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Present and future changes in winter climate indices relevant for access disruptions in Troms, northern Norway

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Abstract. In some seaside communities in northern Norway the vulnerability to weather induced access disruptions is high, due to frequent high impact weather in the region and the dependency on one or few roads particularly exposed to avalanches, wind and rockfall. In this paper we study changes in typical winter weather indices known to potentially cause such access disruptions in the region. A gridded observation-based dataset is used to analyse changes in present climate (1958-2017), while an ensemble of 10 EURO-CORDEX climate model simulations are used to assess expected future changes in the same indices, towards the end of this century. We focus on weather indices associated with snow avalanches, such as maximum snow amount and snowfall intensity and frequency, but also freeze-thaw cycles in terms of temperatures crossing zero degrees Celsius (zero-crossings), total water supply and the frequency of high wind speed are studied. Our results show that there are large climate gradients in Troms county and also in detected changes. In both focus areas, however, we find an increase in studied snow indices in present climate, while a strong decrease is expected in near and far future, particularly in low elevations where snow during winter might become a rarity by 2100. Heavy water supply is rather infrequent in the present climate of Troms, but we show that these events are likely to occur more often in all inland areas in the future. Although the risk of dry snow-related access disruptions might decrease, a warmer and wetter winter climate may increase the risk of wet-snow avalaches and sluchflows. We find that zero-crossings, known to destabilize the snow pack and cause rockfall, have increased in most parts of Troms during the last decades, and a further increase is expected for inland regions in the future, while coastal regions can expect less zero-crossings. The higher risk of water and rainfall-induced hazards and more frequent freeze-thaw conditions calls for careful coordination of climate adaptation, cooperation between different sectors, as well as guidance and training of local authorities, especially in exposed and remote regions.

1 Introduction

Landslides and snow avalanches have caused more than 2000 deaths in Norway in the past 150 years, with snow avalanches being responsible for about 1500 fatalities, according to Kalsnes et al. (2016). They further state that snow avalanches affect large parts of western and northern Norway and are the geohazard which most frequently leads to loss of lives and infrastructure damage in Norway. Climate change has been shown to influence winter season natural hazards in several areas (Jaedicke et al. 2008; Dyrrdal et al. 2012; IPCC 2012). In quite a few seaside communities in northern Norway, the inhabitants have experienced sudden winter weather-induced events that affect local lifeline infrastructure (Jacobsen et al., 2016; Platt, 1991); highway closures and electricity and telecommunication outages. Such problems have become increasingly serious given the advance of the 24/7 society that expects and necessitates unrestricted road access. In Norway, one in ten municipalities are especially vulnerable as they have only one connection to the national road network (Holand & Rød, 2013). Moreover, it has been estimated that no less than one fourth of Norway's public roads are vulnerable to avalanches and rockslides (Frauenfelder et al., 2013: 36, 57) and most road blockages have been caused by snow avalanches (Public Roads Administration Hordaland, 1995). Small communities located in areas where access highways are exposed to extreme winter weather incidents and snow avalanches are especially vulnerable to such erratic lifeline cut-offs. Social science studies have revealed that roadside avalanches and weather-induced road closures lead to worries about winter road travel and numerous practical problems for inhabitants, businesses, and the public sector (Hovelsrud et al., 2018; Leiren & Jacobsen, 2018). Although many residents have been able to prepare and adjust to reduce their vulnerabilities to recurrent lifeline disconnections (Jacobsen et al., 2016), such winter climate-induced perils may in the longer term possibly not appeal to prospective residents (Hovelsrud et al., 2018; Leiren & Jacobsen, 2018) and perhaps also cause relocations of people and businesses.

Given unclear perceptions of future climate-induced hazards, the present study will scrutinize climate change in Troms County in northern Norway, where many seaside communities sporadically have experienced lifeline cut-offs due to snow avalanches, blizzards, heavy snowfalls, and/or snowdrifts. The article will supplement social science investigations and advance natural hazard understandings by providing an overview of historical development and projected future changes in weather indicators associated with winter season road travel safety and lifeline disruptions in Troms County.

Using a daily interpolated dataset, Dyrrdal et al. (2012) performed a Norwegian national analysis of past changes in weather variables that can trigger natural hazards. For Troms, they found that the frequency of moderate to strong precipitation events, and the intensity of strong precipitation events, had increased during the period 1957–2010. Snow amounts had increased in colder areas (inland), while in warmer areas (coast and seaside fjord areas) snow amounts were somewhat reduced. Analyzing large snowfalls and the number of snow days revealed similar patterns, but trends were weaker. The number of near-zero events had also increased during the same period.

According to a report on projected climate-related changes in Troms: "Troms climate fact sheet" (Hisdal et al., 2017) from the Norwegian Centre for Climate Services (NCCS; klimaservicesenter.no), annual mean temperature is expected to increase by about 5 °C as approaching the end of this century (compared to the historical period 1971–2000) under a high emission

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scenario (RCP8.5), with a slightly larger increase during winter. Annual precipitation is expected to increase by about 15%, with a larger (30%) increase during summer. Further, days with heavy precipitation are expected to become more frequent and with higher precipitation intensity, resulting in an increased probability of precipitation-induced debris avalanches, debris flows, debris floods and slushflows. The same report states that snow amounts will likely decrease drastically in lower altitudes and episodes of melting will become more frequent in winter, while some higher altitude regions might expect increasing snow amounts towards the middle of the century. In these regions the probability of snow avalanches might increase during the first decades, followed by reduction towards the end of the century. In northern Norway, wind induced hazards represent a significant challenge along the coast and exposed mountain passes. Wind projections are highly uncertain and show no strong indication of change according to Hisdal et al. (2017) and Hanssen-Bauer et al. (2015). However, some studies have shown a change in cyclone density in the region, e.g. a study by Bengtsson et al. (2006) indicating that the location and intensity of storms are expected to change considerably in the future while the change in the total number of cyclones will be small. Empirical-statistical downscaling of CMIP5 simulations suggest an increase in storm activity in northern Norway and the Barents region in the far future (Parding & Benestad, 2016).

Despite the expectation of more frequent snow avalanches and landslides as a consequence of a warmer and wetter climate in some Nordic regions, a recent study by Hestnes & Jaedicke (2018) indicated that global warming altogether will reduce the impact of slushflows and avalanches on humans. They explained this reduction with milder weather, shorter winters with less snow and rising snowlines in populated regions. The same study indicated that the total risk due to rapid mass movements will most likely increase.

The present study will go deeper into selected winter climate indices known directly or indirectly to trigger natural hazards or somehow generate lifeline interruptions and difficult and risky road/transport conditions in exposed coastal and fjord areas in Troms, northern Norway. First, we present the study region and climate (chapter 2), we describe the data and method, and identify relevant weather indices (chapter 3), before presenting results (chapter 5) and wrapping up with discussion and conclusions (chapter 6).

2 Study region

Troms is the second northernmost county in Norway (see map in Figure 1), located between 68.3 and 70.3 degrees north, thus forming a part of the Sub-Arctic region. The Sub-Arctic and Nordic Arctic regions further north have experienced a major change in climate over the past few decades (AMAP, 2017; Vikhamar Schuler et al. 2016; Hanssen-Bauer et al. 2019). Troms consisted in 2018 of 24 municipalities with a total area of nearly 26 000 km² and around 165 000 inhabitants. The long coast line with thousands of small islands and islets, including some of Norway's largest islands, meets steep mountains

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further inland, resulting in a complex topography (see map in Figure 1). Large parts of the population and infrastructure in Troms are located in narrow zones along the seashore, particularly in fjords surrounded by steep mountain slopes. The topography, along with geological and meteorological conditions, makes the county particularly prone to avalanches. More than 250 people have been killed in avalanches in Troms in the past, where of most died in snow avalanches (Walberg and Devoli, 2014). Several small but enterprising communities there have recurrently been cut off from the rest of the county. The present study will focus particularly on three communities; Jøvik/Olderbakken in Tromsø municipality and Senjahopen and Mefjordvær in Berg municipality (See Figure 1). Both municipalities lie within or close to an avalanche zone as defined by Norwegian Water Resources and Energy Directorate (NVE; https://www.nve.no/flaum-og-skred/kartlegging/aktsemdkart/aktsomhetskart-for-snoskred/). Numerous stretches of roads in the study region have steep slopes on one side, making them prone to closures and damages due to slides and avalanches, as well as representing a threat to people's safety. According to Jacobsen et al. (2016), several communities in Troms experience sudden access interruptions nearly every winter due to snow/slush avalanches, heavy snowfall, and/or strong winds and drifting snow in these areas.

The climate in Troms is strongly influenced by the complex topography with large gradients between coast and inland regions. During winter season, Troms is characterized by a relatively mild and wet climate in coastal areas, while inner parts of the county are cold and dry (see Figure 2). Mean winter temperatures range from slightly above zero along the coast to around -12 degrees Celsius in high elevated areas inland. Valley regions in the inner parts of Troms are particularly dry, with mean winter precipitation of less than 200 mm, while values in southern coastal regions reach about 1200 mm. Polar lows, common for this region, can give strong winds and heavy precipitation in winter time. The largest snow depth measured in Troms county was 330 cm on April 23 in 2014 at the weather station Lyngen - Gjerdvassbu in Lyngen municipality, at 710 masl. The largest 1- day winter precipitation of 106.5 mm/day was measured Gullesfjord - Eidet in Kvæfjord municipality on January 11 2002, at 19 masl.

In Figure 3 we show how winter temperature and precipitation has varied over the last 150 years at a meteorological station in the administrative center of the municipality in the city of Tromsø. Winter temperature fluctuates between -5 and 0.5 degree Celsius, and winter precipitation fluctuates between 250 and 950 mm. The temperature time series indicate multi-decadal variability, with a relatively cold period between 1910s and 1920s, a relatively warm period during the subsequent two decades, a temperature decrease from the 1950s to the 1960s, and thereafter a general temperature increase. Other parts of the Arctic have similar pattern (e.g. Polyakov et al. 2003). The linear trend during the 60-year period 1958-2017, which is the period we focus on in the current study, shows a significant increase in winter temperature (0.26 °C/decade) and a moderate increase in winter precipitation (2.2 %/decade) in Tromsø.

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3 Data and method

Three weather variables are of main interest in this study, namely precipitation (including snow), air temperature, and wind, and combinations of these. We compute changes in selected indices (see chapter 3.3) based on these weather variables using datasets that cover the recent climate (1958-2017) and projected future climate (2041–2070 and 2071–2100). As most disruptions due to weather occur during the extended winter season, this is our season of focus. Winter season is defined here as the months October through April (212 days in total).

3.1 Gridded observation-based data

To obtain spatially continuous information on the recent climate, observations of daily temperature (T) and precipitation (P) have been interpolated onto a 1x1 km grid over the Norwegian mainland. The gridded data referred to as "seNorge" is available at www.senorge.no, and covers the period 1957–present. Different versions of seNorge exist, based on different interpolation methods and input data. For temperature, we here analyse seNorge1 (e.g. Tveito et al., 2002) as it includes minimum (Tmin) and maximum temperature (Tmax) from which we calculate zero-crossings. seNorge1 temperature was developed through residual kriging using terrain and geographic position to describe the deterministic component. For precipitation, however, we use seNorge2 (Lussana et al. 2018), based on Bayesian spatial interpolation and Optimal Interpolation (OI) to propagate information from coarser to finer scales. Snow variables, including daily snow water equivalent (SWE), fresh snow water equivalent (FSW; water equivalent of last days snowfall) and snow depth (SD), are computed from seNorge1 T and P using the seNorge snow model v1.1.1 (Saloranta, 2014), but as precipitation from seNorge2 is now used as input, the gridded snow products are referred to as seNorge v2.0.1. Hereby, we refer to all seNorge-datasets as seNorge, followed by the variable of interest, for instance: seNorge Tmax.

For wind, a dataset of daily mean 10-meter wind speed (FF), named KliNoGrid, is available on a similar grid as seNorge for the period 1957–2015. This dataset is downscaled from a high-resolution (10 km) hindcast of wind and waves for the North Sea, the Norwegian Sea, and the Barents Sea (NORA10; Reistad et al., 2011), which evaluates relatively well along the coast of Norway. The downscaling was performed with a quantile mapping approach (Bremnes, 2004) to match the climatology of the high-resolution numerical weather prediction model (AROME-MEtCoOp, Müller et al., 2017). KliNoGrid is available for public download at https://thredds.met.no/thredds/catalog/metusers/klinogrid/KliNoGrid_16.12/FFMRR-Nor/catalog.html.

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3.1 Future projections

An ensemble of ten simulations from the EURO-CORDEX project (Jacob et al., 2014), representing different combination of General Circulation Models (GCMs) and Regional Climate Models (RCMs) has been downscaled to a similar grid as the seNorge-grid described above (1 km horizontal resolution). The downscaled EURO-CORDEX ensemble was further bias-adjusted towards an earlier version of seNorge (Wong et al., 2016) using an empirical quantile mapping method, for the entire period 1971–2100. We refer to the corrected datasets of temperature and precipitation as "EUR11-Nor1", where EUR11 stands for EURO-CORDEX with 0.11° resolution, Nor stands for Norway and 1 stands for 1 km resolution. These datasets were then forced with a spatially distributed, gridded version of the HBV model (Wong et al., 2016) to generate daily time series of different hydrological components. Here we focus on daily SWE, from which we also compute daily FSW (change in SWE from one day to the next). In line with the Norwegian government "principle of preparedness" with regards to climate change, we only analyse projections using the RCP8.5 emission scenario.
The ten GCM-RCM combinations in the EURO-CORDEX ensemble are shown in Table 1. As this table reveals, the ensemble is somewhat biased towards a few GCMs (particularly EC-EARTH) and RCMs (particularly RCA), representing a weakness along with the relatively limited number of simulations. We use the mean of the 10 simulations in our analyses.
Unfortunately, at the time of this study, there were no high-resolution wind projections available. A downscaled version of the EURO-CORDEX ensemble for mean wind speed has recently been developed at MET Norway, but an evaluation has yet to be performed.

Table 1: GCM/RCM combinations in the EURO-CORDEX ensemble.

GCM/RCM	CNRM	EC-EARTH	HADGEM	IPSL	MPI
CCLM	1	3			9
RCA	2	6	7	8	10
HIRHAM		4			
RACMO		5			

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3.3 Weather indices

To connect weather variables to road closures, we identify indices which in literature are known to be potential triggers of rapid mass movements such as slides and avalanches, or somehow generate difficult road/transport conditions. Indices analyzed here are mostly relevant for snow and slush avalanches, but have also often lead to difficult road and driving conditions. The derived indices are identified from literature referred to in the following text, and presented in Table 2 below.

Jaedicke et al. (2008, 2009) studied the correlation between certain meteorological elements, such as 1-day precipitation, temperature, wind speed and direction, and the occurrence of snow avalanches and mudflows in Norway. Results showed that precipitation is the most frequent cause of avalanches, and in Northern Norway wind is also an important trigger of snow avalanches. Sandersen et al. (1996) found that particularly strong storms with heavy rain and snowfall frequently initiate landslides and snow avalanches, and concluded that debris and slush flows in Norway are often initiated at times of heavy water supply from intense rainfall and/or rapid snowmelt. NVE (2014) indicated a critical threshold of 40 mm/day of total water supply, given by field experience and measurements. In the current study, a threshold of 10 mm/day for water supply is chosen due to the very low number of events exceeding higher thresholds, which inhibits a change analysis. This pragmatic selection of threshold is repeated for other frequency indices in this study. NVE (2014) also states that at least 0.5 m of fresh snow in 2–3 days, along with strong winds, is required to trigger a snow avalanche of significant size. We decided to analyze winter maximum snow amount and snowfall intensity, frequency of heavy snowfall and frequency of strong wind separately.

Another potential trigger of snow avalanches, and even rockfall, are zero-crossing events. Here, a zero-crossing is defined as Tmin < 0 and Tmax > 0 on the same day, meaning that we move between freezing and thawing conditions. Frequent zero-crossings can lead to difficult road conditions and destabilize the snowpack. Ballesteros-Cánovas et al. (2018) also emphasizes that the transformation of dry snow packs into wet snow packs is decisive for the release of snow avalanches. Lied & Kristensen (2003) state that rising temperatures first lead 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.

For our study region Eckerstorfer et al. (2017) concluded that Tamokdalen in Troms (about 50km south of Jøvik/Olderbakken) has a transitional snow climate (between maritime and continental climates), where also mid-winter rain-on-snow events lead to extensive wet snow avalanche cycles. Eckerstorfer et al. (2017) identified the highest magnitude avalanche cycles when non-persistent weak layers, such as buried new snow and wind-transported snow, were forecasted as avalanche problems. Forecasted wet snow avalanche events also resulted in high avalanche activity.

Table 2: Weather/climate indices

Weather index	Dataset Present climate	Dataset Future climate	Details / Abbreviation
Maximum snow amount	seNorge SWE	EUR11-Nor1-SWE	WM-SWE
Maximum snowfall intensity 1 and 5 days	seNorge FSW	EUR11-Nor1-SWE	WM-FSW-1d WM-FSW-5d
Heavy snowfall frequency	seNorge FSW	EUR11-Nor1-SWE	FSW-1d > 5 mm
Zero-crossings	seNorge Tmin/Tmax	EUR11-Nor1-T	Tmax > 0 and Tmin < 0 on the same day
Snowmelt + rainfall (water supply)	seNorge FSW seNorge P	EUR11-Nor1-SWE EUR11-Nor1-P	Water supply > 10 mm/day
Strong wind frequency	KliNoGrid FF		Mean daily windspeed > 6 m/s

3.4 Method

Past trends in winter maxima and peak-over-threshold events are assessed through the rank-based nonparametric Mann-Kendall trend test to identify positive and negative trends, and evaluate their statistical significance at a 5% level. Mann-Kendall tests the null hypothesis that the data are independent and identically distributed, and is well suited to study hydrometeorological time series, as these are usually non-normally distributed (Yue & Pilon 2004). In addition, we compute the percentage change between the mean values from the first 30-year period (1958–1987) and the last 30-year period (1988–2017). For some indices with relatively low frequencies in some areas (water supply and high wind speed) we simply compute the change between the first and the last 30-year period.

To assess expected future change, we compute the change in temporal mean between the historical period 1981–2010 and two future periods; 2041–2070 (near future) and 2071–2100 (far future) through the methods described above. In the results we report on the ensemble mean of the 10 simulations, not individual model simulations.

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For both past and future changes, we extract mean spatial statistics over the two focus regions and present these in a separate table.

In the attempt to identify the period for which snow avalanches may become a larger threat, and at which point they become a decreasing threat, we investigate the past and projected development in maximum snow amounts for different elevations. We also analyze future changes in the median elevation where winter maximum SWE is lower than certain thresholds; 100 mm, 200 mm and 400 mm. Due to the large gradients in climate variables in Troms, the latter analysis is performed for separate inland and coastal regions as defined in Figure 1.

4 **Results**

4.1 Past development

Figure 4 shows mean winter maximum snow water equivalent (WM-SWE) and the spatial trends and changes during the study period 1958–2017. The largest values of WM-SWE are found in higher elevations (see map in Figure 1) near the coast and along the fjords, while decreasing towards the Swedish border to the east (Figure 4a). In Figure 4b, significant positive trends are seen inland and in the north-eastern part of the county, with an increase of 20-60% from the first to the last 30-year period (Figure 4c). Some coastal regions, especially in the southern and north-western outermost areas, are dominated by significant negative trends in WM-SWE. These areas show a decrease of 20-40% between the first 30-year period (1958-1987) and the last 30-year period (1988-2017).

The mean, trends and changes in winter maximum fresh snow water equivalent for 1 and 5-day durations (WM-FSW-1d, WM-FSW-5d), are shown in Figure 5 and 6, respectively. There are no large areas of significant negative trends in these variables, but decreases of about 10% in WM-FSW-1d are evident inland and in some coastal areas in the south and the north-west (Figure 5c). These areas of weak negative trends become smaller with the longer duration; for WM-FSW-5d only islands north of the city Tromsø (see map in Figure 1) inhibit weak negative trends (Figure 6b). Positive trends, some of them significant, dominate the middle regions and the coastal areas north-east and far south. Areas of positive trends increase with the longer duration. Increases of 20-40% (Figure 5c) and 30-50% (Figure 6c) are seen for WM-FSW-1d and WM-FSW-5d, respectively, except a small area of even stronger increase in the far north-east.

The frequency of heavy snowfall events (FSW-1d > 5 mm) is presented in Figure 7, showing a similar spatial distribution of trends as WM-SWE but with smaller areas of significant trends. Mean values for the extended winter season (Figure 7a) range from about 10 (far inland) to about 50 events (some high-elevated areas near the coast). Significant negative trends are found in and around Ringvassøya (Figure 7b), with decreases of around 20% from the first 30-year period to the last (Figure

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7c). Southern areas inland and coastal areas in the north-east show significant positive trends, with 30-50% more events in the last period compared to the first.

Figure 8 shows a clear increase in the number of zero-crossings in the entire county, with large parts being dominated by significant positive trends (Figure 8b). The frequency of events for the extended winter season (212 days in total) increases westwards, with 10–50 events inland to 70–90 events along the coast and in valley bottoms (Figure 8a). A clear increase in the number of zero-crossings is visible in the entire county, with large parts being dominated by significant positive trends (Figure 8b), reflecting increasing temperatures over the period. The percentage increase between the first and the last 30-year period ranges from about 10% to 40%, with no obvious spatial pattern (Figure 8c).

The next two figures show changes between the first and the last 30-year period for number of days with water supply exceeding 10 mm/day (Figure 9) and frequency of days where mean wind speed exceeds 6 m/s (Figure 10). Changes are reported as absolute values, due to the relatively small number of such events per winter season in some areas. Mean values of water supply > 10 mm/day range between 0 (far inland), where the number of events have decreased slightly by 1-2 events (Figure 9b), to about 40 events along the coast (Figure 9a), where an increase of up to about 20 events is seen in a few areas (Figure 9b). In most areas, however, there has been an increase of about 2-10 events between the two 30-year periods. Frequency of strong wind exhibit large spatial variability, with no events in certain valley regions and up to ~150 events at higher altitudes (Figure 10a). Changes between the first and the last 30-year period are small, with decreases of 1-2 events far inland and along most of the coast, and increases of 3-5 events near the coast in the south and along the mountain areas inland (Figure 10b).

4.2 Future development

Figure 11 presents projected percentage changes in WM- SWE for near (2041-2070) and far (2071-2100) future, as given by EUR11-Nor1-SWE. Changes are mainly negative, with strong gradients from coast (largest decrease) to inland (weakest decrease). As expected, the changes become larger with time. The largest projected decrease, in the islands along the coast, are in the order of 60-80% for near future (Figure 11a) and 80-100% for far future (Figure 11b).
Figure 12 shows the same change in WM-SWE, but in different elevation levels, including past changes in the upper panel computed from seNorge SWE (change in mean values from the first 30-year period (1958-1987) to the last 30-year period (1988-2017)). Again we see that changes in WM-SWE are mainly positive in the past, but become negative in the future. The higher elevated areas show the largest increase in the past, and the smallest decrease in the future, explained by the lower temperature in these regions. At some point between present time and near future, the temperature in these region will, however, reach levels that give declining snow amounts also here. This is further investigated in Figure 13, showing the median elevation where maximum snow amounts stay below certain thresholds (100, 200 and 400 mm). Due to the strong gradients in Troms county, we analyze projected changes in WM-SWE for inland regions and coastal regions separately (see

map in Figure 1), thus elevation on the x-axis differs between Figure 13 a) and b). Median elevation in the inland region (Figure 13a) shows a steep increase as approaching the end of the century, particularly for WM-SWE < 100 mm, meaning that we need to go to higher and higher altitudes to find snow in the future. The narrowing range between smaller and larger snow amounts (Figure 13a) indicates a decrease in the variability between lower and higher altitudes, which might simply be explained by the complete disappearance of snow in the lowlands. In the highest altitudes along the coast (Figure 13b), however, the variability between snow amounts in medium to high altitudes will not decrease as much.

WM-FSW-1d and WM-FSW-5d in the future (Figures 14-15) are projected to decrease with a similar spatial pattern as WM-SWE, i.e. most along the coast and more in far future compared to near future. Projected decreases along the coast in far future range between 30 and 60% for WM-FSW-5d and between 40 and 70% for WM-FSW-5d. The frequency of snowfall events exceeding 5 mm/day (Figure 16) is also expected to decrease in the whole region, by up to 60-70% along the coast in near future, and 100% in far future. This means that in these regions most heavy precipitation events will come as rain instead of snow as approaching the end of the century, as a consequence of milder winters.

Similar to the frequency of zero-crossings in the present climate, projected changes in zero-crossings (Figure 17) also show an increase in many areas, reflecting that increasing temperatures in a relatively cold region approach the zero degree threshold for a larger part of the time. However, in the mildest areas along the coast, where mean winter temperatures are already close to zero, these events will become less frequent. Both increases and decreases are expected to become stronger towards the end of the century.

Figure 18 shows that the frequency of heavy water supply (rainfall and/or snow melt) is projected to increase significantly in the future, as compared to 1981-2010. This seems to already be happening in the next few decades (Figure 18a) and might be explained both by an increase in precipitation frequency and intensity (e.g. Hanssen-Bauer et al., 2015), higher temperatures giving more precipitation as rain instead of snow, and increasing snow melt due to longer periods of temperature above zero degrees.

In Table 3 we summarize the results of past and future changes for the two focus areas, Senjahopen and Jøvik, as these areas are significantly exposed to high-impact weather and especially vulnerable to road closures as a consequence of weather indices analyzed here. Senjahopen have and will experience the largest changes in snow variables. The largest change in the past is seen for WM-FSW-5d with an increase of 31.6%, while Jøvik had an increase of only 13.5%. Zero-crossings has, however, become more frequent in Jøvik with an increase of 23.2%, as opposed to only 3.8% in Senjahopen. Jøvik has also had an increase in heavy wind frequency of about 2 events per winter season, but this change is not statistically significant. In the future, Senjahopen is expected to have much less snow-related challenges, with 71 (91)% decrease in the maximum snow amount in near (far) future, while Jøvik shows a decrease of 52 (75)%. Zero-crossings are expected to decrease in

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Senjahopen, but increase by up to 39% in Jøvik in far future. Although changes in heavy water supply have been insignificant in the past, they are expected to increase by about 27 (34)% in Senjahopen in near (far) future, and 60 (65)% in Jøvik.

Table 3: Estimated changes in weather indices in the two focus areas, based on spatial mean values. *Absolute change

Weather index	Past change (1958-2017)		Change in near future		Change in far future	
	Senjahopen	Jøvik	Senjahopen	Jøvik	Senjahopen	Jøvik
WM-SWE	13.9 %	11.3 %	-70.6 %	-52.0 %	-90.5 %	-74.8 %
WM-FSW-1d	27.8 %	13.5 %	-30.7 %	-18.8 %	-59.4 %	-34.9 %
WM-FSW-5d	31.6 %	13.5 %	-38.5 %	-22.0 %	-70.6 %	-42.4 %
FSW-1d > 5mm	16.4 %	3.8 %	-67.6 %	-43.2 %	-90.7 %	-69.1 %
Zero-crossings	3.8 %	23.2 %	1.4 %	36.2 %	-25.0 %	39.1 %
Water supply > 10 mm/day *	9.9	5.7	26.9 %	59.8 %	34.1 %	65.4 %
Wind speed > 6m/s *	0.8	2.3				

5 Discussion and conclusions

Our analyses of past development points to areas in Troms country where snow amounts and heavy snowfall events have increased, thus increasing the potential for dry snow avalanches. These areas are characterized by relatively low temperatures, typically at high altitudes and inland regions and our results correspond well with those of Dyrrdal et al. (2012). Ensemble mean projections of snow conditions in the future period 2040–2100, however, show a decrease in maximum snow amounts and heavy snowfall intensity and frequency in all areas, particularly low altitude regions, indicating that the transition from increasing to decreasing dry snow avalanche risk takes place before 2040 even in the highest elevated and coldest areas. However, the probability of wet snow avalanches and slushflows may increase as the transformation of dry snow packs into wet snow packs generally is decisive for the release of snow avalanches (cf. Ballesteros-Cánovas et al., 2018). This is in line with observed changes in the European Alps (Naaim et al. 2016), as well as for predicted changes in the Nordic Arctic region (Hanssen-Bauer et al. 2019). However, as pointed out by Hestnes and Jaedicke (2018) a general reduction of slushflows and avalanched might be realistic in a warmer climate with shorter winter season and less snow.

As snow amounts have mainly increased in the past, explained by an increase in precipitation and still low temperatures despite the warming trend, the amount of snow melt has likely not changed much. Thus, we find no significant trends in the frequency of heavy water supply (rainfall + snow melt). Actually, these events occur relatively seldom in todays' climate. Over the next few decades, our results indicate that this will change quite dramatically, and events of water supply exceeding

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10 mm/day are expected to increase significantly in all regions except along the coast and in deep valleys. As stated in Hisdal et al. (2017), snow melt avalanches will occur earlier in the spring and become less frequent towards the end of this century, thus a likely explanation of more frequent heavy water supply is the projected increase in winter precipitation coming as rain. More rain during winter may also point to increased risks of wet snow avalanches and slushflows in the actual areas of Troms. In addition other studies show that increase in the liquid water content of snow in motion will tend to reduce friction, increasing avalanche runout distances (Naaim et al. 2013), while conserving high-impact pressures even close to the point of rest (Sovilla et al. 2010) and thus high damage potential (cf. Ballesteros-Cánovas et al. (2018)). In the areas of no change or decrease, there might not even be much snow available for melting during winters in the future.

With our definition, a zero-crossing occurs when air temperature fluctuates from below zero to above zero, even for a short period of time. It is worth noting that such atmospheric zero-crossings do not necessarily capture freeze-thaw cycles in the ground or snowpack, and additional information about the duration of thawing and freezing may be required to better represent the potential trigger of snow avalanches. Dyrrdal et al. (2012) also found positive trends in near-zero events in the entire region (1957-2010), but trends were mainly statistically non-significant, except in small regions along the Swedish border. Their analysis was based on daily mean temperature and ended in 2010, thus our results are more robust and the pronounced positive trends in the entire county seem realistic. Trends are, however, very sensitive to the choice of period.. This is clearly shown by Kerguillec (2015), who studied atmospheric freeze/thaw cycles (zero-crossings) in Norway using daily thermal data from 20 meteorological stations for the period 1950–2013. Different decades displayed different trend directions and magnitudes at the different stations. Although he found now obvious trends, he did find a cyclicity at many stations that coincided well with phases of the North Atlantic Oscillation (NAO). He claims that a strong negative NAO index generally increases zero-crossings in coastal regions, particularly those of central Norway including two stations in Troms county. According to Gillett et al., (2013) most climate models simulate some increase in the winter NAO index in response to increasing concentrations of greenhouse gasses. If this is true, we might speculate that more frequent positive NAO in the future might give fewer zero-crossings in Troms. This is indeed what we find for coastal areas, while inland areas are expected to have more zero-crossings in the future compared to present climate. These are the coldest areas today, and an increase in temperature will bring winter temperatures closer to zero.

We have shown that high wind speed frequency has not changed significantly in Troms over the past decades. This is in line with earlier studies. Wind is, however, a tricky element to study due to its very local character.
We do show a slight increase in the most exposed areas in the mountains of Troms, including the higher altitudes of our focus areas. Weather these changes are due to a change in the frequency of cyclones as suggested by Parding & Benestad (2016), or a more general increase in wind activity, is not trivial. Storm track activity in the Northern Hemisphere is well correlated with NAO and the North Pacific Oscillation (PNA) (e.g. Lee et al., 2012). Positive anomalies of the NAO Index are associated with a strengthening of the mid-latitude westerly flow over the North Atlantic, which manifests itself as an

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intensification and poleward deflection of the North Atlantic mid-latitudinal storm track (e.g. Sorteberg et al., 2013). Thus, an increase in the winter NAO index, as suggested by Gillett et al., (2013), might result in more frequent storms at our latitudes.

Our two focus areas, Senjahopen and Jøvik, have and will experience many of the same changes in weather indices relevant for access disruptions. However, as Senjahopen is more exposed towards the ocean and any incoming weather, we find that changes in snow amount and frequency of snowfall events are larger here compared to Jøvik. In both areas an increase in snow variables has occurred in the last decades, while a decrease is expected towards the end of this century. This means a potential for less dry snow-related access disruptions in the future, but wet-snow avalanches and slushflows may increase. In the far future, we have shown that zero-crossings and events of heavy water supply are projected to increase, and more so in Jøvik. In areas where there is still a significant amount of snow in 2071-2100, these weather indices might become a larger threat as potential triggers of avalanches. Our findings support to a large degree the Troms climate fact sheet of Hisdal et al. (2017), which states that debris avalanches, debris flows, and slushflows will become an increased threat in Troms county in the future, and that snow avalanches may become a larger threat in the short run due to more rain-on-snow events, but reduced snow amounts in the long run will decrease the risk for snow avalanches.

In a changing climate it is particularly important to identify areas of increased vulnerability and risk of weather-induced hazards. Remote seaside communities, such as Senjahopen and Jøvik, require specific measures for climate adaptation that sustains the safety of local citizens and businesses. According to Kalsnes et al., (2016) there is a lack of technical competence and capacity in the municipalities, who, by Norwegian law, are responsible for preventive measures and risk management, associated with e.g. weather-induced landslides. Literature on weather vulnerabilities and climate adaptation recommends increased public sector coordination (Leiren & Jacobsen, 2018), but the different mandates of responsible public authorities sometimes clash. With a higher risk of water and rainfall-induced hazards and more frequent freeze-thaw conditions in certain areas, a better coordinated climate adaptation, cooperation between different sectors, as well as guidance and training of local authorities is crucial.

Data availability: Gridded observation-based data, described in Section 3.1, is available upon request to the Norwegian Meteorological institute or the corresponding author. Future projections downscaled to a 1x1 km grid over Norway, as described in Section 3.2, are available for download on https://nedlasting.nve.no/klimadata/kss (in Norwegian).

Author contribution: AVD designed the experiments in close collaboration with KI, and carried out most of the analyses. IBN provided data and code for analysing zero-crossings. JKSJ supervised the process and provided the social scientific perspectives. AVD prepared the manuscript with contributions from all authors.

Competing interests: The authors declare that they have no conflict of interest.

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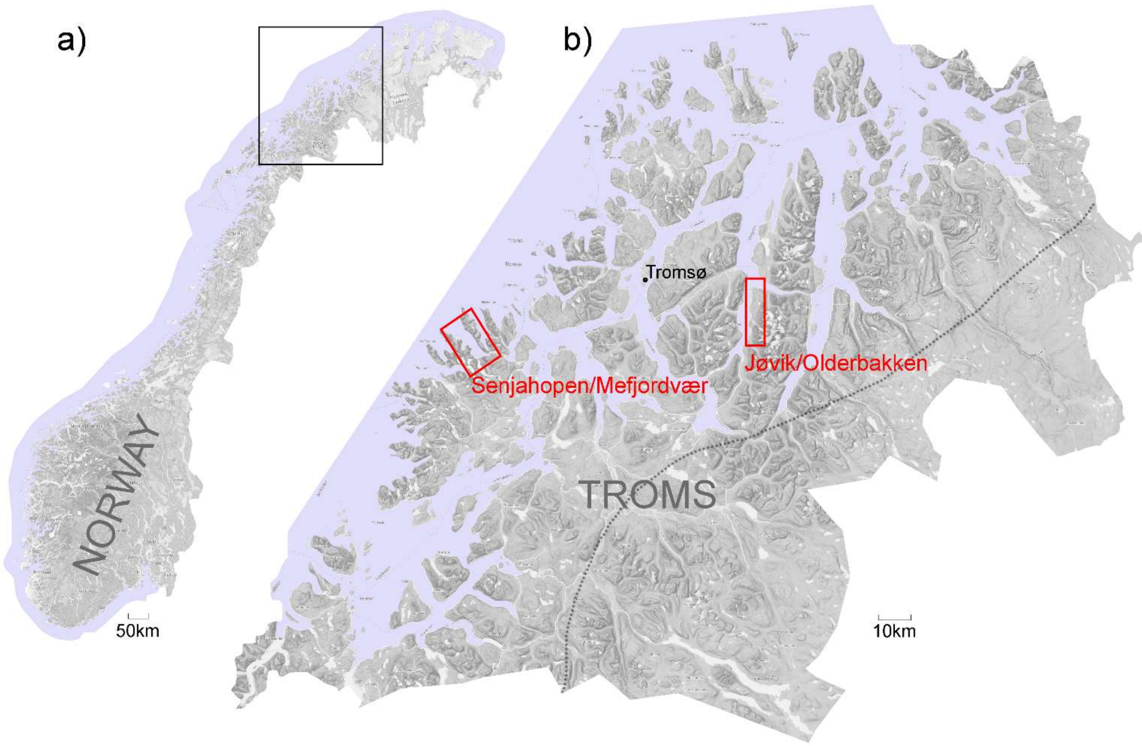

Figure 1: Map of Norway (left) and Troms county (right), with inland and coastal regions separated by the stippled line, and our two focus areas, Senjahopen and Jøvik in red squares.

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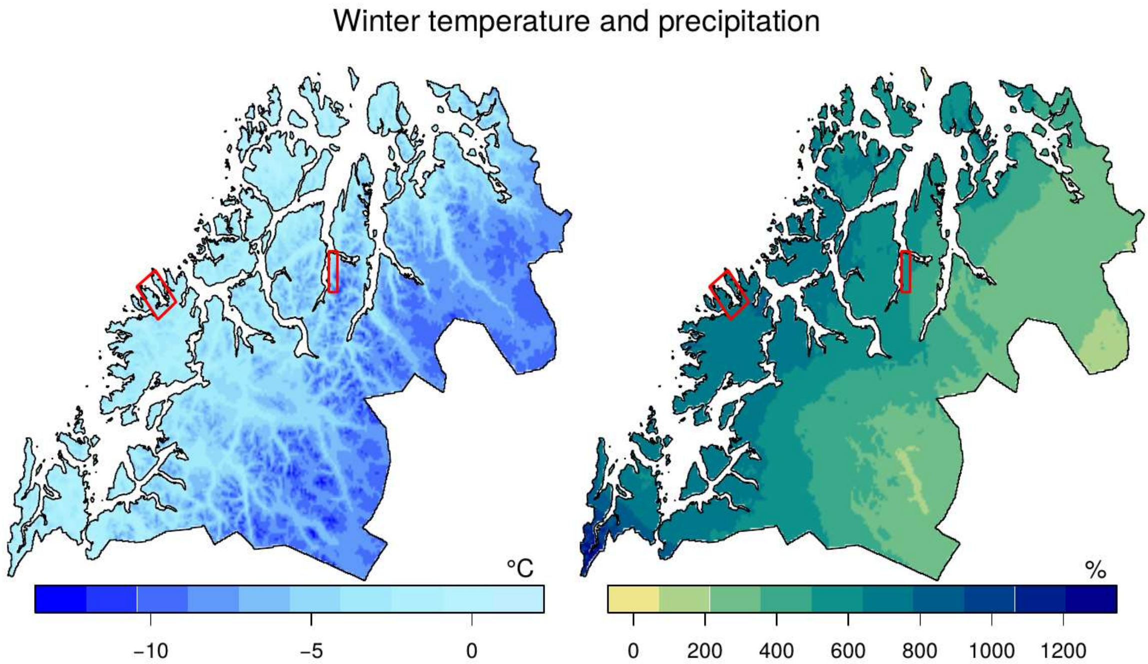

Figure 2: Mean winter temperature and total winter precipitation averaged over the period 1981–2010.

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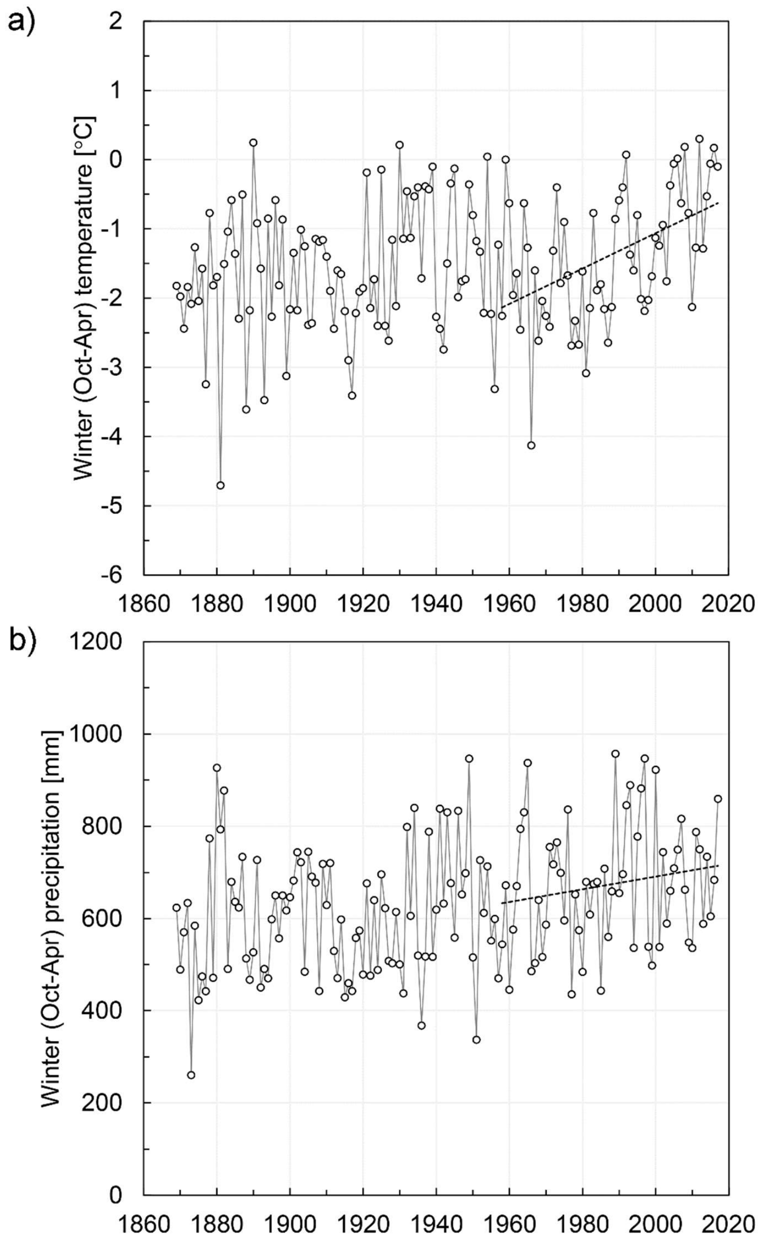

Figure 3: Mean winter temperature (a) and total winter precipitation (b) measured at Tromsø meteorological station in the period 1867-2017. The stippled line indicates the trend in the period 1958-2017.

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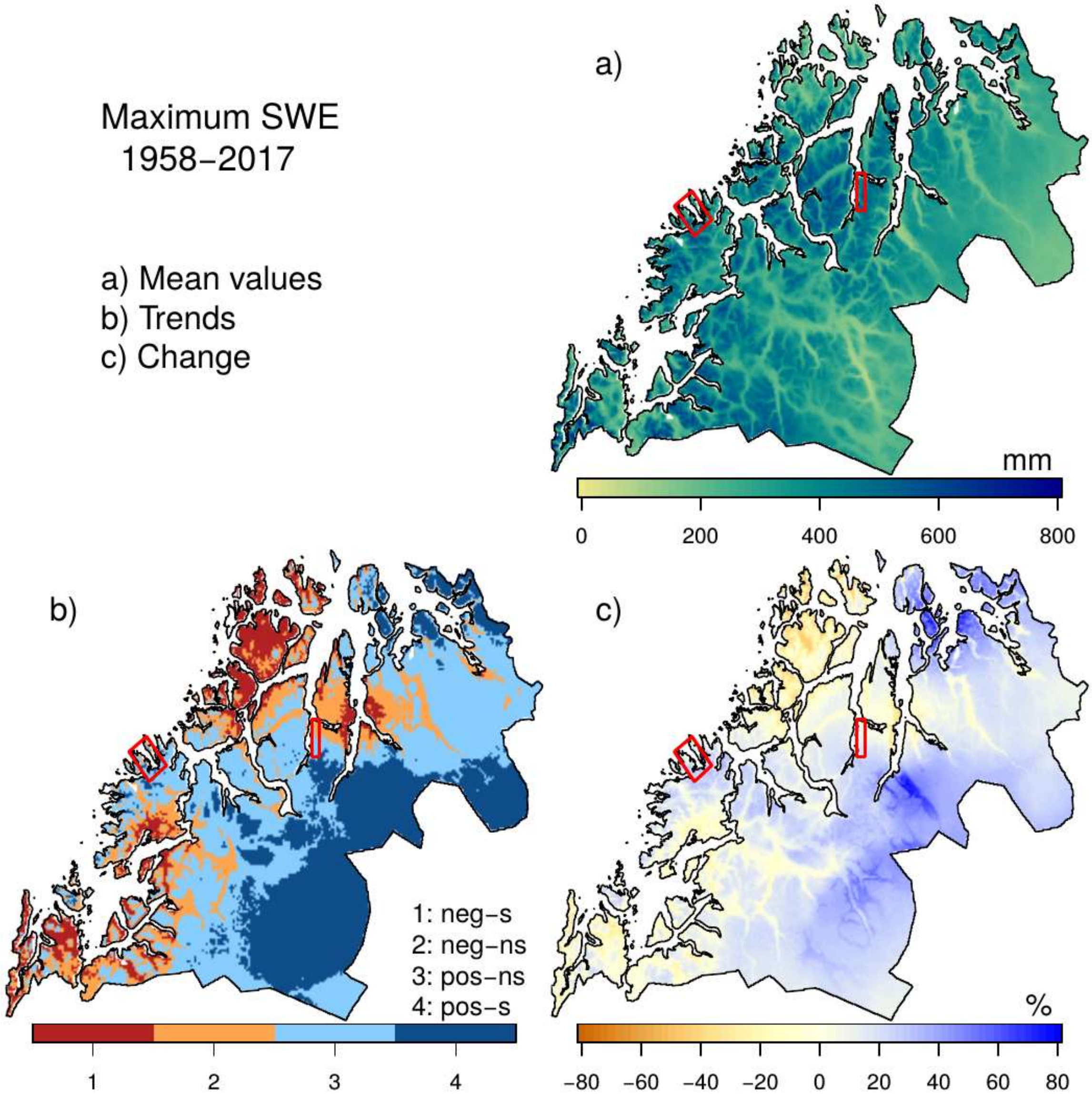

Figure 4: Mean values (a), trends (b) and changes (c) in winter (Oct–Apr) maximum snow water equivalent (SWE) for the period 1958–2017. In b), positive trends are illustrated in blue and negative trends in red; dark red and blue colors represent statistically negative and positive significant (s) trends, respectively. Light colors represent statistically not-significant (ns) trends. In c), percentage changes between the two 30-year periods 1958–1987 and 1988–2017 are shown.

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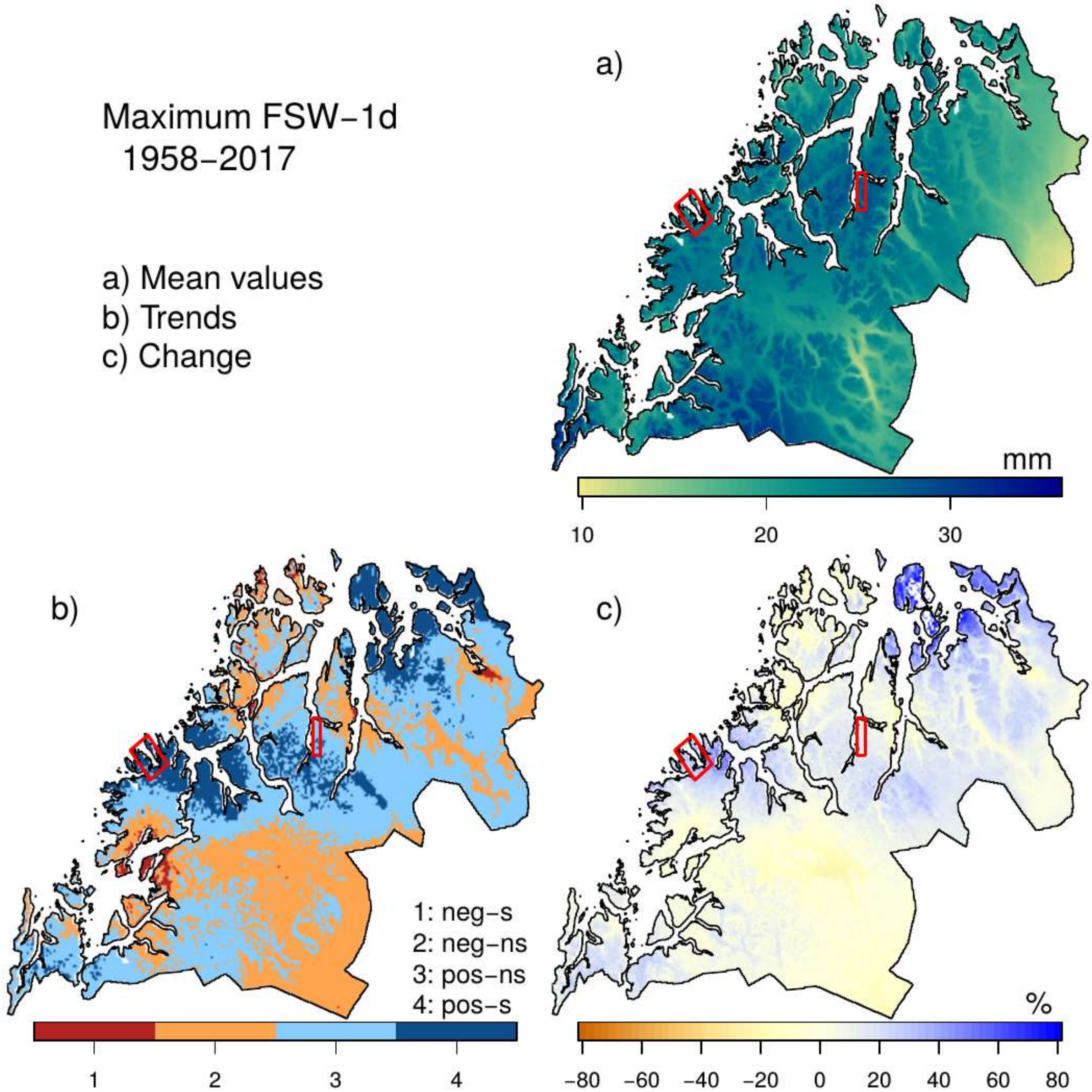

Figure 5: Maximum 1-day snowfall during winter (Oct–Apr) for the period 1958-2017, based on maximum fresh snow water equivalent for 1-day duration (WM-FSW-1d). Mean values (a), trends (b) and changes are shown in the same way as in Figure 3.

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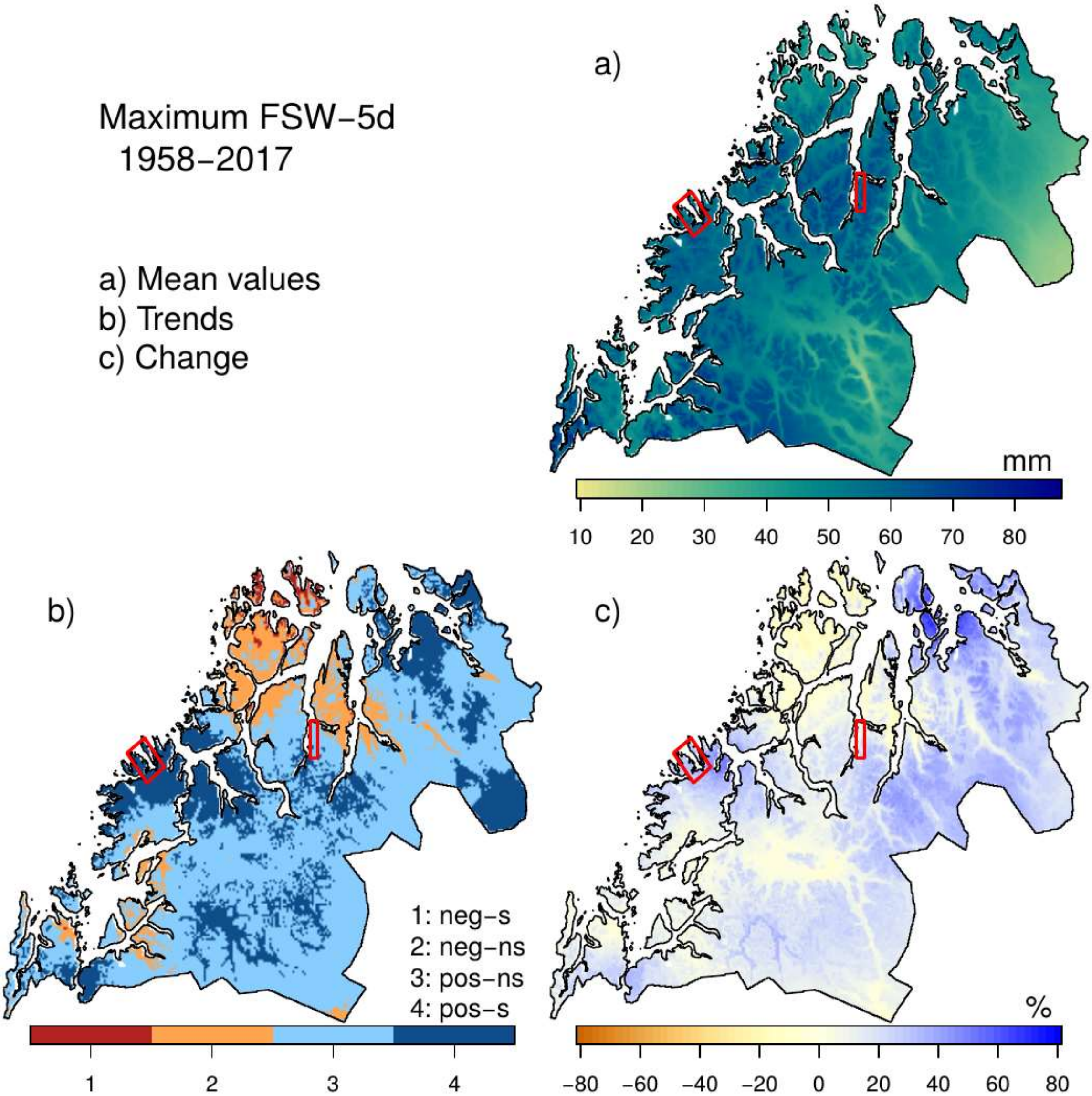

Figure 6: Maximum 5-day snowfall during winter (Oct–Apr), based on maximum fresh snow water equivalent for 5-day duration (WM-FSW-5d). Absolute mean values (a), trends (b) and changes are shown in the same way as in Figure 3.

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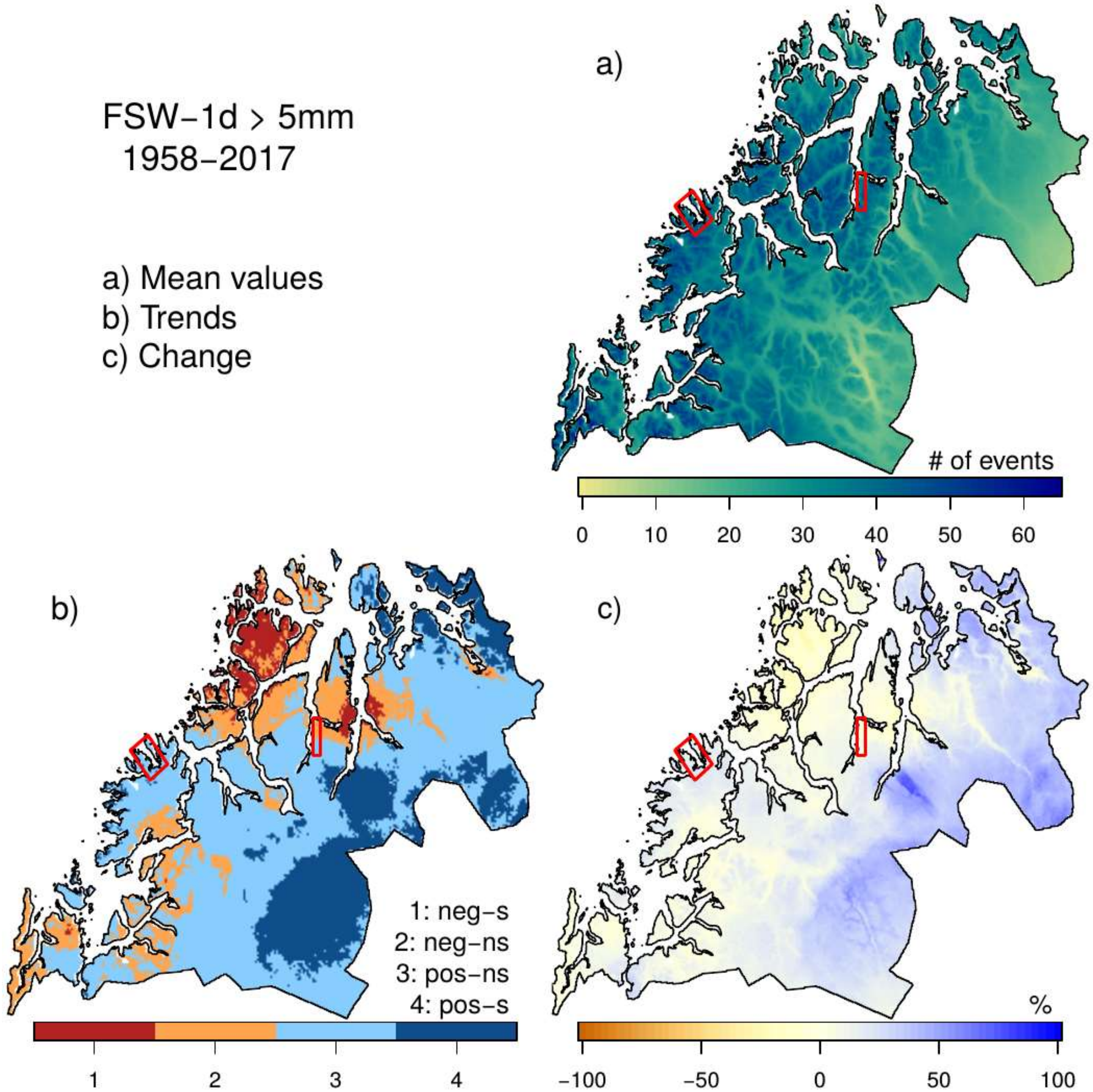

Figure 7: Frequency of 1-day snowfall exceeding 5 mm during winter (Oct-Apr) for the period 1958-2017, based on fresh snow water equivalent for 1-day duration (FSW-1d > 5 mm). Mean values (a), trends (b) and changes are shown in the same way as in Figure 3.

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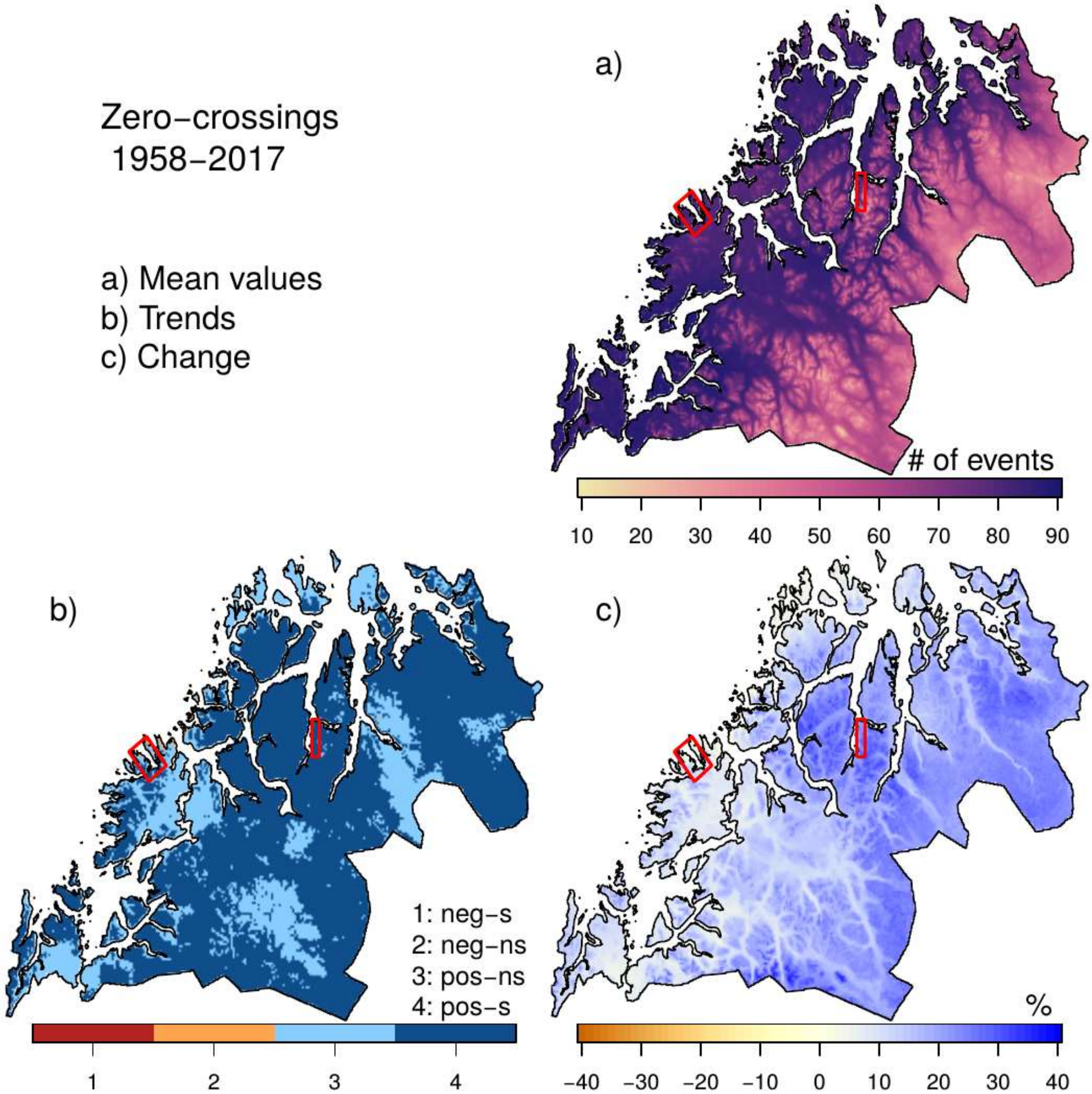

Figure 8: Frequency of zero-crossings during winter (Oct-Apr) for the period 1958-2017, based on minimum and maximum daily temperature. Mean values (a), trends (b) and changes are shown in the same way as in Figure 3.

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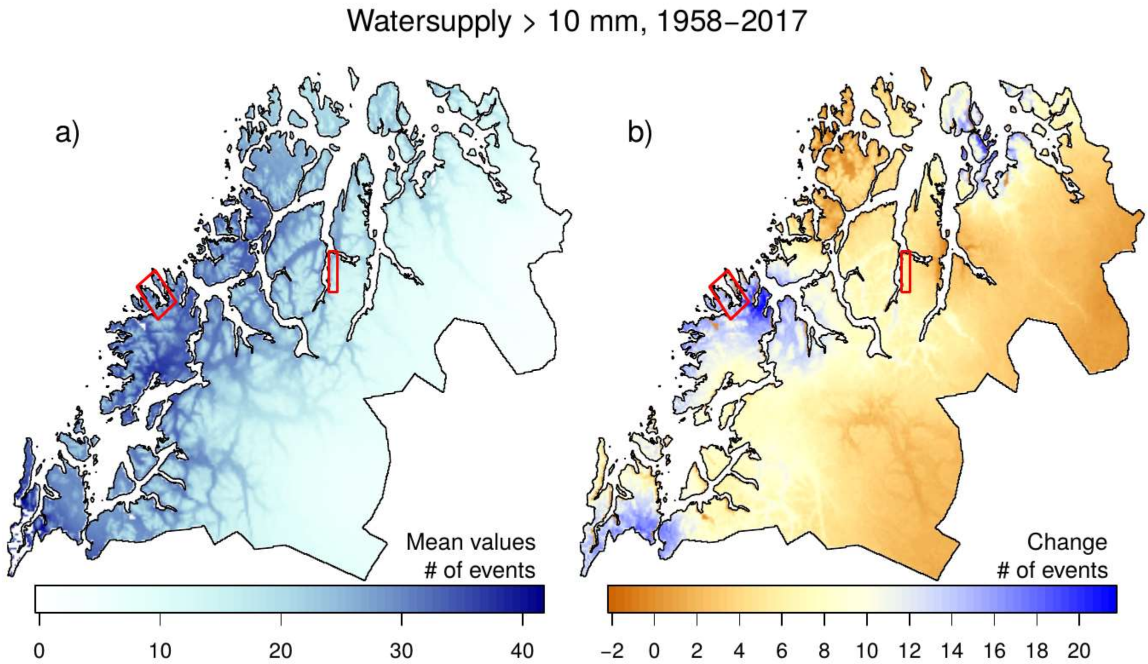

Figure 9: Frequency of days with water supply exceeding 10 mm during winter (Oct-Apr) for the period 1958-2017, based on precipitation and snow melt. Mean values (a) and absolute changes between 30-year periods 1958–1987 and 1988–2017 (b) are shown.

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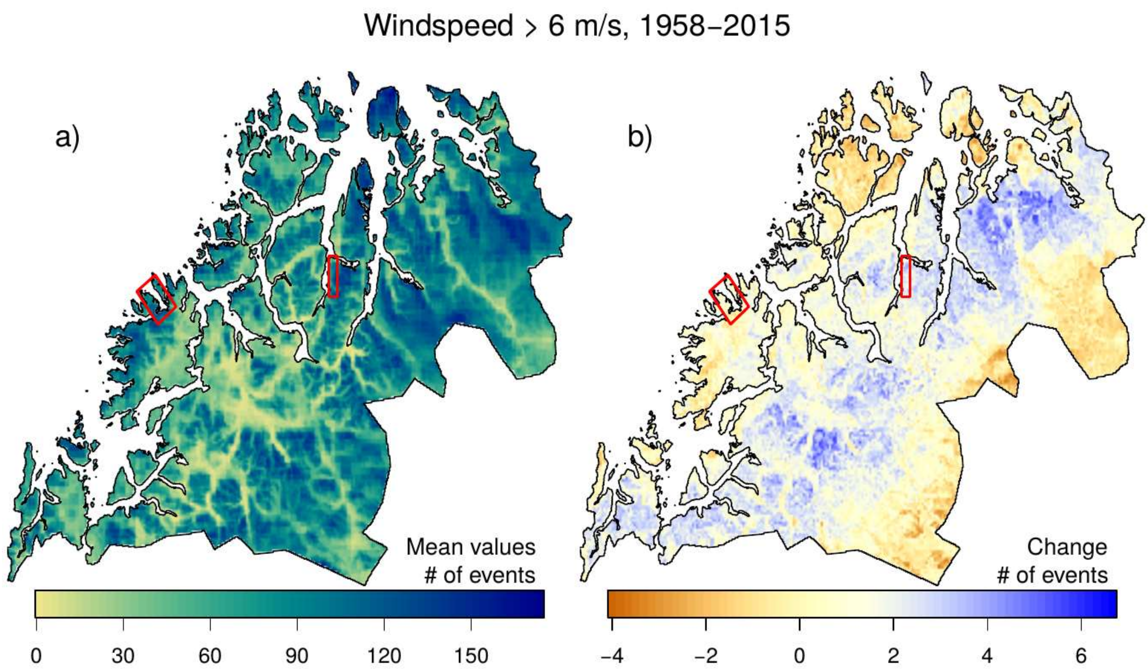

Figure 10: Frequency of days with 10-meter wind speed exceeding 6 m/s during winter (Oct-Apr) for the period 1958-2015. Mean values (a) and absolute changes between 30-year periods 1958–1987 and 1988–2017 (b) are shown.

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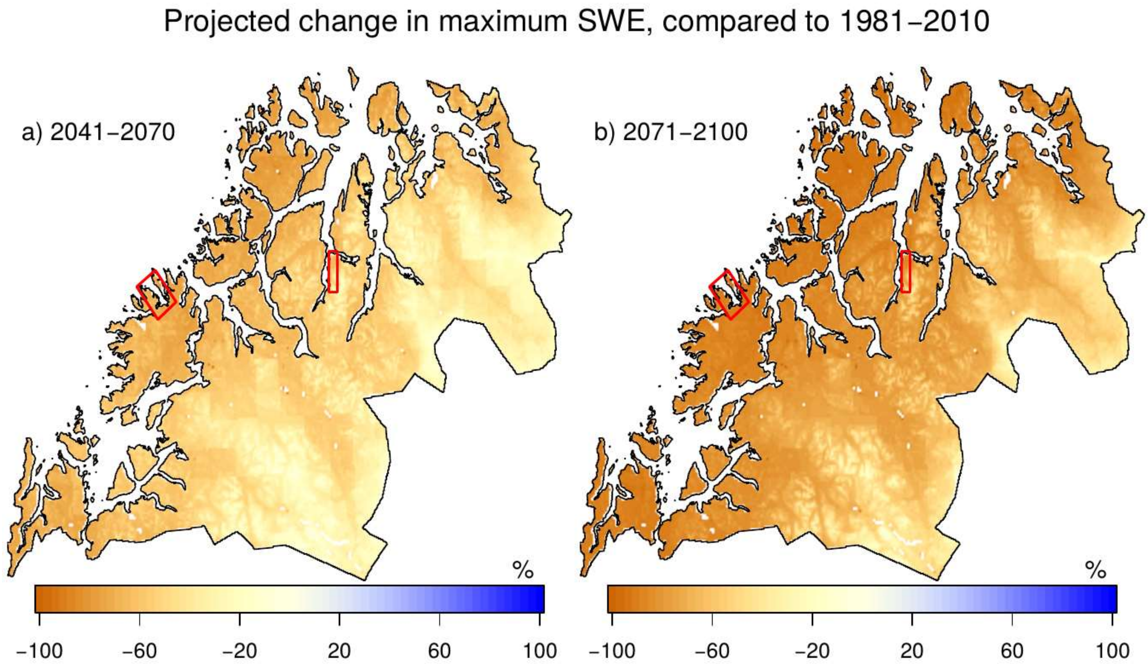

Figure 11: Projected change in maximum snow water equivalent (SWE) during winter (Oct–Apr) between 1981-2010 and a) near future (2041-2070); b) far future (2071-2100.

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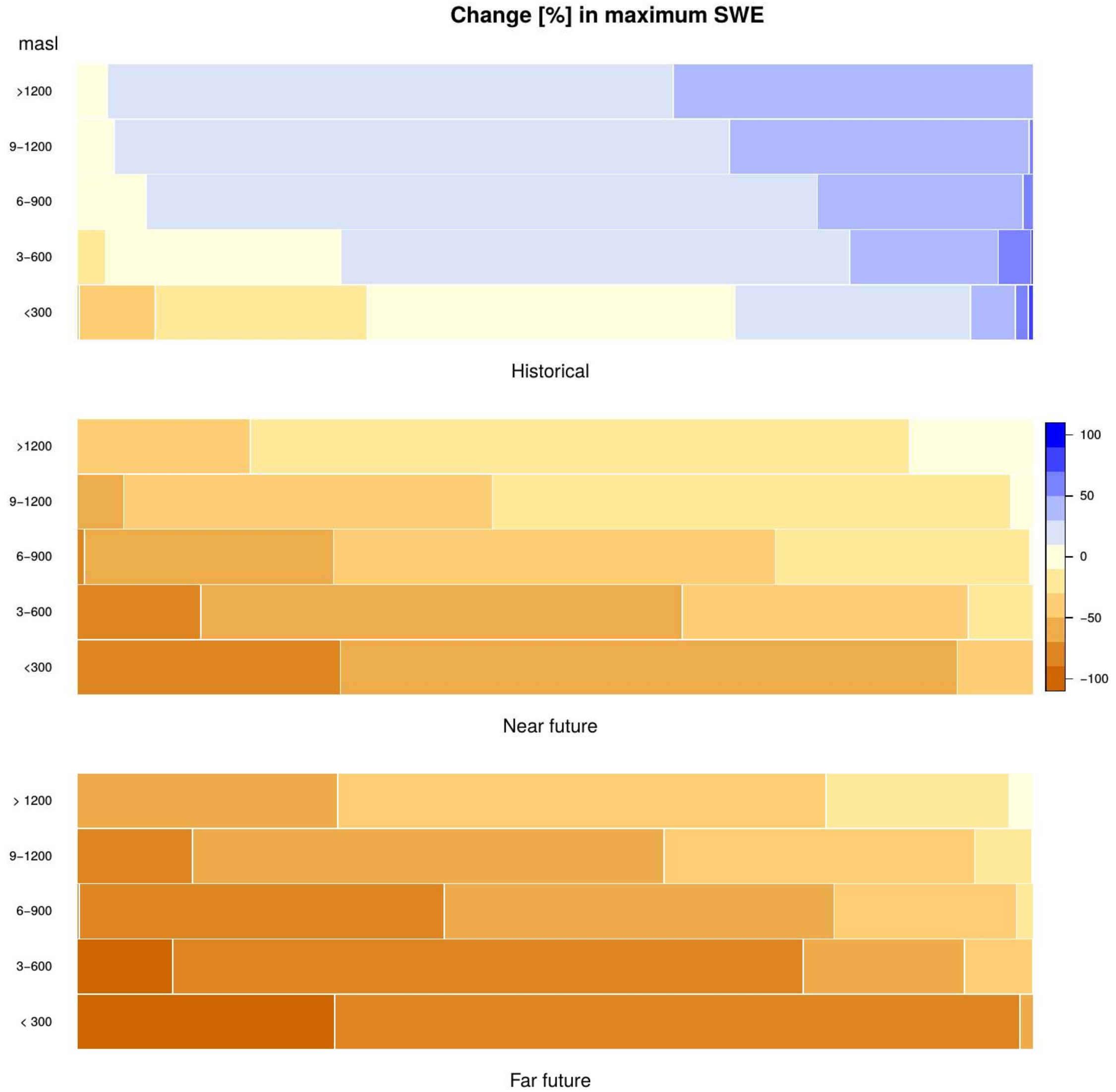

Figure 12: Percentage change in winter maximum SWE in different elevation levels for: historical period (change between 1958-1987 and 1988-2017; upper panel), near future (change between 1981-2010 and 2041-2070; middle panel) and far future (change between 1981-2010 and 2071-2100; lower panel). The length of the colored bars represent the fraction of grid cells within the different intervals given by the legend.

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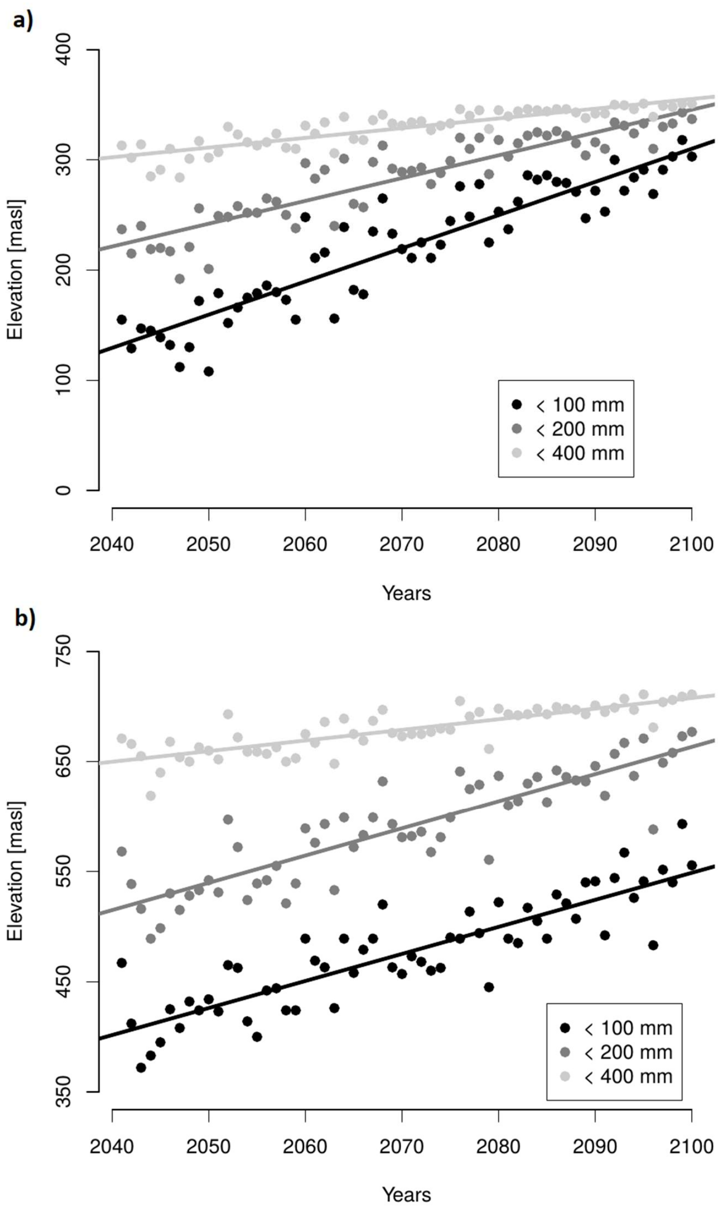

Figure 13: Projected future development in median elevation where winter maximum SWE is below 100 mm (black), 200 mm (dark grey) or 400 mm (light grey). a) Inland and b) coast (see map in Figure 1).

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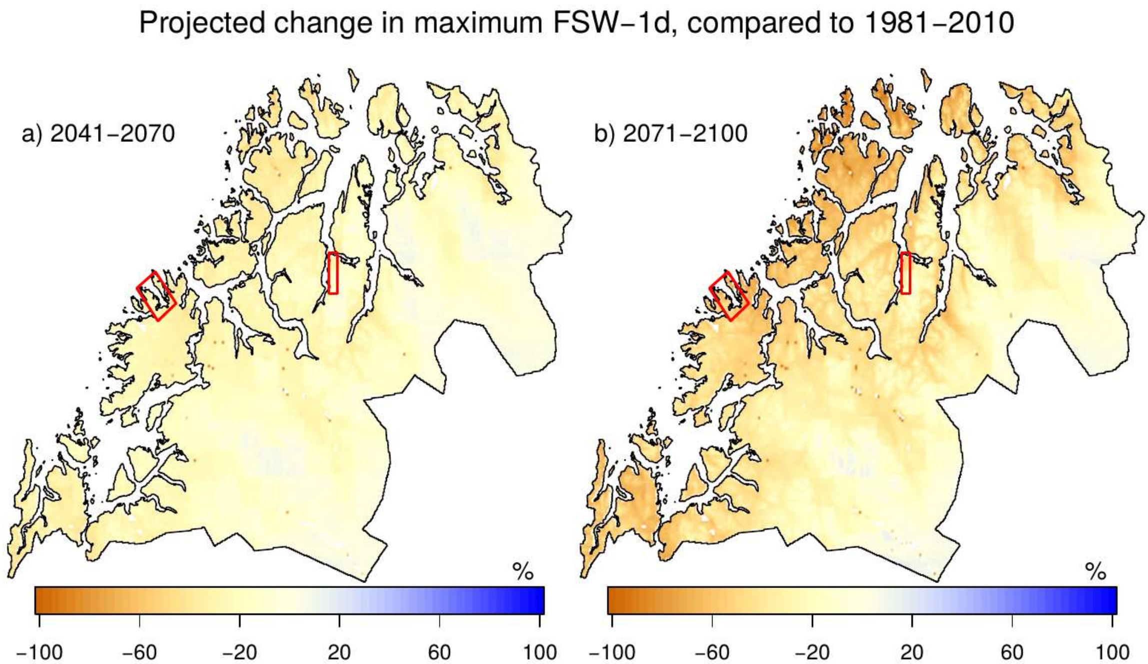

Figure 14: Projected change in maximum 1-day snowfall during winter (Oct–Apr) between 1981-2010 and a) near future (2041-2070); b) far future (2071-2100, based on maximum fresh snow water equivalent for 1-day duration (WM-FSW-1d).

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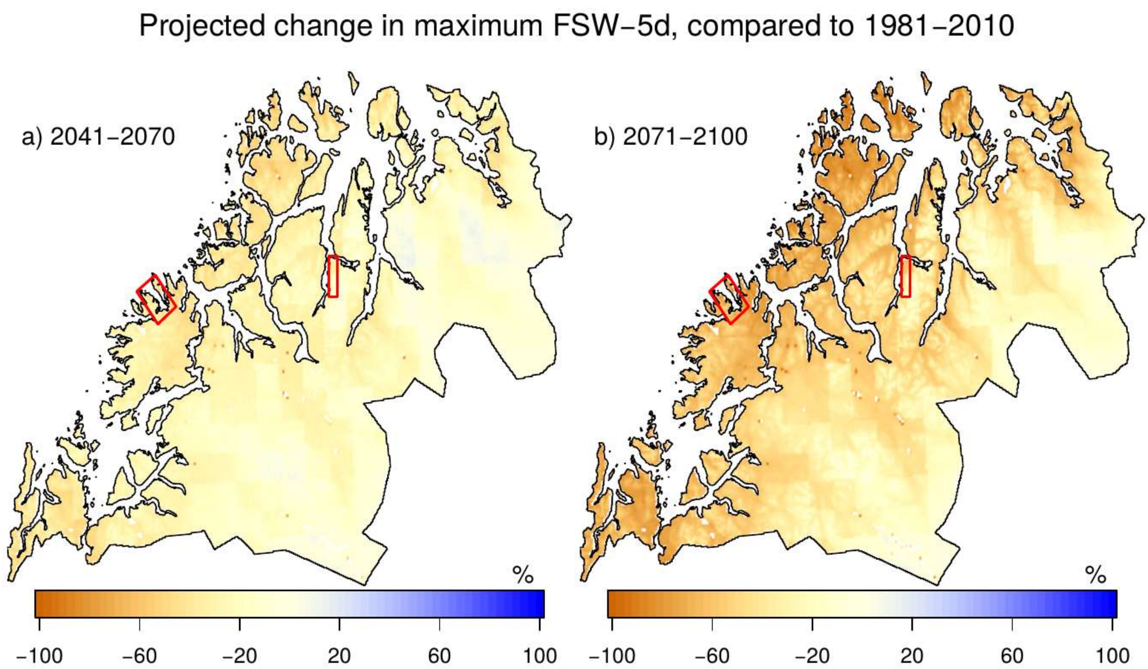

Figure 15: Projected change in maximum 5-day snowfall during winter (Oct–Apr) between 1981-2010 and a) near future (2041-2070); b) far future (2071-2100, based on maximum fresh snow water equivalent for 5-day duration (WM-FSW-5d).

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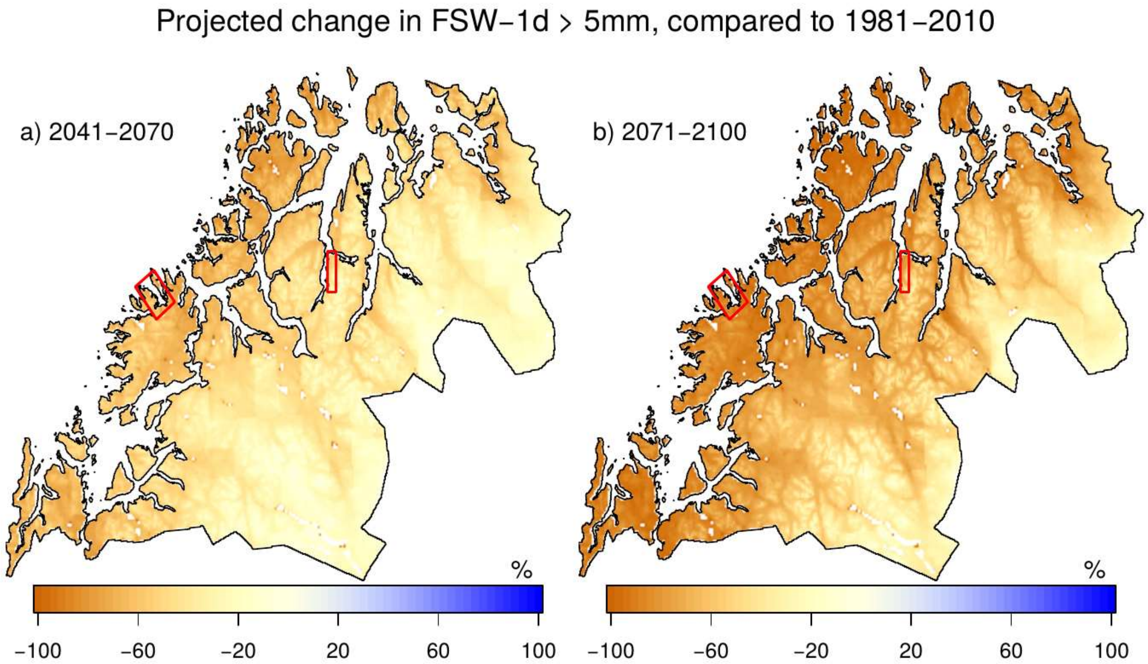

Figure 16: Projected change in the frequency of 1-day snowfall exceeding 5 mm during winter (Oct-Apr) between 1981-2010 and a) near future (2041-2070) and b) far future (2071-2100), based on fresh snow water equivalent for 1-day duration (FSW-1d > 5 mm).

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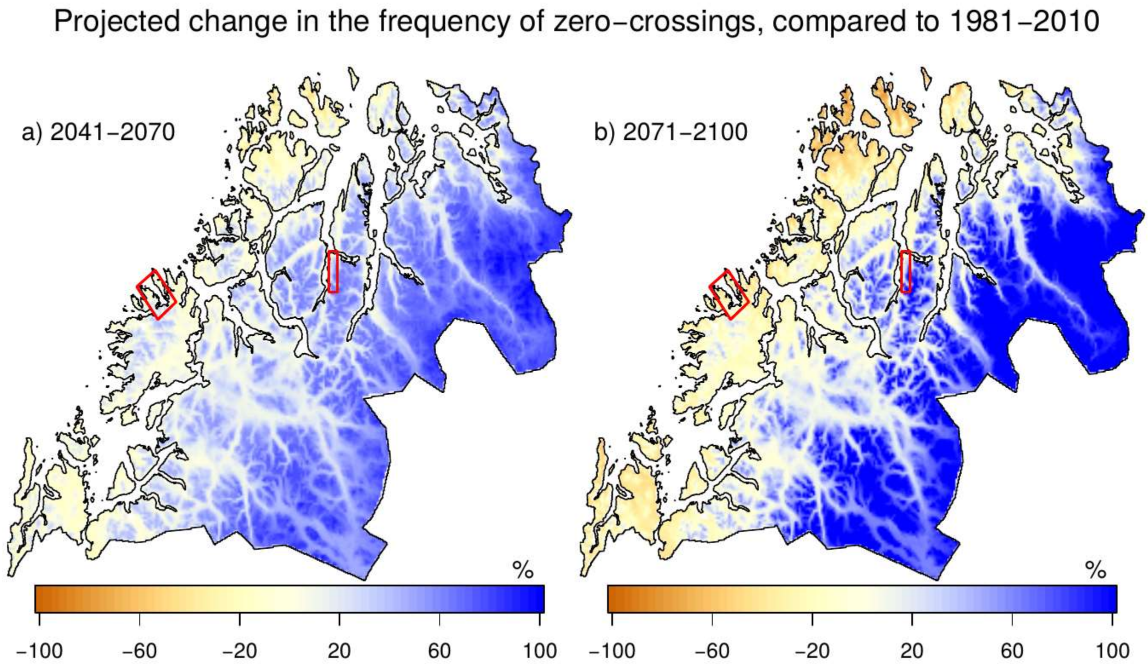

Figure 17: Projected change in the frequency of zero-crossings during winter (Oct-Apr) between 1981-2010 and a) near future (2041-2070) and b) far future (2071-2100), based on minimum and maximum temperature.

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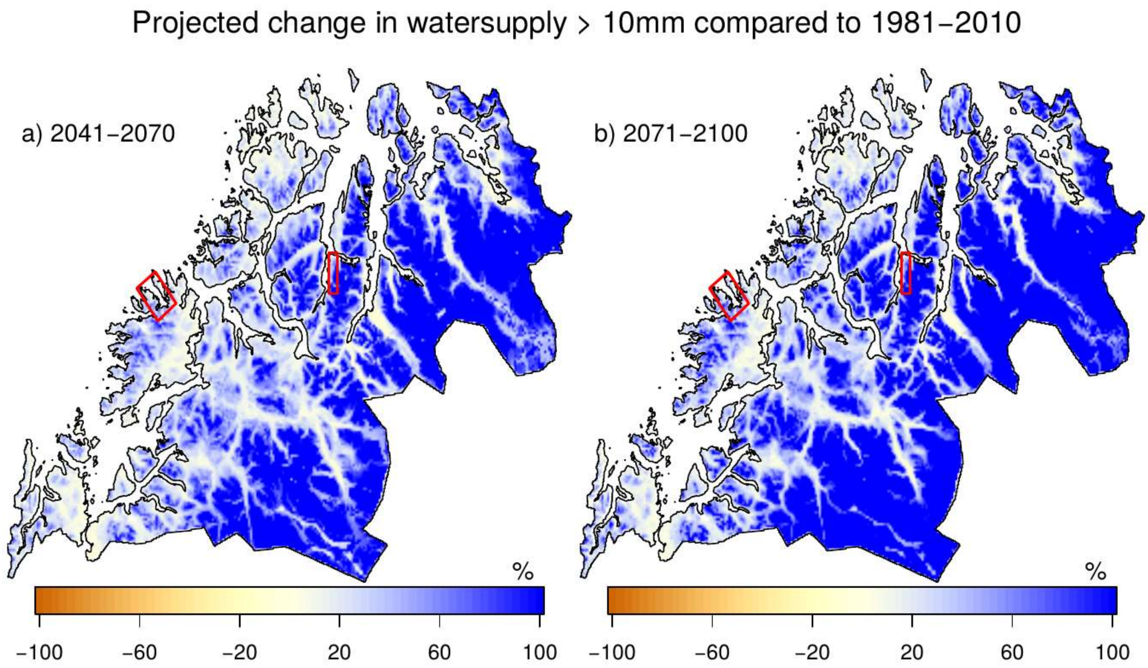

Figure 18: Projected change in the frequency of water supply exceeding 10 mm during winter (Oct-Apr) between 1981-2010 and a) near future (2041-2070) and b) far future (2071-2100), based on snow melt and rainfall.

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