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Climate

Past changes in frequency, intensity, and spatial occurrence of meteorological triggering variables relevant for natural hazards in Norway

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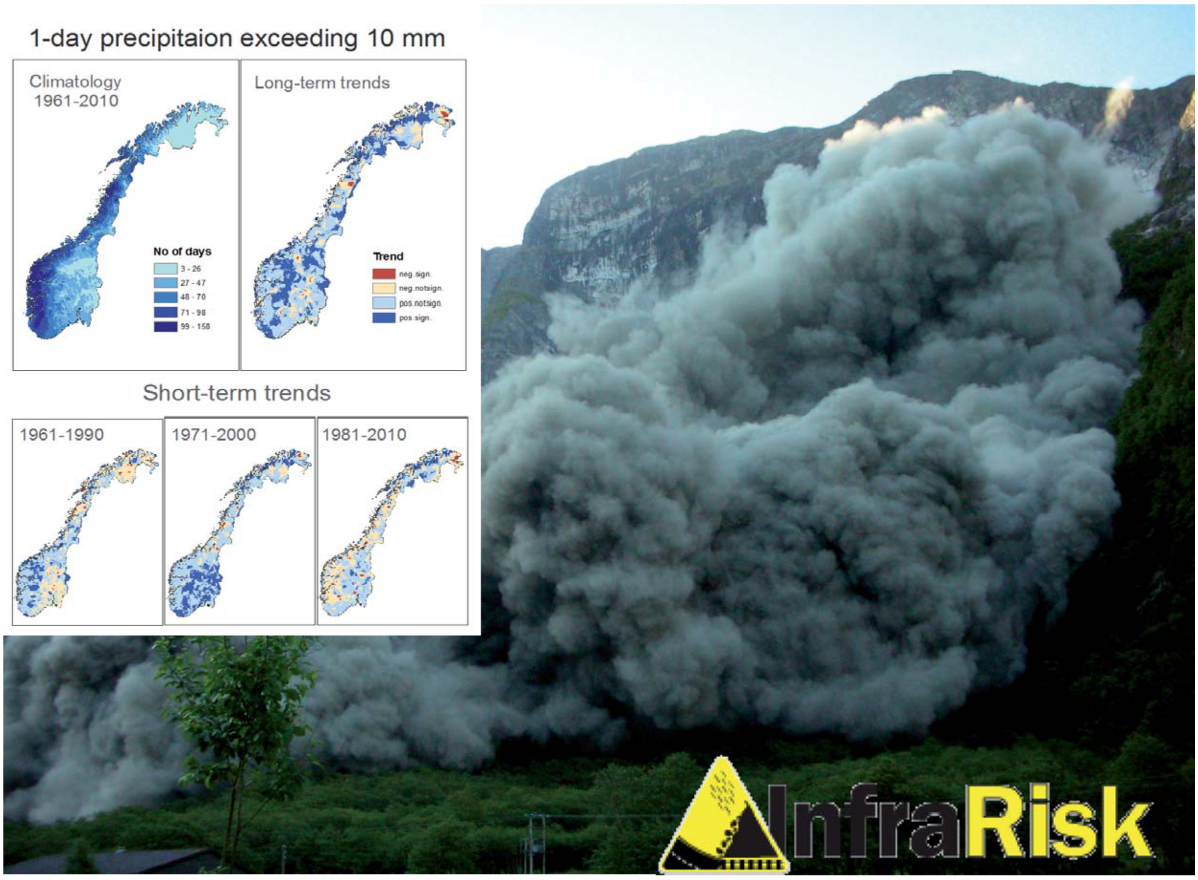

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Abstract

A set of climate variables with the potential to trigger natural hazards in Norway have been defined and analyzed according to past changes in frequency, intensity and spatial distribution. The focus has been on weather events that might be directly or indirectly harmful to transportation routes and related infrastructure. Trends in annual maximum daily precipitation sums for the entire period 1961-2010 are generally positive, except in some regions in the southeast and in central Norway. Trends are stronger and show a more distinct pattern for longer duration precipitation. The frequency of moderate to strong precipitation events has increased in most parts of the country since 1961, and changes are more robust than for annual maximum precipitation. Snow depth has increased in cold areas, most likely due to increased winter precipitation, and decreased in warm areas due to increased winter temperatures. Patterns are similar for snowfall, but with weaker trends. Snowfall combined with wind give few results due to the limited occurrence in our data. The number of freeze-thaw events show mainly positive trends in the entire country except near the coast in southern Norway.

Keywords

Extreme weather, natural hazards, trend analysis, past climate, climate grids

Disciplinary signature	Responsible signature
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Contents

1 Introduction

Natural hazards in Norway, the most important being avalanches, landslides, and floods (*Gregersen & Sandersen*, 1989; *Furseth*, 2006), are often triggered by extreme weather events (EWEs). *Sandersen* et al. (1996) found that particularly major storms with heavy rain- and snowfall frequently initiate landslides and avelanches. It is also concluded that debris flows are more closely related to weather factors than rockfalls and rockslides, and are often triggered in periods with heavy water supply to the soil. In the Geoextreme project (*Jaedicke* et al., 2008) it was shown that snow avelanches have the highest correlation with meteorological elements such as wind and precipitation while rockfalls have the lowest correlation. According to **?**, winter precipitation in Norway has increased by 5-25% between the two 30-year periods 1961-90 and 1979-2008. *Alfnes & Førland* (2006) found an increasing tendency in annual maximum 1-day precipitation during the 20th century at two thirds of the analyzed stations. However, few trends were found to be statistically significant and there was no systematic correlation between trends and location. An analysis of trends in extreme precipitation for the period 1961-2004 was performed by *Achberger & Chen* (2006). They found no spatially coherent pattern for Norway and Sweden, yet the overall aggregated trend was positive. Climate models indicate increased precipitation over Northern Europe in the future, and EWEs are expected to become more frequent and intense (*Lemke* et al., 2007). These changes are likely to threaten important infrastructure that are designed along the guidelines based on known historical precedence.

Due to the possibility of more frequent EWEs, the robustness of infrastructure and built environment may be exposed to more powerful strain than intentionally constructed for, and may have to be upgraded accordingly. This study is carried out under the project InfraRisk, Module A, which aims to improve the understanding of past and future variability of EWEs in Norway and its connection to natural hazards affecting Norwegian transport infrastructure. The focus is on major roads, railways and related buildings. InfraRisk is an interdisiplinary research project funded by the Research Council of Norway (NFR) and coordinated by Norwegian Geotechnical institute (NGI). The first step in the project is to assess which types of EWEs are most relevant in the triggering of natural hazards, to analyze changes in frequency and intensity of these events, as well as their spatial distribution. Future work will be to assess whether climate change projections indicate future changes in EWEs.

In the present study we refer to EWEs as events with the potential to cause severe damage to transportation routes and related infrastructure. This might differ to some extent from the more common definitions of EWEs, but corresponds somewhat to the level of so called OBS-warnings from Norwegian Meteorological institute (http://metlex.met.no/wiki/OBS-varsler, in Norwegian). The purpose of these warnings is to make the public aware of coming weather that can affect them, but not serious enough to send out a severe weather warning.

2 Data and Methods

2.1 Gridded climate data

Estimates of daily temperature and precipitation obtained from observations are interpolated to a 1x1 km^2 grid covering the Norwegian mainland (*Tveito* et al., 2005; *Mohr*, 2009; *Jansson* et al., 2007). Daily grids are available for the period 1957 until today and are presented at www.seNorge.no. Temperature is estimated from a a residual interpolation technique using terrain and geographic position to describe the deterministic component (*Tveito* et al., 2002), while precipitation is spatially distributed applying irregular triangular networks (TINs). A precipitation TIN is established based on measured precipitation corrected for systematic gauge undercatch according to the model suggested in *Førland* et al. (1996). Different correction factors are applied for snow and rain, and since most precipitation stations do not have temperature measurements, temperature is interpolated to these stations by the method desribed above in order to determine the state of the precipitation. An elevation TIN based on the altitude at the meteorological stations is also established. A terrain adjustment is performed on the precipitation grid, according to the assumption that precipitation increases by 10% per 100 m up to 1000 masl and 5% above that (*Førland*, 1979, 1984). Precipitation and temperature grids are input in a precipitation/degree-day snow model similar to the snow routine in the HBV model (*Bergström*, 1992) and is described in *Engeset* et al. (2004). Temperature dependent thresholds are used to seperate snow from rain (T = 0.5 °C) and to determine snow melt and refreezing (T = 0.0 °C). Snow depth is estimated from the amount of existing snow and fresh snow reduced by melting and compaction (*Alfnes*, 2008). The gridded climate data described in the current section are denoted as "climate grids" thoughout this study.

2.2 Wind

The number of long-term wind series in the met.no station network that are relevant in our analysis is limited to the following four stations: 13160 Kvitfjell (1993-2010, 1030 masl), 25830 Finsevatn (1994-2010, 1210 masl), 46510 Midtlæger (1968-1990;1995-2010, 1079 masl), and 55290 Sognefjellhytta (1979-1988;1994-2010, 1413 masl). Hourly wind speed data for the time periods specified in parenthesis are analyzed here. Some years back, a homogeneiety test was performed on all wind measurements in the met.no station network, and no irregularities were found at the stations included in this study (unpublished report). However, the study period here is much extended compared to the test period.

An alternative to observations is to use modeled wind or reanalysis data. In this case we chose to apply 850 hPa wind from the Hindcast archive (*Reistad* et al., 2011). Hindcast consist of regional downscaling of ERA40 reanalysis (*Uppala*, 2005) obtained with the high resolution limited area model HIRLAM (*Undén*, 2002). Data are available on 3 and 6 hour intervals from 1957 to present and have a spatial resolution of approximately 11 km. Since Hindcast was mainly developed for offshore wind statistics, a systematic validation of surface wind over the mainland does not exist. However, the 850 hPa wind is likely to be reasonable as it is not significantly affected by surface friction.

2.3 Trend analysis

A simple trend analysis is performed using the rank-based nonparametric Mann-Kendall trend test. Mann-Kendall tests the null hypothesis that the data are independent and identically distributed, and it is known to be well suitable for the study of hydro-meteorological time series as these are usually non-normally distributed (*Yue & Pilon*, 2004). Trends are computed for different time periods and evaluated for statistical significance at the 95% confidence level. Long-term trends are computed for the 50-year period; 1961-2010 (entire period), and short-term trends are computed for three 30-year periods; 1961-1990 (period1), 1971-2000 (period2), and 1981-2010 (period3). It is important to keep in mind that the results of the trend analysis is highly sensitivity to the analyzed time period and its length. A 30-year period is relatively short for a trend analysis, however, in this context it is convenient in studying the variability of trends throughout the entire period. Some meteorological events occur only a few times per year, hence it does not make sense to perform a trend analysis. For these variables we simply investigate the changes between period1 and period3.

3 Climate variables

Climate variables are defined and presented in Table 1 below. Snow variables and freeze-thaw events are computed for the winter season (November - May), while other variables are computed for the calendar year.

Intense and/or prolonged precipitation are typical events known to potentially trigger natural hazards, thus such events are of main focus in this study. We have analysed both annual maximum values and frequency of events exceeding a set threshold (peak over threshold) for precipitation sums over one to several days.

The most frequent trigger of avalanches is fresh snow, often in combination with wind (*McClung & Schaerer*, 2006). Due to the complex character of wind, snowfall and snowfall combined with wind are analyzed separately. In this study fixed thresholds for snowfall and wind speed are specified by the snow avalanche department at the Norwegian Geotechnical institute (NGI). Like most wind simulations Hindcast tends to underestimate extreme events, and additionally surface friction will in many cases reduce the wind speed. As a result of this and the coarse time resolution (wind between prognoses is not known), it was decided to decrease the threshold from 10 m/s initially suggested by NGI to 5 m/s, which is in agreement with knowledge on initiation of snow drift (*Lied & Kristensen*, 2003). Prognoses with 6 hour intervals (four prognoses per day) are applied in the analysis, and at least one of the prognoses within the last day of snowfall and the following day must exceed the specified threshold for the particular event to be counted. Due to the limited occurence of snowfall combined with wind in our data, quantitative changes in mean values between period1 and period3 have been investigated rather than trends. As wind simulations are of coarse resolution and of variable quality over land, we supplement the study with wind observations in mountain areas from the met.no station network. Annual maximum hourly wind speed at four mountain stations is investigated, as well as the number of events of wind speed exceeding 10 m/s, 17.2 m/s (gale), and 20.8 m/s (strong gale). It is worth mentioning that due to the limited number of wind series only point specific conclusions can be made. Also note that the measurements are from different time periods.

For the purpose of evaluating changes in the frequency of days with snowfall, particularly of interest to authorities for snow removal, a lower snowfall threshold (5 mm) is also investigated

Another potential trigger of snow avalanches are freeze-thaw events, as these may cause instability in the snow pack. *Lied & Kristensen* (2003) state that rising temperatures lead on a first stage to decreased stability, but as time passes the snow metamorphosis will again stabilize the snow pack. In addition, very low temperatures might maintain an unstable situation. Since the climate grids have a temporal resolution of one day, we need to assume a range for daily mean temperature in which it is likely that temperature crosses 0 °C. Fig. 1 shows an example from Oslo-Blindern meteorological station, indicating that -1.5 °C - 1 °C is an adequate range.

Table 1: Climate variables

Climate variable	Duration	Threshold(s)
Annual maximum precipitation sum	1 day 5 days 10 days	
Precipitation - peak over threshold	1 day 5 days 10 days	10 mm 40 mm 60 mm
Annual maximum snow depth	1 day	
Annual maximum snowfall	1 day	
Snowfall - peak over threshold	1 day 3 days 5 days	5 and 30 mm 50 mm 80 mm
Heavy snowfall combined with wind	1 day 3 days 5 days	20 mm and 5 m/s 35 mm and 5 m/s 50 mm and 5 m/s
Annual maximum measured wind speed	1 hour	
Measured wind speed - peak over threshold	1 hour	10, 17.2, and 20.8 m/s
Number of freeze-thaw events	1 day	$-1.5\,°C$ - $1\,°C$

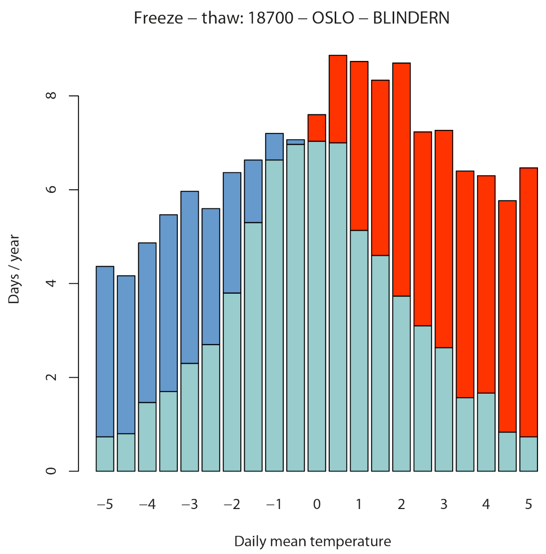

Figure 1: Number of observed freeze-thaw events at Blindern, plotted against daily mean temperatures from the climate grids. Light blue indicates freeze-thaw events, dark blue and red indicates number of non freeze-thaw events

4 Results and Discussion

4.1 Precipitation

4.1.1 Annual maximum precipitation

Most of the precipitation in Norway is carried by moist air from the Atlantic ocean, during all seasons, and the geographical distribution of precipitation is greatly influenced by the mountain range oriented across the prevailing winds from the west in the southern part of the country. This results in heavy long duration precipitation upwind of the mountain range (west), due to orographic effects, while the eastern parts are predominantly in the rain shadow of the mountain range, receiving less precipitation. Central parts of Norway also receive great amounts of precipitation from incoming low-pressure systems, while the far northern parts are somewhat sheltered from these. Figs. 2, 3 and 4 show annual maximum 1, 5, and 10-day precipitation, respectively, presented as an average for the period 1961-2010, along with long-term and short-term trends. Trends in annual maximum 1-day precipitation do not reveal a systematic pattern. Long-term trends in central Norway are mainly negative, while the rest of the country shows positive trends overall. For the short-term trends we see a different pattern in the last period compared to the first two periods, with trends being more negative most places, particularly in central Norway. For longer precipitation periods, short-term trends are positive along the west-coast in the first period, and in the southeast in the second period. Patterns become more distinct as we go from 1-day precipitation to 10-day precipitation, showing positive long-term trends in all of southern Norway, and only small areas with negative trends in the far north. Trends in the mountain areas in the south are significantly positive. Short-term trends are positive in the southwestern and northern parts in period1. In period2 there are nearly no significant trends, only weak positive trends in the south and north, and weak negative trends in central parts. Trends in period3 are positive in the southeast and mostly weakly negative elsewhere. An ambiguous signal in shorter precipitation periods is to be expected as single precipitation events will have a greater impact on the results.

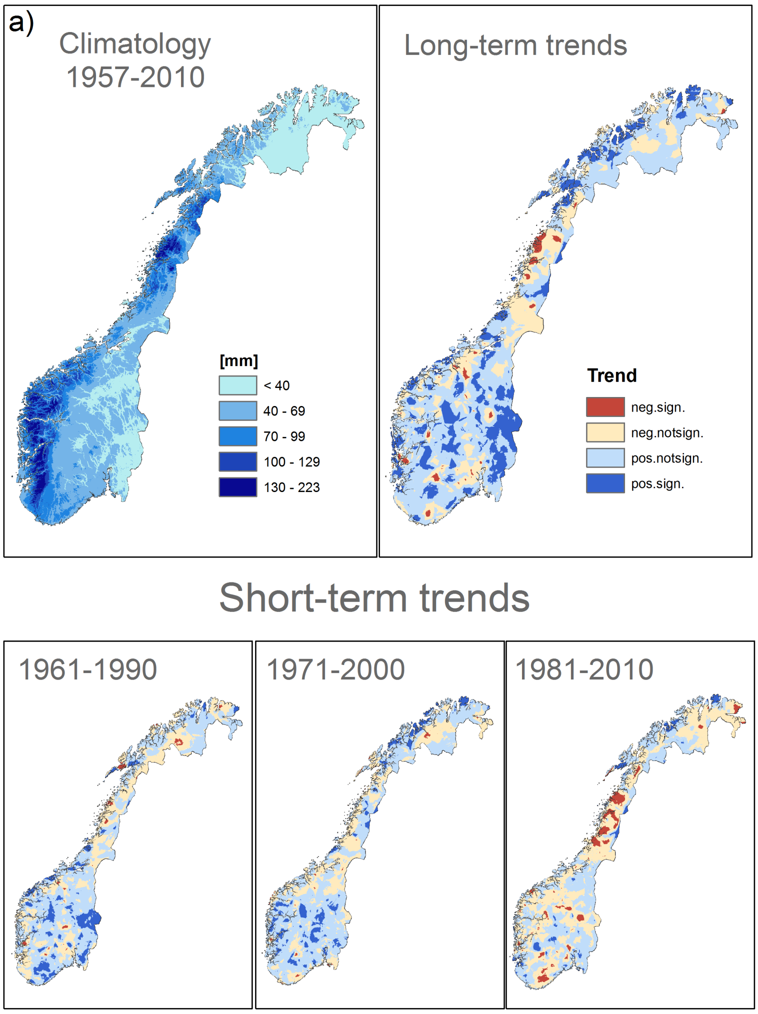

Figure 2: Annual maximum 1-day precipitation

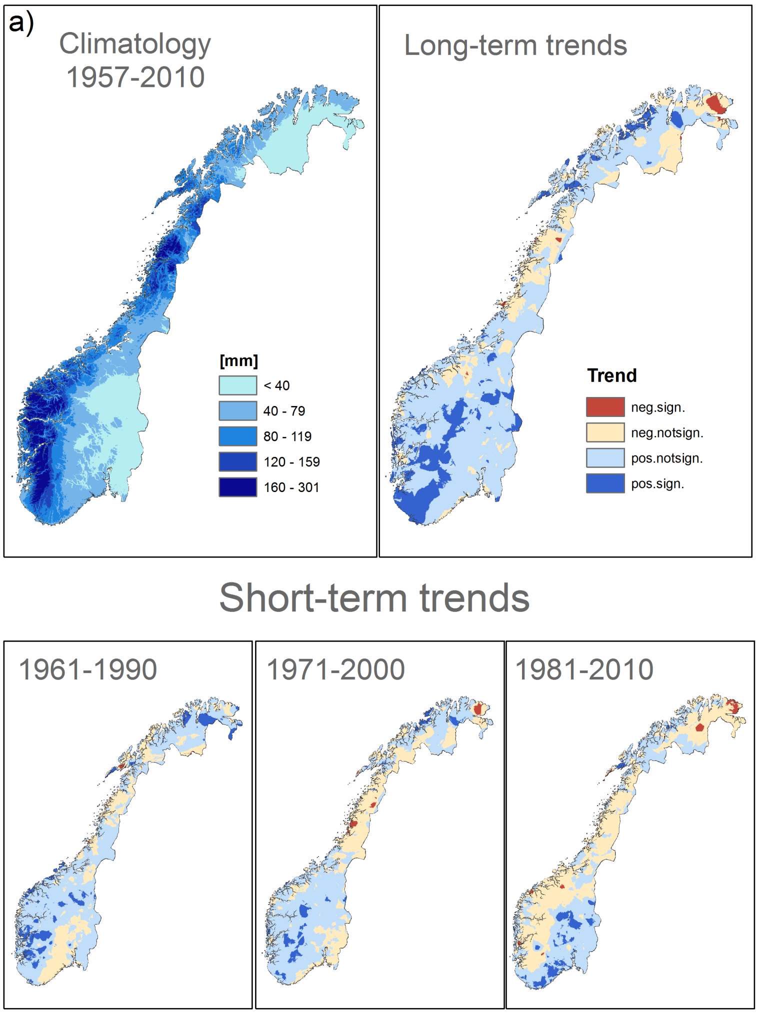

Figure 3: Annual maximum 5-day precipitation

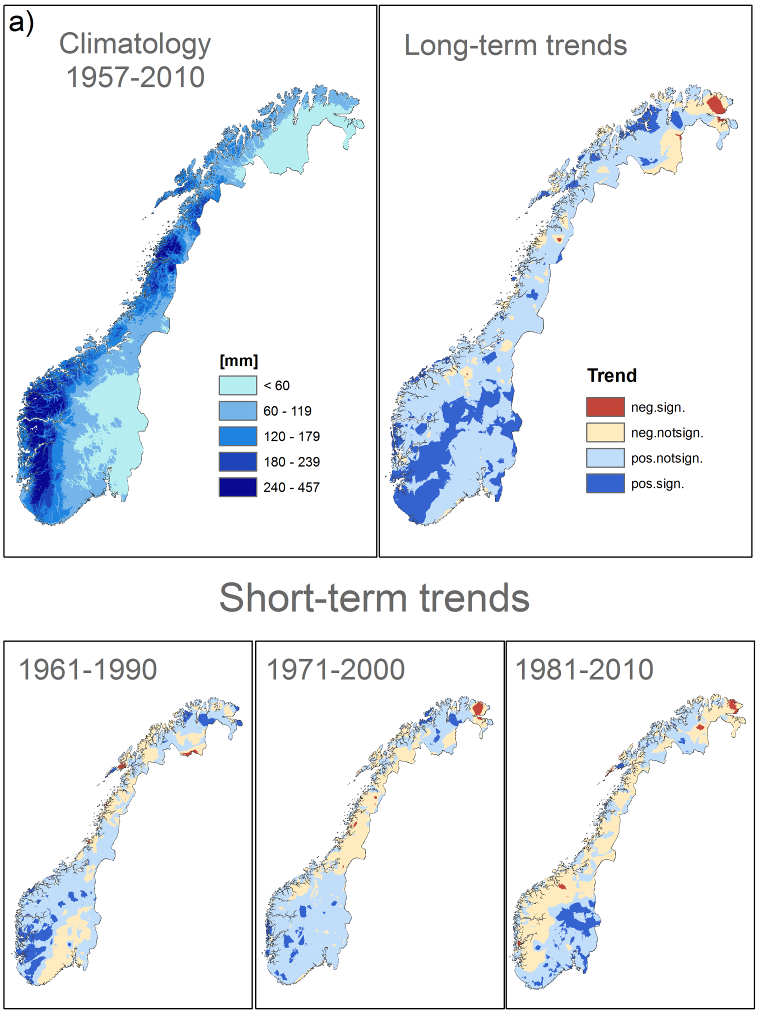

Figure 4: Annual maximum 10-day precipitation

4.1.2 Precipitation - peak over threshold

Figs. 5, 6 and 7 present peak over threshold for 1-day, 5-day, and 10-day precipitation, given thresholds of 10 mm, 40 mm, and 60mm, respectively. These thresholds are chosen for the evaluation of frequency in medium to large rainfall events, as these might trigger natural hazards in the same manner as extreme precipitation events depending on the water content of the ground previous to the events. Results for the different precipitation sums are similar, showing mainly positive long-term trends for the entire country, with increased areas of significant trends for the shorter precipitation periods. Short-term trends for the first period are divided in positive in the western parts of South-Norway and both weakly negative and positive in other regions. In the second period there are many significant positive trends in the eastern parts of South-Norway and along the western coast of North-Norway, while trends are weak in other regions. In the last period trends are very weak in general but generally negative along the western coast and positive elsewhere for 1-day precipitation, while for 5 and 10-day precipitation trends are negative in the most southern regions. It seems that trends in peak over threshold events are stronger than trends in maximum values, indicating a more significant change in moderate to intense precipitation rather than the real extreme precipitation events.

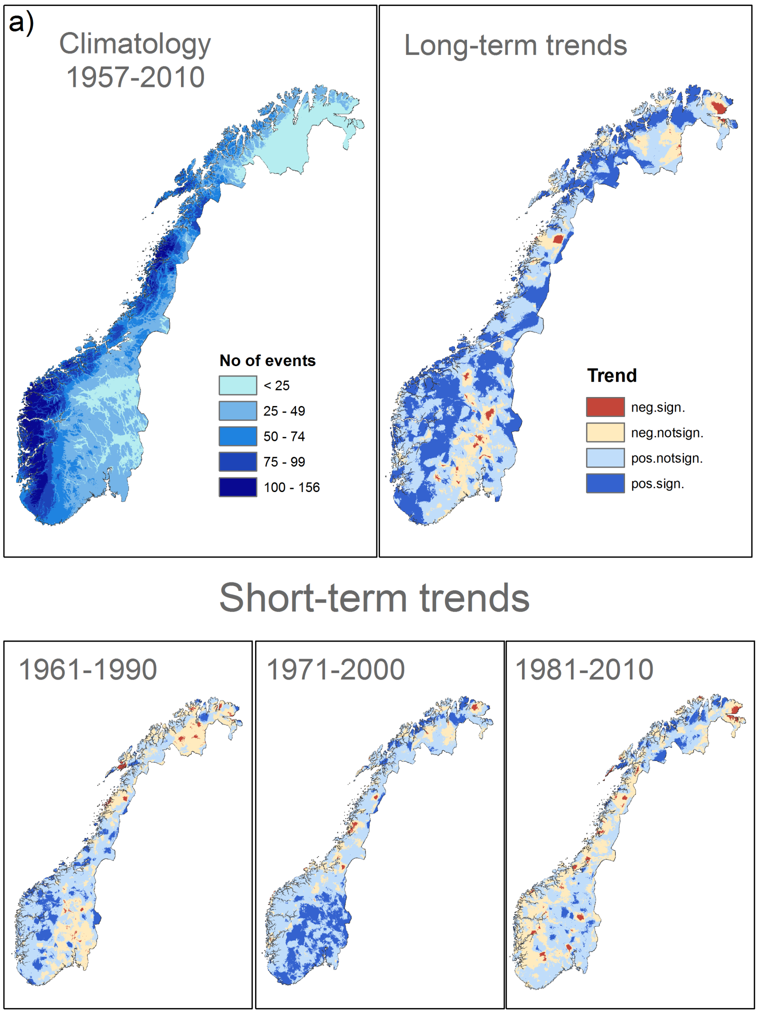

Figure 5: Peak over threshold (10 mm) of 1-day precipitation

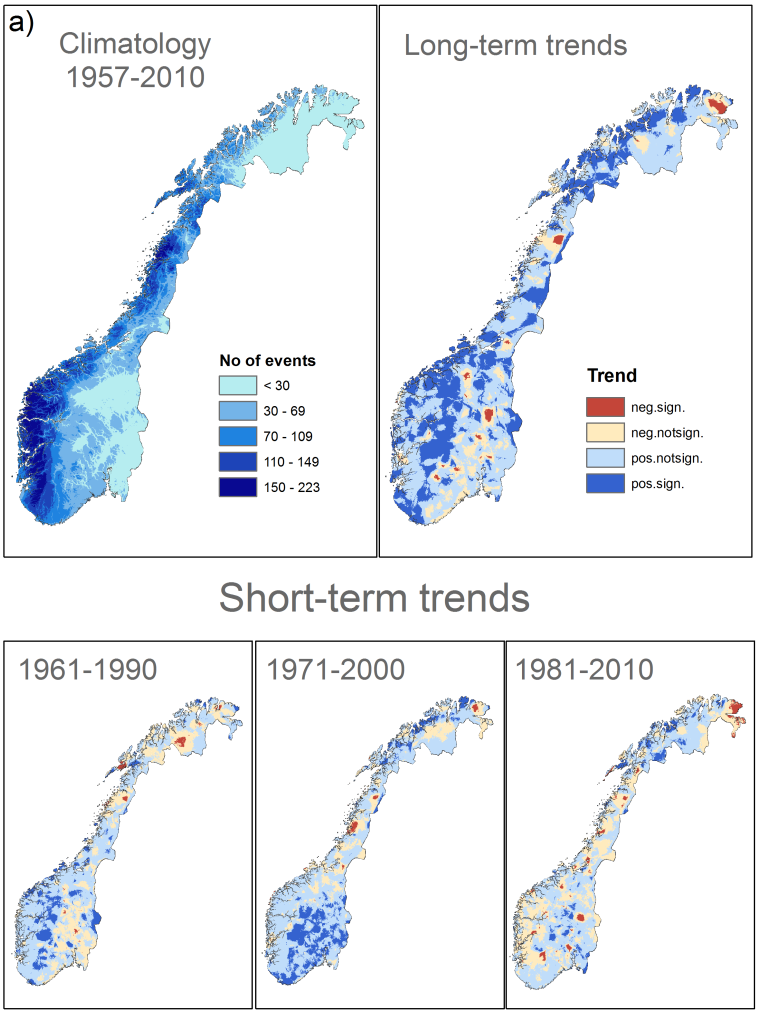

Figure 6: Peak over threshold (40 mm) of 5-day precipitation

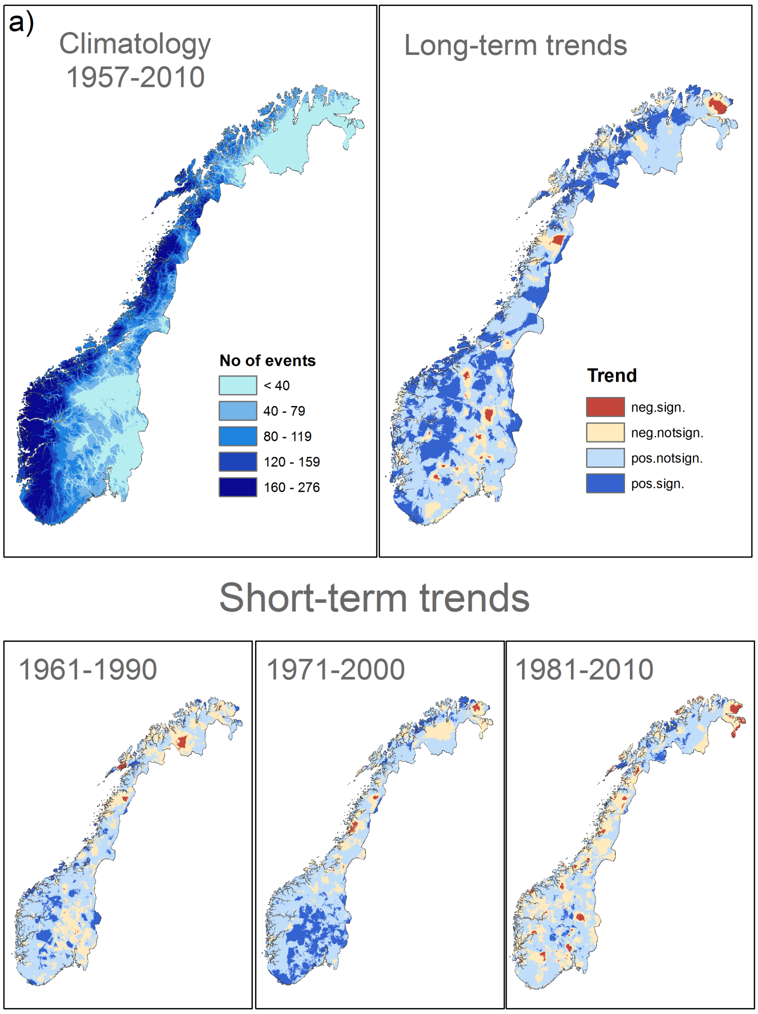

Figure 7: Peak over threshold (60 mm) of 10-day precipitation

4.2 Snow

4.2.1 Annual maximum snow depth

Due to the latitudinal length of the country and the different coastal, mountain and inland climates, there is great spatial variability in snow depth in Norway. Annual maximum snow depth (Fig. 8) is often used as a proxy for snow accumulation throughout the winter season, and typically occurs in late spring. Largest snow depths are found in the mountains and in central Norway, while the coastal areas and Finnmarksvidda have less snow. Long-term trends are generally positive in regions characterized by colder winter climate (mountain and inland), and negative in regions of warmer winter climate (coast). Short-term trends go from mostly positive in the first two periods to mostly negative in the last period. This is in line with recent warming, as more an more precipitation falls as rain and melting increases. However, there are still a few areas with sufficiently cold winters where we see positive trends in the last period most likely due to the increase in winter precipitation the last decades. Our results are consistent with previous studies by e.t.*Dyrrdal* (2010) and *Roald* et al. (2002).

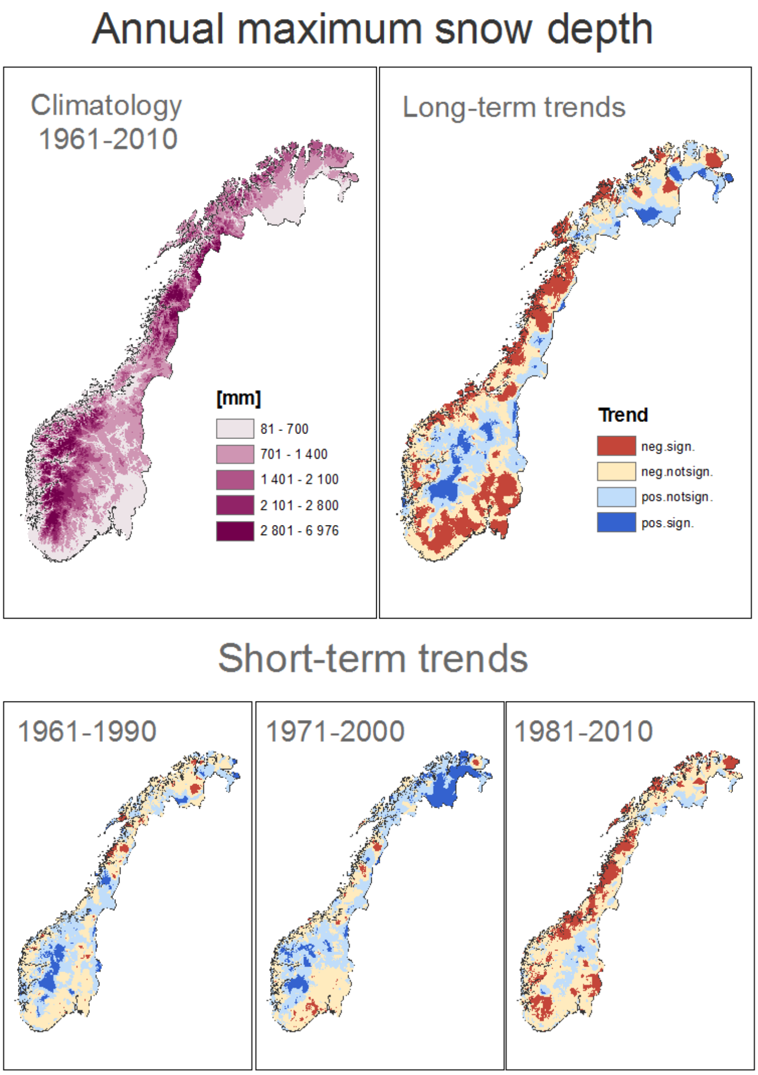

Figure 8: Annual maximum snow depth

4.2.2 Annual maximum snowfall

Snowfall depends strongly on both temperature and precipitation, and in Norway both before mentioned variables show an increase during winter. Thus it is a non-trivial task to analyze changes in snowfall related variables. Annual maximum snowfall (Fig. 9) varies much according to winter precipitation, thus the highest values are found on the west side of the mountains in the south and in central Norway. Finnmarksvidda and south-eastern part of South Norway show the lowest values. Long-term trends are relatively ambiguous, but we see a tendency to positive trends in mountain areas, and negative trends in central Norway. Short-term trends go from positive in cold areas in the first period (1961-1990) to mostly negative in most areas in the last period (1981-2010), particularly on the western side og the mountains in the south and along the coast in central Norway, in other words, in the areas with large mean annual snowfall.

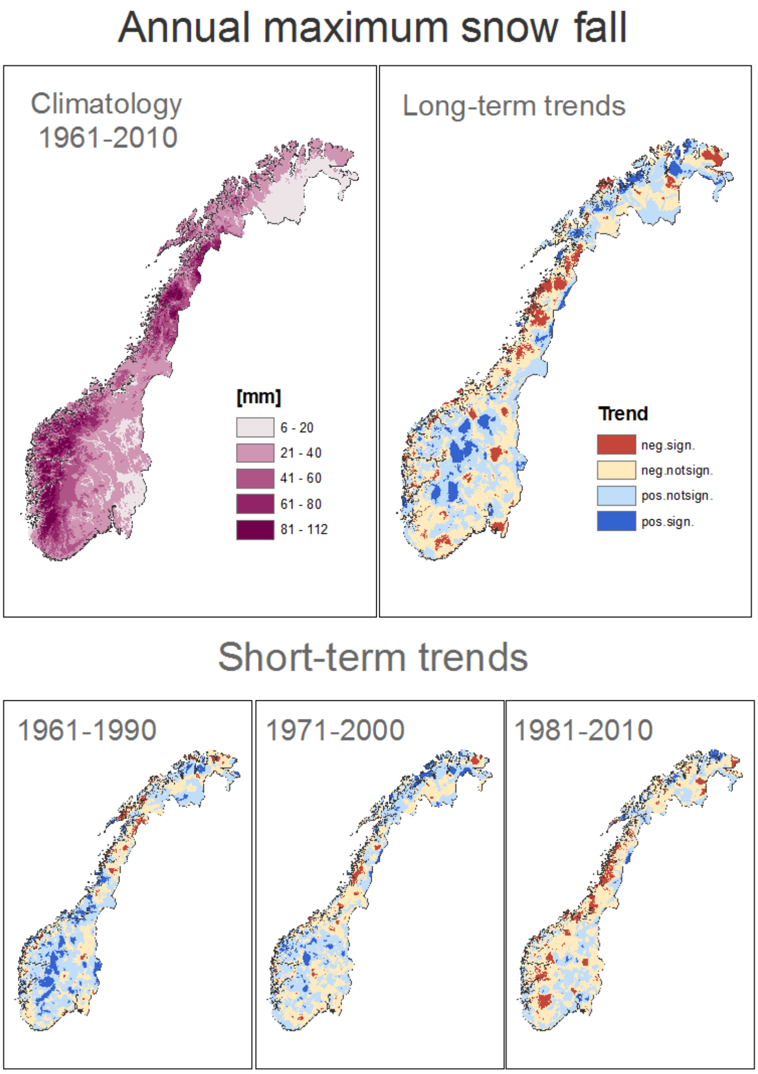

Figure 9: Annual maximum snowfall

4.2.3 Snowfall (combined with wind) - peak over threshold

Most event exceeding the specified thresholds for snowfall occur in western parts of South-Norway and in central Norway, i.e. in areas with more precipitation (Figs. 10, 11, 12). Changes in mean number of events between the first and the last period show decreases along the coast (warmer regions) and increases in mountains, inland and northern areas (colder regions). Snowfall followed by wind is shown in the same figures. Even with lowering the threshold for wind, there are very few such events occurring in our dataset each year, and almost exclusively along the coast. Changes between period1 and period3 are mainly negative but small. 1-day snowfall exceeding 5mm, specified to consider changes in days with snowfall, is shown in Fig. 13. We see the same pattern as annual maximum snow depth and snowfall, still, trends are weaker than for annual maximum snow depth and stronger than annual maximum snowfall. This means that we have an increase of so-called snow days in cold areas and a decrease in warm areas, which matches expected signature of global warming. Increased winter temperature causes more precipitation to fall as rain instead of snow in warm areas, while in cold areas temperatures stay cold enough thoughout winter for precipitation to fall as snow despite the recent warming, at the same time as winter precipitation has increased. Results from the analysis of snowfall is in accordance with *Serquet* et al. (2011) who analyzed the proportion of snowfall days relative to precipitation days for up to 100 years in Switzerland. They found clear negative trends in snowfall days, which was explained by increasing temperatures. Trends were stronger at lower elevations where temperatures stay closer to the melting point.

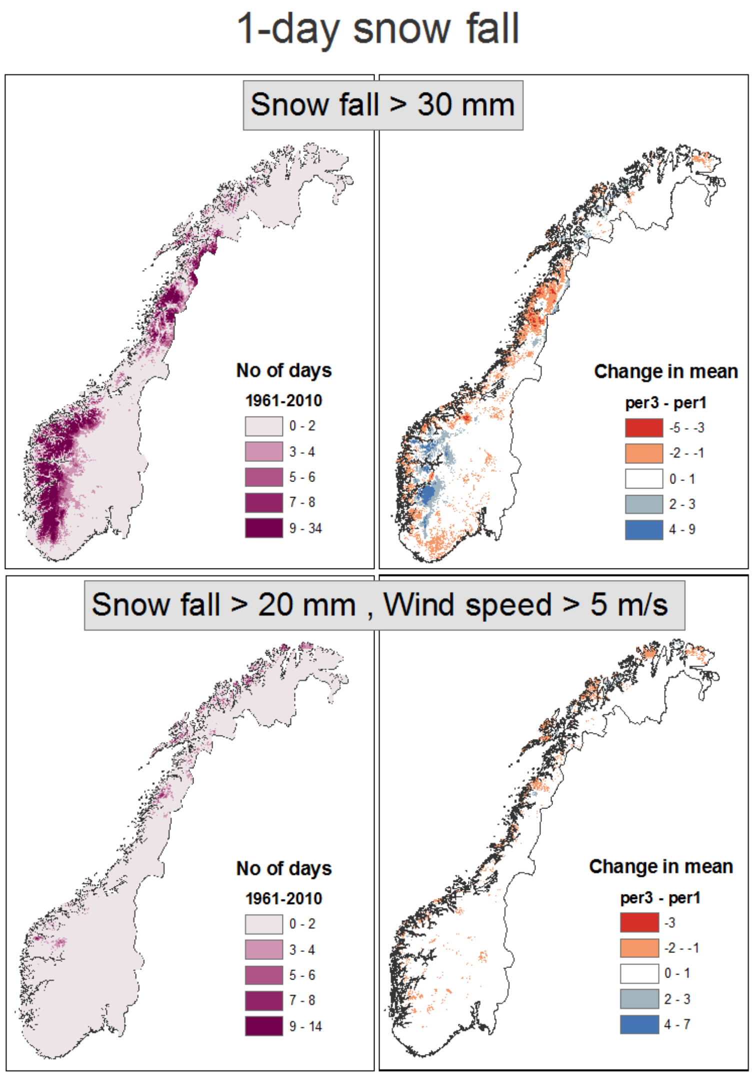

Figure 10: Peak over threshold of 1-day snowfall (combined with wind)

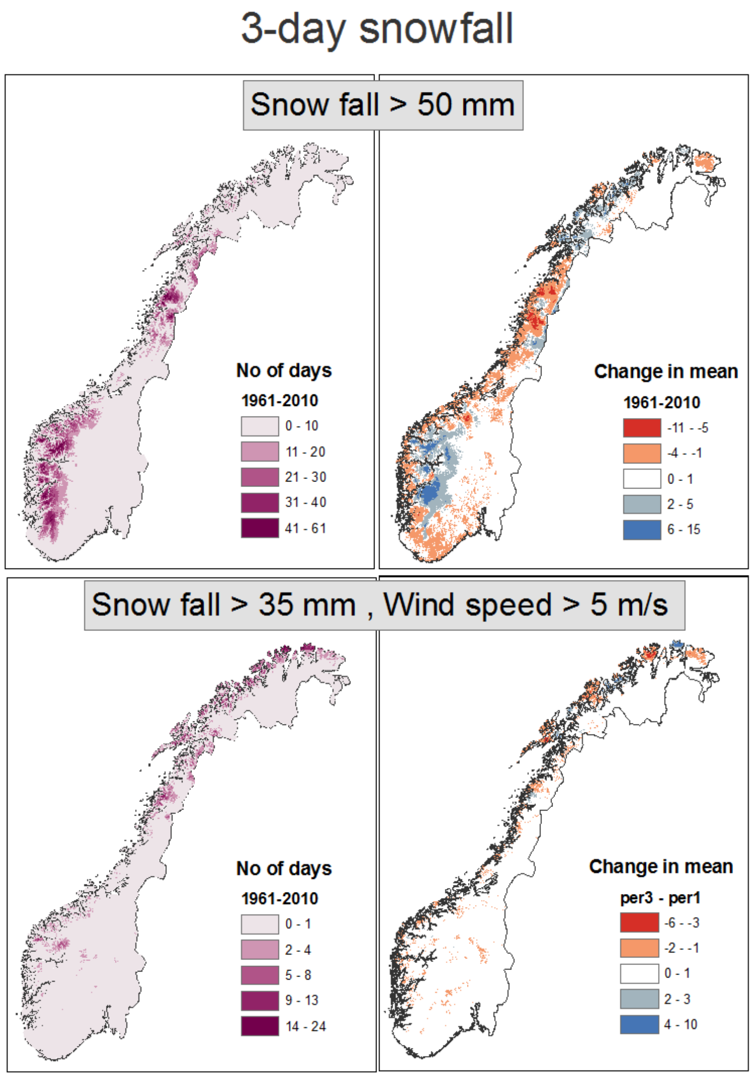

Figure 11: Peak over threshold of 3-day snowfall (combined with wind)

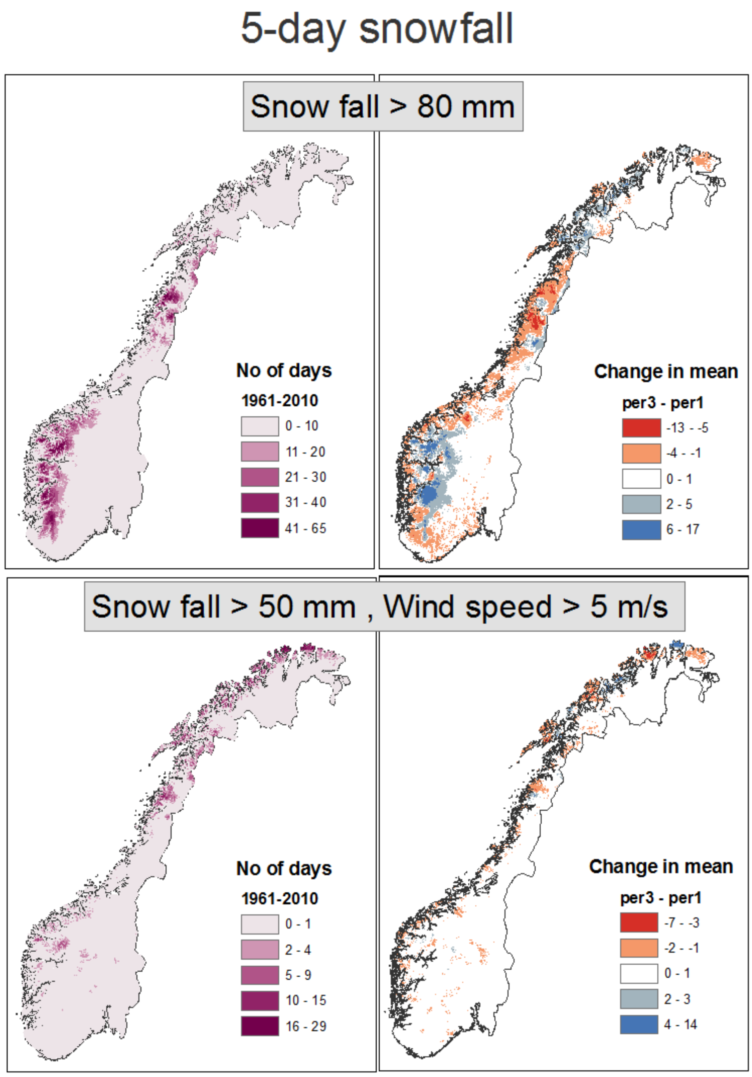

Figure 12: Peak over threshold of 5-day snowfall (combined with wind)

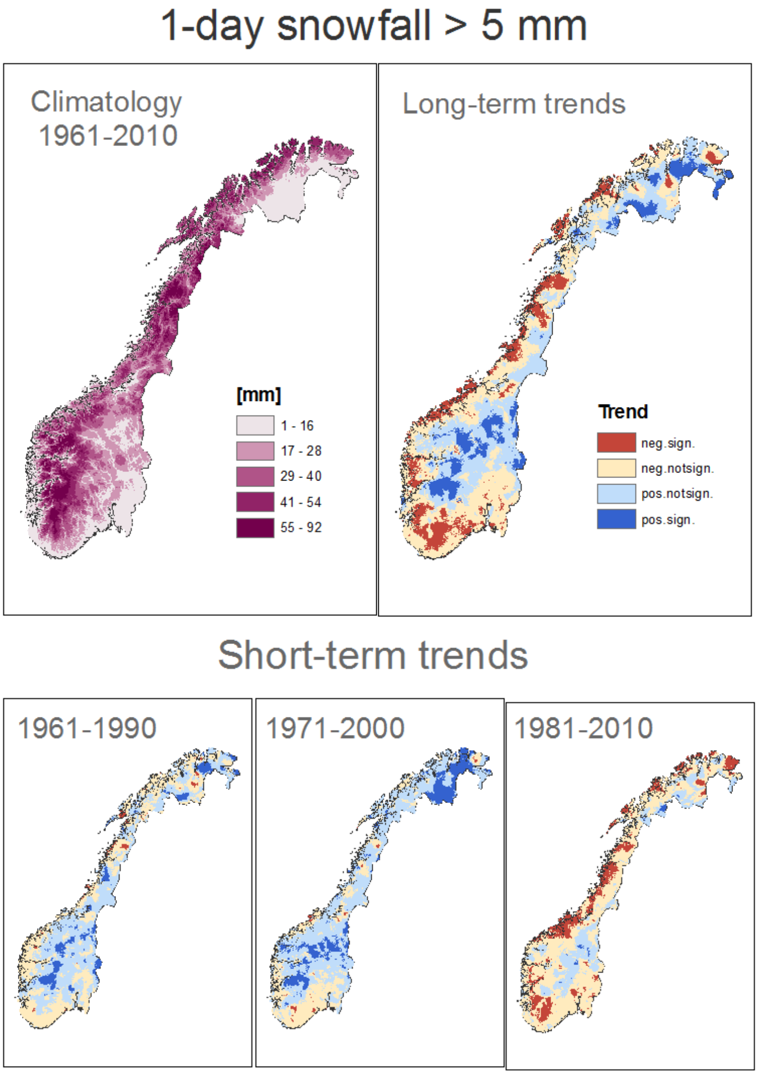

Figure 13: Number of 1-day snowfall events exceeding 5mm

4.3 Measured wind speed

At the southernmost station, 46510 Midtlæger, all analyzed variables show significant positive trends for the joint periods 1968-1990 and 1995-2010 (Fig. 14). Station 25830 Finsevatn show negative trends for all variables during the period 1994-2010, but only annual maximum wind speed and wind speed exceeding 10 m/s are statistically significant. Trends in wind speed exceeding 17.2 m/s is significantly positive at station 55290 Sognefjellhytta for the joint periods 1979-1988 and 1994-2010. At 13160 Kvitfjell all trends are non-significantly negative during the period 1993-2010. With such few and somewhat diverging results we are not able to conclude on general trends or the geographical distribution. In the latest assessment report of the Intergovernmental Panel on Climate Change (IPCC) (*Lemke* et al., 2007) it is stated that confidence in future changes in windiness is relatively low, however, according to the same report, it seems more likely than not that there will be an increase in average and extreme wind speeds in Northern Europe.

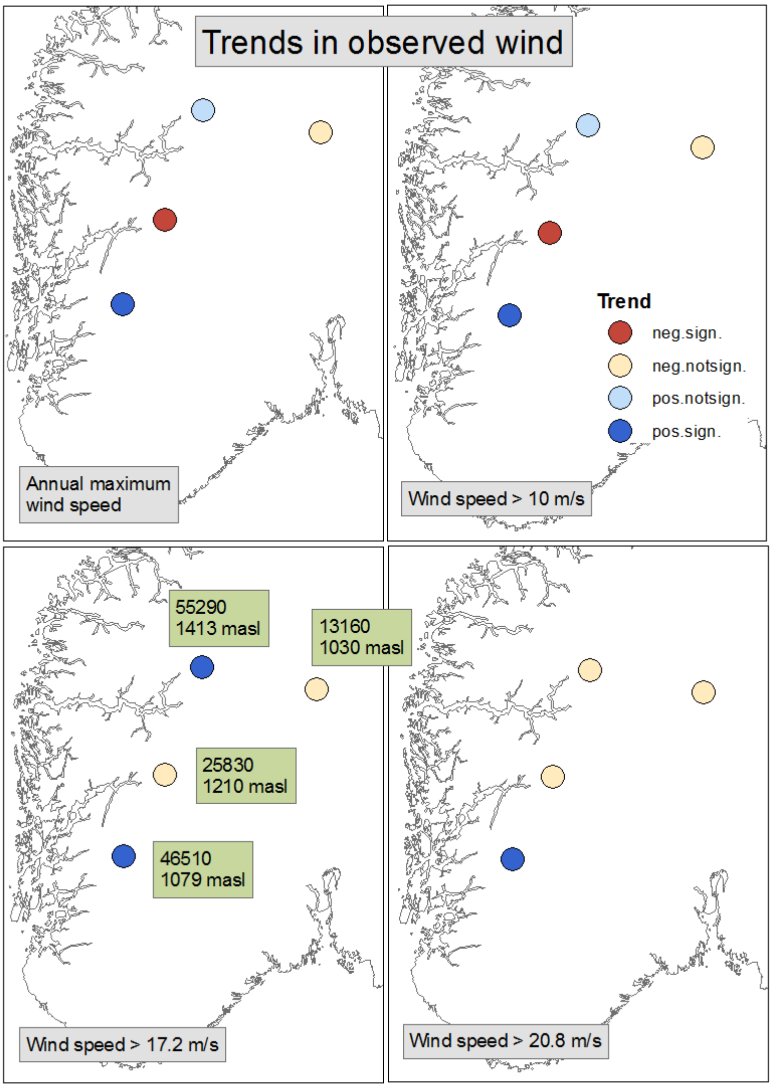

Figure 14: Trends in measured wind speed

4.4 Freeze-thaw events

The number of freeze-thaw events (daily mean temperature within -1.5 °C - 1 °C) obviously depend on the winter temperature in any location. Fig. 15 reveals mostly positive trends in the entire country except near the coast in South-Norway. Long-term trends are stronger in regions characterized by low winter temperatures, most likely due to the recent warming forcing temperatures closer to zero. Thus conditions are more favorable for freeze-thaw events to occur. Short-term trends in the latest period are similar to the long-term trends, while trends in the two first periods are weaker.

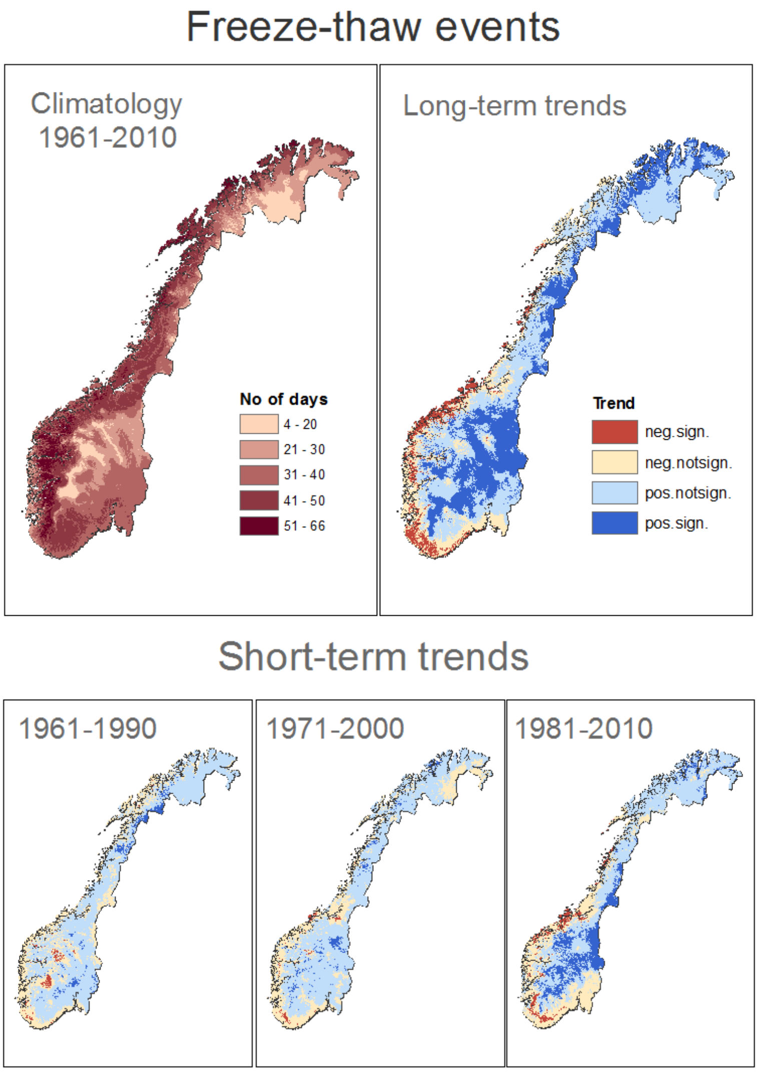

Figure 15: Number of freeze-thaw events

4.5 Uncertainties in the climate grids

The main uncertainties in this study are associated with the climate grids. According to *Tveito* et al. (2005) temperature grids perform well except in cases of inversion during winter time, while precipitation deviates more from reality because of its complex nature. Several uncertainties are introduced from interpolation, particularly due to the complex topography in Norway and the coarse station network in some areas such as montains. The collection of measurements going in to the interpolation varies from day to day depending on availability and quality, which might have a certain influence on temporal trends. Additionally, the correction for gauge undercatch is based on a simple model, as is the increase in precipitation with elevation, and both are known to be highly inaccurate in some cases. Further uncertainties also arise through the snow model. Despite the mentioned uncertainties in the climate grids the general spatial distribusion is considered sufficiently accurate for the purpose of regional scale analysis.

5 Conclusions

In this study we have examined several climate variables known to be potential triggers of natural hazards in Norway. It has not been a trivial task to identify these variables as many natural hazard events are a consequence of the joint contribution from many factors. At the same time as records of observed natural hazards are short and non-systematic over time, it is difficult to isolate the most significant triggering factor. As a result we have defined somewhat general climate variables which show regional signals of change in the past. Trends in annual maximum daily precipitation sums for the entire period 1961-2010 are generally positive, except in some regions in the southeast and in central Norway. Trends are stronger and show a more distinct pattern for longer duration precipitation. The frequency of moderate to strong precipitation events has increased in most parts of the country since 1961, and changes are more robust than for annual maximum precipitation. The increase was stronger in the southwest in the first period and in the southeast in the second period, while there was a weak decrease overall in the last period. Annual maximum snow depth reveals positive trends in cold areas, which might be explained by increased winter precipitation, and negative trends in warm areas due to increased winter temperatures. For snowfall we do not see such strong trends, however patterns are similar. Events of snowfall combined with wind above the specified thresholds only occur a few places along the coast in our dataset, and trends here are generally negative. This is most likely due to changes in snowfall rather than changes in wind speed. The number of freeze-thaw events obviously depends on the winter temperature in any location. There are mainly positive trends in the entire country except near the coast in southern Norway. Trends are stronger in cold areas, which can be explained by recent warming forcing temperatures closer to zero and creating more favorable conditions for freeze-thaw events to occur. The climate grids introduce several uncertainties which must be kept in mind when analyzing trends, thus general spatial patterns have been the focus in this study.

6 Acknowledgement

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