

## Trends in snow water equivalent in Norway (1931–2009)

Thomas Skaugen, Heidi Bache Stranden and Tuomo Saloranta

### ABSTRACT

Trends in time series of snow water equivalent (SWE) are analyzed for different time periods and as a function of elevation. Since 1914, hydropower companies have measured snow at the expected snow maximum. Most of the measurements are located at high elevations, 700–1,700 meters above sea level (masl), providing a unique dataset in areas poorly covered by meteorological stations. For single stations, significant positive and negative trends are found using the Mann–Kendall trend test. The trends depend on region, observation period and elevation. In southern Norway negative trends are found for sites below 1,350 masl for the periods 1931–1960 and 1991–2009, and below 850 masl for the period 1961–1990. Above these elevations, positive trends are found. For the entire period, 1931–2009, positive trends are found for stations located above 850 masl. These findings can be explained by varying trends in precipitation and temperature in winter and spring. For central and northern Norway, the pattern in trends is similar, although less pronounced. High and low values of the North Atlantic Oscillation (NAO) index correlate differently with SWE. High NAO index is positively correlated with SWE at high elevations and negatively at low elevations. Low NAO index is positively correlated with SWE at all elevations.

**Key words** | NAO index, Norway, snow water equivalent, trends

**Thomas Skaugen** (corresponding author)  
**Heidi Bache Stranden**  
**Tuomo Saloranta**  
Norwegian Water Resources and Energy  
Directorate,  
P.O. Box 5091,  
0301 Oslo,  
Norway  
E-mail: [ths@nve.no](mailto:ths@nve.no)

### INTRODUCTION

In many areas north of latitude  $35^\circ$ , winter precipitation comes as snow. Precipitation as snow plays an important role in defining the hydrological regime and information on snow conditions is thus instrumental for the design of infrastructure in waterways, for the economy, and for mitigating hazards. In Norway, the typical hydrological regime is comprised of a winter low flow period, a clearly defined snowmelt flood in spring, a summer low flow period, and the occasional autumn flood due to precipitation as rain (Gottschalk *et al.* 1979). The public, the hydropower industry and various sectors and activities related to the water supply (for example, agriculture and public consumption), and tourism have all adjusted to the prevailing hydrological regime. Possible changes thereof call for strategies for adaptation.

Snow conditions are very much dependent on the regime of precipitation and temperature, and changes in these regimes naturally lead to changes in snow conditions. Analyses of over a century of historic records of temperature and precipitation in Norway show positive trends for both

precipitation and temperature. Annual temperature has increased by  $0.5\text{--}1.5^\circ\text{C}$ , annual precipitation has increased in almost all of Norway and by as much as 15–20% in the northern areas (Hanssen-Bauer 2005). Future scenarios (2071–2100) of temperature and precipitation for Norway indicate that the trends will continue to be positive. The projections suggest that temperature and precipitation will increase for all regions, but the increase in precipitation will be higher for the western region than for the inland regions of Norway (Beldring *et al.* 2008).

Studies of historic snow conditions indicate, with few exceptions, that the snow season has become shorter and the amount of snow has decreased. Lemke *et al.* (2007), show that snow cover has decreased in the northern hemisphere for the past five decades although Brown & Mote (2009) point out regional, seasonal and altitudinal variations to this general trend. Many studies (especially in the USA) have investigated possible trends in snow water equivalent (SWE) over the last 50–60 years. SWE is, as the name

suggests, the depth of water that would result from the complete melting of a column of snow. Kalra *et al.* (2008) analysed changes in discharge and SWE in the western USA for the period 1941–2004 and found a general decline for both parameters, with the exception of one location in the southern Rocky Mountain range. Barnett *et al.* (2008) analysed changes in the ratio of SWE to winter precipitation (1950–1999) in the western USA, and found a decline in the ratio for all areas, except for the southern part of Sierra Nevada, where the trend was slightly positive. This finding is consistent with an increase in winter temperature and possibly a shorter snow season. Howat & Tulaczyk (2005) found both increasing and decreasing trends in SWE for increased winter temperature for the period of 1950–2002 in the western USA. Increases in SWE were found for high elevations where winter precipitation had increased, and decreasing trends were found in areas where increased winter precipitation could not compensate for the temperature increase. Several other studies focusing on the western USA confirm this pattern in which trends in SWE become less negative with increasing elevation (Mote 2003, 2006). Burakowski *et al.* (2008) analysed trends in the winter climate in the north-eastern part of the USA and found that the total snowfall during the winter months had decreased in the period 1965–2005. The trend, however, was not statistically significant. In Switzerland, investigations show an unprecedented series of low snow winters during the past 20 years. In the low elevation zone, the reduction in snow days is over 50% (Marty 2008). Durand *et al.* (2009) analysed snow depth and the number of days with snow in the French Alps and found that both snow depth and the number of snow days were decreasing with time, especially at lower elevations. Investigations in the Nordic countries show that in Finland, SWE has been increasing in the eastern and northern part during 1946–2001 and decreasing in the southern and western part (Hyvärinen 2003). Dyrddal (2010) found decreasing trends in the number of snow days in periods 1961–1990 and 1979–2008. Decreasing trends were also detected in maximum snow depth, except in the coldest areas where positive trends were detected. Time series of glacier mass-balance and glacier length from Norway show that for the period 1962–2000, a mass surplus for maritime glaciers (located in the southwest of Norway) is found, whereas mass deficits are found for glaciers in the dryer inland areas (Andreassen

*et al.* 2005). All glaciers, however, exhibited an overall retreat in the same period, suggesting increased temperatures in the ablation area. Subsequent to 2000, all glaciers show a mass deficit and a pattern of continuous retreat.

Climate scenarios for 2071–2100, using both Hadley and ECHAM global climate models downscaled by the regional climate model HIRHAM, predict a decrease in maximum snow water equivalent (SWE) for the whole of Norway (Vikhamar-Schuler *et al.* 2006). However, a more topographically detailed hydrological study of the same scenario data set, suggests that for certain high elevation areas, annual maximum SWE may increase (Vikhamar-Schuler & Førland 2006). Studies of the duration of the snow season (Vikhamar-Schuler *et al.* 2006; Dyrddal & Vikhamar-Schuler 2009) project a shorter snow accumulation season due to later snowfall and earlier snowmelt. The magnitude of the decrease in the duration of the snow season, however, diminishes with increasing elevation and distance from the coast. The above studies thus suggest that the trends found from historical data will, for Norway, continue into the future.

The aim of this study is to detect and quantify temporal trends in SWE in Norway. The data to be analyzed from the period 1914–2009 are mostly from upland locations, which provide an informative complement to the snow measurements (snow depth) from lowland areas carried out by the Norwegian Meteorological Institute ([met.no](http://met.no)). Areal statistics of Norway show that 68% of the area is above 300 meters above sea level (masl) and 40% is above 600 masl. As suggested by the studies of USA snow conditions, directions of trends in SWE are closely linked to elevation, as higher elevations are generally associated with colder air temperatures. An increase in precipitation and temperature may result in both an increase and decrease in SWE, depending on the specific location of the measurement site. The regional and temporal patterns of trends in SWE are investigated in relation to the elevation of the individual snow measurement sites so that possible time-variant critical elevations can be identified.

## DATA AND METHODS

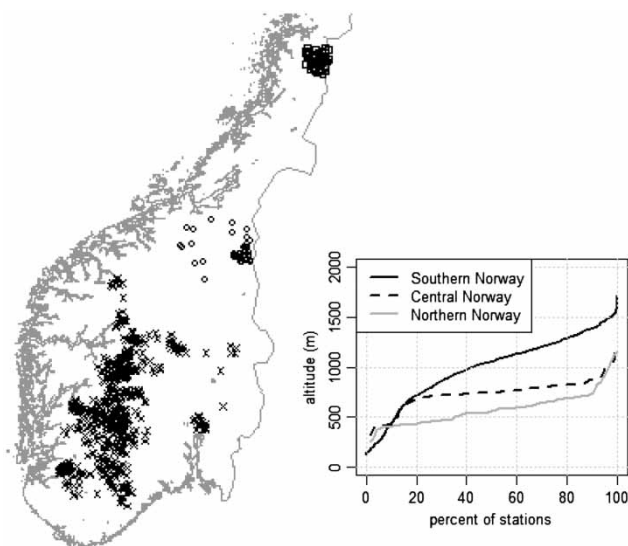
Since 1914, snow has been measured in Norway in relation to hydropower production and flood forecasting. The

observations are mainly carried out by the hydropower companies once a year at the time of the expected snow maximum (middle of March to middle of April) and are reported to the Norwegian Water Resources and Energy Directorate (NVE). The number of snow stations is currently approximately 1,300. Most of the stations are located in the southern part of Norway (Figure 1). The elevation of the stations range from ~100 to over 1,700 masl, and approximately 50% of the stations are located above 1,000 masl.

For most of the stations, snow depth is measured at multiple points along a snow course. An average snow density for the snow course is estimated from one or two snowpits dug at sites with average snow depth along the course. A value of SWE is estimated for each point along the course, and the average becomes the data point for each station. For some stations, however, there have been changes in measurements techniques, e.g. from point measurements to snow courses over the period of record. Data were quality checked and values considered as outliers were corrected or omitted.

### Temporal trends

With such an extensive data set to hand, it is important to carry out a study for detecting possible temporal trends in



**Figure 1** | Location of the snow stations used in trend and correlation analysis (Figures 2, 3, 4 and 7). The crosses (x) denote south Norway, circles (o) central Norway and squares (□) north Norway. The right panel shows cumulative distribution of station altitudes for the three regions (stations with less than 10 years of observations are excluded).

a manner that reduces statistical noise due to the choice of time period, the choice of climatic region or by neglecting the dependence of SWE on elevation. See, for example, Mote *et al.* (2008) for a discussion on uncertainties in regional assessments of SWE caused by changing horizontal and vertical coverage of snow stations.

First, the snow stations are classified into three regions: southern Norway, central Norway and northern Norway, as shown in Figure 1. These regions are partly dictated by the data set and partly from precipitation regions composed by Hanssen-Bauer *et al.* (1997). Second, to investigate how the trends may vary with time, the entire dataset is further divided into different meteorological normal periods. The years 1914–2009 are divided into two complete normal periods, the periods 1931–1960 and 1961–1990, and an incomplete normal period, 1991–2009. Data prior to 1931 are not included as the number of stations with data for this period is too small. Also, the entire period 1931–2009 was analysed in order to investigate any possible long term trends. Finally, as the long-term trends in both temperature and precipitation are found to be positive (Hanssen-Bauer 2005), the investigation of possible trends in SWE must take into account that an increase in these two factors has, in principle, the opposite effect on SWE. The effect of an increase of one factor can, however, be compensated for by the increase of the other. The degree of compensation is linked to the elevation of the station in question, so the variation in trend with elevation must be examined. The trend is estimated for each station and plotted against elevation and the east–west coordinates for each region and time period. Only stations with data from more than 50% of the years within each analysed period are included in the trend analysis (i.e. more than 15 years of data for the two first 30-year normal periods, and more than 10 years of data for the most recent period 1991–2009). For the period 1931–2009, an additional requirement was that data existed at least for 2 years at the start (1931–1935) and at the end (2005–2009).

### Test for detection of trends

To detect trends in our time series of SWE, the non-parametric Mann–Kendall test (see e.g. Hipel & McLeod 1994; Yue *et al.* 2002) was applied. This test is based on rank-transformed time series, where only the relative magnitude of

SWE observations is considered in the trend analysis. The Mann–Kendall trend can thus indicate the presence of a trend but cannot quantify its absolute magnitude. The main advantage of this test is that it is non-parametric and, therefore, does not require assumptions regarding the underlying statistical distribution of the time series. It is therefore robust to, for example, skewed distributions which often characterize environmental data arising from multiple and complex natural processes.

The Mann–Kendall test for trend detection tests the null hypothesis that the data come from a population where the random variables are independent and identically distributed, i.e. that the time series is independent of time. The alternative hypothesis is that there is a monotonic trend in the data over time. The Mann–Kendall test statistic  $S$  is calculated as

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^n \text{sgn}(x_j - x_k) \quad (1)$$

where

$$\text{sgn}(x) = \begin{cases} +1, & x > 0 \\ 0, & x = 0 \\ -1, & x < 0 \end{cases}$$

The test statistic,  $S$ , thus compares all pairs of observations in the time series and sums up the total number of times the observation  $x_j$  exceeds  $x_k$  more than  $x_k$  exceeds  $x_j$  (for  $j > k$ ).  $S$  is asymptotically normally distributed and well-suited for testing the significance of a trend. We use the two-sided  $p$ -values from this significance test to indicate the presence of a weakly significant ( $0.05 < p < 0.2$ ) and strongly significant ( $p < 0.05$ ) trend, as in Wilson *et al.* (2010). The direction of the trend is indicated by the sign of  $S$ .

A robust estimate of the magnitude  $b$ , of the trends,  $b$ , were also estimated, by taking the median of the slopes for all pairs of years in the time series (see e.g. Yue *et al.* 2002):

$$b = \text{Median} \left( \frac{x_j - x_k}{j - k} \right), \quad \forall k < j \quad (2)$$

## RESULTS

In Figures 2–4 and 7, each snow station in each region is represented with a triangle or a circle and is positioned

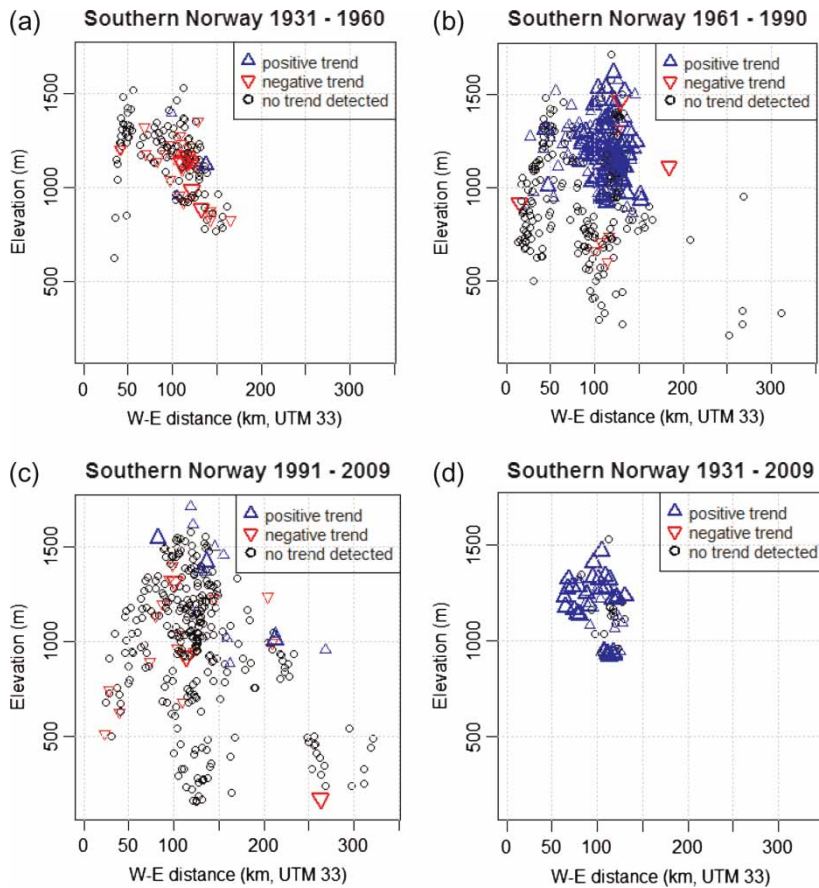
according to its altitude and E–W coordinate (UTM 33). The  $y$ -axis indicates the elevation, whereas the  $x$ -axis indicates the location in the west–east direction. For each station, the direction of a trend and its  $p$ -value are estimated. The upward triangles denote significant positive trends, while the downward triangles denote significant negative trends. Black circles denote stations with no significant trend ( $p > 0.2$ ). The two different sizes of the triangles indicate how significant the trend is (large triangle  $p < 0.05$ , small triangle  $0.2 > p > 0.05$ ).

In southern Norway, negative or no trends are generally found for the period 1931–1960 (Figure 2(a)) for the stations spanning an elevation range between 750–1,350 masl. For the period 1961–1990 (Figure 2(b)) the situation is rather reversed, as a majority of positive trends are found above the elevation of ~850 masl. Below ~850 masl all the detected trends are negative, although at many stations no trends are found. For the latest period 1991–2009 (Figure 2(c)), negative or no trends are generally found, except for stations above approximately 1,350 masl, where all the few detected trends are still positive. A few positive trends are detected down to ~900 masl. For the period 1931–2009, mostly positive trends are found above ~850 masl. Note that there were no stations below ~850 masl that met the requirement for data selection.

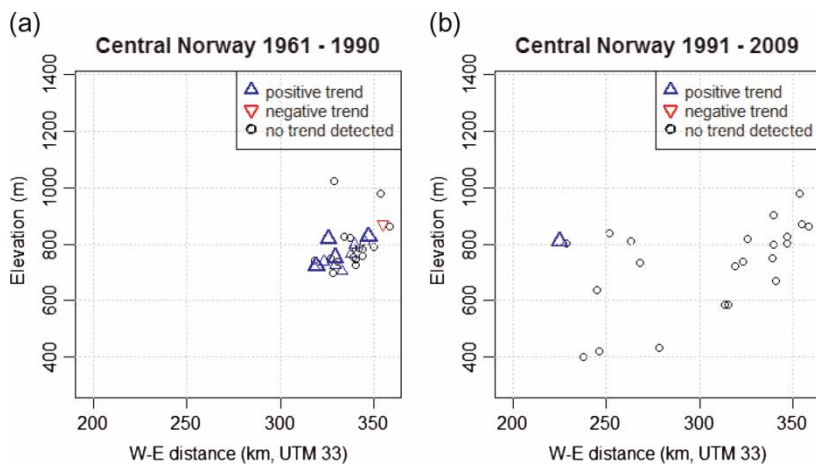
In central Norway, no station has more than 15 years of data during 1931–1960, so this period is not analyzed. For the period 1961–1990 (Figure 3(a)), generally no trends or positive trends are found for the spatially rather confined cluster of stations between 700–1,000 masl. For the most recent period 1991–2009 (Figure 3(b)), only one station at ~800 masl has a significant positive trend, whereas no significant trends are found for the other stations located between 400–1,000 masl. Only four stations (700–800 masl) are available in central Norway during the period 1931–2009. No significant trends in SWE were detected for these stations (no figure shown).

In northern Norway, only the period 1961–1990 have stations that comply with the condition of more than 15 years of data, and the majority of the stations, spanning an elevation range between 300–1,200 masl, show positive trends (Figure 4). During 1991–2009 only one station had more than 10 years of data (no figure shown). No trend in SWE was detected for this station.

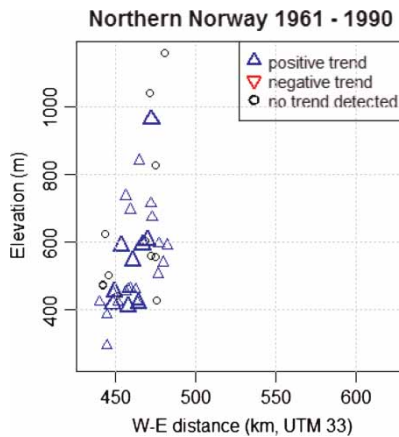




**Figure 2** | Temporal trends in SWE for southern Norway for the periods (a) 1931–1960, (b) 1961–1990, (c) 1991–2009 and (d) 1931–2009. Each snow station is positioned according to its altitude and E–W coordinate (UTM 33). The upward triangles denote significant positive trends, while the downward triangles denote significant negative trends. Black circles denote stations with no significant trend ( $p > 0.2$ ). The two different sizes of the triangles indicate how significant the trend is (large triangle  $p < 0.05$ , small triangle  $0.2 > p > 0.05$ ).



**Figure 3** | Temporal trends in SWE for central Norway for the periods (a) 1961–1990 and (b) 1991–2009. Each snow station is positioned according to its altitude and E–W coordinate (UTM 33). The upward triangles denote significant positive trends, while the downward triangles denote significant negative trends. Black circles denote stations with no significant trend ( $p > 0.2$ ). The two different sizes of the triangles indicate how significant the trend is (large triangle  $p < 0.05$ , small triangle  $0.2 > p > 0.05$ ).



**Figure 4** | Temporal trends in SWE for northern Norway for the period 1961–1990. Each snow station is positioned according to its altitude and E–W coordinate (UTM 33). The upward triangles denote significant positive trends, while the downward triangles denote significant negative trends. Black circles denote stations with no significant trend ( $p > 0.2$ ). The two different sizes of the triangles indicate how significant the trend is (large triangle  $p < 0.05$ , small triangle  $0.2 > p > 0.05$ ).

A summary of the above findings with respect to region, time period and threshold elevation level (elevation level where the trends switch signs) is presented in Table 1.

Table 2 shows the median of the trend slope,  $b$  (mm year<sup>-1</sup>), with 5 and 95% percentiles, for the different regions and time periods.

## DISCUSSION

Analysis of trends in SWE is complex due to the fact that although isolated increases in temperature and precipitation will decrease and increase SWE, respectively, the combination of increased precipitation and temperature may

both increase and decrease SWE. As SWE is a function of these two variables and their history throughout the snow season, it is difficult to predict, at a specific location, how changes will affect SWE. When temperature and precipitation increase, an increase in SWE may result if the effect of increased temperature is more than compensated for by the increase in precipitation. Additionally, the increase in temperature may not be sufficient to bring about a change in phase from solid to liquid precipitation. At certain elevations, however, the increase in temperature is not compensated by the increase in precipitation and SWE decreases. Very detailed information of topography and meteorology is, therefore, required to determine changes in SWE, and it is thus difficult to produce a regional assessment of the effect of climate change on SWE.

Hisdal et al. (2001) point out the sensitivity of trend analysis to the choice of time periods. The tendency of wet and dry periods to cluster may influence the trend analysis quite severely. Figure 5 shows SWE values above and below the long-term median. The long-term median is estimated from the entire record length of the station in question. Record lengths are indicated by the length of the horizontal lines in the figure.

A clear pattern of clustering of wetter and dryer years is apparent. The banded structure in the figure indicates persistence both in time and space as the bands are distinct for all stations and over a wide elevation interval. The wet and dry clusters are, however, numerous and quite uniformly distributed such that their effects should not bias the trend analysis significantly.

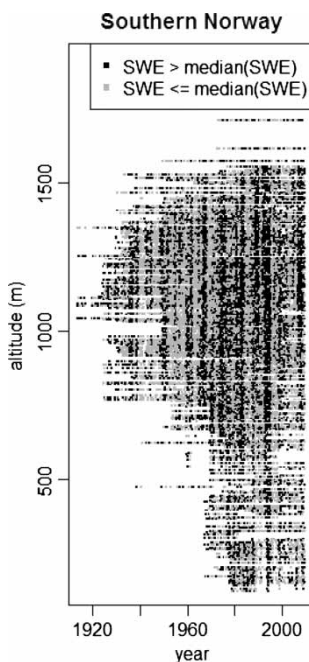
The trend analysis presented in Figures 2–4 was also tested with a more strict requirement for the number of missing values in the time series, namely that more than

**Table 1** | General tendency, abundance and threshold elevation (where the trends change signs) of the detected trends for the different regions and time periods. The table is based on visual inspection of Figures 2–4. Note that on many stations no trends were detected

	Southern Norway	Central Norway	Northern Norway
Trends 1931–1960	Many negative (800–1,350 masl)	Not enough data	Not enough data
Trends 1961–1990	Few negative (600–1,500 masl)	Many positive (>850 masl)	Many positive (700–800 masl)
Trends 1991–2009	Few negative (<1,350 masl)	No trends detected (400–1,000 masl)	Many positive (300–1,000 masl)
Trends 1931–2009	Few positive (>900 masl)	No trends detected (700–800 masl)	Not enough data
	Many positive (850–1,500 masl)		Not enough data

**Table 2** | Median of the distribution of trend magnitudes of SWE (mm/year) for the different regions and time periods. Values in parentheses are the 5 and 95% percentiles of the distribution

Period	Southern Norway	Central Norway	Northern Norway
1931–1960	–1.6 (–8.7, +2.2)	<i>Not enough data</i>	<i>Not enough data</i>
1961–1990	+3.4 (–4.5, +12.5)	+1.7 (–4.3, +4.7)	+9.9 (–2.0, +17.4)
1991–2009	–2.0 (–18.5, +11.1)	+5.1 (–0.2, +15.0)	<i>Not enough data</i>
1931–2009	+1.3 (+0.1, +2.9)	<i>Not enough data</i>	<i>Not enough data</i>



**Figure 5** | Time series of SWE in southern Norway for stations at different altitudes. Grey and black dots denote years when SWE is below and above the station median SWE, respectively. Stations with less than 10 years of observations are excluded.

75% years of data must be present within each period. This requirement naturally reduced the number of stations available for analysis, but did not change the general picture presented in the previous section (Figures 2–4).

### Regional patterns of changes in SWE

The pattern of regional trends in SWE is compared with trends in precipitation and temperature presented by Hansen-Bauer (2005). This latter study did not specifically investigate the meteorological normal periods used in the present study, so information is extracted from visual inspection of figures showing time series of standardized, low-pass filtered regional values of winter (December, January and

February) and spring (March, April and May) precipitation and temperature.

In southern, central and northern Norway the winter temperature decreased and the spring temperature increased in the periods 1931–1960 and 1991–2004, whereas for the period 1961–1990 both winter- and spring temperature increased. For the period 1931–2004, spring temperature increased for all regions and the winter temperature increased in southern Norway, and was stable for the other regions.

Winter precipitation decreased for southern and central Norway and spring precipitation increased for the period 1931–1960 and 1991–2004. Northern Norway experienced an increase in precipitation in the same periods. For the period 1961–1990 all regions had an increase in precipitation. For the period 1931–2004 spring precipitation increased in all regions whereas winter precipitation was stable in central Norway and increased in the other regions.

The spring months appear to have steadily increasing trends for all periods, both for temperature and precipitation. For the winter months, however, the trends for temperature and precipitation vary with the time periods.

Table 3 shows a comparison of the general trends of temperature, precipitation and SWE. For the period 1931–1960, decreasing winter precipitation together with increased spring temperature produced a decreasing trend in SWE for southern Norway. For the period 1961–1990, increased temperature for both winter and spring did not compensate for increased winter and spring precipitation, and SWE increased in all regions. For the most recent period (1991–2004), an increase in spring temperature combined with decreased winter precipitation led to a decrease in SWE in southern Norway and a stable SWE in central Norway. For the period 1931–2004, increased precipitation more than compensated for the increased temperature in southern Norway, giving an increased trend in SWE. The

**Table 3** | Comparison of the trend analysis of precipitation and temperature (Hanssen-Bauer 2005) and SWE. +, - and NT denote whether a dominating trend is increasing, decreasing or not present. Note that the results for the winter months (Dec.–Feb.) and the spring months (Mar.–May) are shown separately and denoted (W) and (Sp), respectively. The regions are denoted by South. (southern), Cent. (central) and North. (northern)

Period	Temperature.			Precipitation			SWE (data to 2009)		
	South.	Cent.	North.	South.	Cent.	North.	South.	Cent.	North.
1931–1960 (W)	–	–	–	–	–	+	–		
1931–1960 (Sp)	+	+	+	+	+	+			
1961–1990 (W)	+	+	+	+	+	+	+	+	+
1961–1990 (Sp)	+	+	+	+	+	+			
1991–2004 (W)	–	–	–	–	–	–	–	NT	
1991–2004 (Sp)	+	+	+	+	+	+			
1931–2004 (W)	+	NT	NT	+	NT	+	+		
1931–2004 (Sp)	+	+	+	+	+	+			

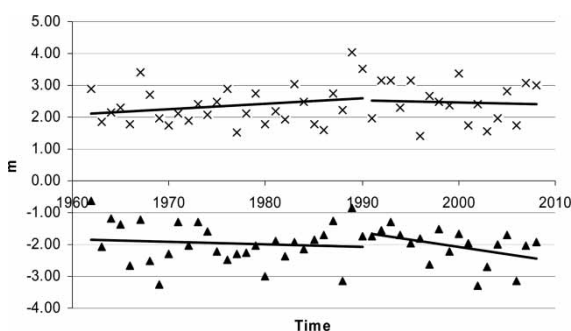
study of Hanssen-Bauer (2005) and the present study are reasonably consistent, and it appears that winter precipitation and spring temperature play a decisive role in determining annual maximum SWE. Recall that the present study includes data of SWE up to 2009. Furthermore, the seasonal classification in Hanssen-Bauer (2005) and the present study differ in that winter and spring includes the months from December to May. For most of the snow stations in this study (especially for stations at higher elevations) winter lasts from November until April, and the annual SWE measurements are carried out at the expected snow maximum in the middle of March or April.

Glaciological time series corroborate the results found for trends in SWE for southern Norway. In Figure 6, the winter balance (water gained due to snow) and summer balance (water lost due to melt) of the glacier Nigardsbreen located in southwest Norway, with an average elevation of

1,600 masl, is presented. Mass balance is measured by NVE on a regular basis for this and 13 other glaciers in Norway. There is a clear positive trend in the winter balance for the years 1962–1990 and a slightly negative trend for the years 1991–2008. For the summer balance there is a slightly negative trend in the years 1962–1990 and a clear negative trend for the years 1991–2008. The winter balance glacier data corresponds very well with the behavior of SWE for the two periods as can be seen when we compare Figure 6 with Figures 2(b) and (c).

#### Temporal trend of SWE as a function of elevation

From previous studies in the USA we find that, at lower elevations, increasing temperature is a likely cause of a decline in SWE. At higher elevations, increasing precipitation is most likely responsible for an increase in SWE (Mote 2003; Howat & Tulaczyk 2005). The combination of precipitation and temperature determines the threshold elevation level at which the trends in SWE change sign. This aspect of changes in SWE was only assessed for southern Norway due to lack of data for the other regions. Figure 2 clearly shows that the threshold elevation varies for the different periods. The cold and dry winters of the periods 1931–1960 and 1991–2004, combined with relatively warm springs, resulted in decreasing trends detected in SWE up to ~1,350 masl in southern Norway, whereas increased precipitation for the period 1961–1990, that clearly compensated for increased winter- and spring temperature, decreased the threshold elevation level to



**Figure 6** | Winter and summer balance of the Nigardsbreen glacier. The negative values are the summer balance (water lost due to melt) and the positive values are the winter balance (water gained through snow). Linear trend lines are shown for 1962–1990 and 1991–2008.



~850 masl. It is worth bearing in mind, however, that at many stations throughout the studied elevation range, no trends could be detected (i.e.  $p > 0.2$ ). For the period 1931–2009 there were no stations below ~850 masl so the long term trend with respect to elevation could not be assessed for elevations below ~850 masl. Our results emphasize that assessments and predictions of amounts and coverage of snow cannot be made from annual trends of precipitation and temperature alone. Seasonal trends of both precipitation and temperature have to be taken into account.

The estimated median slopes (in Table 2) show a high variability across the time periods and regions. The positive median slope for southern Norway for the period 1961–1990 is much higher than the slope estimated for the period 1931–2009. So, even if the positive trends detected for the period 1931–2009 are, for the most part, strongly significant, the slope of the trend is not very high ( $+1.3 \text{ mm year}^{-1}$ ).

### SWE and the NAO index

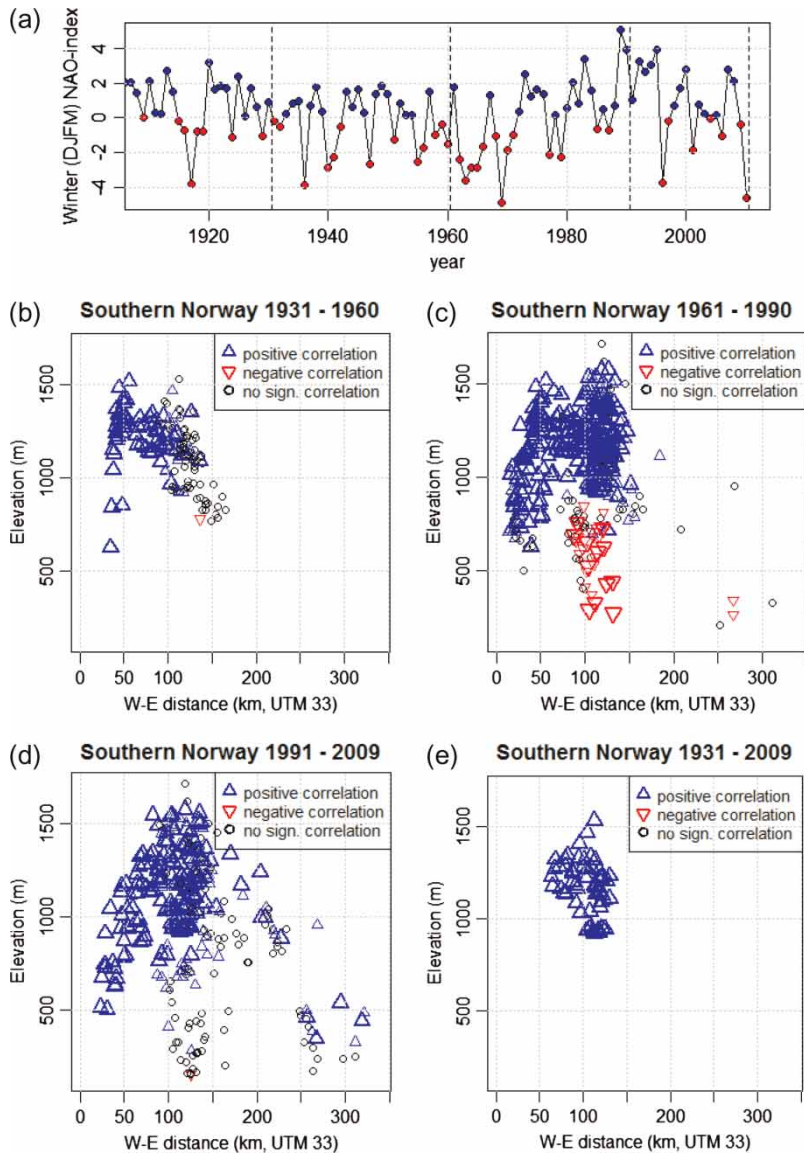
Several studies have identified a correlation between the NAO index (Hurrell 1995), and temperature and precipitation conditions in Norway (Benestad 2002; Cherry *et al.* 2004; Hanssen-Bauer 2005). Hanssen-Bauer (2005) found strong positive correlations between the winter temperature and precipitation, and the winter NAO index (Dec.–April) especially for central and southern Norway. Correlations between winter temperature and winter NAO index were positive for all regions in Norway, and correlations between winter precipitation and winter NAO index were only found to be negative in the extreme north-eastern part of Norway. The NAO index explained 40–75% of the variance in precipitation in the western part of southern Norway, whereas in central and northern Norway, less than 20% of the variation in the winter precipitation could be explained by the NAO index. Mysterud *et al.* (2000) investigated large-scale climatic indices (NAO index) in relation to conditions for populations of red deer on the west coast of Norway. The study found that snow depth was negatively correlated with the NAO index at low elevations (below 400 masl), and positively correlated at higher elevations. Analysis of correlation between SWE and the winter NAO index in this study agrees very well with that of Mysterud *et al.* (2000) for the period 1961–1990, but suggests a more complex relationship

between NAO index and SWE. Figure 7 shows time series of the winter (December–March) NAO index (Hurrell 1995) and plots of rank correlation between SWE and NAO index for southern Norway (Figure 7(b)–(e)). In Figure 7(c) there is a clear change in signs of correlation at approximately 750 masl. For this period, the NAO index was positive and quite high in the latter part of the period. The correlations in Figure 7(c) correspond to moist and warm weather, in which snow is accumulated at high elevations and not at lower elevations. For the other time periods, there are positive correlations for all elevation levels. The NAO index was clearly lower for 1931–1960 than for 1961–1990 and has a decreasing trend for the period 1991–2009. The positive correlations in Figures 7(b) and (d) correspond to low values of SWE, which is expected for low NAO index periods where cold and dry conditions prevail. The conclusions of Mysterud *et al.* (2000) concerning the relationship between SWE and NAO index thus appear to be valid only for periods of positive NAO index.

### CONCLUSIONS

Different time periods show different patterns of trends in SWE for Norway. An increasing trend was found in southern, central and northern Norway for the period 1961–1990, and a decreasing trend was found for southern Norway for the periods 1931–1960 and 1991–2009. Although the winter and spring temperatures were increasing in the period 1961–1990, increased winter precipitation ensured positive trends above ~850 masl. For the period 1931–2009, positive trends of SWE were found for stations in southern Norway above ~850 masl, but the magnitude of the trend slope is much less than that for the period 1961–1990. A decrease in winter precipitation together with increased spring temperature gave decreasing trends in SWE for the periods 1931–1960 and 1991–2009. This study shows that seasonal trends of precipitation and temperature must be the basis for assessing trends for snow conditions.

For southern Norway, the threshold elevation level where the direction of trends change signs, varies for the different periods. Periods with decreasing trends in SWE had a higher threshold elevation than for the period with increasing trends in SWE, even when this period had



**Figure 7** | (a) Time series of winter (Dec–Mar) NAO index in 1910–2010. Lower panels show rank correlation between the winter NAO-index and SWE for southern Norway for the periods (b) 1931–1960, (c) 1961–1990, (d) 1991–2009 and (e) 1931–2009. Each snow station is positioned according to its altitude and E–W coordinate, as in Figure 2 (UTM 33). The upward triangles denote significant positive correlations, while the downward triangles denote significant negative correlations. Black circles denote stations with no significant correlation ( $p > 0.2$ ). The two different sizes of the triangles indicate how significant the correlation is (large triangle  $p < 0.05$ , small triangle  $0.2 > p > 0.05$ ).

increased winter temperature and precipitation. This emphasizes the importance of winter precipitation for SWE.

The NAO index was found to be positively correlated with SWE at high elevations and negatively correlated at low elevations for periods of high NAO index. For periods with low NAO index, SWE was positively correlated also at lower elevation levels.

## ACKNOWLEDGEMENTS

This study is funded by the Norwegian Research Council through the NorClim project (project no. 174286). The provision of data by various Norwegian hydropower companies and the help of Thomas Vikhamar-Schuler in preparing the data are gratefully acknowledged.

## REFERENCES

- Andreassen, L. M., Elvehøy, H., Kjöllmoen, B., Engeset, R. & Haakensen, N. 2005 **Glacier mass-balance and length variation in Norway**. *Ann. Glaciol.* **42**, 317–325.
- Barnett, T. P., Pierce, D. W., Hidalgo, H. G., Bonfils, C., Santer, B. D., Das, T., Bala, G., Wood, A. W., Nozawa, T. T., Mirin, A. A., Cayan, D. R. & Dettinger, M. D. 2008 **Human-induced changes in the hydrology of the western United States**. *Science* **319**, 1080–1083.
- Beldring, S., Engen-Skaugen, T., Førland, E. J. & Roald, L. A. 2008 **Climate change impacts on hydrological processes in Norway based on two methods for transferring regional climate model results to meteorological station sites**. *Tellus* **60A**, 439–450.
- Benestad, R. E. 2002 **Empirically downscaled multimodel ensemble temperature and precipitation scenarios for Norway**. *J. Climate* **15**, 3008–3027.
- Brown, R. D. & Mote, P. W. 2009 **The response of northern hemisphere snow cover to a changing climate**. *J. Climate* **22**, 2124–2145.
- Burakowski, E. A., Wake, C. P., Braswell, B. & Brown, D. P. 2008 **Trends in wintertime climate in the northeastern United States: 1965–2005**. *J. Geophys. Res.* **113**, D20114.
- Cherry, J., Cullen, H., Visbeck, M., Small, A. & Uvo, C. 2004 **Impacts of the North Atlantic Oscillation on Scandinavian hydropower production and energy markets**. *Water Resour. Manag.* **19**, 673–691.
- Durand, Y., Giraud, G., Laternser, M., Etchevers, P., Mérindol, L. & Lesaffre, B. 2009 **Reanalysis of 47 years of climate in the French Alps (1958–2005): Climatology and trends for snow cover**. *J. Appl. Meteorol. Climatol.* **48**, 2487–2512.
- Dyrrdal, A. V. 2010 **Analysis of Past Snow Conditions in Norway**. Report Climate no 10/2010, Norwegian Meteorological Institute, Oslo.
- Dyrrdal, A. V. & Vikhamar-Schuler, D. 2009 **Kortere og kortere snøsesong (Shorter and shorter snow season)**. *Klima* **3**, 30–31. (In Norwegian.)
- Gottschalk, L., Jensen, J. L., Lundquist, D., Solantie, R. & Tollan, A. 1979 **Hydrologic regions in the Nordic countries**. *Nordic Hydrol.* **10**, 273–286.
- Hanssen-Bauer, I. 2005 **Regional temperature and precipitation series for Norway: Analyses for time-series updated to 2004**. Report Climate no 15, Norwegian Meteorological Institute, Oslo.
- Hanssen-Bauer, I., Førland, E. J., Tveito, O. E. & Nordli, P. Ø. 1997 **Estimating precipitation trends comparison of two methods**. *Nordic Hydrol.* **28**, 21–36.
- Hipel, K. W. & McLeod, A. I. 1994 **Time Series Modelling of Water Resources and Environmental Systems**, Chapter 23, Elsevier, Amsterdam. (Electronic reprint of the book can be found at <http://www.stats.uwo.ca/faculty/aim/1994Book/>)
- Hisdal, H., Stahl, K., Tallaksen, L. M. & Demuth, S. 2001 **Have streamflow droughts in Europe become more frequent?** *Intl. J. Climatol.* **21**, 317–333.
- Howat, I. M. & Tulaczyk, S. 2005 **Trends in spring snowpack over a half-century of climate warming in California, USA**. *Ann. Glaciol.* **40**, 151–156.
- Hurrell, J. W. 1995 **Decadal trends in the North Atlantic Oscillation: regional temperatures and precipitation**. *Science* **269**, 676–679.
- Hyvärinen, V. 2003 **Trends and characteristics of hydrological time series in Finland**. *Nordic Hydrol.* **34**, 71–90.
- Kalra, A., Piechota, T. C., Davies, R. & Tootle, G. A. 2008 **Changes in U.S. Streamflow and Western U.S. Snowpack**. *J. Hydrologic Eng.* **13**, 156–163.
- Lemke, P., Ren, J., Alley, R. B., Allison, I., Carrasco, J., Flato, G., Fujii, Y., Kaser, G., Mote, P., Thomas, R. H. & Zhang, T. 2007 **Observations: Changes in snow, ice and frozen ground**. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor & H. L. Miller, eds). Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 337–383.
- Marty, C. 2008 **Regime shift in snow days in Switzerland**. *Geophys. Res. Lett.* **35**, L12501.
- Mote, P. W. 2003 **Trends in snow water equivalent in the Pacific Northwest and their climatic causes**. *Geophys. Res. Lett.* **30**, 1601–1604.
- Mote, P. W. 2006 **Climate-driven variability and trends in mountain snowpack in Western North America**. *J. Climate* **19**, 6209–6220.
- Mote, P., Hamlet, A. & Salathé, E. 2008 **Has spring snowpack declined in the Washington Cascades?** *Hydrol. Earth Syst. Sci.* **12**, 193–206.
- Mysterud, A., Yoccoz, N. G., Stenseth, N. C. & Langvatn, R. 2000 **Relationships between sex ratio, climate and density in red deer: the importance of spatial scale**. *J. Animal Ecol.* **69**, 959–974.
- Vikhamar-Schuler, D., Beldring, S., Førland, E. J., Roald, L. A. & Engen-Skaugen, T. 2006 **Snow cover and snow water equivalent in Norway: current conditions (1961–1990) and scenarios for the future (2071–2100)**. met. no Climate Report no. 01/2006.
- Vikhamar-Schuler, D. & Førland, E. J. 2006 **Comparison of snow water equivalent estimated by the HIRHAM and the HBV (GWB) models: current conditions (1961–1990) and scenarios for the future (2071–2100)**. met. no Climate Report no. 06/2006.
- Wilson, D., Hisdal, H. & Lawrence, D. 2010 **Has streamflow changed in the Nordic countries? Recent trends and comparisons to hydrological projections**. *J. Hydrol.* **394**, 334–346.
- Yue, S., Pilon, P. & Cavadias, G. 2002 **Power of the Mann–Kendall and Spearman’s rho tests for detecting monotonic trends in hydrological series**. *J. Hydrol.* **259**, 254–271.

First received 16 November 2010; accepted in revised form 8 March 2011. Available online 27 January 2012