Changes in snow depth in Norway during the period 1961–2010

Anita Verpe Dyrrdal, Tuomo Saloranta, Thomas Skaugen and Heidi Bache Stranden

ABSTRACT

Observed trends in annual maximum snow depth (SD) in Norway are analyzed and examined in the context of changes in winter climate from 1961 until today. Trends are evaluated for the 50-year period (1961–2010) and for three 30-year periods (1961–1990, 1971–2000, 1981–2010). The analyzed dataset is the most extensive and geographically representative for the country so far, and the analysis gives an up-to-date picture of the recent development in snow accumulation. In regions characterized by colder winter climate long-term trends are found to be positive in general, while short-term trends shift from strongly positive in the first period to predominantly negative in the last period. Variation in SD is here mainly linked to variation in precipitation. In regions of warmer winter climate variation in SD is dominated by temperature, and long-term trends are mainly negative. Short-term trends start out weak overall in the first period but become strongly negative most places in the last period. It is likely that, although more and more regions in Norway will experience declining maximum annual SD in a projected wetter and warmer future climate, some inland and higher mountain regions may still accumulate more snow in the coming decades.

Key words | Norway, snow, snow depth, trend analysis

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INTRODUCTION

Water storage in the form of seasonal snow cover is an important element in the water cycle in many countries, including Norway where approximately 30% of the annual precipitation falls as snow. Consequently, good knowledge of the snow cover is an important factor in for example hydropower production planning, flood forecasting, and water resources management. Snow conditions influence many aspects of the society like traffic flow, construction safety, recreation, and also play an important role in population dynamics and survival of many animal and plant species (Beniston *et al.* 2003; Stenseth *et al.* 2004; Tahkokorpi *et al.* 2007). Moreover, snow cover is an essential part of the climate system as it affects greatly the surface energy balance, mainly due to its high albedo. The geographic distribution of snow is highly irregular due to the importance of local topography and wind effects, in addition to differences in precipitation patterns. In mountainous regions dominated by complex topography, such as Norway, such effects are further amplified. Accordingly, a realistic representation of snow distribution and its variability requires a dense observational network over time.

The latest assessment report of the Intergovernmental Panel on Climate Change (IPCC) concluded that snow cover has generally decreased in the northern hemisphere over the past five decades (Lemke *et al.* 2007). In Norway, increasing winter temperatures and precipitation have been observed in most parts of the country in the past century (Hanssen-Bauer *et al.* 2009), and according to Dyrrdal & Vikhamar-Schuler (2009) and Dyrrdal (2009) there has been a decrease in snow depth (SD) and number of snow days at lower elevations since the early 1960s. Skaugen *et al.* (2011) analyzed trends in seasonal maximum snow

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water equivalent (SWE) in the highland and mountain regions of Norway and found increasing trends for the period 1961–1990. They concluded that increased winter precipitation ensured positive trends in this period, despite of the winter temperature increase. Moreover, Skaugen *et al.* (2011) found negative trends for the earlier and later periods 1931–1960 and 1991–2009 (stations in southern Norway), which they associated with decreased winter precipitation and increased spring temperature. Vikhamar-Schuler *et al.* (2006) studied future snow projections downscaled from a Regional Climate Model, and found that both mean maximum SWE and the length of snow season are expected to decrease in most parts of the country.

In the current study an extensive dataset of long-term snow depth series has been compiled by combining annual observations of SD and SWE taken by the hydropower companies (data are hosted and managed at the Norwegian Water Resources and Energy Directorate (NVE); see Skaugen *et al.* 2011), and SD observations from the Norwegian Meteorological Institute (met.no) station network. This generates a total number of 926 stations covering a broad elevation profile from 1 to 1,713 meters above sea level (masl). The main objectives of this collaborative study between NVE and met.no are to assess possible changes in annual maximum SD in Norway by analyzing trends for four different time periods, and to explain the geographical distribution of trends and relate these to recent climate change. Additionally, we will project the sensitivity of further increase or decrease in SD due to changes in climatic characteristics.

DATA AND METHODS

Most of the stations of the hydropower companies (hereinafter referred to as 'HPC-stations') are located at high elevations (700–1,700 masl), whereas met.no stations are mostly located at lower elevations (1–1,000 masl). SD at met.no stations is measured every day at a fixed point (a snow stake) and the annual maxima can easily be extracted from these time series. The snow season is here defined to be from the start of November through May. At the HPC-stations, on the other hand, SWE is the main parameter of interest and is measured normally only once a year at the time of assumed snow maximum (mid-March to mid-April). For most stations the reported SWE value represents an average of several measurements taken along a snow course (Skaugen *et al.* 2011). For a subset of these stations also SD is reported, which makes it possible to compute the bulk snow density $\rho = \mathrm{SWE/SD}$. In order to create a consistent dataset it is necessary to convert the SWE observations to SD at the stations where only SWE is reported. Thus, we need somehow to estimate ρ at these stations. Since we are applying the Mann–Kendall trend test (see below), where the data are rank transformed, any additional data transformation that does not affect the ranking of the data will not affect the results of the trend analysis. Such transformations are for example multiplication by a constant, log-transformation or conversion by a monotonically increasing function. Jonas *et al.* (2009) estimated SWE from SD data in the Swiss Alps and found four main factors affecting ρ, namely: (1) season; (2) SD; (3) site elevation; and (4) snow-climate region. Since we are studying trends at particular stations at a given time of the year (at least for the HPC-stations where SWE needs to be converted to SD), the above factors, season, site elevation and snow-climate region are constant over the time period. The only factor that varies in time is SD. Since SD, in Jonas *et al.* (2009), is described as a monotonically increasing function of SWE, (i.e. increase in SWE leads to increase in SD), it follows that the results from a Mann–Kendall trend test would be identical regardless of whether they were calculated from 'raw' SWE data or SD data converted from SWE using the model in Jonas *et al.* (2009).

By representing the time series of annual densities ρ_i (at the time of max SWE) as a product of a mean density over the whole time series $\bar{\rho}$ and an annual density anomaly factor $f_{\rho i} = \rho_i/\bar{\rho}$ we can write

$$\mathrm{SD}_i = \frac{\mathrm{SWE}_i}{\bar{\rho} \cdot f_{\rho i}}$$

Since $\bar{\rho}$ is a constant, its value does not affect our rank-based trend analysis (i.e. it can be arbitrarily set) and we can use converted 'surrogate' SD time series in our trend analysis, where each annual SWE value is divided by the median annual density anomaly factor $f_{\rho i}$ computed from the available density data from 120 HPC-stations situated in southern Norway. Figure 1 shows a comparison of τ-values

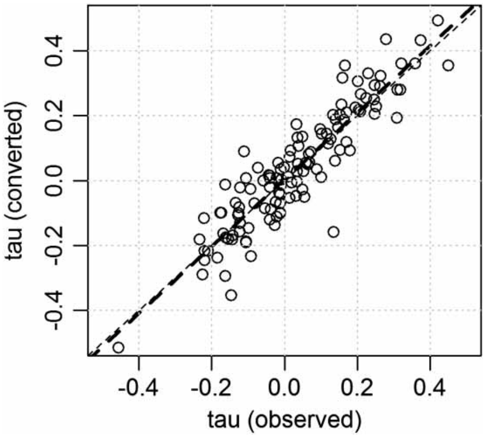

Figure 1 | Comparison of the calculated Mann–Kendall trend estimates (τ-values) between the observed and converted SD time series from a same set of 120 stations. The thin and thick dashed lines denote perfect fit and a linear regression fitted to the points, respectively.

(correlation coefficient ranging from −1 to 1, indicating the strength and direction of the Mann–Kendall trends) computed from both observed and converted SD time series from the same set of stations. Although there is some random deviation, there is no significant systematic difference between the two trend estimates, justifying the use of converted SD time series in our trend analysis, alongside the observed time series. Some uncertainty, beyond that of measurement uncertainty, is introduced through converting SWE to SD due to the fact that there might be discrepancies between measured maximum SWE and actual maximum SWE. Also the maximum SWE does not usually occur at the exact same time as maximum SD. Another source of uncertainty is the effects of wind speed and direction on point measurements of snow. Particularly at high elevations

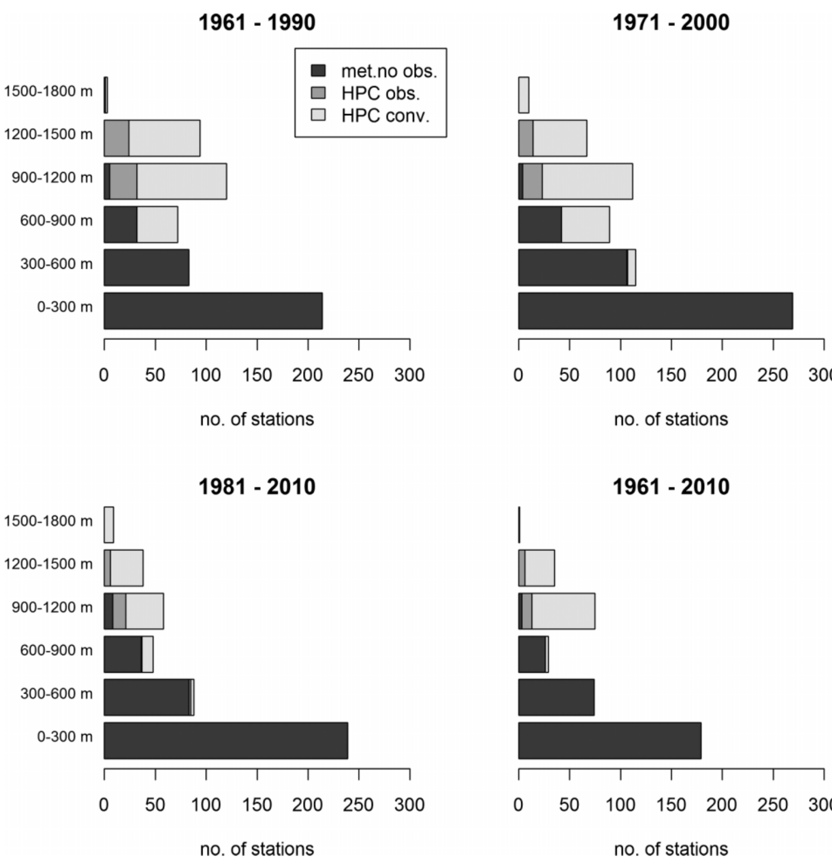

Figure 2 | Distribution of stations in different elevation intervals and time periods. The darkest shading denotes analyzed time series from met.no station network, and the lighter shadings observed and converted time series from the stations of the hydropower companies (HPC).

wind is important for redistribution of snow and, as the effects of wind varies from year to year, the confidence in time series from high elevations are slightly reduced.

The combined dataset of annual maximum SD time series consists of 926 stations (416 HPC-stations and 510 met.no stations). However, only time series with at least 80% complete observations (years) within each period were selected for trend analysis, and thus the number of analyzed time series varies between the different periods. Trends for the entire 50-year period 1961–2010 (393 stations were analyzed) and trends for the 30-year periods 1961–1990 (586 stations), 1971–2000 (662 stations), and 1981–2010 (480 stations) are examined. The distribution of the stations with elevation in the different time periods is shown in Figure 2, and the station locations are shown in Figure 5 under section 'Results and Discussion'. In addition, 30-year moving window trends for the entire period 1961–2010 are computed and plotted against mean winter temperature, an illustrative method inspired by Scherrer *et al.* (2004).

The rank-based nonparametric Mann–Kendall test is applied in the analysis, and trends are evaluated for statistical significance at the alpha level of 0.05 (two-sided *p*-value). The Mann–Kendall test is commonly used to evaluate the significance of monotonic trends in non-normally distributed series, such as hydro-meteorological time series (Yue & Pilon 2004). The null hypothesis tested is that two variables, in this case annual maximum SD and consecutive years, are independent. The trend slope magnitude is estimated in a robust non-parametric way by taking the median of the slopes calculated for all pairs of measurements in the time series (see e.g. Yue *et al.* 2002, Appendix B).

Earlier studies by e.g. Mote (2003) and Scherrer *et al.* (2004) suggest that local temperature and, in some locations, precipitation have great impact on local snow conditions. To investigate this hypothesis at our observation sites, the correlation between annual maximum SD and winter temperature and precipitation is computed using the rank-based Kendall correlation test. Winter is here defined as November through March (NDJFM). Since observations of

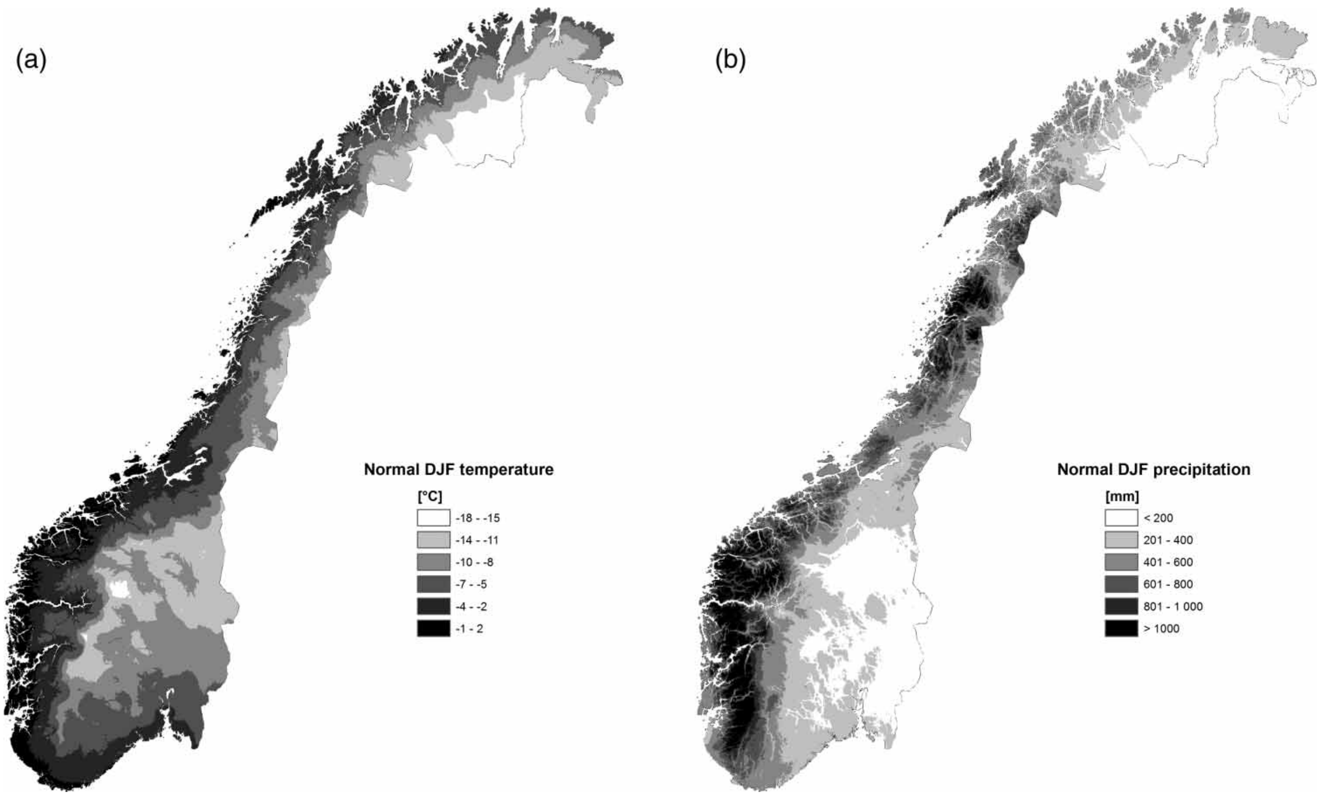

Figure 3 | Average winter (DJF) temperature (left) and precipitation (right) for the standard normal period 1961–1990.

temperature and precipitation are only available at a few stations, we extract time series from the daily climate grids presented at www.seNorge.no (Engeset *et al.* 2004; Tveito *et al.* 2005). These daily grids go back to 1957, and are interpolated values based on observations from the met.no station network.

Climate in Norway

Figure 3 presents mean winter climate in Norway for the standard normal period 1961–1990, indicating colder/warmer and dryer/wetter regions referred to throughout this study. Values are extracted from the climate grids described above (www.seNorge.no). In southern Norway, where a majority of the stations are located, the western part is characterized by a steep elevation gradient, where orographic precipitation dominates. The eastern part is characterized by a coastal climate in the south and a continental climate in the north, and is predominantly in the rain shadow of the western mountain range. A dry and cold continental winter climate is also found in the far northeastern part of the country. The rest of the country, mainly situated along the coast, is dominated by a maritime climate which, moving northwards, becomes more and more influenced by polar weather systems. Figure 4 shows time series of deviations from the mean value for the standard normal period 1961–1990 for winter – (December–January–February, DJF) temperature and accumulated precipitation for the whole of Norway for the period 1961–2010. These average deviations are computed from a gridded dataset of monthly values obtained with the method presented in Hanssen-Bauer *et al.* (2006). For the two most recent decades, mean winter temperatures are well above the normal for almost all years. Previous to 1990, winter temperatures rose from a colder period in the late 1960s to warmer in the early

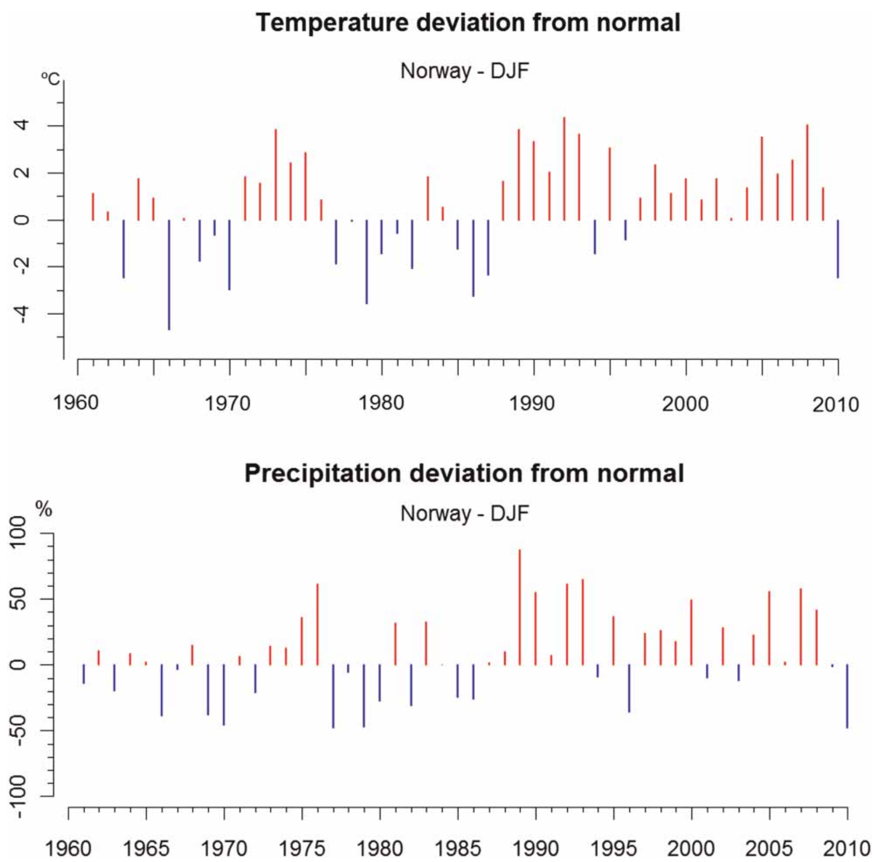

Figure 4 | The deviations of winter (DJF) temperature (upper) and precipitation (lower) from 1961–1990 normal period means.

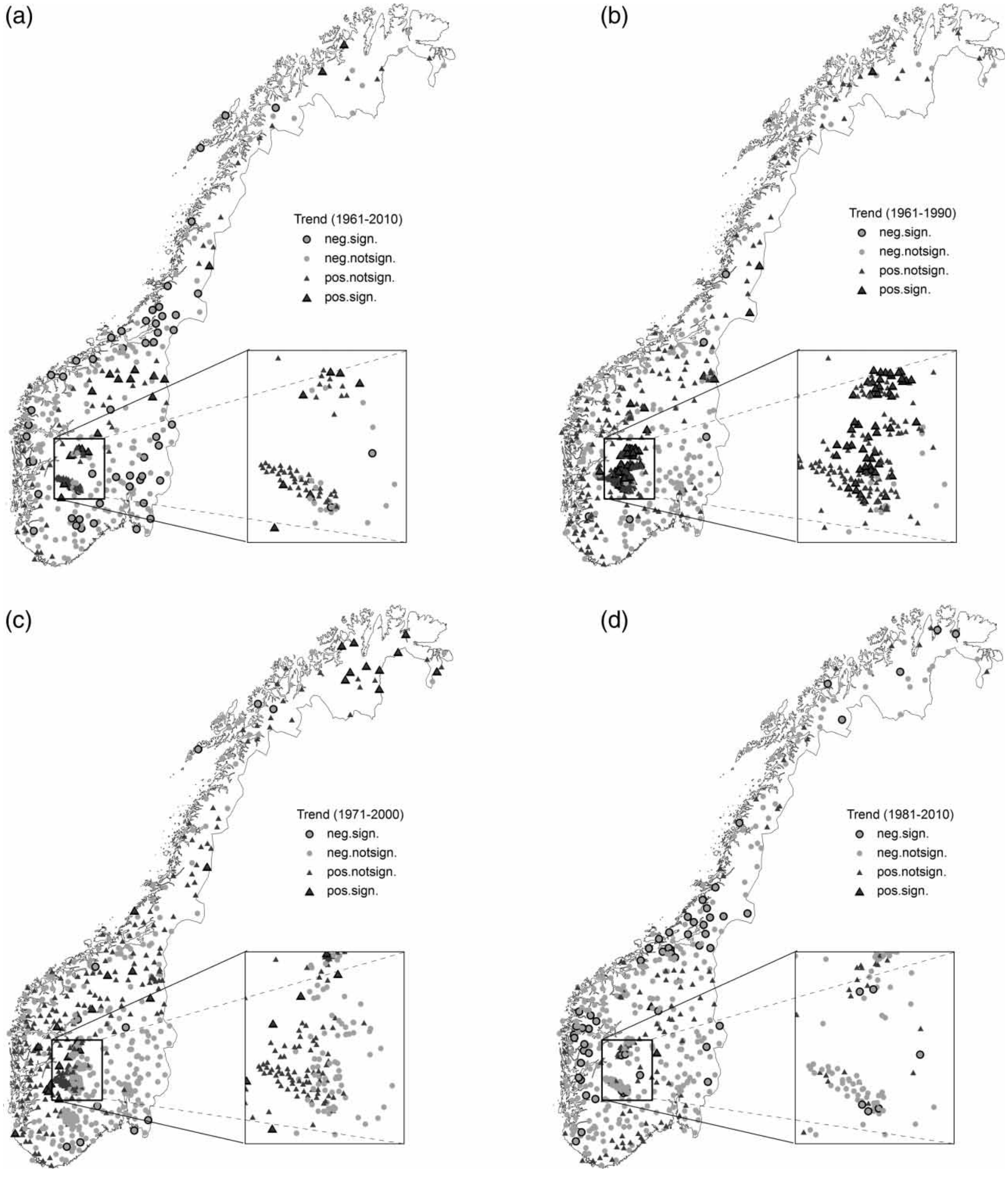

Figure 5 | (a). Trends in maximum SD in the period 1961–2010. Warm (cold) shaded symbols indicate negative (positive) trends, where darker shaded symbols denote statistically significant trends at the 0.05 alpha level (see legend). Topography is illustrated by shades of grey. The central mountain area is zoomed to facilitate better distinction of the stations, (b) (upper left): Trends in the period 1961–1990, (c) (upper right): Trends in the period 1971–2000, (d) (lower): Trends in the period 1981–2010.

1970s and to colder again around 1980. For precipitation we can identify two drier periods around 1970 and around 1980; however, the last two decades have been wetter than normal for most of the years. One must bear in mind, however, that while Figure 4 shows an average over the entire country, more localized areas may have experienced stronger or weaker changes in temperature and precipitation.

RESULTS AND DISCUSSION

The geographical distribution of trends in annual maximum SD is presented in Figure 5. For the 50-year period 1961–2010 trends are mainly negative along the entire western and southern coast, and in the southeastern part of the country (Figure 5(a)). In colder regions such as the mountains in South Norway, mid-elevations in the southeast inland regions (governed by continental climate), and in the northernmost part of the country, trends are mainly positive. In these regions winter temperatures stay low throughout the winter despite the recent documented warming (Hanssen-Bauer *et al.* 2009), and winter precipitation falls as snow. Therefore, the increased winter precipitation, as observed in the last decades, causes more snow to accumulate. There are quite a large number of statistically significant trends in the entire country, the majority of those being negative.

The 30-year trends for the period 1961–1990 (Figure 5(b)) reveal a number of significant positive trends in higher elevations and only four significant negative trends in locations that share no obvious geographic properties. This is in accordance with Skaugen *et al.* (2011) who found positive trends in SWE above ~850 masl. However, trends in SWE can generally be expected to differ slightly from those in SD, since density changes do not have direct effect on SWE. In addition, e.g. a rainfall retained or refrozen in the snow pack would likely decrease the SD while increasing the SWE. Trends become more and more negative as we move to the second and third period, 1971–2000 (Figure 5(c)) and 1981–2010 (Figure 5(d)), where the latter only shows two significant positive trends. These correspond to stations located in rather cold areas inland at 628 and 823 masl. However, it is worth remembering that a low number of significant trends (less than 5% of the stations) may arise by chance, and thus cannot be used to base a general conclusion on. The last period shows many significant negative trends in the entire country, in particular along the western coast of South Norway. Southeastern Norway is characterized by mostly negative trends in all periods, and in the second period 1971–2000 in particular we see a clear division between eastern and western parts of South Norway. Areas to the west show mostly positive trends, while areas to the east show mostly negative trends. This is most likely due to the different precipitation patterns in the two regions, as the mountain range separating them is oriented across the prevailing wind from the west.

Thirty-year moving window trends for the entire country are presented in Figure 6. The first 30-year periods are characterized by positive trends in colder regions and negative trends in warmer regions, while the most recent 30-year periods, beginning in the early 1970s, show mostly negative trends in all regions. The general increase in winter temperatures is reflected in the slight positive inclination of the point cluster shown in Figure 6.

Figure 7 shows the distribution of the relative trend slope magnitudes in the analyzed time series, binned by the mean winter (NDJFM) temperature as in Mote *et al.* (2005). This figure confirms the change seen in Figures 5 and 6 towards an increasing number of stations with declining annual maximum SD, as one moves from the first (1961–1990) to the last (1981–2010) 30-year period. The effect of mean winter temperature in enhancing the magnitude of the declining trend in SD is particularly clear in the last period 1981–2010. In the 50-year period 1961–2010 the average annual change in SD

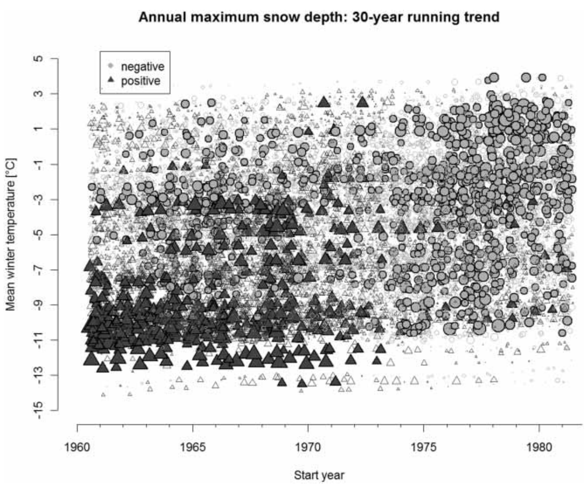

Figure 6 | 30-year moving window trends plotted against mean winter (NDJFM) temperature. Dark and light shading denote negative and positive trends, respectively. The larger the circle, the more significant the trend (the legend symbol size indicate a Kendall's tau coefficient of 0.5) Outer black circles denote trends that are statistically significant at the 0.05 alpha level. The *x*-axis refers to the start year of the 30-year window. To avoid hiding some symbols behind others, trends were randomly plotted within the appropriate year ± 0.45.

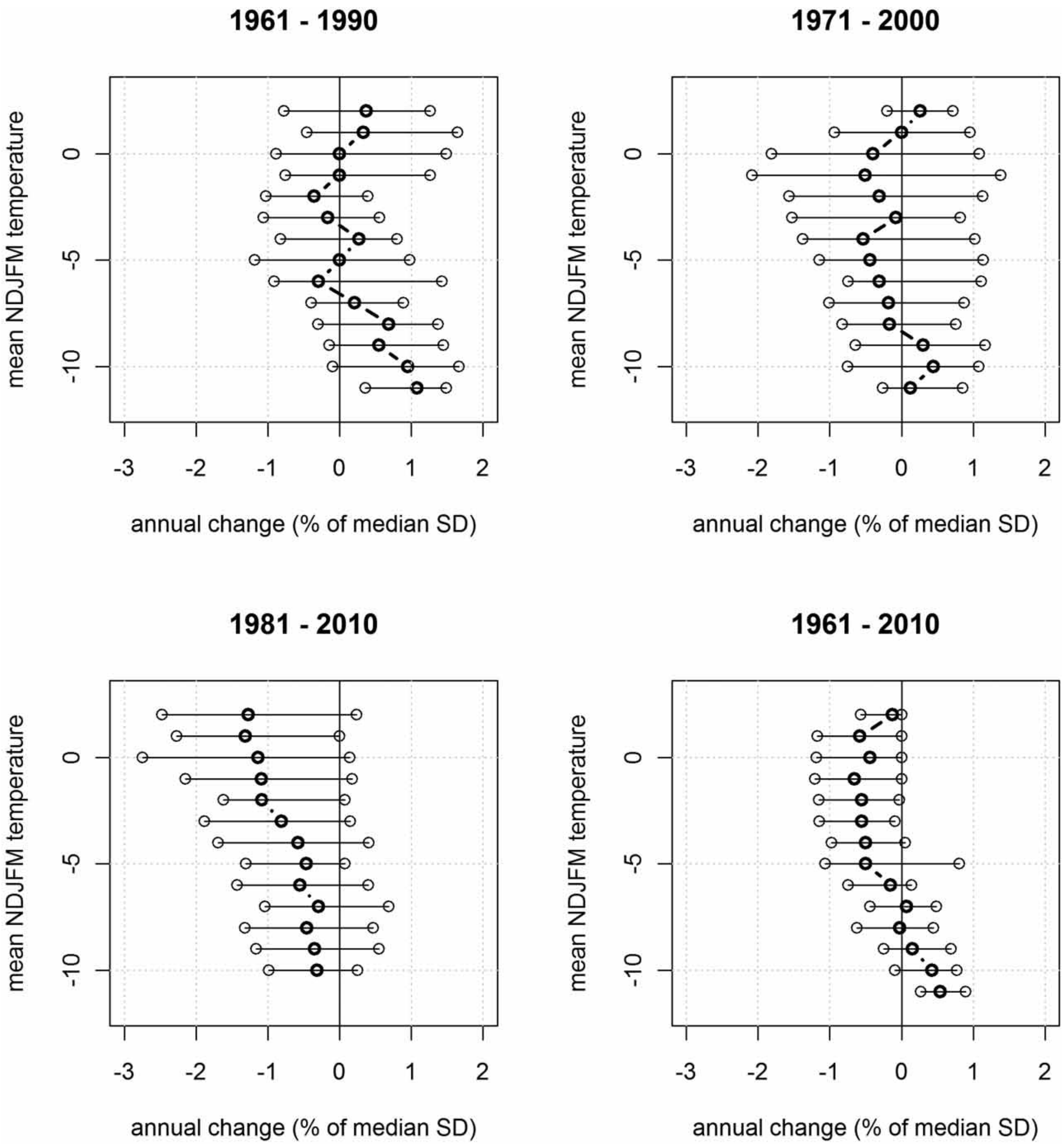

Figure 7 | The distribution of the relative annual trend slope magnitudes in SD in the four periods, binned by mean winter (NDJFM) temperature of the period. The thick circles in the middle denote the medians of the distributions per temperature bin, and the error bars the 10 and 90% percentile intervals. Only those temperature bins with time series from more than 15 stations are included.

has been basically negative for all stations with mean winter temperature above −5 °C. The shape of this curve resembles those shown for western North America and Switzerland in Lemke *et al.* (2007), where the magnitude of the slope of the trends move from positive (or near zero) towards negative values along increasing mean winter temperature, except above 1–2 °C where trend slope magnitudes again move closer to zero.

Air temperature is strongly related to SD via its effect on (i) the fraction of precipitation that falls as snow, (ii) snow melt and (iii) snow compaction (density). The effect of total precipitation on SD is thus conditional on the temperature, and the temperature dependencies (i) and (ii) mentioned above show a strong threshold response around the water freezing point. In addition, since warmer air can contain more humidity, temperature also affects the amount of precipitation, as illustrated in Figure 9. Precipitation, in addition to being the source of snow, can also have a decreasing effect on SD, as rain water can enhance compaction and melting (melting either directly or via wettening the snow and lowering its albedo). The variability

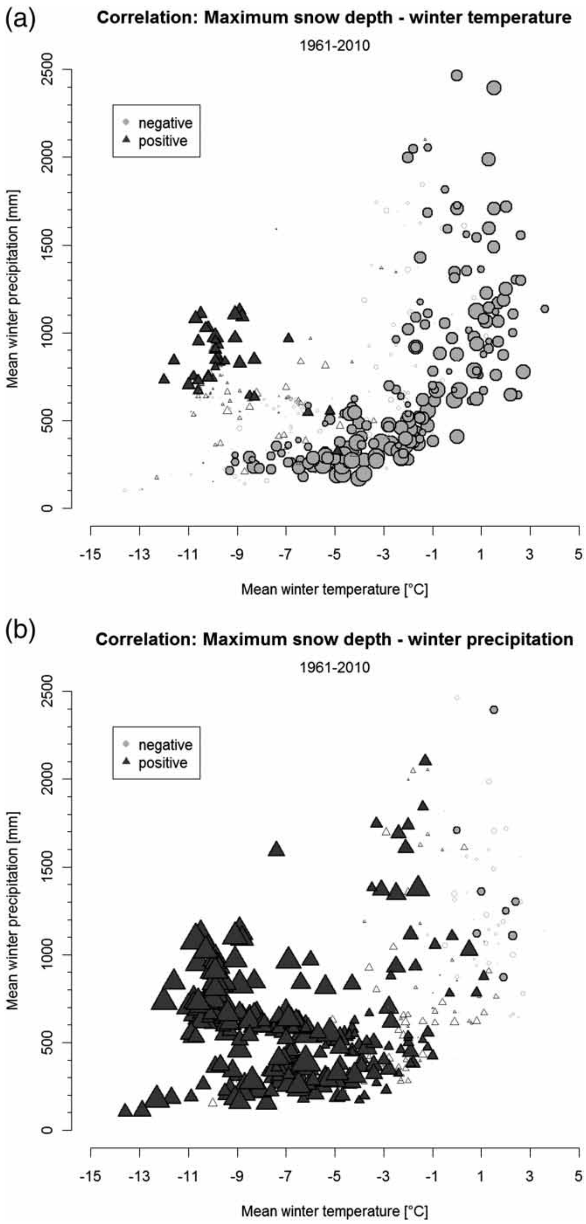

Figure 8 | Correlation between annual maximum SD in 1961–2010 and (a) winter (NDJFM) temperature and (b) winter precipitation, plotted against mean winter climate. Circles denote negative correlation, and triangles positive correlation. The larger the symbol the stronger the correlation (the legend symbol size indicate a Kendall's tau coefficient of 0.5). Outlined symbols denote correlations that are statistically significant (i.e. significantly different from zero) at the 0.05 alpha level.

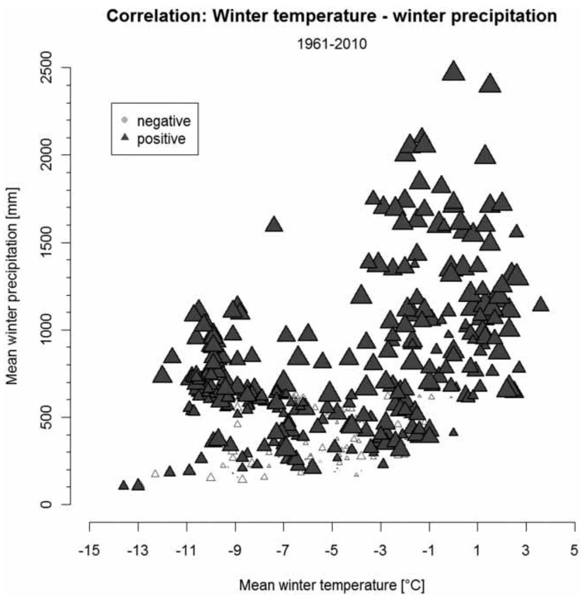

Figure 9 | Correlation between winter temperature and winter precipitation, plotted against mean winter climate. Circles denote negative correlation, and triangles positive correlation. The bigger the symbol the stronger the correlation, and outlined symbols denote correlations that are statistically significant (i.e. significantly different from zero) at the 0.05 alpha level.

and interplay of all these mechanisms finally governs the maximum SD of a particular year.

Not surprisingly, annual maximum SD shows both strong negative correlation to winter temperature (Figure 8(a)), and strong positive correlation to winter precipitation (Figure 8(b)) at most stations. There are, however, areas of exception, especially at the coldest and warmest stations, where the snow accumulation is governed by a more subtle relationship with precipitation and temperature. These exceptions (positively correlated with temperature and, and negatively correlated with precipitation) are most likely related to the positive correlation between winter temperature and precipitation (Figure 9). This intercorrelation can be explained by the fact that the Norwegian winter climate is closely linked to the North Atlantic Oscillation (NAO), especially in the western parts of southern Norway (Hanssen-Bauer 2004; Cherry *et al.* 2005). This means that periods of higher winter temperatures are accompanied by more precipitation, while periods of lower temperatures, often associated with stable high pressure systems, have generally less precipitation. Figure 10 shows locations where annual maximum SD is (1) strongly correlated to winter temperature and less to precipitation,

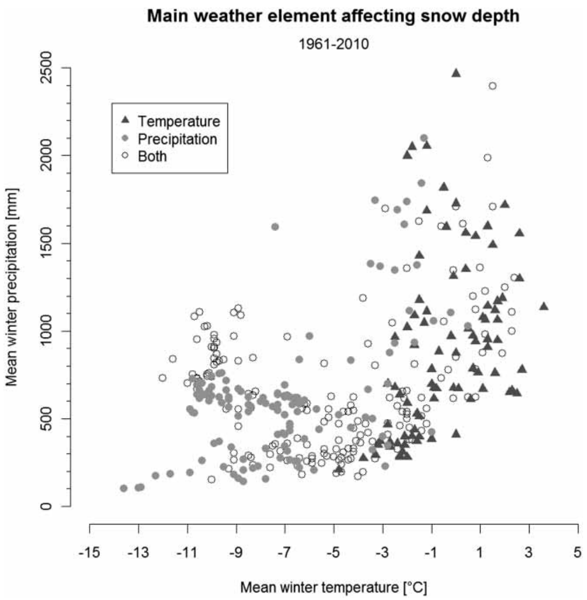

Figure 10 | Stations with clearly temperature dominated (triangle) precipitation dominated (circle) maximum snow depth regime. Open circles denote stations where neither temperature nor precipitation alone dominates variations in SD.

(2) strongly correlated to winter precipitation and less to temperature, and (3) reasonably correlated to both precipitation and temperature. The criteria used to select the three clusters were as follows: (1) significant correlation to winter temperature at the 0.05 alpha level ($p < 0.05$) AND non-significant correlation to winter precipitation at the 0.1 alpha level ($p \geq 0.1$); (2) significant correlation to winter precipitation at the 0.05 alpha level ($p < 0.05$) AND non-significant correlation to winter temperature at the 0.1 alpha level ($p \geq 0.1$); (3) neither 1 nor 2.

In the relatively cold areas, both wet and dry, the temperature stays sufficiently cold throughout the winter season so that variation in precipitation is the main modifier of SD here. In warmer areas, also both wet and dry, temperature can often vary around 0 °C, and precipitation might fall as rain or snow. Thus, SD is very sensitive to temperature variations. The winter temperature division line below which temperature ceases to dominate variations in SD varies from ~−5 °C at the driest stations to ~0 °C at the wettest stations. Stations where neither temperature nor precipitation alone dominates variation in SD are located in all regions.

CONCLUSIONS

In this paper we have presented the geographical distribution of trends in annual maximum SD in Norway from 1961 until today. The collection of time series we have analyzed is the most extensive and geographically representative for the country so far, compared to earlier studies. As almost half of the time series end after 2008, our study gives an up-to-date picture of recent development in snow accumulation in Norway. Due to some uncertainty in snow measurements (conversion of SWE to SD, wind effects, etc.) we have focused our conclusions on general trend patterns rather than results at single sites.

In regions characterized by colder winter climate (i.e. inland and mountain regions, where mean winter (NDJFM) temperature is a few degrees below zero; see Figure 10) variations in SD are dominated by precipitation. Long-term (50-year) trends in these regions are found to be positive in general, while short-term (30-year) trends shift from being strongly positive in the first period (1961–1990) to becoming predominantly negative in the last period (1981–2010). In other words, variation in SD is here mainly linked to variation in precipitation, since temperature stays sufficiently low in these areas to have a major reducing effect on SD via the mechanisms described above. In the coldest regions, a temperature increase can even lead to increased SD, due to its positive correlation with precipitation, as discussed in the previous section and shown in Figure 9. In lowland and coastal regions characterized by warmer winter climate variation in SD is dominated by temperature, and here we found mostly negative long-term trends. Short-term trends start out weak overall in the first period but become strongly negative at most stations, particularly along the western coast, in the last period.

It seems that, although more and more regions in Norway will experience declining maximum annual SD in a projected wetter and warmer future climate, some inland and higher mountain regions, where the winter (NDJFM) temperature is well below zero, may still accumulate more snow in the coming decades. Most of the Norwegian population lives, however, at lower elevations, where the projected continued decrease in snow accumulation will be most visible and lead to for example less favorable conditions for recreational winter activities. It is worth noting, however, that the climate system is complex, and that significant uncertainty is associated especially with regional climate projections.

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