or more, depending on location (personal communication from J. Andersen, 2009).

The temperature grids are created from around 150 observations along with residual interpolation. The interpolation is based on the kriging method (Journel & Huijbregts 1978), which is one of the preferred methods for establishing climatological maps. Temperature is interpolated to all meteorological stations, since many of them only measure precipitation. Precipitation is more complicated due to discontinuous distribution, the strong influence of terrain, distance to the sea and the topography in Norway. The precipitation grids are created using observations from around 630 stations and triangulation with terrain adjustment, where triangles are created between three and three points (Tveito & Førland 1999; Tveito *et al.* 2000). A surface describing the elevation between the precipitation stations is established because the model simulates a 10% increase in precipitation for every 100 m increase in altitude (5% for altitudes above 1,000 m a s l) (Jansson *et al.* 2007). Observed precipitation is corrected for systematic wind losses according to Førland *et al.* (1996), and observed or estimated temperature at the station is used to determine the state of the precipitation (Engeset *et al.* 2004*b*).

The snow model makes use of a straightforward inverse distance weighting technique (Tveito & Schöner 2002), with a snow routine similar to that applied in the Swedish HBV (Hydrologiska Byråns Vattenbalansavdelning) model (Engeset *et al.* 2004*a*). Temperature-dependent thresholds are used to separate snow from rain ($T = 0.5°C$) and to recognize snow melt and refreezing ($T = 0.0°C$). Snow depth, which is the variable of interest in the present analysis, is estimated from the three following factors: decrease in snow depth due to melting, change in snow depth due to snowfall including compaction due to the weight of the fresh snow and decrease in snow depth due to ageing (Alfnes 2008). The snow depth algorithm is based on the Variable Infiltration Capacity (VIC) hydrologic model (Liang *et al.* 1994; Cherkauer & Lettenmaier 1999), and constants are obtained from the snow and soil model SNTHERM (SNow THERmal Model) (Jordan 1991).

In order to compare the snow maps with observations at the eleven selected stations, we obtained simulated daily values from a 1 × 1 km pixel that contains the same coordinates as the station in question. This means that the height above sea level used in the snow model can be different from the real elevation of the station. This elevation difference is presented in Table 1.

We focused on comparing the start and end of the snow season and the number of snow days. Start of snow season is defined here as the first day of permanent snow cover; the end of the snow season is the last day of permanent snow cover. The indices used in this study are as follows:

1. number of snow days: number of days with snow cover of 50% or more per hydrologic year (1 September–31 August);
2. start of snow season: ten or more consecutive snow days; and
3. end of snow season: last snow day followed by at least ten consecutive days of less than 50% snow cover and no events of five snow days after that.

The comparison of these three variables was carried out for the years 1961 to 2003. In addition, we performed a simple trend analysis on the complete observational time series, going back as far as 1900 at station 7 (Os i Østerdal). The period at each station is specified in Table 1.

Since snow cover is of greater interest and higher accuracy over a larger area, this was the variable in focus when evaluating the observed snow season. Unfortunately, snow cover is not simulated by the snow model. Consequently, we had to convert snow depth using 1 cm or more as an indicator of 50% or more snow cover (personal communication from E.J. Førland, 2008). From 1961 to 1970 only snow water equivalent is simulated. We converted

SWE to snow depth using the rule: 2 mm SWE is equivalent to 1 cm snow depth. This conversion was defined by searching through years with both SWE and snow depth simulations. The conversion seems to be quite accurate, with only smaller differences of 1–2 days between dates found using SWE compared to snow depth.

There is great uncertainty associated with the indices for snow season. Consequently, we also chose to examine some more stable features. We considered yearly accumulated snow depth from September to August and the snow depth on certain dates (15 December, 15 January, 15 February and 15 March) for the years 1971–2003.

RESULTS AND DISCUSSION

Below follows a short summary of the trend analysis performed on observed data, looking at the entire time series (see Table 1 for the extent of the different time series). Next we present results from the comparison between observed and simulated snow season for the period 1961–2003. Data for the station with the worst results (station 7, Os i Østerdal) and the best results (station 9, Gardermoen) are presented in Figures 2–5.

We found negative trends in snow season length (either a later start and/or an earlier end) and total number of snow days at all eleven stations. However, the decreasing trend in snow season length is statistically significant only at stations 2 (Cuovddatmohkki), 7 (Os i Østerdal), 8 (Vauldalen), 9 (Gardermoen), 10 (Ukkestad) and 11 (Eidsvoll-verk). In addition, the decrease in snow days is statistically significant at stations 8 (Vauldalen) and 9 (Gardermoen).

The statistical results shown in Table 2 imply a systematic negative bias in the snow model, resulting in underestimation of snow depth. Station 7 (Os i Østerdal) demonstrates the largest difference in observed and simulated snow accumulation (Figure 2(a)) along with stations 3 (Karasjok), 4 (Sihcajavri) and 6 (Aursund). The only location where the model simulates more accumulated snow compared to observations is station 8 (Vauldalen). This might be because Vauldalen has the highest elevation of the eleven stations (830 m a s l). An earlier study by Engeset *et al.* (2004*b*) states that the elevation gradient is

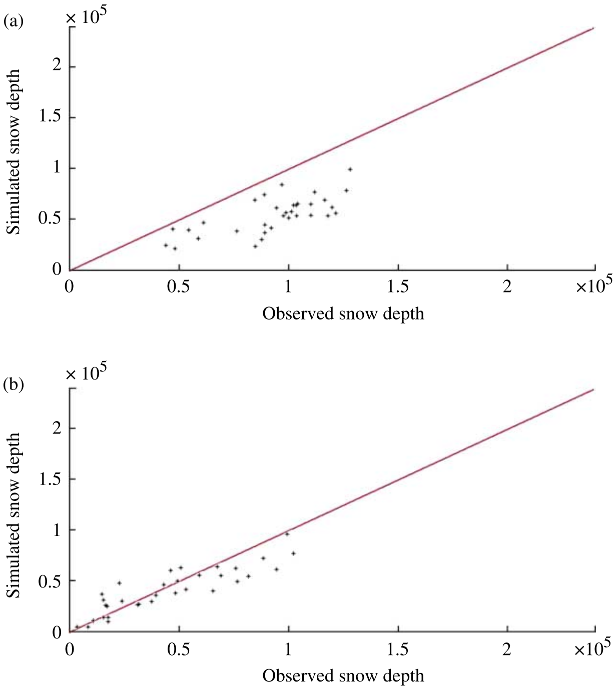

Figure 2 | Observed versus simulated total snow depth for the winter season at station. (a) 7 (Os i Østerdal) and (b) 9 (Gardermoen).

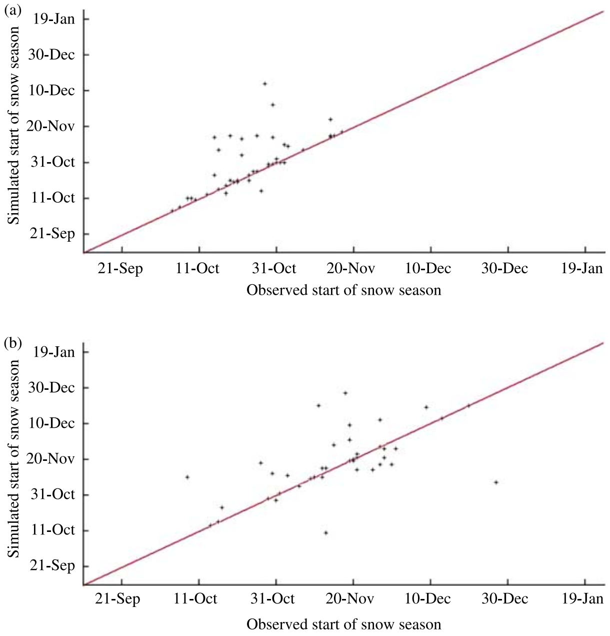

Figure 3 | Observed versus simulated start of snow season at station (a) 7 (Os i Østerdal) and (b) 9 (Gardermoen).

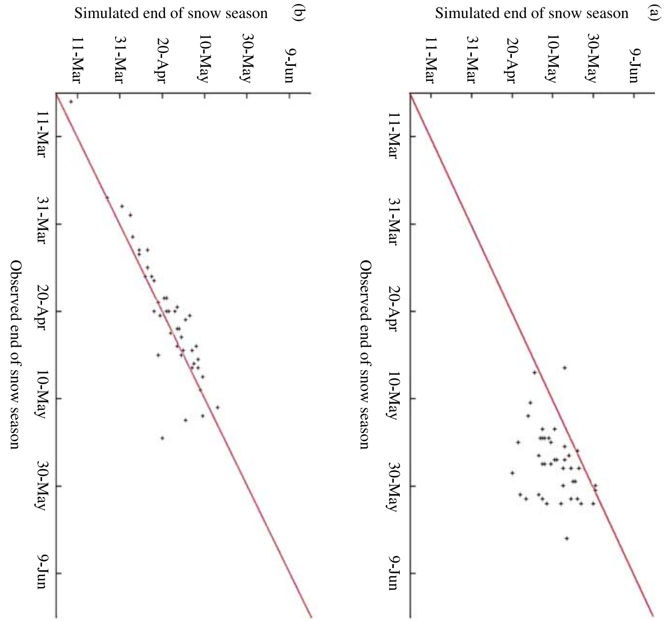

Figure 4 | Observed versus simulated end of snow season at station (a) 7 (Os i Østerdal) and (b) 9 (Gardermoen).

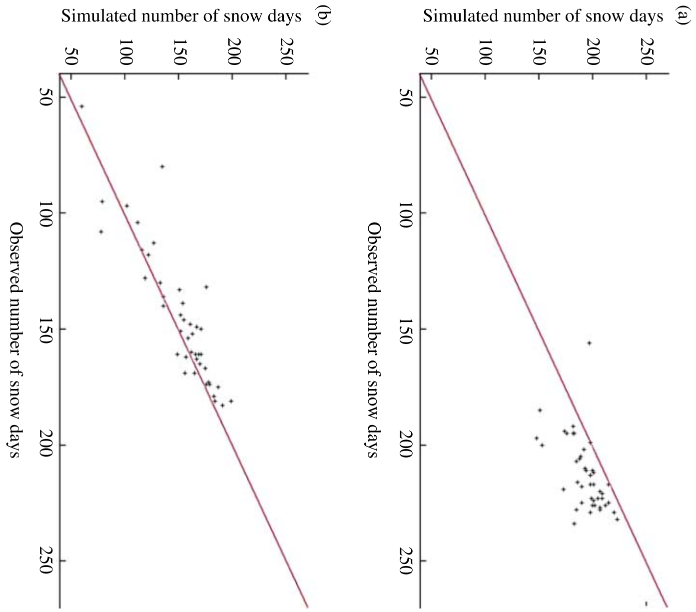

Figure 5 | Observed versus simulated number of snow days per winter season at station, (a) 7 (Os i Østerdal) and (b) 9 (Gardermoen).

Table 2 | Statistical results of simulated and observed: (1) mean snow depth on four selected dates and (2) mean yearly accumulated snow depth (1971–2003)

	Mean snow depth on a particular date (cm) ± standard deviation								**Accumulated snow depth (cm)**	
	15 Dec		**15 Jan**		**15 Feb**		**15 Mar**			
Region/Station	**Obs**	**Sim**	**Obs**	**Sim**	**Obs**	**Sim**	**Obs**	**Sim**	**Obs**	**Sim**
Region 1										
1. Jotkajavre	29.8 ± 13.5	30.9 ± 12.7	44.6 ± 18.7	42.0 ± 13.0	56.3 ± 17.6	50.9 ± 14.1	73.1 ± 23.5	56.1 ± 14.9	10,640 ± 2956	8973 ± 2486
2. Cuovddatmohki	22.4 ± 8.4	18.9 ± 6.9	30.7 ± 9.5	25.3 ± 7.5	39.8 ± 13.4	30.8 ± 8.4	44.5 ± 17.1	32.6 ± 7.8	6248 ± 2068	5032 ± 1500
3. Karasjok	28.0 ± 16.1	15.2 ± 7.9	39.6 ± 19.4	20.7 ± 9.0	48.4 ± 17.4	25.0 ± 8.1	49.2 ± 15.8	25.2 ± 8.4	6996 ± 2516	3690 ± 1321
4. Sihcajavri	28.4 ± 7.6	17.0 ± 5.4	38.1 ± 8.2	23.3 ± 8.3	45.3 ± 8.0	27.9 ± 8.8	48.8 ± 9.5	30.0 ± 9.0	7692 ± 1503	4677 ± 1570
Region 2										
5. Røros	31.3 ± 18.1	29.1 ± 14.4	50.7 ± 26.2	41.0 ± 15.5	64.3 ± 24.6	53.2 ± 14.2	68.0 ± 23.7	58.6 ± 16.0	7983 ± 2541	7867 ± 2428
6. Aursund	46.1 ± 21.3	31.7 ± 19.3	64.5 ± 21.0	44.8 ± 22.8	84.2 ± 21.0	60.2 ± 21.9	95.1 ± 21.1	67.3 ± 24.3	12,757 ± 3032	9229 ± 3570
7. Os i Østerdal	33.3 ± 13.8	20.8 ± 11.1	49.1 ± 16.3	28.9 ± 11.5	62.1 ± 17.1	37.5 ± 11.7	70.3 ± 18.0	41.0 ± 12.9	9308 ± 2329	5403 ± 1839
8. Vauldalen	44.2 ± 21.7	48.1 ± 13.6	64.4 ± 22.7	65.8 ± 18.0	83.6 ± 22.1	81.9 ± 16.4	92.9 ± 24.2	90.4 ± 18.3	13,116 ± 3381	14,079 ± 2692
Region 3										
9. Gardermoen	16.1 ± 14.5	15.5 ± 11.4	26.6 ± 23.8	26.3 ± 15.6	39.8 ± 27.3	34.8 ± 18.5	43.8 ± 28.6	37.4 ± 21.6	4521 ± 2913	4108 ± 2214
10. Ukkestad	12.6 ± 12.0	13.7 ± 10.6	21.4 ± 22.7	23.3 ± 15.0	33.8 ± 27.5	31.0 ± 18.7	38.7 ± 30.3	33.1 ± 20.9	3991 ± 2777	3554 ± 2051
11. Eidsvoll-verk	16.4 ± 14.8	13.5 ± 10.2	29.1 ± 23.3	22.8 ± 15.1	41.5 ± 26.8	30.3 ± 18.1	45.1 ± 28.9	31.7 ± 20.4	4803 ± 2981	3512 ± 2035

Table 3 | Mean observed and simulated dates for start and end of snow season and number of snow days (1961–2003) (RMSE: root mean squared error; R^2: coefficient of determination)

		Mean ± standard deviation			
Region/station		**Obs**	**Sim**	**RMSE**	**R^2**
Region 1					
1. Jotkajavre	Start	12–Oct ± 12	15–Oct ± 14	7.48	0.76
	End	6–Jun ± 9	1–Jun ± 10	7.98	0.60
	Number of days	241 ± 12	232 ± 15	12.27	0.68
2. Cuovddatmohkki	Start	17–Oct ± 10	20–Oct ± 13	12.74	0.25
	End	22–May ± 6	18–May ± 8	8.50	0.45
	Number of days	220 ± 16	214 ± 18	13.58	0.56
3. Karasjok	Start	19–Oct ± 10	24–Oct ± 14	12.11	0.39
	End	11–May ± 9	10–May ± 11	7.17	0.56
	Number of days	203 ± 14	200 ± 18	9.18	0.78
4. Sihcajavri	Start	17–Oct ± 12	17–Oct ± 13	6.97	0.71
	End	28–May ± 11	22–May ± 10	10.95	0.40
	Number of days	223 ± 17	219 ± 16	11.86	0.58
Region 2					
5. Røros	Start	2–Nov ± 14	31–Oct ± 14	8.50	0.67
	End	9–May ± 9	16–May ± 9	9.72	0.51
	Number of days	190 ± 13	201 ± 14	12.96	0.77
6. Aursund	Start	27–Oct ± 12	31–Oct ± 16	11.18	0.57
	End	23–May ± 8	19–May ± 10	9.83	0.26
	Number of days	209 ± 12	204 ± 15	10.57	0.63
7. Os i Østerdal	Start	25–Oct ± 11	31–Oct ± 16	12.91	0.45
	End	25–May ± 8	10–May ± 9	18.19	0.07
	Number of days	213 ± 16	193 ± 17	24.77	0.30
8. Vauldalen	Start	26–Oct ± 12	19–Oct ± 12	12.99	0.33
	End	28–May ± 10	31–May ± 9	8.43	0.46
	Number of days	217 ± 12	229 ± 13	14.42	0.61
Region 3					
9. Gardermoen	Start	16–Nov ± 17	18–Nov ± 18	15.36	0.40
	End	19–Apr ± 12	20–Apr ± 16	11.50	0.50
	Number of days	145 ± 30	151 ± 31	14.94	0.81
10. Ukkestad	Start	24–Nov ± 21	20–Nov ± 22	14.89	0.60
	End	21–Apr ± 13	15–Apr ± 21	17.02	0.42
	Number of days	138 ± 32	143 ± 33	13.88	0.84
11. Eidsvoll–verk	Start	20–Nov ± 18	20–Nov ± 19	7.86	0.83
	End	18–Apr ± 11	17–Apr ± 21	14.88	0.52
	Number of days	144 ± 25	145 ± 31	12.14	0.85

too large, resulting in overestimation of precipitation at higher altitudes and slight underestimation of precipitation at lower altitudes. Note also that the altitude of Vauldalen in the model topography is 50 m too high compared to the real station elevation (Table 1). Least underestimation of snow accumulation was found at the three stations in

Region 3, particularly at station 10 (Ukkestad) which did not show much difference from observations.

In an analysis of the snow depth algorithms used in the snow model by NVE, it is concluded that the VIC approach for calculating snow depth due to compaction tends to compact the snow slightly too much, resulting in too high snow density (Alfnes 2008). This might be one of the reasons for the negative bias in the model. The same study shows that SWE is in many places higher than that observed, compensating for the elevated snow density. However, this might not be the case everywhere. Another possible explanation for under-prediction of snow depth can be biases in the precipitation and temperature data used as input in the snow model.

It is obvious that the snow model misses some peak snow depth values. This is most likely a consequence of simulating less precipitation during extreme snow events, which is a common problem among climate models. In the validation of the interpolated temperature and precipitation values used in the snow model described in Jansson *et al.* (2007), it was found that interpolated values of temperature are generally lower than observations. Interpolated precipitation is higher for small precipitation amounts and lower for large precipitation amounts compared to observations.

For our analysis regions, we found that simulated temperature shows very high resemblance to observations at the stations where measurements are available. However, simulated precipitation values are higher than observed values at most stations, except at station 10 (Ukkestad). This overestimation does not seem to be consistently linked to the nature of the difference between real and model elevation. It is therefore probably due to the correction for gauge undercatch because of wind effects (Førland *et al.* 1996). The greatest overestimations were found at stations 5 (Røros), 6 (Aursund) and 8 (Vauldalen), although Røros also showed underestimation occasionally. The snow depth simulations at these three stations were however relatively good. This leads us to believe that the VIC approach is the main reason for the model's underestimation of snow depth, as discussed above. It is possible that the strong overprediction of snow fall at stations 5 (Røros), 6 (Aursund) and 8 (Vauldalen) compensates for the exaggerated snow

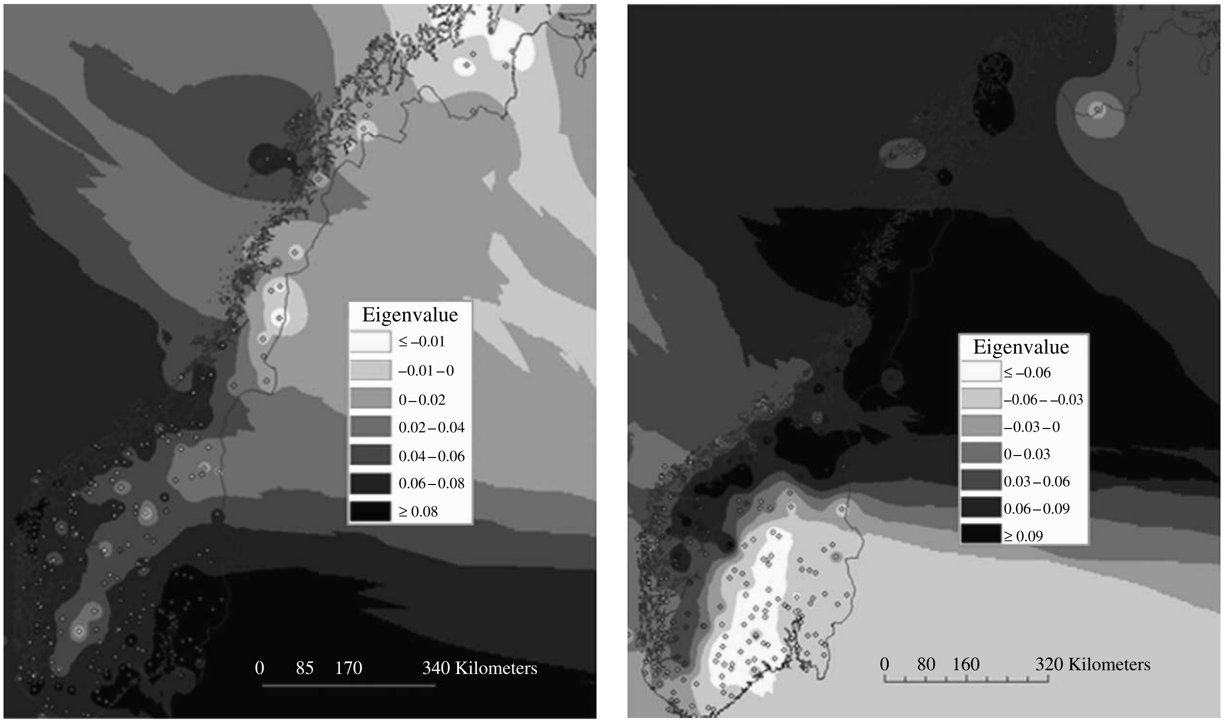

Figure 6 | (a) EOF1 loadings and (b) EOF2 loadings with inverse distance weighted (IDW) interpolation (regions 1–3 circled).

Table 4 | Observed and simulated trend slope of snow season parameters (1961–2003)

Region/Station	Parameter	Observed slope	Simulated slope
Region 1			
1. Jotkajavre	Start of snow season	0.0623	0.0235
	End of snow season	−0.1683	−0.0343
	Number of snow days	−0.2099	−0.0426
2. Cuovddatmohkki	Start of snow season	0.1909	0.0327
	End of snow season	−0.3910***	−0.3204***
	Number of snow days	−0.7749***	−0.3408*
3. Karasjok	Start of snow season	0.2372*	0.2771*
	End of snow season	−0.1592	−0.2462**
	Number of snow days	−0.2605	−0.4061*
4. Sihcajavri	Start of snow season	−0.0639	−0.1041
	End of snow season	−0.0082	−0.1112
	Number of snow days	−0.1094	−0.0385
Region 2			
5. Røros	Start of snow season	0.2132	0.0450
	End of snow season	0.0162	−0.2753**
	Number of snow days	−0.2826	−0.3257**
6. Aursund	Start of snow season	0.0630	0.0038
	End of snow season	−0.0581	−0.3202***
	Number of snow days	−0.1569	−0.2567
7. Os i Østerdal	Start of snow season	0.1074	0.1124
	End of snow season	0.0142	−0.1930*
	Number of snow days	0.0984	−0.2711
8. Vauldalen	Start of snow season	0.1971	−0.0690
	End of snow season	−0.1333	−0.1206
	Number of snow days	−0.3315$^{*\,*}$	−0.1053
Region 3			
9. Gardermoen	Start of snow season	0.0250	0.3132
	End of snow season	−0.4035***	−0.6371***
	Number of snow days	−1.0810***	−1.2288***
10. Ukkestad	Start of snow season	−0.0959	0.1320
	End of snow season	−0.3599***	−0.6579***
	Number of snow days	−1.1211***	−1.2331***
11. Eidsvoll–verk	Start of snow season	0.2707	0.3304
	End of snow season	−0.3579***	−0.6829***
	Number of snow days	−0.8596***	−1.1530***

Statistically significant at alpha levels: 0.1 (*), 0.05 (**), 0.01 (***).

compaction, resulting in simulated snow depth closer to the observed value (or higher than the observed value in the case of station 8, Vauldalen).

The snow model simulates a shorter snow season at all four stations in Region 1 (see Table 3), ending 3–7 days earlier than the observed snow season. This is consistent with the findings in the first part of the analysis, where the model shows significant underestimation of snow depth at all four stations. Although the snow model does not underestimate snow to the same extent in Region 2 compared to Region 1, the poorest results in the comparison of the snow season are found here. In this region, the difference in number of snow days go up to 20 days at the most (station 7, Os i Østerdal), and we see the lowest correlation on average (Table 3). There is also no consistency between the differences, as stations 5 (Røros) and 8 (Vauldalen) reveal a longer simulated snow season and more snow days while stations 6 (Aursund) and 7 (Os i Østerdal) reveal a shorter simulated snow season (Figures 3–4(a)) and fewer snow days (Figure 5(a)). Note, however, that the difference between model and real altitude is at maximum for Os i Østerdal. This may be the reason for the poor results at this station.

An Empirical Orthogonal Function (EOF) analysis was carried out as a part of this study to determine dominant spatial patterns of winter snow depth in Norway. The two most important modes of variability, EOF1 and EOF2 which account for 41.4% and 18.6% of snow depth variability in Norway, respectively, are shown in Figure 6. These patterns illustrate that Region 2 is located in a transition area between climate regimes, which might influence the performance of the snow model in this region and explain the inconsistent results we find at the four stations. This is supported by the Norwegian precipitation regions (PRs) defined by Hanssen-Bauer *et al.* (1997). Regions 1 and 3 from the present paper each fit nicely into a specific PR, while region 2 from the present paper is located at the boarder between two PRs. Another possibility might be the fact that three of the four stations do not have observations of temperature, meaning temperature is interpolated at these stations.

Region 3 shows the best overall result (see results from station 9, Gardermoen, in Figures 3–5(b)) with the highest average correlation. This is the only region where all three snow season parameters show significant correlation between simulations and observations at the 0.05 alpha level. The simulated and observed snow season show strong similarities, and there is only a 1–6 days difference in the average number of snow days.

The varying performance of the snow model might be explained by the fact that the distance between stations is much larger in Region 1 than in the other regions, while in Region 2 the variance in station elevation is much greater than in the other regions. Hence, by examining the spread between the stations at the three regions, we find that Region 3 is more homogeneous with this respect than the other two.

Table 4 reveals some differences between the slopes of observed and simulated linear trend. In general the simulated trend is stronger than the observed trend for the end of the snow season and number of snow days. This is particularly obvious in Region 3. It is worth mentioning that the simulated trend for end of snow season at station 5 (Røros) is significantly negative at the 0.05 alpha level, while the observed trend is slightly positive and statistically insignificant. This is also the case at station 7 (Os i Østerdal), where the simulated trend is significantly negative at the 0.1 alpha level while the observed trend is slightly positive and statistically insignificant. However, there is no statistical evidence that the trend lines are different at any of the eleven stations.

CONCLUSIONS

From the trend analysis of complete time series we found, unsurprisingly, an overall negative trend in daily snow depth at all stations except at station 3 (Karasjok). The decrease in snow depth at station 6 (Aursund) is minimal. A later start of snow season was seen at all stations in Regions 1 and 2, while the stations in Region 3 reveal a slightly earlier start of snow season. There is an earlier end of snow season and a decrease in the number of snow days at all eleven stations. Region 3 shows the strongest decrease in the number of snow days and daily snow depth, which is in line with previous findings of Vikhamar-Schuler *et al.* (2006), stating that the strongest decrease in length of snow season will occur in low altitudes and areas close to the sea.

In comparing simulations to observations at the eleven stations we find that the precipitation/degree-day snow model exhibits a negative bias in simulating snow depth. This is most likely due to the VIC hydrologic model demonstrating excessive compaction of snow. The performance of the model in simulating start and end of the snow season and the total number of snow days is variable between the different stations studied. In Region 1 in northern Norway the snow model simulates on average a 3–9 days shorter snow season than what is observed at all four stations. Poorer results are found in Region 2 in central Norway. There is no consistency in the results from the four stations, and the difference in the number of snow days is as high as 20 days at one of the stations. The model performs best in Region 3 in southeast Norway, where the correlation between the three observed and simulated snow season indices are all significant at the 0.05 alpha level.

There are several possible reasons to explain why the model performs better in some locations. The most important issue is the difference between elevation used in the model and the real station elevation, and we already know that the elevation gradient for precipitation is too large in the model. Elevation differences are greater in Region 2. In addition, Regions 1 and 2 show higher variance in station elevation than Region 3, and the distance between stations is greater due to the lack of stations at high elevations. We also believe that Region 2 is more sensitive to random variability due to its placement in the transition area between positive and negative loadings of the two leading modes of snow depth variability. The EOF analysis confirmed that different climatic regimes dominate different parts of the country, resulting in climate and weather modelling being a great challenge. Differences in atmospheric variability and dynamics suggest that a separate snow model for each climate regime would be ideal.

A future analysis of snow depth variability is recommended for additional stations in order to determine if our conclusions can be extended to other parts of the country. A fourth region along the western coast is of particular interest, since we are likely to find snow conditions that differ significantly from the three regions studied here. Some of the largest glaciers are situated in west Norway, and the region is generally sensitive to temperature fluctuations. Snow conditions and particularly snow melt are of great concern here due to its importance in hydroelectric power production. It is also relevant to perform this type of analysis in typical flood and avalanche areas.

Furthermore, we would recommend a cluster analysis using averages from stations sharing the same characteristics. However, results found in this study support the use of snow simulation in areas outside the observational network, which is highly important when examining both historical and future snow conditions.

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