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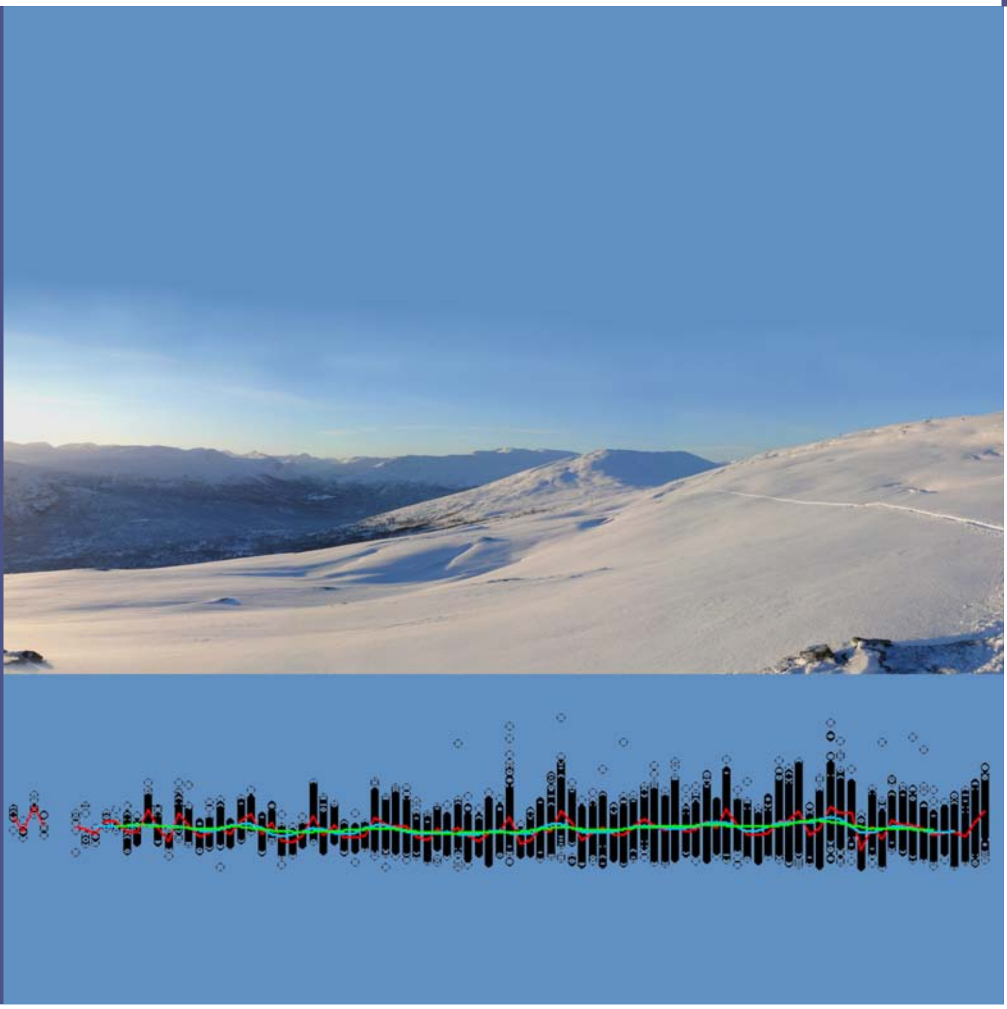

REPORT

Trends in annual maximum snow water equivalent in Norway (1914-2008)

The Norwegian Water Resources and Energy Directorate (NVE)
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Abstract: In this report, the large number of annual snow data measured annually by the power production companies and reported to NVE, is analysed for the detection of possible temporal trends. There are no indications of significant trends in the mean annual SWE in Norway when data is pooled nationwide or for regions. When investigating temporal trends as a function of altitude for single stations, significant trends, both positive and negative, occur.

Subjects: snow, snow water equivalent (SWE), trends, climate change

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Contents

Preface

As NVE is the national technical authority for hydrology, and snow is an important parameter in Norwegian hydrology, it is our responsibility to observe, collect, verify and study the snow conditions in the past, the present and in the future. Traditionally, snow water equivalent (SWE) is measured annually for resource monitoring in relation to hydropower production and for emergency purposes in relation to flood forecasting. In this report, the large number of annual snow data measured annually by the power production companies and reported to NVE, is analysed for the detection of possible temporal trends.

The analysis is carried out as a part of the NorClim-project, work package 6.3: "Downscaling- Series and analyses of historical snow parameters". The NorClim-project is a nationally coordinated climate research project funded by the Norwegian Research Council program NORKLIMA for the period 2007-2010.

Oslo, October 2009

for Morten Johnsrud
Director,
Hydrology Department

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Summary

Temperature and precipitation have showed positive trends in Norway for the past century and the snow cover has decreased in the northern hemisphere in the past 50 years. Future scenarios (2071-2100) of temperature and precipitation for Norway indicate that the trends will continue to be positive. In this study, we have analyzed temporal trends in snow water equivalent (SWE), including trend analysis within different normal periods and analysis of temporal trend as a function of altitude.

Since 1915, snow has been measured in mountainous areas in Norway in relation to power production and flood forecasting. The observations are mainly performed by the power production companies at the time of expected snow maximum. Most of the measurements are located at high altitudes, which give us a unique opportunity to do analyses in areas that are poorly covered by meteorological stations.

There are no indications of significant trends in the mean annual SWE in Norway when data is pooled nationwide or for regions. The absence of trends may be explained by the applied method of pooling all stations, independent of elevation, locale climatic differences and different record length. .

When investigating temporal trends as a function of altitude for single stations, significant trends, both positive and negative, occur. The temporal trends in SWE in South Norway are stronger in 1961-1990 for westerly, maritime stations than for the periods 1931-1960 and 1991-2008. These findings are consistent with glacier mass balance data from this area and can explained by a steadily increasing temperature which effect cannot, after 1990, be compensated by increased winter precipitation.

1 Introduction

In many areas north of latitude 35°, winter precipitation comes as snow. Precipitation as snow plays an important role in defining the hydrological regime and thus is instrumental in the design of infrastructure in waterways, economy and hazards. In Norway, the typical hydrological regime is winter low flow, a clearly defined snowmelt flood in spring, summer low flow and the occasional autumn flood due to precipitation as rain (Gottschalk, 1987). The hydropower industry, water supply for agriculture and consumption, tourism and the general way of life of the public have adjusted to this hydrological regime and changes thereof will call for strategies of adaption.

Temperature and precipitation have showed positive trends in Norway for the past century. Annual temperature has increased by 0.5-1.5°C and annual precipitation has increased statistically significant in almost all of Norway and 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. Temperature and precipitation will increase for all regions, but the increase in precipitation will be higher for the western part than for the inland (Beldring et al., 2008). Snow cover has decreased in the northern hemisphere for the past 50 years (Lemke et al., 2007). 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 entire country (Vikhamar-Schuler et.al, 2006), but a more, topographically detailed hydrological study of the same scenario data set suggest that for certain high elevation areas, annual maximum SWE might increase (Vikhamar-Schuler and Førland, 2006). Studies of the duration of the snow season (Dyrrdal and Vikhamar-Schuler, 2009a; Vikhamar-Schuler et.al, 2006) project a shorter snow accumulation season due to later snowfall and earlier snowmelt. The decrease in the duration of the snow season is smaller with increasing altitude and distance from the coast. In some mountainous areas, we expect more snow especially in extreme wet years.

A possible interpretation of these studies concerning future snow conditions is thus that the season of precipitation as snow, in general, becomes shorter in all areas. The exception is for areas of high elevation, where increased winter precipitation, (e.g. the western part of Norway) dominates over increased temperature. Many studies (especially in the US) on recent historical data have investigated possible trends in SWE during the last 50-60 years. Kalra et al. (2008) analysed changes in discharge and SWE in the western U.S. for the period 1941-2004 and found a general decline for both parameters with the exception of one station in the southern Rockies. Barnett et al. (2008) analysed change in the ratio of SWE to winter precipitation (1950-1999) in the western US, and found a decline in the ratio for all areas, except in the southern part of Sierra Nevada, where the trend was slightly positive. This finding is consistent with an increase of winter temperature and possibly a shorter snowy season. Howat and Tulaczyk (2005) found both increasing and decreasing trends in SWE for increased winter temperature for the period of 1950-2002. Increases in SWE are, of course, found for high elevations where winter precipitation had increased, and decreasing trends were found where increased winter precipitation could not compensate for the temperature increase. Several other studies, concerning the western US, confirm the picture that decreases in SWE are found for most locations except for the high elevation sites where an increase in winter precipitation dominates the increase in temperature, i.e. that trends in snow become less negative with increasing elevation (Mote, 2003; Mote, 2006). Burakowski (2008) analysed trends in the winter climate in northeastern part of the US and found that the total snowfall during the winter months has decreased in the period 1965-2005. The trend, however, was not statistically significant.

Mote (2006) focused on variations in SWE due to latitude, but found it difficult to distinguish between variations due to latitude and variations due to elevation since the elevation of the snow stations decreased with latitude (and the correlations of SWE with precipitation and temperature are clearly dependent on elevation).

The timeperiod chosen for analysis is important when investigating possible trends in SWE. Mote (2008) showed how changing the start of the analysis from 1940 to 1960 influenced the number of snow courses available for analysis and thus the distribution of stations with elevation. The mean elevation of the oldest snow stations is higher than that of the younger stations, and since SWE at low elevation is more sensitive to increased temperature than SWE at high elevations, it influences the result and conclusion of the study. In Mote (2008), the analysis for 1960 – 2006 gave a clear negative trend on SWE, whereas when older stations with records from 1940 are included, the conclusion is that only small changes in SWE are present. Hisdal et al. (2001) also point out the sensitivity of trend analysis to the choice of time-periods. The tendency of wet and dry periods to cluster may influence any trend analysis quite severely.

In Switzerland, investigations show an unprecedented series of low snow winters during the past 60 years. In low altitude zone, the reduction in snow days is over 50% (Marty 2008). Durand et al. (2009) analysed snow depth and number of days with snow in the French Alps and found that both snow depth and number of snow days were decreasing with time, especially at lower altitudes.

Investigations in the Nordic countries show that in Finland, SWE has been increasing in the eastern and northern part during 1946 - 2001, whereas there was a decrease in SWE in the southern and western part (Hyvärinen, 2003). Dyrrdal (2008) found an overall decrease in snow depth in Norway for three eastern sites located south (Gardermoen), in the middle (Røros) and in the north (Finnmark) respectively. Glaciological time series from Norway provide very interesting climatological information and from series of glacier mass-balance and length variation in Norway, we find a mass surplus for maritime glaciers (located in the southwest of Norway) with a high mass turnover during the period from 1962 to 2000. For glaciers in dryer inland areas, there are mass deficits during the same period (Andreassen et al. 2005). All glaciers, however, had an overall retreat in the same period suggesting, increased temperatures in the ablation area. Later than 2000 all glaciers show a mass deficit and continuous retreat.

The aim of this study is to qualify and detect trends in Norwegian snow data, especially at higher altitudes. In contrast to the Norwegian Meteorological Institute (met.no), which do their snow measurements (snow depth) at lower altitudes (Dyrrdal and Vikhamar-Schuler 2009 b)) more than 40 % of the snow stations in NVE's database are located above 1000 m a.s.l. This gives us a unique opportunity to do analyses in areas that are poorly covered by meteorological stations.

In this study, we will analyse temporal trends in SWE. The temporal trend analysis includes trend analysis within different normal periods (1931 - 1960, 1961 - 1990, 1991 - 2008) and analysis of temporal trend as a function of altitude.

This analysis is carried out as a part of the NORCLIM-project funded by the Norwegian Research Council.

The data used in the analysis is presented in the following section, while the method of analysing the data is described in section 3. In section 4, the results are shown, and discussion and conclusion are presented in sections 5 and 6.

2 Data

Since 1915, snow has been measured in Norway in relation to hydropower production and flood forecasting. The observations are mainly done by the power production companies once a year at expected snow maximum (middle of March – middle of April) and reported to the Norwegian Water Resources & Energy Directorate (NVE). Throughout this report, the acronym, "SWE", is used for annual measurements of maximum snow water equivalent.

In the database of NVE data from more than 1 300 snow stations are available. In addition to the manual measurements (1 279 in total), NVE has data from more than 30 snowpillows and close to 1 100 manual snow measurements from glaciers. In this study, we focus on the manual snow measurements done on bare ground, so neither the snow-pillows nor the glacier-measurements are included.

As shown in Figure 1a), most of the stations are located in the southern part of Norway. The stations are located between 125 and 1713m a.s.l. and 40 % of the stations are located above 1000m a.s.l. (see Figure 2a). The oldest data are from 1915 and in average; each station has 22 years of annual data (see Figure 2 b). Figure 1 b) shows a regional classification of snow stations which divides Norway in three regions; South Norway, Central Norway and North Norway. The distribution of stations related to altitude within each region is illustrated in Figure 3. The northernmost regions have fewer stations at higher altitudes compared to South Norway and the number of stations in Central- and North Norway is also less than in South Norway.

For most of the stations, snow has been measured along snow courses and the average SWE for the snow course is represented as the data point from each station. For some stations, although, there has been changes in measurements techniques, e.g. from point measurements to snowcourses and this can cause inhomogeneities in the data. Analyses of homogeneity were, however, not performed. Data were checked against temporal and spatial consistency. Some data, considered as outliers, were omitted.

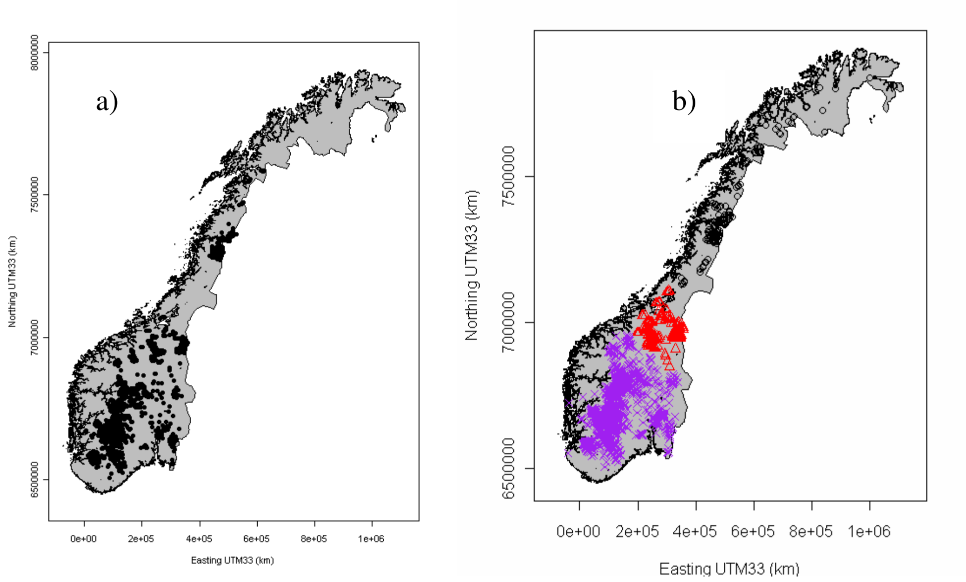

Figure 1. a) Location of the snow stations (in total 1279 stations). b) Regions with snow measurements; South Norway (x, 1062 stations), Central Norway (▲, 154 stations) and North Norway (o, 103 stations).

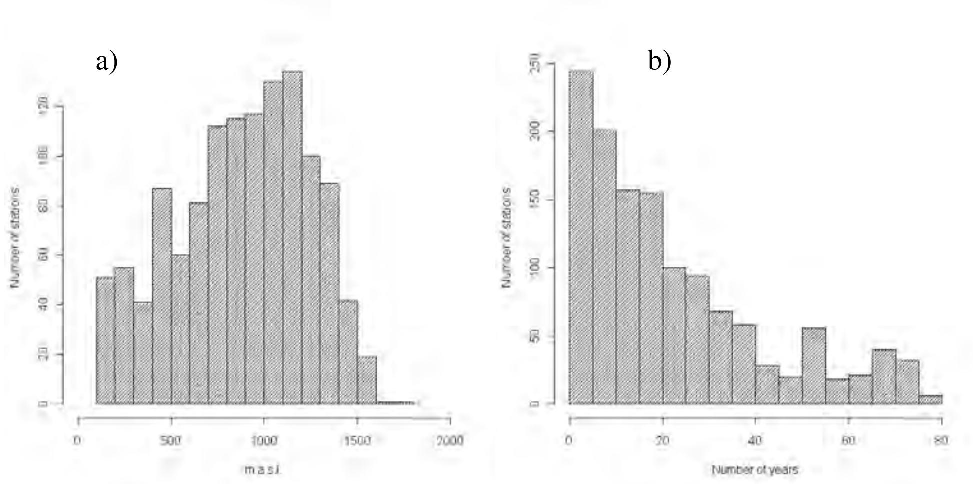

Figure 2. a) Distribution of the stations related to altitude, b) Number of station related to number of years with measurements.

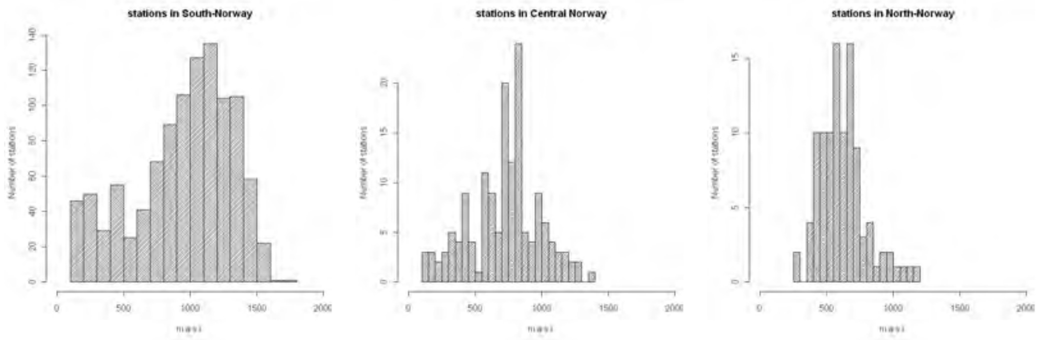

Figure 3. Distribution of snow stations within a region (South Norway, Central Norway and North Norway respectively) related to altitude

3 Methods

3.1 Temporal trends

With such an extensive data set at hand, it is important to carry out the study of detecting possible temporal trends in a manner in which the detection of possible trends are not lost in statistical noise due to choice of time period, choice of climatic region or by not taking into account the dependence of SWE on altitude.

Possible trends were investigated after organising the data in three ways. First, the temporal trends are evaluated for the entire dataset, covering all years from 1914 – 2008, for all of Norway and for different regions. Norway is divided into three regions; North Norway, Central Norway and South Norway. Figure 1b shows the different regions and the density of snow measurements within each region. In order to compare the change in SWE from station to station without the analysis being compromised by local climatic differences, a normalization procedure was carried out. For each station, the annual data point of SWE is divided by the long-term mean of the station. A mean annual value estimated from all available stations for each year, is the subject for trend analysis. Second, to investigate how the trends may vary with choice of timeperiod, the entire dataset is further divided into the different meteorological normal periods. Also here, the normalization procedure was carried out. The years from 1914 to 2008 are divided into two and a "half" normal periods: the years from 1931 - 1960 and 1961- 1990, and the years from 1991 - 2008. Before 1931, the number of stations with data is too small, so data from this period is not included. Finally, since both temperature and precipitation are found to be increasing on an annual basis (Hanssen-Bauer, 2005), the investigations of possible trends in SWE can be made difficult by the fact that changes in these two factors have the opposite effect on SWE. If we assume that increased precipitation can compensate for decreasing temperature at higher altitudes, we would expect to find a trend ranging from negative at lower altitudes and to more positive at higher altitudes. To examine the variation in trend with elevation, the trend, estimated for each station, is plotted against elevation and location (E-W). In this part of the study, we use the measured SWE instead of the normalized SWE described above. Only stations with more than 15 years of data within each 30-years period are included in the analysis. From 1991 - 2008, stations with more than 8 years of data are included in the analysis.

The structure of the analysis described above is illustrated in Figure 4.

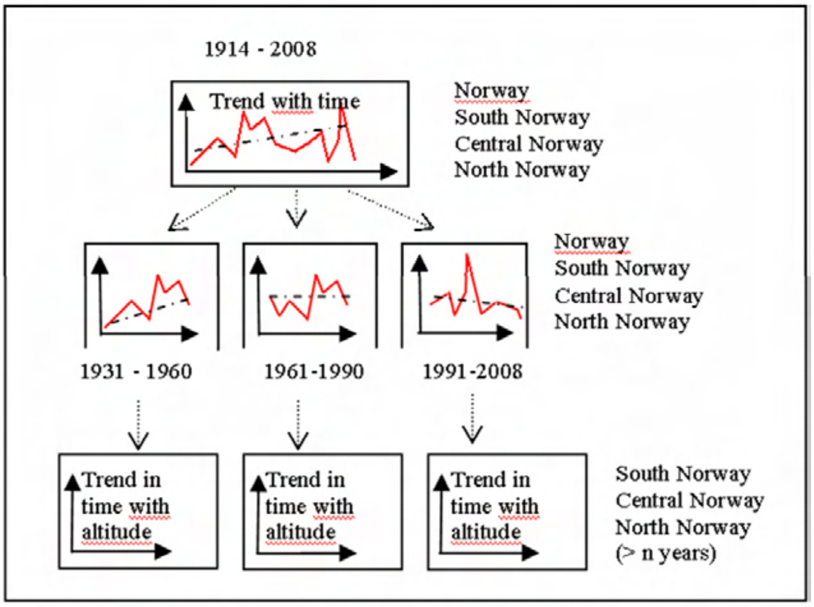

Figure 4: The structure of the trend analysis.

3.2 Time series analysis

To determine the significance of possible trends in time, linear trend analysis is performed.

A linear regression model of the form

$$y = a + b\,x \tag{1}$$

is fitted to the measurements. *y* denotes the dependent variable (SWE), whereas *a* and *b* are constants. *a* denotes the intersection for the trend line, while *b* denotes the slope. When *b* equals zero, no trend is present.

A two-sided t-test is carried out to check statistical significance on *b*. The t-test assumes that the population is normally distributed or that the sample size exceeds 30. The one-sample t-test statistics is given as:

$$t = \frac{\overline{x} - \mu_0}{\left(s/\sqrt{n}\right)}, \text{ with n-1 degrees of freedom.} \tag{2}$$

where $\overline{x}$ is the sample mean, μ_0 is the hypothesized population mean. *s* is the sample standard deviation ,*n* is the sample size and *t* measures the compatibility between a given hypothesis and the data. The hypothesis to be tested is if *b* is significantly different from zero. A null hypothesis is established as H_0: No trend. If $b \neq 0$ *(in Eq. 1.),* it indicates an increase or a decrease in SWE. In order to determine whether the trend is significant or not, the level of significance is determined as p0 = 0, 05, which means that the probability of rejecting H_0 when in fact H_0 is true, is 5% (Moore and McCabe, 2002).

4 Results

4.1 Temporal trend

Temporal trend in SWE for all stations from 1914-2008 is shown in Figure 5. Data for the years 1918 - 1919 are missing. Linear trend analysis on the mean annual value shows neither an increase nor a decrease, and the linear trend does not differ significantly from zero at a level *p0* = 0, 05. Figure 6 presents the temporal trend from all stations within different normal periods. For the first normal period (1931-1960) and the last period (1991-2008), the average SWE appears to be slightly decreasing, whereas there are hints of a slight increase for the period 1961-1990. The slopes, however do not differ significantly from zero for the chosen, *p0* = 0, 05 for any of the periods.

Figure 7 shows the temporal trend in SWE for stations in South Norway. Linear trend analysis on the mean annual value shows neither an increase nor a decrease, and the slope does not differ significantly from zero at a level *p0* = 0, 05 for any of the time periods or for the total length of records (not shown).

Figure 8 presents the temporal trend in SWE for stations in Central Norway. From 1931-1960 we found a significant decrease in the average on a level *p0*=0,05 with a *p*-value of 0,02. The decrease corresponds to an average decrease in the SWE of 0,007 m/year. For the periods from 1961-1990 and 1991-2008, the linear trend does not differ significantly from zero. For the entire period (not shown), no significant trend is found.

Figure 9 shows the temporal trend in SWE in North Norway. The number of stations is small, and before 1966, no data is present. The amount of annual data after 1993 is also modest. Analysis shows no significant linear trend for the different periods 1961-1990, 1991-2008 or for the entire period.

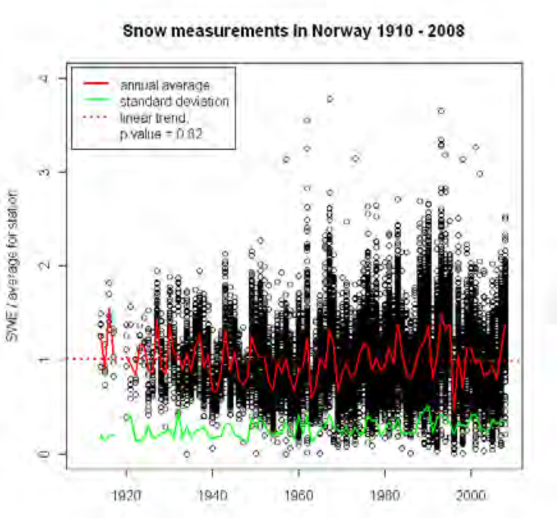

Figure 5. Temporal variations in SWE for all stations. The red line shows the annual average, while the green line shows the standard deviation. The linear trend in the average (dotted line) is not significant different from zero at level *p0* = 0,05.

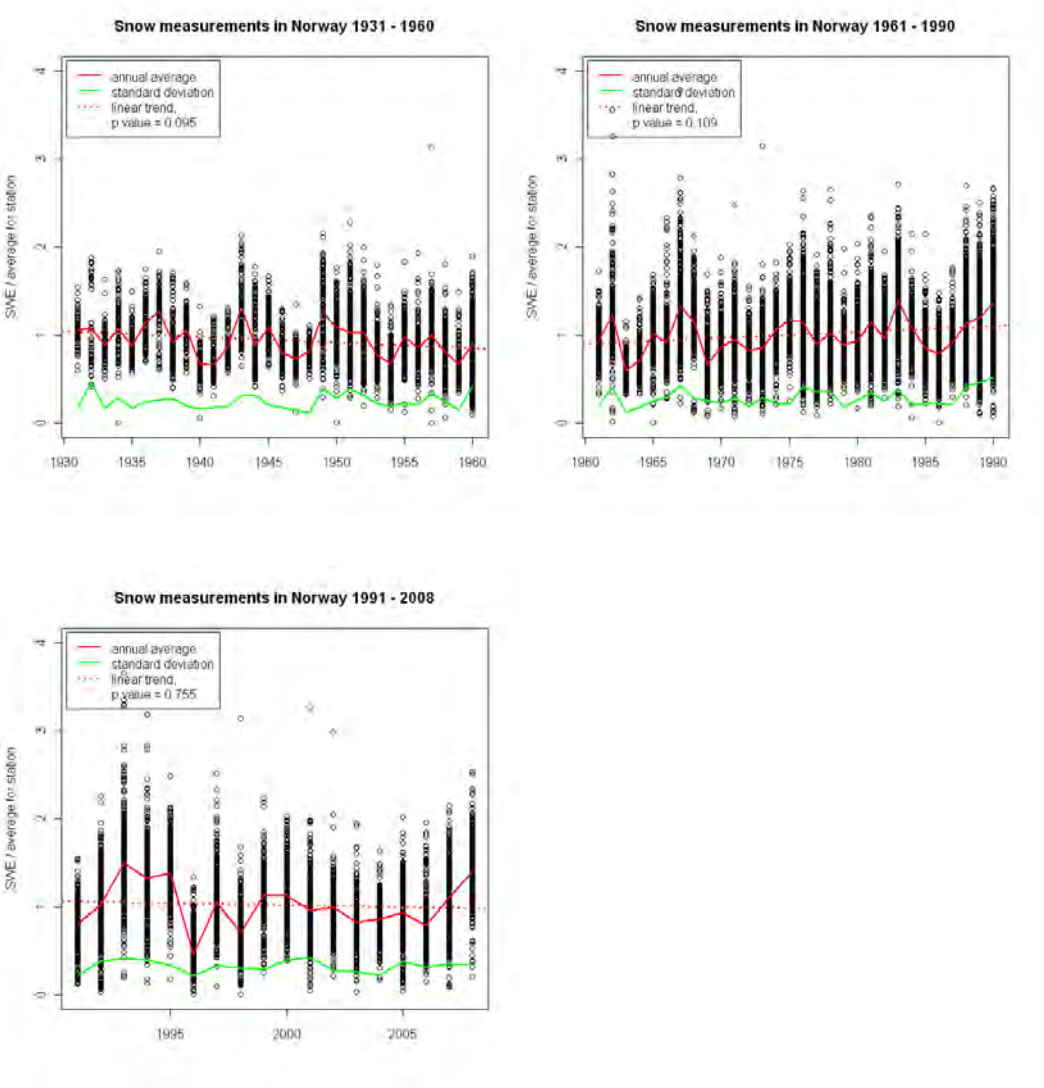

Figure 6. Temporal variations in SWE for all stations, for different periods (1931-1960, 1961-1990, 1991 - 2008). The red line shows the annual average, whereas the green line shows the standard deviation. The linear trend in the average (dotted line) is not significant different from zero at level *p0* = 0,05.

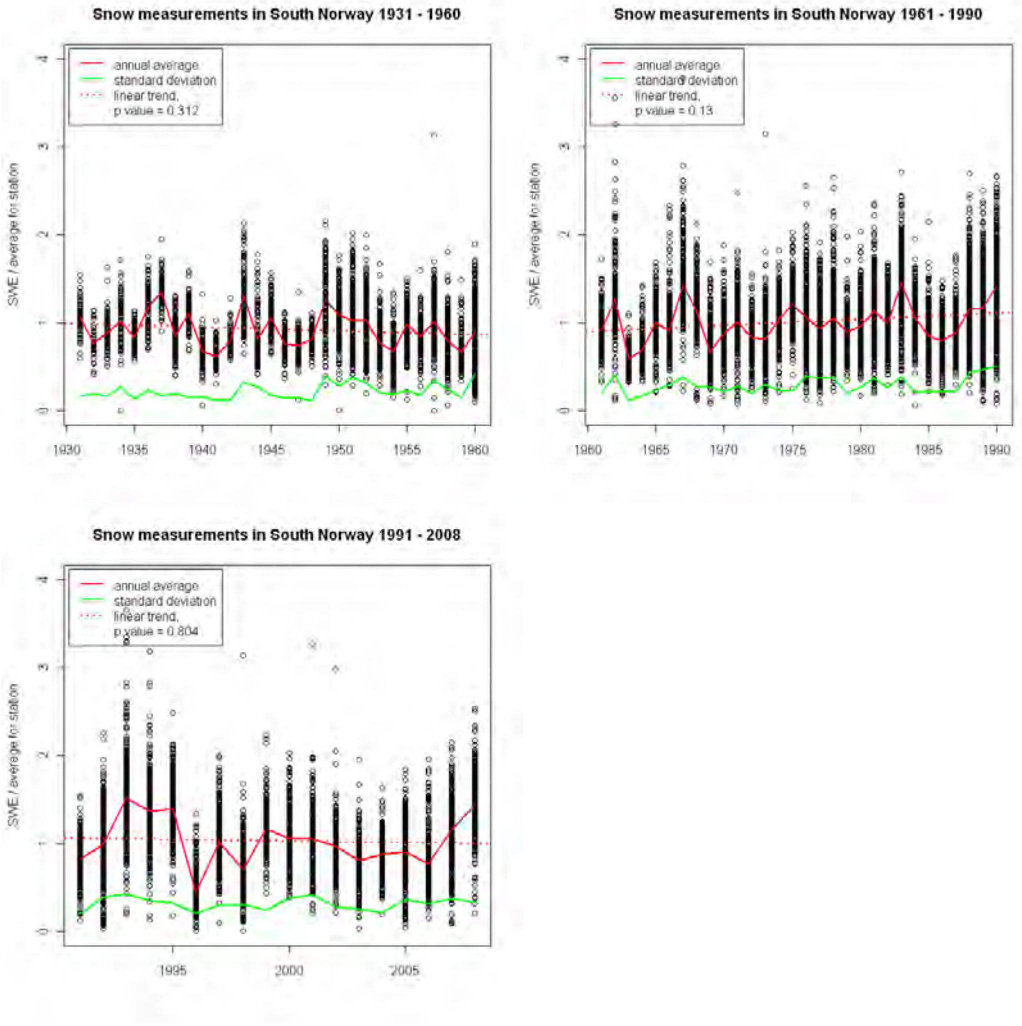

Figure 7: Temporal variations in SWE for stations in South Norway for different periods (1931-1960, 1961-1990, 1991 - 2008). The red line shows the annual average, whereas the green line shows the standard deviation. The linear trend in the average (dotted line) is not significant different from zero at level *p0* = 0,05.

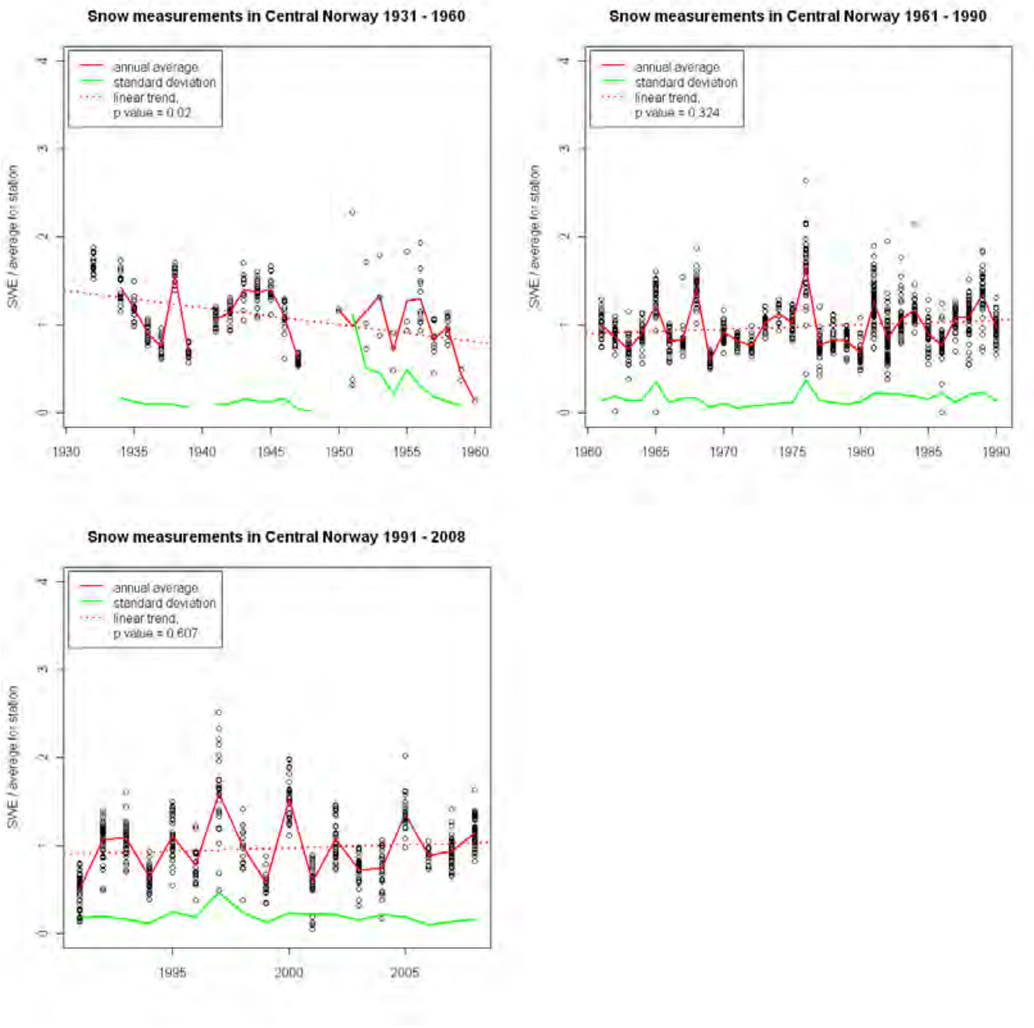

Figure 8: Temporal variations in SWE for stations in (Central Norway) for different periods (1931-1960, 1961-1990, 1991 - 2008). The red line shows the annual average, whereas the green line shows the standard deviation. The decreasing linear trend from 1931-1960 is significant at a level *p*0=0,05. The linear trend in the average in 1961-1990 and 1991-2008 is not significant different from zero.

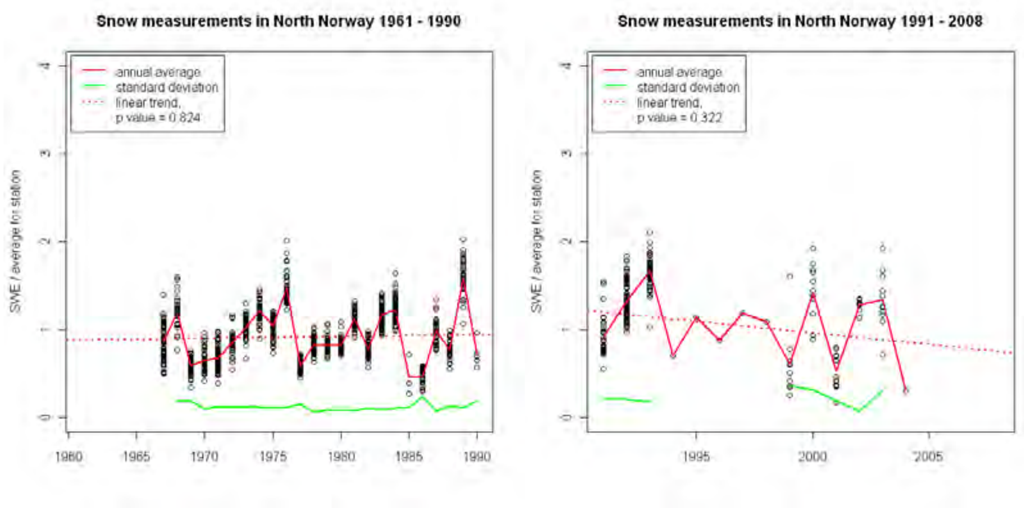

Figure 9. Temporal variations in SWE for stations in North Norway for different periods (1961-1990, 1991 - 2008). The red line shows the annual average, while the green line shows the standard deviation. Number of stations is just below 200. Before 1966 there are no measurements, and the data available after 1993 is sparse. The linear trend in the average (dotted line) is not significant different from zero at level *p0* = 0,05.

4.2 Temporal trend with altitude for different regions

In Figure 10 - Figure 12, each station in each region is represented with a triangle or a circle. The x-axis indicates the altitude whereas the y-axis indicates the location in the west-east direction. For each station, trend and p-value is estimated, and illustrated with blue and red triangles with varying sizes denoting significant positive trend and significant negative trend, respectively. The larger the triangle, the stronger is the linear trend. Black circles denotes no significant trend in SWE *(p>p0)*.

During 1961-1990 positive trends at extreme westerly stations in South -Norway (Figure 10), are more common than in 1931-1960 and 1991-2008. For both 1961-1990 and 1991-2008 most of the stations with negative trends are located at lower altitudes (below 700 m a.s.l.) ,and stations with positive trend to be located above 900 m a.s.l., specially in the central highland. The strongest absolute trend in 1931-1960 is the quite modest 0,006 m/yr, whereas the strongest absolute trend in 1961-1990 and 1991-2008 is quite high, with 0,031 and 0,036 m/yr respectively. The only station with a positive trend at lower altitudes in South Norway in 1991-2008 (see Fig.11) is considered as an outlier due to poor data quality.

In Central Norway, no stations have more than 15 years of data during 1931-1960. In 1961-1990, nearly 30 stations have more than 15 years of data and five of the stations have a significant negative trend. The strongest trend is - 0,002 m/yr. During 1991 - 2008, there is only one station with significant negative trend (-0,010 m/yr).

During 1961-1990, 41 stations in North Norway (see Fig. 12) have more than 15 years of data and the majority of the stations have positive trends. The strongest trend is 0,021 m/yr and most of the stations have positive trends larger than 0,010 m/yr. The stations with more than 15 years of data tend to cluster in the western part, and no stations with more than 15 years of data are present in the eastern part. During 1991-2008 (the figure is not shown) only one station has more than 8 years of data, but with no significant trend.

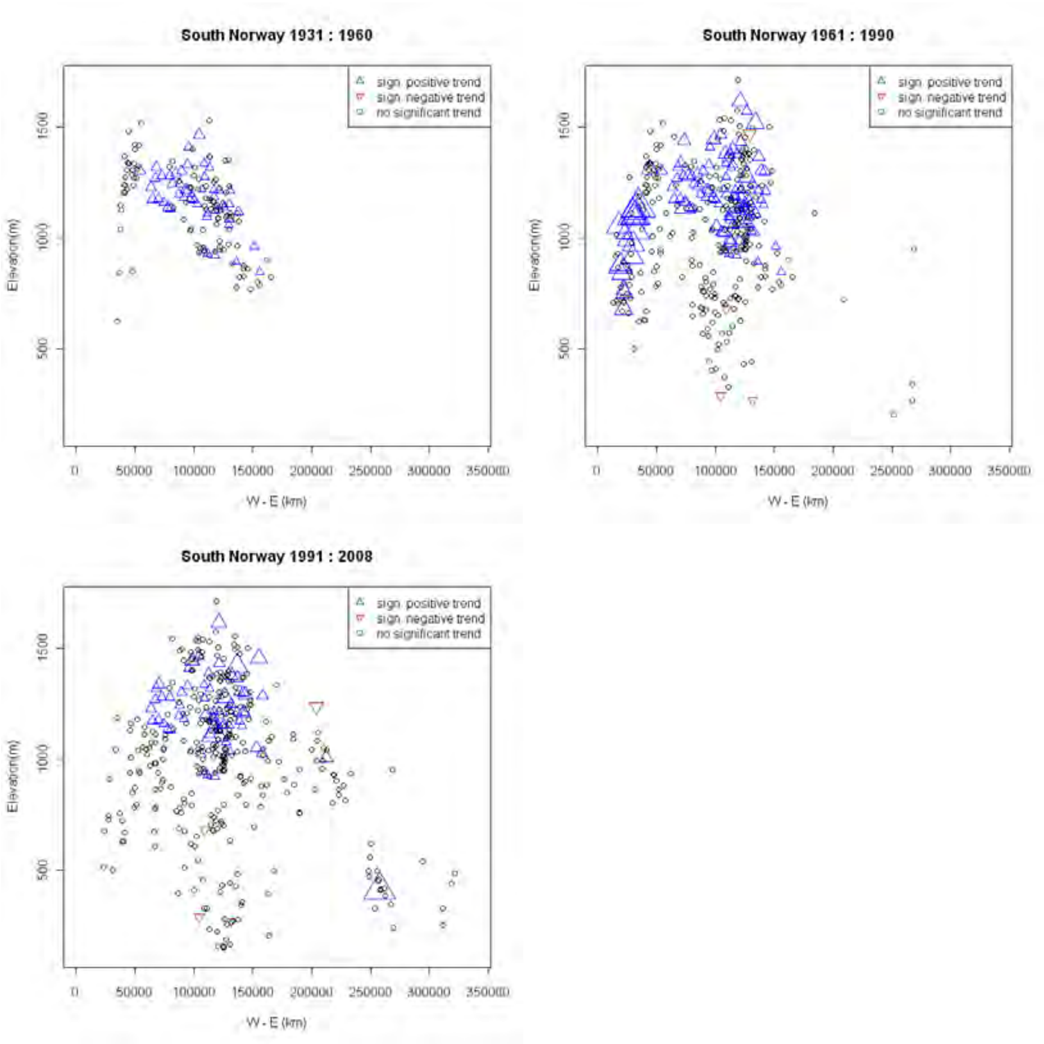

Figure 10. South Norway; each snow station is positioned according to altitude and E-W coordinates (UTM 33). The blue, "upward" triangles denote significant positive trend (at level *p0* = 0,05), while the red, "downward" triangles denote significant negative trend (at level *p0* = 0,05). Black circles are stations with no significant trend. The sizes of the triangles indicate how strong the trend is, related to the range of the trend in each plot.

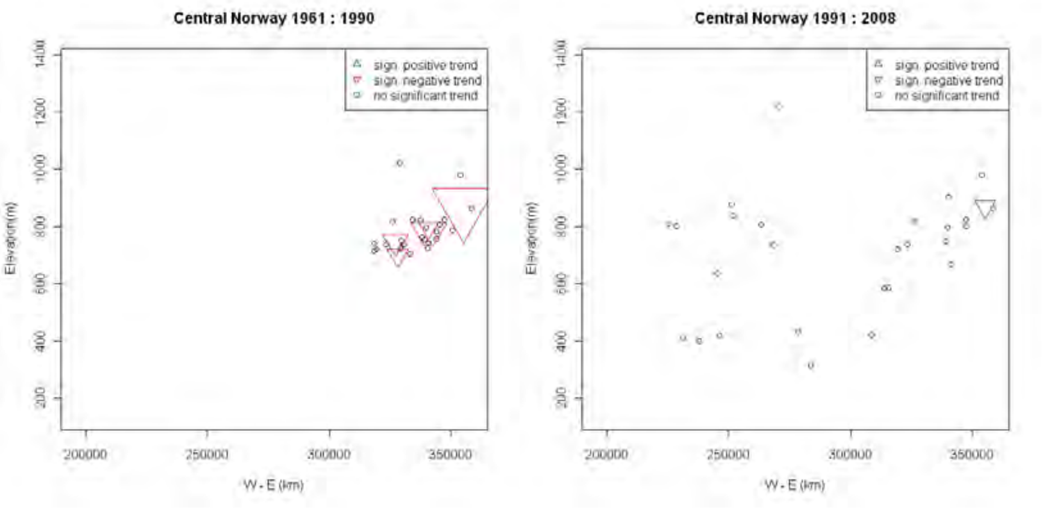

Figure 11. Central Norway; each snow station is positioned according to altitude and E-W coordinates (UTM 33). The blue, "upward" triangles denote significant positive trend (at level *p0* = 0,05), while the red, "downward" triangles denote significant negative trend (at level *p0* = 0,05). Black circles are stations with no significant trend. The sizes of the triangles indicate how strong the trend is, related to the range of the trend in each plot.

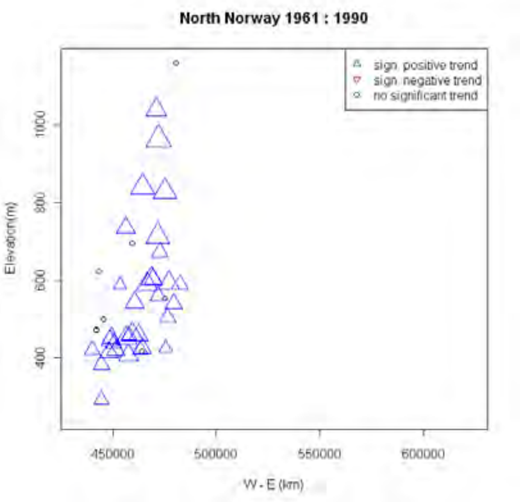

Figure 12. North Norway. Each snow station is positioned according to altitude and E-W coordinates (UTM 33). The blue, "upward" triangles denote significant positive trend (at level *p0* = 0,05), while the red, "downward" triangles denote significant negative trend (at level *p0* = 0,05). Black circles are stations with no significant trend. The sizes of the triangles indicate how strong the trend is, related to the range of the trend in each plot.

5 Discussion

Analysis of trends in SWE is made complicated due to the fact that the projected isolated increases in temperature and precipitation will decrease and increase SWE respectively. As SWE is a product of the two parameters and a product of the history of the two parameters during the snow season, it is difficult to tell, at a certain location how changes in the two parameters will affect the SWE. When temperature and precipitation increase, we might experience an increase in SWE, as the effect of an increase in temperature is more than compensated for, by the increase in precipitation. It might also be the case that the increase in temperature is not sufficient to bring about a change in phase from solid to liquid. At some point, however, the effect of an increase in precipitation is not be compensated by the increase in temperature and we will have a decrease in SWE. We can speculate that this will occur at a critical altitude specific for a certain location where the local climatic history during the snow season is such that a decrease of SWE can occur. It is thus difficult to obtain a regional view on the effect of climate change (manifested in changes in temperature and precipitation) on SWE, in that, to a certain degree, each snow point only represents the history of the local climate at its specified altitude.

In this study, we investigated linear trends. The Mann-Kendall test for investigating trends is recommended by the World Meteorological Organization (WMO) for studying climatic series (Hisdal et al., 2001) and searches for both linear and non-linear trends. The Mann- Kendal test, however, requires complete series, and as many of our series are incomplete, we resolved to do our analysis using the t-test for linear trends. The snow-conditions in the first and last years of the data period will influence the sensitivity of the linear trend, especially when the data points are few and there is a lot of noise in the dataset (for example like in the data for Central Norway, 1931-1960). This weakness by using linear trend is discussed in Mote (2008) and Hisdal et al. (2001). The t-test that we have used requires that the data is normal distributed or that the amount of data exceeds 30. Test for normality has not been performed, but we believe that the amount of data is sufficient to detect possible trends.

5.1 Temporal trend

The lack of significant trend in the mean annual SWE (see figures 5-9) may be caused by the mixing of all stations, independent of elevation, locale climatic differences and different time periods even though we use the normalized SWE (annual SWE divided by the longterm mean of each snow station). From studies in the US, we find that at lower altitudes, increasing temperature is likely to cause a decline in SWE, whereas at higher altitudes; increasing precipitation is likely to cause an increase in SWE (Howat and Tulaczyk, 2005; Mote 2003). Mote (2006) showed that the correlation between trends in SWE and temperature were clearly dependent on elevation. Mixing stations with different altitudes thus disguise the pure impact of increasing temperature and increasing precipitation.

Different number of stations is present in each period. The distribution of stations with altitude thus changes for the different time periods and may affect our results. Mote

(2008) showed that the discrepancy in the results among different periods strongly correlates with the elevation-distribution of the stations. A very small number of stations in this study have continuous annual measurements through 1914 - 2008, and many of the stations suffer from years with missing data. The number of stations, their locations and distribution with altitude are thus different for each timeperiod which may impair the comparison of trends for the different time periods.

By separating the data into different regions and different time periods, some of the uncertainty which is introduced by looking at the entire dataset, is reduced. Another source of uncertainty, however, becomes important when the amount of data is reduced. A small number of stations increases the uncertainty of the estimates of the trend, and in Central Norway and North Norway, the number of SWE stations is small. The negative trend from 1931-1960 in Central Norway (see Fig. 8) appears to be significant at a level $p0$=0,05, but the number of stations is small especially between 1950 and 1953 and in 1960. The latter year has a large influence on the trend, and by omitting the only measurement present in 1960; the trend would be classified as “not significant”. In North Norway (see Fig. 9), there is also a limited amount of data, especially between 1994 and 1998 and in 2004. There is only one data point available each year in that period, and this clearly affects the estimate of the linear trend.

Even when looking at regions, like South-, Central or North Norway, the dataset is influenced by regional climatic differences. Different meteorological processes dominate in South Norway in an east-west direction. In Figure 7, showing data from South Norway, stations in continental, inland climate are grouped together with stations located in a maritime climate. According to Andreassen et al. (2005), the maritime glaciers in Southern Norway have increased their mass during the years 1962 up to 2000, whereas the glaciers located inland have been steadily decreasing in the same period, and still do. Evidence of this behavior in SWE was expected for this area, but no trend is observed (see Fig.7). An attempt to be able to compare stations with different SWE regime was done by normalizing the SWE data by dividing the annual data point of SWE by the long-term mean of the station. Still, positive trends in temperature and precipitation may have different effects on SWE within the region. An increase in temperature in maritime climate is likely to cause more precipitation as rain during the winter, whereas on the other hand, raising temperature in a cold inland areas is likely to results in more precipitation as snow, due to the enhanced capacity of air to contain more moisture (Howat and Tulaczyk, 2005; Mote, 2006).

When comparing our results of temporal trends with the study of temporal trends in temperature and precipitation (Hanssen-Bauer, 2005) the relationship between trend in SWE and trends in temperature and precipitation appears as very weak. There are no significant trends in SWE, whereas Hanssen-Bauer (2005) found significant trends in precipitation and temperature. One reason for this discrepancy, besides that of SWE depending jointly on temperature and precipitation, as discussed above, may be the different time periods used in the two studies: Starting, like Hanssen-Bauer (2005), in 1870 and not in 1914 (as in this study) may affect the significance of the trend, even tough Hanssen-Bauer (2005) claims that the last years (since 1997) have the greatest influences on the trend. We do, however, include the years up to 2008 in pour analysis, which gives us four more years, but still no significant trends are found. In South Norway, Hanssen-Bauer (2005) found a significant increase in winter temperature (with a level of significance *p0*=0,05) from 1870 - 2004, but no significant trend for winter precipitation. From these results, we should expect a decrease in SWE, but no such trend was found. In Central Norway, Hanssen-Bauer (2005) found no significant trend in neither winter temperature nor winter precipitation, which in general corresponds to the findings in this study, in particular when 1960 is omitted. In North-Norway, no significant trend in winter temperature was found, whereas there was a significant trend of increasing precipitation during winter (Hanssen-Bauer, 2005). Analysis of SWE shows, however, no significant trend and thus no indication of increasing SWE as a result of increased precipitation.

Another reason for the diverging results between this study and the study of Hanssen-Bauer (2005), could be the seasonal classification done in Hanssen-Bauer (2005). In Hanssen-Bauer (2005), “winter” is defined as December, January and February, whereas for most of the snow stations in this study (especially stations at higher altitudes) winter last from November until April. Most of the annual SWE measurements are measured at expected snow maximum in the middle of March or April, and when just look at the “winter months” as defined by Hanssen-Bauer (2005), vital snow accumulation months like November, March and partly April are excluded.

Several studies have pointed out the correlation between the North Atlantic Oscillation (NAO)-index[1] and winter temperature and winter precipitation. Hanssen-Bauer (2005) found that the winter-temperature was strongly correlated with the NAO-index, especially in the western part of South-Norway. The correlation between winter temperature and NAO-index was also significant for other regions. The NAO-index did explain 40-75% of the variance in precipitation in the western part of South Norway, while in North- and Central Norway, less than 20 % of the variation in the winter precipitation could be explained by the NAO-index, even though the correlation has been increasing since 1960. Mysterud et al. (2000) found that snow depth was negatively correlated with the NAO-index at low altitudes (below 400 m a.s.l.), and positively correlated at higher altitudes. Analysis of correlation between SWE and the NAO-index shows that only about 14 % of the variance of SWE is explained by the NAO index in South -Norway from 1961-1990 and 1991-2008. For the other regions or periods, the relationship was weaker. The mixing of all stations, regardless of altitude and climatic differences as described above, can, especially when considering the results of Mysterud et al. (2000), explain the weak correlation.

5.2 Trend in time with altitude

Consistent with the climatic studies of SWE from the US (Howat and Tulaczyk, 2005; Mote 2003, 2006), we did expect to find trends ranging from negative at lower altitudes and to positive at higher altitudes. Even though the number of stations is limited and the stations are unevenly distributed with elevation, a pattern in South-Norway (see Figure 10) was found. Stations with negative trends tend to be located below 700 m a.s.l.,

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[1] The NAO index is defined as the difference in normalized pressure between the Azores High and the Icelandic Low during winter months (Hurrel, 1995). A positive index results in a wetter and milder Scandinavia due to enhanced westerlies in the North Atlantic.

whereas stations with positive trends tend to be located above 900m a.s.l., especially in the central highland.

Many of the stations with positive trend in South-Norway are located in the western part of the mountains (see the plot in Figure 10 showing data from 1961-1990). From 1931-1960 to 1961-1990 and further on to 1991-2008, there is a change in how the most westerly stations behave. During 1931-1960 no, or very modest positive trends are present, whereas in 1961-1990, we see relatively strong positive trends in the westerly area. In 1991-2008 most of the trends have disappeared and the plot appears similar to that of 1931-1960. In Figure 13, the winter balance (water gained due to snow) and summer balance (water lost due to melt) of the glacier Nigardsbreen located in South West Norway, with an average elevation of 1600m a.s.l., is presented. Mass balance is measured by NVE at a regular basis for this and 13 other glaciers in Norway. We clearly see that there is a positive trend in the winter balance for the years 1962-1990 and a slight negative trend for the years 1991-2008. For the summer balance there is a slight negative trend in the years 1962-1990 and a clear negative trend for the years 1991-2008. The glacier data corresponds very well to the behaviour of SWE for the two periods. The steadily decreasing summer balance is due to a generally increased temperature whereas the increase in winter balance in the period of 1962-1990 is due to increased winter precipitation, especially in the two latter years of the period. The winter balance stays quite high in the years 1991-2008, but a steeper decrease of the summer balance indicates a steadily increase in temperature and suggests that the effect of increased precipitation can no longer compensate for of increased temperature and the positive trend in SWE is discontinued. The glacier data illustrates well the complicated nature of SWE, where the complex interactions of climatic variability of precipitation and temperature and elevation have to be taken into account.

All the stations with significant negative trend in Central-Norway (Figure 11) are located in an eastern area, which has a relatively dry, continental climate. These findings are also consistent with the snow depth-analysis done by Dyrrdal (2008) and with the steadily decreasing mass balance of glaciers in this area (Andreassen et al. 2005).

It can be noted that the number of stations with significant positive trends decrease by nearly 50 % from the period 1961-1990 (30 % of the stations have a positive significant trend) to the next period, 1991-2008, (16 % of the stations have a positive significant trend) in South-Norway. The same pattern is seen in Central Norway, whereas the number of stations in the time period 1991-2008 is too few in Northern Norway to draw any conclusions. This tendency is consistent with the findings above that the effect of a steadily increasing temperature compensates for the effect of increased precipitation during the last period.

The two analysis of trend in annual SWE performed in this report (temporal trend and temporal trend with altitude) is not directly comparable due to 1) the normalization procedure performed prior to the analysis of temporal trend and 2) the selection of stations that have more than 15 or 8 years of data prior to the analysis of temporal trend with altitude.

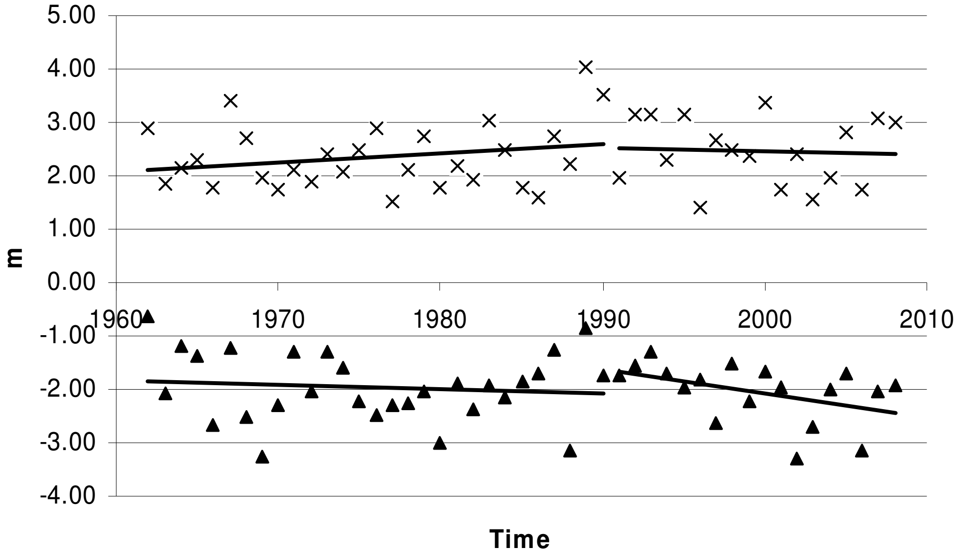

Figure 13. Winter and summer balance of the Nigardsbreen. The negative values are the summer balance (water lost due to melt) and the positive values are the winter balance (water gained trough snow). Trend lines for 1962-1990 and 1991- 2008 are shown.

6 Conclusions

There are no indications of significant trends in the mean annual SWE in Norway when data is pooled nationwide or for regions. Also, no significant trends are found when investigating the regionally pooled data for different time periods. The absence of trends, despite the documented evidence of trends in precipitation, temperature and glacier data (Hanssen-Bauer, 2005, Andreassen et al. 2005), may be explained by the applied method of pooling all stations, independent of elevation, locale climatic differences and different record length. An additional explanation to the discrepancy in results can be the different time periods used by the different studied analysis, different accumulation season or related to the uncertainties in the snow analysis.

Analysis of correlation between SWE and the NAO-index shows a weak positive correlation in South -Norway from 1961-1990 and 1991-2008. For the other regions or periods, the correlation was minimal. The pooling of stations, regardless of e.g. altitude and climatic differences as described earlier, could explain the weak relationships.

When investigating temporal trends as a function of altitude for single stations, significant trends, both positive and negative, occur. The stations with significant positive trend seem to be located in snow rich areas. The temporal trends in SWE in South Norway are stronger in 1961-1990 for westerly, maritime stations than for the periods 1931-1960 and 1991-2008. These findings are consistent with glacier mass balance data from this area. The demonstrated behavior of SWE can be explained by a steadily increasing temperature which effect cannot, after 1990, be compensated by increased winter precipitation.

A topic for further study is to compare the results from this analysis to the results from the snow depth analysis carried out by met.no (Dyrrdal and Vikhamar-Schuler, 2009 b)). The snow depth stations of met.no are, to a large degree, located in lower lying areas, in which the trend is likely to behave different from trends in mountainous areas (Howat and Tulaczyk, 2005; Mote, 2003; 2006). Snow depth and SWE are, however, not directly comparable, and differences in trends can be due to trends in snow density. Mild winters, as a consequence of a warmer climate, may increase the snow density so that we may experience increase in SWE and decrease in snow depth.

7 References

Andreassen, L. M., H. Elvehøy, B.Kjøllmoen, R.V. Engeset and N. Haakensen, 2005. Glacier mass-balance and length variation in Norway. *Ann. Glaciol.*, 42, 317-325.

Barnett, T.P., D. W. Pierce, H. G. Hidalgo, C. Bonfils, B. D. Santer, T. Das, G. Bala, A. W. Wood, T. T. Nozawa, A. A. Mirin, D. R. Cayan, M. D. Dettinger, 2008: Human-Induced changes in the hydrology of the western United States, *Science* 319, 1080 (2008)

Beldring, S., T. Engen-Skaugen, E.J. Førland and L.A. Roald, 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.

Burakowski, E.A, C. P. Wake, B. Braswell and D. P. Brown, 2008: Trends in wintertime climate in the northeastern United States: 1965 - 2005, *Journ. of Geophysical Research*, vol. 113, D20114.

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. *Journ. of Applied Meteorology and Climateology*: In Press.

Dyrrdal, A. V., 2008. A statistical analysis of snow depth variability in Norway and evaluation of Norwegian Snow Maps. Msc. Thesis, North Carolina State University, US.

Dyrrdal, A. V. and D. Vikhamar-Schuler, 2009 a). Kortere og kortere snøsesong (shorter and shorter snow season, in Norwegian). *Klima*, 3-2009.

Dyrrdal, A and Vikhamar-Schuler, D., 2009 b). Analysis of long-term snow series at selected stations in Norway. *met.no Climate report 05/2009.*

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.

Hisdal, H., K.Stahl, L. M. Tallaksen and S. Demuth, 2001: Have streamflow droughts in Europe become more frequent?. *Int. J. Climatol.* 21:317-333.

Howat, I.M and S. Tulaczyk, 2005: Trends in spring snowpack over a half-century og climate warming in California, USA, *Annals of Glaciology* 40, pg 151-156, 2005

Hurrel, 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 Hydrology*, 34 (1/2), 2003, pg 71-90

Kalra, A, T. C. Piechota, R. Davies and G. A. Tootle, 2008: Changes in U.S. Streamflow and Western U.S. Snowpack., *Journal of hydrologic engineering*, 2008, pg 156 – 163

Lemke, P., J. Ren, R.B. Alley, I. Allison, J. Carrasco, G. Flato, Y. Fujii, G. Kaser, P. Mote, R.H. Thomas and T. Zhang, 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* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Marty C., 2008. Regime shift in snow days in Switzerland, *Geophys. Res. Lett.,* 35 L12501, doi: 10.1029/2008GL033998

Moore D.S. and G. McCabe, 2002: *Introduction to the practice of Statistics,* 4th edition.

Mote, P.W., 2003: Trends in snow water equivalent in the Pacific Northwest and their climatic causes, *Geophys. Res. Lett.,* 30 (12), 1601, doi: 10.1029/2003GL017258

Mote, P.W., 2006: Climate-Driven Variability and Trends in Mountain Snowpack in Western North America*, *Journal of Climate* vol. 19, pg 6209 - 6220

Mote, P.W., A. Hamlet and E. Salathe, 2008:, Has spring snowpack declined in the Washington Cascades?, *Hydrol. Earth Syst. Sci.*12, pg 193 - 206, 2008

Mysterud, A., N. G. Yoccoz, N. C. Stenseth and R. Langvatn, 2000; Relationships between sex ratio, climate and density in red deer: the importance of spatial scale, *Journal of Animal Ecology*, 69, 959-974.

SeNorge (2009) "Climate. Normal annual maximum of snow amount in mm for normal period 1961-1990". Norwegian Water Resources and Energy Directorate and the Norwegian Meteorological Institute. Available at: http://senorge.no/mapPage.aspx Accessed: 12.08.2009

Vikhamar-Schuler, D. S. Beldring, E.J. Førland, L.A. Roald and T. Engen-Skaugen, 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. and E. J. Førland, 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.

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