Changes in meteorological variables that can trigger natural hazards in Norway

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ABSTRACT: Using a daily interpolated dataset, we studied several climate variables known to be potential triggers of natural hazards in Norway. A trend analysis for different time periods was performed to assess temporal changes in the climate variables, and trends were evaluated for field significance and average changes on a regional level. The study shows that the frequency of moderate to strong precipitation events has increased in most parts of the country since 1957, particularly in wet regions. Regional averages were mainly in the range of 10 to 30%, and positive trends were field-significant in most regions. The intensity of strong precipitation events also showed a general increase, except in parts of central and northern Norway. The average increase in some regions was as high as 90%; however, the changes might in part be a result of inconsistencies in the station network, which can affect the precipitation grid. Snow amounts have increased in colder areas, while in warmer areas, field-significant negative trends were found, with reductions of almost 50% in some regions. Analyzing large snowfalls and the number of snow days revealed similar patterns, but trends were weaker. The number of near-zero events, defined as days with mean temperature between −1.5 and 1.0°C, has mainly increased, except in coastal southern Norway. The detected trends may have led to an increased number of snow avalanches at higher elevations, and an increase in floods and some types of landslides. The climate dataset was shown to be a valuable supplement to the analysis of past climate on a regional scale.

KEY WORDS: Natural hazards · Climate variables · Trend analysis · Precipitation · Norway · Snow

1. INTRODUCTION

Natural hazards in Norway, the most important being snow avalanches, landslides, and floods (Gregersen & Sandersen 1989, Furseth 2006), are often triggered by extreme weather events (EWEs). According to the Geological Survey of Norway, more than 2000 people have lost their lives in different types of avalanches and slides in Norway the last 150 yr (www.ngu.no/en-gb/hm/Geohazards/). A major trigger of floods is intense and/or prolonged rainfall, particularly in combination with snowmelt (Hanssen-Bauer et al. 2009, NVE 2011). Precipitation amount during one or several days is, as pointed out by Førland et al. (2007), an important trigger of slides in most of the country. Sandersen et al. (1996) found that particularly strong storms with heavy rain and snowfall frequently initiate landslides and snow avalanches. They also concluded that debris flows are more closely related to weather factors than rockfall and rock slides. Debris flows in Norway are often triggered at times of heavy water supply, due to for example intense rainfall and/or rapid snowmelt, causing high soil saturations and positive pore pressures (Sanderson et al. 1996, Nadim et al. 2009). In the GeoeXtreme project (Jaedicke et al. 2008), it was shown that snow avalanches have the highest correlation with meteorological elements, such as wind and precipitation, while rockfalls have the lowest correlation. Another potential trigger of snow ava-
lanches are freeze-thaw events, as these may cause instability in the snowpack. Lied & Kristensen (2003) state that rising temperatures lead first to decreased stability, but as time passes the snow metamorphosis will again stabilize the snowpack. In addition, very low temperatures might maintain an unstable situation. Although several studies have shown a general relationship between rainfall and rockfall, freeze-thaw events seem to be more closely associated with this event (Matsuoka 1990, Krautblatter & Moser 2009). Sandersen et al. (1996) point to temperature variations causing frost weathering and related frost wedging (caused by repeated freeze-thaw cycles)—2 weather-dependent processes known to reduce rock stability. Frost wedging is the process of rainwater or snowmelt accumulating in cracks in the rocks and expanding when frozen, as temperature drops below zero at night, causing the cracks to split further and open wider. The ice melts again during the day and water seeps deeper into the cracks.

According to Hanssen-Bauer et al. (2009), an increase in mean precipitation occurred in Norway over the last century, particularly since the end of the 1970s, and temperatures have increased in the entire country and during all seasons. In the same study, winter precipitation in Norway was shown to have increased by 5 to 25% between the two 30 yr periods 1961 to 1990 and 1979−2008. Dyrredal et al. (in press) studied trends in annual maximum snow amounts in Norway, and found mainly negative trends in relatively warm areas, and positive trends in colder areas for the period 1961 to 2010. Alfnes & Forland (2006) found a tendency for annual maximum 1 d precipitation to increase 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 to 2004 was performed by Achberger & Chen (2006). They found no spatially coherent pattern for Norway and Sweden, yet the overall aggregated trend was positive. For northern Europe, an increase in the frequency of heavy precipitation events has been observed (Trenberth et al. 2007) and, according to Groisman et al. (2005), this increase is greater than the increase in mean annual precipitation. 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).

More frequent EWEs may affect the robustness of infrastructure and the urban environment, by violating the applied design criteria, and structures may have to be upgraded accordingly. The aim of the present study is to assess which types of EWEs are most relevant in triggering natural hazards, by analyzing past changes in frequency and intensity of these events, as well as their spatial distribution. As intense and/or prolonged precipitation is known to trigger natural hazards, these events are the main focus of this study. Additionally, trends in snow depth and events of temperature near zero degrees are studied for the winter months. Daily gridded climate data from 1957 to the present with 1 km horizontal resolution enables a spatial analysis over the entire mainland of Norway. The present study is the first extensive trend analysis performed in Norway on the climate elements and derived variables from this specific dataset, and presents a simple approach for obtaining climate information on a regional level.

In the recently published Intergovernmental Panel on Climate Change (IPCC) special report on ‘Managing the risk of extreme events and disasters to advance climate change adaptation’ (IPCC 2011, p. 30), an extreme weather or climate event is called a climate extreme and is defined as ‘the occurrence of a value of a weather or climate variable above (or below) a threshold value near the upper (or lower) ends of the range of observed values of the variable’. In the present study, we refer to EWEs as events with the potential to cause severe damage to transportation routes and related infrastructure, which might differ to some extent from the more common definitions of EWEs.

2. DATA AND METHODS

2.1. Gridded climate data

Estimates of daily temperature and precipitation are obtained from observations interpolated to a 1 × 1 km² grid covering the Norwegian mainland (Tveito et al. 2005, Jansson et al. 2007, Mohr 2009). Daily grids are available for the period 1957 until today and are presented at www.seNorge.no. Temperature is estimated from a residual kriging approach 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 due to wind according to the model suggested in Forland 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 described 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 m above sea level (m a.s.l.) and 5% above that (Førland 1979, 1984). Precipitation and temperature grids are inputted into a precipitation/degree-day snow model with a snow routine similar to the HBV model (Bergström 1992) and is described in Engeset et al. (2004a). Temperature-dependent thresholds are used to separate snow from rain \( (T = 0.5°C) \) and to determine snowmelt 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’ throughout this study.

There are relatively large uncertainties associated with the climate grids and these are mainly related to the gridding procedure. The collection of measurements applied in the interpolation varies from day to day depending on availability and quality, which might have a certain influence on temporal trends. More than 200 temperature measurements and approximately 400 precipitation measurements are used (M. Mohr pers. comm. 2011). According to Tveito et al. (2005), temperature grids perform well, except in cases of inversion during winter time. This is also revealed in a leave-one-out cross-validation performed in an unpublished study by Mohr & Tveito (M. Mohr, O. E. Tveito pers. comm. 2012). Further, the cross-validation showed that the temperature grids generally perform better during the summer months and that errors increase with decreasing temperatures. The 25th and 75th percentile error is approximately ±1°C during winter months. Precipitation is a more challenging element to interpolate because of its complex nature, thus precipitation grids deviate more from reality. The variable topography in Norway and the coarse station network in some areas such as mountains makes it particularly difficult. In addition, 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. For instance, Engeset et al. (2004b) found that the vertical precipitation gradient is exaggerated, leading to overestimation at high elevations and underestimation at some low elevations. With regards to gauge undercatch, which can be significant for snow due to its light weight, we must question whether the observed increased precipitation is exclusively associated with more precipitation or whether the undercatch has decreased due to more precipitation falling as rain instead of snow (Førland & Hanssen-Bauer 2000). Snow parameters are also affected by further uncertainties introduced by the relatively simple snow model, in which snowmelt is inaccurately represented in some places (Dyrrdal 2009) and compaction is known to be slightly too high (Alfnes 2008, Dyrrdal 2010). These uncertainties associated with the climate grids should be kept in mind; however, despite these, we consider the general spatial distribution to be sufficiently accurate for the purpose of regional-scale analysis.

### 2.2. Trend analysis

A simple trend analysis is performed locally on individual grid-pixels, using the rank-based non-parametric 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 suited to the study of hydrometeorological 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 5% error level. Long-term trends are computed for the period 1957 to 2010 (entire period), and short-term trends are computed for three 30 yr periods: 1961 to 1990 (Period 1), 1971 to 2000 (Period 2), and 1981 to 2010 (Period 3). It is important to realize that the results of the trend analysis are highly sensitive to the analyzed time period and its length, due to natural variability. A 30 yr period is relatively short for a trend analysis; however, in this context it is convenient for studying the variability of trends throughout the entire period. In addition, some regions in higher elevated areas and in the north have a very sparse station network; thus, the influence of single stations on the gridding procedure is large. The establishment or closure of a station in such areas might impact the local trends.

To determine whether the significant local trends could have occurred by chance, a field significance test is carried out applying the ‘false discovery rate’ (FDR) procedure of Benjamini & Hochberg (1995). Local p-values, sorted in increasing order, are evaluated against a critical level given by the largest local p-value that is smaller than \( \alpha(j/K) \), where \( \alpha \) is the error level, \( j \) is the rank in the sorted collection, and \( K \) is the total number of trends evaluated. The proportion of falsely rejected null hypotheses relative to the
total number of rejected hypotheses is thus controlled. If at least one local p-value is lower than the critical level, field significance can be argued. As both positive and negative local trends can be found within a single region, the 2 trend types are evaluated separately, considering the opposite trend as non-significant. Likely spatial correlation between neighboring grid-pixels might make the FDR approach too liberal, since it assumes independence between data. However, Wilks (2006) found that the FDR approach yields good results even when dependence between local tests is present. Ventura et al. (2004) also compared the original approach of Benjamini & Hochberg (1995) to other FDR procedures that account for dependence (Yekutieli & Benjamini 1999, Benjamini & Yekutieli 2001), but found that the potential gain is minimal. Therefore, we believe that the FDR approach described above, together with a relatively conservative error level of 5%, will give a robust picture of regional trends.

Hanssen-Bauer & Førland (1998) defined 13 regions in Norway according to the long-term trends and decadal-scale variability of monthly precipitation. A few of the southernmost regions are subject to large topographic variations, and since many climate variables are highly sensitive to elevation, we further divided the 13 regions at about 1000 m a.s.l., separating mountains and lowland. Region 10 was also divided into two according to temperature regions defined by Hanssen-Bauer & Nordli (1998). Field significance is tested on the resulting 19 regions (Fig. 1), and average regional changes during the entire period, computed from a linear trend analysis, are presented. Some of the selected climate variables only occur a few times per year; hence, a trend analysis is unsuitable. For these variables, we simply investigate the changes between Period 1 and Period 3.

3. CLIMATE VARIABLES

Climate variables are defined and presented in Table 1. It was not 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 (Jaedicke & Kleven 2008, Jaedicke et al. 2008), it is difficult to isolate the most significant triggering factor. As a result, we have defined somewhat general climate variables that show regional signals of change in the past. Snow variables and near-zero events are computed for the winter season (November to May),

Fig. 1. Precipitation regions defined in Hanssen-Bauer & Førland (1998) (---), further divided according to temperature regions in Hanssen-Bauer & Nordli (1998) (—) and elevation above 1000 m above sea level (m a.s.l.) (). See Section 2.2 for details

<table>
<thead>
<tr>
<th>Variable</th>
<th>Duration (d)</th>
<th>Threshold</th>
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<tbody>
<tr>
<td>Annual maximum (am) precipitation sum</td>
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<td></td>
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<tr>
<td>Am1</td>
<td>1</td>
<td></td>
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<tr>
<td>Am5</td>
<td>5</td>
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<td>Am10</td>
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<tr>
<td>Precipitation – peak over threshold (pot)</td>
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<tr>
<td>Pot1</td>
<td>1</td>
<td>10 mm</td>
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<tr>
<td>Pot5</td>
<td>5</td>
<td>40 mm</td>
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<tr>
<td>Pot10</td>
<td>10</td>
<td>60 mm</td>
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<tr>
<td>Annual maximum snow depth (SD) and snowfall (SF)</td>
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<tr>
<td>MaxSD</td>
<td>1</td>
<td></td>
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<tr>
<td>MaxSF</td>
<td>1</td>
<td></td>
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<tr>
<td>Snowfall – peak over threshold</td>
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<tr>
<td>SF1-5</td>
<td>1</td>
<td>5 mm</td>
</tr>
<tr>
<td>SF1-30</td>
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<td>30 mm</td>
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<tr>
<td>SF3-50</td>
<td>3</td>
<td>50 mm</td>
</tr>
<tr>
<td>SF5-80</td>
<td>5</td>
<td>80 mm</td>
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<tr>
<td>No. of near-zero events</td>
<td>1</td>
<td>−1.5 to 1.0°C</td>
</tr>
</tbody>
</table>
starting in 1958, as the winter season is denoted by the year of its end. Other variables are computed for the calendar year, thus starting in 1957.

For precipitation accumulations over one to several days (n-day precipitation sum), annual maximum values and frequency of events exceeding a set threshold (peak over threshold) are studied. Thresholds are selected for evaluation of the frequency of medium to large precipitation 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 event. The relatively low thresholds also facilitate the detection of trends, as a series of very low values or even zeros are not suitable for a trend analysis.

Due to the complex character of wind and thus limited high-resolution data, wind and snowfall in combination with wind are not included in the present study. Annual maxima are also studied for snow depth, and both annual maxima and peak over threshold are studied for snowfall. Many different thresholds for snowfall amounts with the potential to trigger snow avalanches are defined in Norway. Krohnholm et al. (2006) found that the most important factor for the release of 805 observed snow avalanches was the 5 d precipitation sum with an intensity of 5.52 mm, although this threshold was found to be too low. Bakkehøi (1986) performed a statistical analysis of observed snow avalanches and weather conditions (precipitation, wind, and temperature) at a research station in western Norway. Only precipitation was appropriate for suggesting a measure of snow avalanche probability on the 5 selected paths. The 3 d precipitation sum with a 50% probability of causing snow avalanches was shown to be between 45 and 60 mm, while 90 mm gave a probability of 95 to 98%.

In the present study, fixed thresholds for snowfall are specified by the snow avalanche warning group at the Norwegian Geotechnical institute (NGI), and are intended to capture the very intense snowfall events. Thresholds are based on experience within the everyday avalanche warning routine. The 3 d threshold of 50 mm is within the values reported in Bakkehøi (1986). 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.

The number of events with temperature near 0°C during the winter season is studied. These indicate likely freeze-thaw events. Since the climate grids have a temporal resolution of 1 d (average over 24 h), and no minimum and maximum temperature grids are available, we need to assume a range for daily mean temperature in which it is likely that temperature crosses 0°C. Fig. 2 shows an example from Oslo-Blindern meteorological station, suggesting that daily mean temperatures from −1.5 to 1.0°C is an adequate range. A similar distribution is seen in other parts of the country.

Frequency series have not been declustered, as it can be argued that any single event might be the triggering event of a natural hazard. Ideally, we would have compared trends in climate variables directly with trends in the occurrence of slides and snow avalanches. However, hazard databases suffer from changes in routines and practices around registration of such events and are not considered temporally consistent. Thus, we focus on plausible consequences of the observed changes in climate variables on different natural hazards.

### 3.1. Climate and topography in Norway

Fig. 3a,b presents mean winter temperature and precipitation in Norway for the standard normal period 1961 to 1990. These are the official temperature and precipitation maps for Norway created by the Norwegian Meteorological institute (met.no) (Tveito et al. 2000) and are not the same as the climate grids described in Section 2.1. Fig. 3c shows the topography from a digital elevation model with 1 km resolution.
Fig. 3. (a) Annual mean temperature and (b) annual precipitation for the period 1961 to 1990. (c) Topography and meteorological stations (red dots). m a.s.l.: m above sea level. (d) Registered slides in Norway during the period 1990 to 2008.
and the distribution of meteorological stations applied in the interpolation described in Section 2.1 (March 2012; H. Szewczyk-Bartnicka pers. comm. 2012). Registered slides during the period 1990 to 2008, taken from the online portal www.skrednett.no, are presented in Fig. 3d. 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 steep elevation gradient on the western side of the mountain range. 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, 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. The inner eastern parts of southern Norway and the far northeastern part of the country are characterized by a dry and cold continental winter climate. 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.

4. RESULTS AND DISCUSSION

4.1. Precipitation

4.1.1. Annual maximum precipitation

Figs. S1a, S2a, & S3a in the supplement (www.int-res.com/articles/suppl/c055p153_supp.pdf) show the annual maximum 1, 5, and 10 d precipitation, respectively, presented as an average for the period 1957 to 2010, along with long-term and short-term trends. Trends in annual maximum 1 d precipitation do not reveal a systematic pattern. Except for parts of central Norway, long-term trends are mainly positive, meaning that the intensity of strong precipitation events has increased. Short-term trends differ in Period 3 compared to the first 2 periods, with trends being more negative in most places, particularly in central Norway. Due to reduced spatial variability, patterns become more apparent as we go from 1 d precipitation to 10 d precipitation. Positive long-term trends are evident in all of southern Norway, and there are only small areas with negative trends in the far north. Trends in the mountainous areas in the south are significantly positive. Short-term trends are positive in the southwestern and northern parts in Period 1. In Period 2, there are nearly no significant trends, but only weak positive trends in the south and north, and weak negative trends in central parts. Trends in Period 3 are positive in the southeast and mostly weakly negative elsewhere. An ambiguous signal for shorter-duration precipitation is to be expected, as single precipitation events will have a greater impact on the results. The quantitative changes between Period 1 and Period 3 are presented as frequency distributions in Figs. S1b, S2b, & S3b in the supplement. The 10th and 90th percentile, representing the majority of the values, range between −3 and 7 mm for 1 d precipitation. For 5 d precipitation, the range is −1 to 26 mm, while annual maximum 10 d precipitation has increased in most locations by 0 to 45 mm.

4.1.2. Precipitation peak over threshold

Figs. S4a, S5a, & S6a in the supplement present peak over threshold for 1, 5, and 10 d precipitation, given thresholds of 10, 40, and 60 mm, respectively. Results for the different precipitation sums are very similar, showing mainly positive long-term trends in the entire country, except in a few areas in the southeastern, central, and northern parts. Increases are greater in areas of high annual precipitation (refer to Fig. 3b). Period 1 shows a division in south Norway between positive trends in the western parts and weakly negative trends in the eastern parts and locally in central and northern Norway. In Period 2, the eastern parts of south Norway and the western coast of northern Norway are dominated by significant positive trends, while trends are weak in other regions. In Period 3, trends are very weak overall, but generally negative along the western coast and in the far north, and positive elsewhere. It appears that trends in peak-over-threshold events are stronger than trends in maximum values, indicating a more significant change in the frequency of moderate to intense precipitation. Changes between Period 1 and Period 3 are shown in Figs. S4b, S5b, & S6b in the supplement. Most locations have had between 0 and 7 more events of 1 d precipitation exceeding 10 mm in the last few decades. For 5 d precipitation exceeding 40 mm, the range of change is between −1 and 11 events, and for 10 d precipitation exceeding 60 mm, it is between −1 and 14 events.

Historical records of landslide and avalanche events from different authorities and organizations (Norwegian Geological Survey, Norwegian Geotechnical Institute, Road Authorities, and others) in Norway have been integrated into a database including more than
20,000 events all over the country (Jaedicke et al. 2008). The majority of the records are from the last 30 to 40 yr. Analyses indicate that the number of recorded slide events has increased exponentially since 1960 (Førland et al. 2007). A part of the increase in recorded slide events may be due to an increase in the natural release frequency of slide events. However, it is more likely that any natural changes in release frequency are masked by a combination of the following factors: (1) an increase in the number of infrastructural units, and (2) more consistent registration of events. Førland et al. (2007) therefore write that it is impossible to conclude whether the natural release frequency has changed significantly. Still, it is likely that some hazards, such as debris flows and floods, which are closely related to intense and prolonged rainfall, have become more frequent as positive trends are observed in rainfall variables in most places. This is also supported by a large body of the international literature that is concerned with rainfall as a trigger for shallow landslides (e.g. Corominas 2000, Wieczorek & Glade 2005). In addition, many of the largest floods in the past have been followed by other natural hazards (Furseth 2006). Though flood changes are difficult to detect, partly due to the lack of long-term records, Roald et al. (2006) suggest that Norway will experience increased rainfall-induced floods and decreased snowmelt-induced floods in the future. This was, however, not found in the observations of streamflow studied in Wilson et al. (2010). Although the connection between meteorological variables and rockfall is not as strong (Jaedicke et al. 2008), it is reasonable to suggest that a wetter climate will decrease rock stability and favor the initiation of a rockfall or rock slide.

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. S7a in the supplement) 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 the northern plateau areas have less snow. Long-term trends are generally positive in regions characterized by colder winter climate (mountain and inland, refer to Fig. 3a), and negative in regions of warmer winter climate (coast and lowland). Dyrrdal et al. (in press) studied the correlation between observed annual maximum snow depth and both temperature and precipitation. They found that variations in snow depth in colder areas are dominated by precipitation, while temperature dominates in warmer areas. Short-term trends go from mostly positive in the first 2 periods to mostly negative in Period 3. This is in line with recent warming, as more and more precipitation falls as rain and melting increases. However, there are still a few areas with sufficiently cold winters where positive trends are evident in Period 3, most likely due to increased winter precipitation in the last few decades. The amount of change between Period 1 and Period 3 is presented in Fig. S7b in the supplement, and shows that 80% of the values lie between −20 and 14 cm. Thus, values are slightly skewed towards a negative trend; however, many locations have also experienced increased snow amounts. Our results are consistent with previous studies, e.g. Dyrrdal et al. (in press) and Roald et al. (2002).

4.2.2. Annual maximum snowfall

Snowfall depends strongly on temperature and precipitation. In Norway, both variables have increased during winter in the past few decades. Thus, it is a non-trivial task to analyze changes in snowfall-related variables. Annual maximum snowfall (Fig. S8a in the supplement) 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. Northern plateaus and the southeastern part of south Norway have the lowest values. Long-term trends are relatively ambiguous, but there is a tendency to positive trends in mountainous areas, and negative trends in central Norway, and along the southern coast. Short-term trends go from positive in cold areas in Period 1 to mainly negative in most areas in Period 3, particularly on the western side of the mountains in the south and along the coast in central Norway (areas with large mean annual snowfall). Fig. S8b in the supplement shows relatively equal distribution between negative and positive values, with the majority of changes ranging from −5 to 5 mm. Spatial patterns of changes are similar to annual maximum snow depth (Fig. S7a in the supplement), although trends in annual maximum snowfall are weaker. This is most likely due to the dependence of snow depth on several factors including snowfall, rainfall, and temperature.
4.2.3. Snowfall peak over threshold

The number of events of 1, 3, and 5 d snowfall exceeding 30, 50, and 80 mm, respectively, are presented in Fig. S9 in the supplement. Most events occur in western parts of south Norway and in central Norway, i.e. in areas with more precipitation (Fig. 3b). Changes in mean number of events between Period 1 and Period 3 show decreases along the coast (warmer regions) and increases in mountains, inland, and northern areas (colder regions). Changes are more apparent for longer-duration snowfall. Fig. S10a in the supplement shows 1 d snowfall exceeding 5 mm, specified to consider changes in the number of days with snowfall. We find the same pattern as that for annual maximum snow depth (Fig. S7a in the supplement) and snowfall (Fig. S8a in the supplement), with an increase in so-called snow days in cold areas and a decrease in warm areas. Trends are weaker than for annual maximum snow depth but stronger than for annual maximum snowfall. Quantitative changes between Period 1 and Period 3 are shown in Fig. S10b in the supplement, and the majority range between −4 and 4 events.

Detected trends in snowfall-related variables match the expected signature of global warming, as increased winter temperature causes more precipitation to fall as rain instead of snow in warm areas. In cold areas (higher elevations, continental parts, and far north), however, temperatures stay low enough throughout winter for precipitation to fall as snow despite the recent warming, concurrently with an increase in winter precipitation. Results from the analysis of snowfall are in accordance with Serquet et al. (2011), who analyzed the proportion of snowfall days relative to precipitation days for up to 100 yr in Switzerland. They found clear negative trends in snowfall days, which was explained by increasing temperatures. Trends are stronger at lower elevations, where temperatures stay closer to the melting point of snow.

Change in snow avalanche frequency is not easy to determine as it depends mainly on both heavy snowfall events and wind. While for example, precipitation as heavy snowfall is the most important trigger of snow avalanches in the coastal western part of Norway, wind plays an important role in northern Norway (Jae dicke et al. 2008). As mentioned in section 3, we have little knowledge of changes in wind parameters. Based on the obtained trends in snow-related variables, it can be argued that most lower-elevation areas, which is where the majority of the population lives, experience fewer snow avalanches, as there is less available snow. On the other hand, many of these areas are not even prone to snow avalanches due to the lack of steep slopes. Infrastructure at higher elevations, such as mountain roads, ski resorts, and cabin communities, might experience more snow avalanches than a few decades ago due to more frequent and intense snowfall in these areas, and possibly also due to more available snow. Another facilitating condition for snow avalanches might be more events of rain on snow, since more winter precipitation comes as rain, and rainfall events seem to be more intense. Førland et al. (2007) also support this by suggesting that avalanches have increased in wetness over the past 4 decades (since 1970). The reason may be a shift from weather events triggering dry snow avalanches (events of heavy precipitation as snow) to events triggering wet snow avalanches (high temperatures) and slushflows (high temperatures or rain-on-snow events).

4.3. Near-zero events

The number of near-zero events (daily mean temperature between −1.5 and 1.0°C) obviously depends on the winter temperature at any location, and its degree of variability. From the climatology shown in Fig. S11a in the supplement, we find only a few near-zero events per winter season in colder areas, while a large portion of the warmer areas have more than 50 events per winter season. Long-term trends are mainly positive in the entire country, except near the coast in south Norway. Trends are stronger in regions characterized by low winter temperatures. This is most likely due to the recent warming, forcing temperatures closer to zero, creating more favorable conditions for near-zero events to occur. Short-term trends in Period 3 are similar to the long-term trends, while trends in the 2 first periods are weaker and with a few significant negative trends in mountainous areas, especially in the first period. From Fig. S11b in the supplement, it becomes apparent that there is a significant negative skew towards increasing number of near-zero events, with changes between −2 to 7 events from Period 1 to Period 3.

Near-zero events have an effect on snowpack stability, and as they have increased in snow-rich areas, the initiation of snow avalanches might have been facilitated here. Rock stability is also influenced by near-zero events, due to frost weathering.
4.4. Regional changes

Regional results are summarized in Table 2, showing percentage change during the entire period, where bold and italics are used to indicate field significance. In some regions, field significance is true for both positive and negative trends, implying that parts of the region have experienced opposite changes compared to other parts. This can typically occur in regions characterized by large gradients in either temperature or precipitation, such as Regions 2.2 and 11. The latter is also the largest of the 19 regions, enhancing the probability of ambiguous findings. Although regions were partly determined according to similarities in long-term trends of monthly measurements, the time periods studied in Hanssen-Bauer & Førland (1998) and Hanssen-Bauer & Nordli (1998) were different from those used here. Further, our variables, in addition to most of them being derived variables, are based on daily rather than monthly values. Another feature worth clarifying is that the average regional change sometimes reveals the opposite sign to the dominating field significance. Most likely, a large number of local insignificant trends affect this average regional change more than a few significant trends of the opposite kind.

It becomes even more obvious from Table 2 that most regions have experienced an increase in precipitation, and the increase in frequency of moderate to heavy precipitation events is more spatially consistent, with positive trends being field-significant nearly everywhere. An average increase of 32.4 to 41.5% is found in Region 9. We also notice that annual maximum precipitation for longer durations reveal the largest increase, with as much as 91.6% in Region 5.1. It is worth repeating that the trends might have been influenced by inconsistencies in the station network. Particularly in a mountainous region like Region 5.1 with a coarse station network, the sensitivity to single stations is larger, and detected changes can be artifacts of the gridding procedure. However, measurements from stations in the area reveal an increase of 50 to 75% in the period 1957 to 2010, confirming that a major part of the trend in grid series is real. Førland et al. (2007) state that precipitation events during more than 3, 10, or 30 d have been the most important parameters for triggering mudslides and landslides in southern and southwestern Norway in the past. Thus, with the detected positive trends in precipitation variables in this region, such hazards are possibly more frequent than previously.

Table 2. Average regional changes (%) computed from linear trend analysis, and field significance of local trends (1957 or 1938 to 2010) using a false discovery rate (FDR) approach. Bold and italics indicate field significance at the 5% error level. **bold**: dominating negative trends; **bold italics**: dominating positive trends. *italics*: positive and negative trends are nearly equally significant in the region. See Table 1 for climate variable abbreviations.

<table>
<thead>
<tr>
<th>Region</th>
<th>Precipitation</th>
<th>Snow</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Am1 Am5 Am10 Pot1 Pot5 Pot10</td>
<td>MaxSD MaxSF SF1-5 Near-0</td>
</tr>
<tr>
<td>1</td>
<td>11.4 30.8 56.4 16.3 37.9 26.6</td>
<td>−45.7 −22.5 −23.7 −2.1</td>
</tr>
<tr>
<td>2.1</td>
<td><strong>15.7</strong> 32.1 43.2 <strong>7.2</strong> <strong>12.6</strong> <strong>12.4</strong></td>
<td>−21.6 0.6 −6.3 27.9</td>
</tr>
<tr>
<td>2.2</td>
<td><strong>15.1</strong> 58.0 <strong>66.9</strong> <strong>16.7</strong> <strong>27.9</strong> <strong>27.5</strong></td>
<td>9.3 14.6* 19.5 40.3</td>
</tr>
<tr>
<td>3</td>
<td>2.8 29.5 25.2 6.6 4.2 3.2</td>
<td>−47.4 −23.3 −33.0 −8.3</td>
</tr>
<tr>
<td>4</td>
<td>10.4 <strong>74.6</strong> 87.4 20.4 22.7 18.7</td>
<td>−29.6 −6.6 −25.8 −19.2</td>
</tr>
<tr>
<td>5.1</td>
<td>11.8 62.3 <strong>91.6</strong> <strong>14.3</strong> <strong>14.5</strong> <strong>11.0</strong></td>
<td>−6.2 −3.7 −10.1 29.1</td>
</tr>
<tr>
<td>5.2</td>
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<td>−19.5 0.0 −18.1 −11.9</td>
</tr>
<tr>
<td>6.1</td>
<td><strong>14.5</strong> <strong>47.1</strong> <strong>63.9</strong> 22.2 26.3 23.5</td>
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</tr>
<tr>
<td>7.1</td>
<td>24.0 30.9 33.2 <strong>21.3</strong> 26.0 34.9</td>
<td>5.9 −5.5 <strong>27.8</strong> <strong>46.1</strong></td>
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<tr>
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<td><strong>15.9</strong> 12.6 <strong>30.5</strong> <strong>36.9</strong></td>
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<tr>
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<td>4.1 4.9 12.0 22.2</td>
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<tr>
<td>8.2</td>
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<tr>
<td>9</td>
<td>14.3 28.7 30.0 <strong>32.4</strong> <strong>40.1</strong> <strong>41.5</strong></td>
<td>3.1 −0.7 15.6 18.6</td>
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<td>−10.4 −3.8 2.1 <strong>21.5</strong></td>
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<tr>
<td>11</td>
<td><strong>5.7</strong> <strong>15.3</strong> 20.7 <strong>19.4</strong> <strong>27.3</strong> <strong>24.1</strong></td>
<td>−10.2 −2.3 −1.0 19.4</td>
</tr>
<tr>
<td>12</td>
<td>4.7 3.1 9.1 <strong>11.9</strong> 28.5 46.0</td>
<td><strong>8.6</strong> 2.4 <strong>31.5</strong> <strong>12.6</strong></td>
</tr>
<tr>
<td>13</td>
<td>15.9 −14.2 <strong>−10.7</strong> <strong>11.1</strong> <strong>11.4</strong> <strong>1.4</strong></td>
<td>−11.1 −16.7 −6.9 22.7</td>
</tr>
</tbody>
</table>

*Values with small areas of field significance of the opposite sign to that which dominates the region.
The majority of the regions have experienced less snow in the latest years, with the largest reduction of 47.4% for annual maximum snow depth in the southernmost Region 3. The number of near-zero events has increased in most places by up to 40.3% in Region 2.2. Region 6.1 represents a mountainous area where all climate variables show significant positive trends due to increased precipitation and relatively low temperatures. Region 13 is dominated by negative trends in both precipitation and snow amounts, likely because of its sheltered position in the far north.

5. CONCLUSIONS

In this study, we examined several climate variables known to be potential triggers of natural hazards in Norway. We assessed the spatial distribution of temporal trends and evaluated their field significance as well as average regional changes. Since measurements are limited, especially at higher elevations, the national climate grids are a valuable supplement to the analysis of past climate and are able to detect robust tendencies and regional differences.

Detected trends in the selected climate variables can be generalized as follows:

- The intensity of strong precipitation events has increased in most parts of the country, and patterns are more apparent for longer-duration precipitation. In some regions, average regional changes are as high as ~90%. Station measurements confirm this major increase; however, parts of the detected trends in grid series might be a result of inconsistencies in the station network.

- The frequency of moderate to strong precipitation events has increased in most parts of the country since 1957, particularly in wet regions. Positive trends are field-significant in most regions and the regional average increase ranges mainly between 10 and 30%.

- Increased winter precipitation and temperature has led to more snow in cold areas and less snow in warm areas; many regions show field-significant negative trends.

- Near-zero events have become more frequent in most non-coastal parts of the country, especially in cold areas.

The frequency of water-related hazards is expected to increase as a result of more frequent and intense rainfall events, while positive trends in snowfall variables and near-zero events can potentially produce increased frequency of snow avalanches in cold areas. More frequent near-zero events along with more heavy rainfall might also trigger a larger number of rockfalls and rock slides due to decreased rock stability. It must be emphasized that several uncertainties are introduced by the climate grids as well as by the complex relationships between meteorological conditions and natural hazard initiation.

Future work will include analysis of observed extreme precipitation, with emphasis on short durations. A similar analysis to the one performed here will be carried out on climate model simulations, in order to assess possible future changes in the selected climate variables.

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