Review of «Present and future changes in winter climate indices relevant for access disruptions in Troms, northern Norway» by Dyrrdal et. al.

Dear Frank Techel (Referee #1)

We would like to thank you for the very thorough review and valuable feedback on our manuscript. We greatly appreciate the time and effort you have put into this. We agree to a large degree on your suggestions, and try to meet these as best we can. We have done a major rewriting and restructuring of the manuscript, and hope to have clarified many of the issues raised. The introduction and definition of climate indices are more specifically linked to access disruptions, e.g. through difficult road conditions, as well as snow avalanches and slushflows, including relevant literature. In the Results section we now present each index separately, with past and future changes following each other, and for the whole of Troms followed by the Focus areas with selected high and low elevation bands. As suggested, we now highlight some absolute values in the results. Uncertainties are to a greater extent discussed in Section 5, including uncertainties associated with data and methods, and particularly the climate and hydrological projections. Please refer to our answers to your questions and comments below.

The authors present an analysis describing current and future climate in the region of Troms, by focusing on weather indices considered as indicators for snow avalanche activity. The study is motivated by climate models predicting significant changes for the second half of the century, which may lead to a change in the type and frequency of natural hazards affecting access to the often isolated settlements along the coast.

From my perspective, the topic - and the outcome of the study - is of high relevance to decision-makers in the region with climate change already impacting the Arctic significantly. From a scientific perspective, and as far as I can judge, the novel aspects are the derivation and analysis of weather elements from future climate models relevant to avalanche activity. Mostly, the manuscript is easy to read. Figures are of good quality, illustrating the key findings. The methodology is scientifically appropriate, the trend analysis essentially identical to the approach taken in an earlier publication by Dyrrdal et al. (2012).

There are, however, some aspects which should be improved, most notably the use of a more concise language, a better structure in some of the sections, the description/definition of the weather indices, the link between the weather indices and their expected influence on avalanche activity, the discussion of uncertainties associated with the derived indices and their interpretation in regard to trends in avalanche activity, and presenting more often absolute values rather than just percent changes for future predictions. I address these points in more detail below.

1 General remarks

The focus of the manuscript are weather indices related to snow avalanches (Abstract p1l14). However, I feel this point could be emphasized when introducing the goals of the study (p2l20-22, p3l21-22). Potentially, the goals could be more specific by formulating research questions highlighting the focus on deriving and exploring weather elements potentially indicating difficult driving conditions (conditions and changes at sea level are most relevant) and/or relating to increased hazard of snow avalanches (conditions and changes at the elevations of avalanche starting zones and in run-out zones are of interest).

We agree and have made this more clear in the revised version. Our main focus is typical winter climate indices known to potentially cause access disruptions in Troms, northern Norway. Snow avalanches are among the natural hazards that most frequently lead to highway blockages. Also slushflows are among the winter hazards that may lead to dangerous road situations and sometimes also road outages. Finally the selected climate indices for the two above hazards are also associated with access disruptions in general. Indices for the latter also include freeze-thaw cycles (zero-degrees Celsius -crossings) which may lead to slippery road conditions.

Note that we now refer to "climate indices" instead of "weather indices" throughout the paper.

Please reflect the use of the term «risk» throughout the manuscript. In some cases, using hazard, likelihood or frequency would seem more appropriate than risk (e.g. p1l21, p1l22, p14l15, p14l23). From my understanding, risk should refer not just to the frequency or magnitude of an event, but requires something actually being exposed to the risk (here, this could be the risk that a road is hit by an avalanche).

We agree that this is a bit overstated. We have replaced risk with likelihood and frequency as suggested. However, hazard and risk has been used in the first part when we mention road user perceptions, that is, how road users perceive snow avalanches and driving on roads where avalanches might strike.

Wind: As you are lacking wind-data for the future and as wind is spatially highly variable, I wonder whether the manuscript would become more focused by removing wind as a parameter considered in the study.

The wind projections for future, based on downscaling and bias-adjustment of a ten model EURO-CORDEX ensemble, are now ready. We are using that in combination with snowfall to compute changes in snow drift in the most exposed locations in the focus areas. The same analysis is done for past climate. See Section 3.1. We have removed the analysis of wind speed alone.

The terminology is sometimes not fully consistent with existing definitions (e.g. to my knowledge, a «snow melt avalanche» as on p13l2 is not a defined term). You may refer to the glossary of the European Avalanche Warning Services, which includes short descriptions for each term: https://www.avalanches.org/glossary-2/.

In the revised paper, we use <u>snow avalanches</u> as a common term for all kinds of snow avalanches and <u>slushflows</u>, which also are a major natural hazard in Norway (cf. Hestnes 1998, Annals of Glaciology 26). In Chapter 3.3 we also refer to landslides as a common term for rock avalanches

(including rock fall) and debris avalanches (debris flows, mudflows), unless where a specification into type is needed. We have followed the classification from Lundgren et al., (2015 - http://publikasjoner.nve.no/rapport/2015/rapport2015_90.pdf***).***

1.1 Strengthening the link between weather indices and snow avalanche activity

The link between weather indices and avalanche activity should be made stronger, by exploring more specifically what changes are expected at the elevation of avalanche starting zones and in avalanche run-out zones, what weather indices are expected to relate to the release of dry-snow or wet-snow avalanches, and which indices to difficult driving conditions.

Someone responsible to decide on natural hazard mitigation strategies for roads in a changing climate would probably like to know how conditions change at road level, but also at the elevation of avalanche starting zones. This is also in line with the approach taken by Jamieson et al. (2017), who explored expected changes at road level and in avalanche starting zones in Canada in a changing climate.

In your study area, most of the roads and populated places are located close to the sea shore (p4l1-2), at an elevation just above the sea level. This is therefore a highly relevant elevation for decision makers (e.g.: How often will it snow? How much snow will there be in the future?), which may influence driving conditions at road level (less frequent snow falls) or the run-out distance of avalanches (e.g. due to no snow in the run-out zone). Similarly of interest would be to know what changes are expected in the avalanche starting zones, say at elevations of 500 or 800 m. I suggest you specify relevant elevation bands and describe more specifically changes at these elevations, either across the entire coastal region, or for the two focus regions.

Focusing more on the elevations relevant for decision-makers may also provide more details when discussing results and potential influence on future access disruptions.

We have computed changes of all selected climate indices in the highest elevation band known to be avalanche starting zones (between 1000 and 1300 masl in Jøvik/Olderbakken and > 700 masl in Senjahopen/Mefjordvær), and for a low elevation band (< 200 masl) where roads are located in the two focus areas. The high elevation band is defined in collaboration with local avalanche experts. Note that to include more of the higher elevations in the two focus areas, we extended the areas a bit towards the east, thus the computed changes for the focus areas differs somewhat from the last version. See Section 4.

We agree that there should be a larger focus on road conditions, and we have rewritten parts of the manuscript to highlight this.

We have also made more clear what climate indices are expected to relate to the release of snow avalanches, slusflows, and which indices to difficult driving conditions.

1.2 Absolute values for historical, near and far future

Mostly you describe changes in percent only, except for the maps 1958-2017. While this is fine for the spatial data, as a reader, I would appreciate two things:

Would it be possible to always combine the maps of the historical period with the predicted periods? For instance, Fig. 4a-c with Fig. 11a-b as Fig. 4d-e? If these sub-figures were combined in one figure, current observations and future changes would be very close together, facilitating the interpretation of the change values, as compared to looking at Fig. 11 by itself.

This is a good suggestion. We have now restructured the Results section, giving results for each index separately, first for the whole area for both past and future climate, followed by results for the study areas and selected elevation bands. The figure on future climate now follows the figure on past climate for each index.

A second recommendation in that respect: In the text you often only refer to percent changes, which by itself is hard to visualize for the reader. I would appreciate if absolute values could be provided, at least for some examples. Obviously, this will make little sense across the entire region and the whole elevation range, but this could be shown for the two focus regions (for instance included in Table 3) and/or in case you introduce elevation bands of particular interest.

We have added some examples of absolute changes in the text, highlighting the most significant results.

As the reference period for the future is somewhat different than the 30-year periods (1958-1987/1988-2017), please show a table with absolute values for the reference period (1981-2010), together with the projected future changes (again either for the focus regions and/or relevant elevation bands).

We have now included 1981-2010 mean values for the focus areas in Table 3 (now Table 2).

1.3 Abstract

Depending on the before-mentioned more general suggestions, the abstract may have to be partially adjusted.

p1l16: reading just the abstract, the term water supply is not self-explanatory. Rather explain with melt and rain in brackets, or use melt-rain as a variable name.

We have changed this variable to look at only winter rainfall > 10 mm. This seems a more appropriate variable, which is also associated with less uncertainty as the computation is more straight forward compared to water supply. Of course, snow melt is a likely contributor during events of rainfall, as referred to in Chapter 3.3.

p1l17: «In both focus areas» - at this stage, it is unclear what the two focus areas are.

Changed to: "In our two focus areas…"

p1l18: the studied snow indices increase or decrease - at this stage, without having read the manuscript, increase or decrease are difficult to interpret. I suggest sticking to results, which are specific and can be easily understood in the abstract (e.g. «snow during winter might become a rarity by 2100» (p1l19) is a very clear statement).

Thank you for this suggestion. We have re-written the Abstract to be more understandable.

p1l22: two typos in «increase the risk of wet-snow avalaches and sluchflows. »

Thank you, this now corrected.

p1l22-23: «zero-crossings, known to destabilize the snowpack...» - this statement does not reflect what you write in the Discussion on p13l11-13. In fact, the statement in the Discussion indicates that zero-crossings by themselves are not all that relevant in regard to avalanche release, while rain-on-snow or prolonged warming might be.

We agree. The sentence is removed, and zero-crossings are now more focused towards difficult road conditions.

2 Section Introduction

The Introduction provides the necessary information and the motivation for the study. Points which could be improved:

In general, it could be written in a more concise way. A paragraph describing more specifically the objectives of the study would be good (currently, some lines on p2l19-21, p3l21-23). p. 2l2-3: The sentence «Climate change has been shown to influence winter season natural hazards in several areas» seems somewhat misplaced at this location in the text, which introduces the natural hazards in the region. Maybe move to a later paragraph, where you address climate change in the region.

p2l29-p2l17: This section provides a good base for the motivation to explore weather indices related to snow avalanches, as these are the natural hazard causing most road blockages and numerous fatalities. I feel this fact could be emphasized when introducing the goal of the study (p2l21-23), by more specifically putting weather indices related to snow avalanche activity in a changing climate in the focus of the investigation. p2l21: «the article will supplement social science investigations... - Which? Please cite respective studies? State the research questions more explicitly.

You introduce the region of Troms as the region the study focuses on. Some arguments why you chose Troms are highlighted in the Study Area section, some in the Introduction. Could you bundle your reasons for selecting Troms somewhat, and maybe also briefly explain, whether other regions in Norway could have served as exemplary regions.

Thanks for these comments. We have rewritten large sections in the Introduction to make this more clear. The aim of our study is as follows: "The current study presents past and future changes in selected winter climate indices known to potentially cause access disruptions in Troms, northern Norway. We have focused on the most common access disruptions and selected climate indices which in literature are known to be potential triggers of snow avalanches and slushflows (thus focusing on natural avalanche ocurrences), or somehow generate lifeline interruptions and difficult road/transport conditions in exposed coastal and fjord areas in Troms."

In the revised paper, it is now clarified that the two focus areas/communities were chosen because their access highways have been closed nearly every winter (some winters many times) because of snow avalanches and slushflows that have hit the highway(s) or because of danger of avalanches. The study is part of a larger project on winter weather/climate induced natural hazards and access disruptions.

The following section (p2l32-p3l13) is dedicated to predicted changes in the climate/weather in the future, focusing on Troms/Northern Norway. I wonder whether a more general, concise summary of observed and predicted changes in weather/climate in Norway might suffice in the Introduction section. More detailed information on current and future climate could be provided in the following section describing the study area, as this also contains sections on current and future climate and weather, or when comparing the results to other research (in the Discussion). Furthermore, p2l32-p3l13 give the impression that a lot is known about the future climate and natural hazards. Maybe rephrase to point the reader to the specific research gap.

We moved most of the text on future climate from Section 1 to Section 2, and included the following sentence "How the effect of these changes on local communities and different sectors could play out, is however not much studied". We also added a few general sentences and references in the introduction.

p3l15-16: «Despite the expectation of more frequent snow avalanches and landslides as a consequence of a warmer and wetter climate... - Add a citation.

We added two references (and the sentence is a bit modified):

Hanssen-Bauer, I., Førland, E.J., Hisdal, H., Mayer, S., Sandø, A.B., Sorteberg, A.: Climate in Svalbard 2100 – a knowledge base for climate adaptation. Norwegian Centre for Climate Services, Report 1/2019. 207 p, 2019

Hanssen-Bauer, I., Førland, E.J., Haddeland, I., Hisdal, H., Lawrence, D., Mayer, S., Nesje, A., Nilsen, J.E.Ø., Sandven, S., Sandø, A.B., Sorteberg, A. and Ådlandsvik, B.: Climate in Norway 2100 – a knowledge base for climate adaptation. Norwegian Centre for Climate Services, Report 1/2017, 2017.

p3l6-7: «In these regions the probability of snow avalanches might increase during the first decades, followed by reduction towards the end of the century.» - Add a citation.

We have modified to “"From the development of snow amounts alone, we might expect that the probability of snow avalanches in these regions will increase during the first decades, followed by reduction towards the end of the century.” and added the following reference:

Hisdal, H., Vikhamar Schuler, D., Førland, E.J., and Nilsen, I.B.: Klimaprofiler for fylker (Climate fact sheets for counties). NCCS report no. 3/2017, https://cms.met.no/site/2/klimaservicesenteret/rapporter-og-publikasjoner/_attachment/12110?_ts=15ddfbccf32, 2017

3 Section Study region

This section has a clear structure and provides the reader with the necessary background on the regions geography, natural hazards, current and future climate. Some minor points which could be improved:

p3 l29 - 30: «The Sub-Arctic and Nordic Arctic regions further north have experienced a major change in climate over the past few decades.» - I feel this sentence does not really fit into this paragraph, which introduces the geography and the geohazards present in this region.

The section is now rewritten, restructured and some sentences are moved between sections to better fit the purpose of the sections.

p4 l4: «...250 people have been killed in avalanches in Troms in the past, where of most died in snow avalanches...» - What does the first avalanches refer to? What time span does the past address? Do you maybe know how many of these people were killed on roads / in buildings?

We have looked up the numbers and have changed the text in the Introduction to:

“Both snow avalanches and landslides have led to fatalities in Troms. An analysis of the Norwegian mass movement database http://skredregistrering.no/ (database version December 2019) shows that for the period 1730-2014, 376 casualties were registered in Troms. Snow avalanches resulted in 295 casualties, whereof 121 people were hit in buildings and 9 on roads. Since 2014, an additional 12 casualties are registered, according to varsom.no (all were skiing or driving snow mobile). For other landslides, 81 casualties are registered, whereof 57 in buildings and two on roads.”

This database provides a minimum estimate of historical casualties related to mass movements in Norway. Note that this database is incomplete and many of the entries have poor quality, for example, snow avalanche casualties in a database assembled by the Norwegian Geotechnical Institute (NGI) (https://www.ngi.no/Tjenester/Fagekspertise/Snoeskred/snoskred.no2/Ulykker-med-doed) amounts to 183 for the period 1972-2014, compared to 165 in http://skredregistrering.no/ for the

period 1730-2014.

p4 l6-7: «The present study will focus particularly on three communities; Jøvik/Olderbakken in Tromsø municipality and Senjahopen and Mefjordvær in Berg municipality» - I suggest moving the introduction and description of these two focus regions to a separate paragraph, where you should also provide some additional information including information on the surface area of the selected grid points and the elevation range of the grid cells covered.

We have now written an own paragraph on this, including information on the number of grid cells and their elevation. See Chapter 2.

p4 l21: «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.» This information is not very useful for the reader, as the station has existed only since 2011, and as there is no larger network at this elevation it could be compared to. I suggest you either remove this sentence, or you add some information regarding the two points above. If such information were available, you could replace it with some long-term snow depth measurements (does the meteorological station of Tromso have these?).

We agree and have removed the sentence.

p4l30-32: Did you calculate the trends? If yes, it should probably go to the Results section. If no, cite the respective study.

Yes, we agree and have included this in the result section. As far as we know, there are not many studies the Tromsø series is published, and at least not for the winter season definition we have chosen here.

4 Section Data

General remarks: Please provide at least some more details on how the parameters of interest are calculated in the models, not just what spatial interpolation methods the models rely on. For instance, what kind of a model is the seNorge snow model. Is it based on a simple degree-day model, or more complex? How many snow layers does it calculate? If you have information on the performance of the model predictions of the selected parameters, a short statement in that respect would allow the reader to judge the quality of the data (here or in the Discussion section), and hence the results. What air temperature thresholds are used in the models to distinguish between liquid and solid precipitation?

We have added more information of the derivation of the indices and the datasets, particularly the snow model. See Section 3.1 and Section 3.3

p5l9-10: Rephrase this sentence, to make it clear, whether the interpolation was part of this study, or whether it describes the data source used.

The sentence is rephrased as follows: "To obtain spatially continuous information on the recent climate, the Norwegian Meteorological institute (MET Norway) provides gridded datasets of daily temperature and precipitation on a 1x1 km grid over the Norwegian mainland. These are based on observations of daily mean temperature (T) and daily precipitation sum (P) covering the period 1957-present, and the gridded data, available at www.senorge.no, is referred to as "seNorge".

p5ll17: You introduce a variable called snow depth (SD), which is not used afterwards. Either remove it here, or explore and describe results of SD.

We have removed snow depth (SD).

p6l10-12 and Table 1: I find this a rather confusing description. There are ten GCM-RCM combinations mentioned in the text, but from Table 1 it does not become clear which combinations are used. In fact, right now this confuses more than it explains. I suggest rewriting this paragraph and moving the Table 1 to the Appendix or provide it as supplementary material. If this bias is potentially influencing results, it could also briefly be discussed in the Discussion section.

We have moved the table to Appendix, and briefly discuss climate model uncertainties in the Discussion.

Section 3.3 Weather Indices (p7): This in an important section. Restructuring this section may make it easier for the reader to distinguish which meteorological elements are associated with avalanche activity (background research), which of the weather indices address which avalanche type (dry-snow, wet-snow avalanches) or are of importance at lower elevation/road level (run- out distance) and in the starting zones (avalanche release). Furthermore, a more detailed summary table, showing the variables and their calculation would be beneficial. Additionally, at the moment some of the information relating to variables explored can be found in other sections (i.e. for change in SWE p6l9-10). Introduce somewhere that you focus on weather elements which are related to natural avalanche occurrences, at least this is what most of the cited studies have explored.

We have now stated our focus on natural avalanche occurrences in the introduction.

p7l1: it is not the indices which are potential triggers of rapid mass movements, but the indices describe weather elements which may cause such event.

Changed to: "we identify indices that describe weather elements which in literature are known to be potential triggers of rapid mass"

p7l2: Be more specific what slides refers to? Snow slides, mud slides, rock slides?

We have removed slides and rewritten this sentence as follows: We identify indices describing weather elements which in literature are known to be potential triggers of snow avalanches and slushflow, or somehow generate difficult road/transport conditions.

Currently you sometimes refer to other hazards as well, when introducing the weather indices. I propose to stick to the weather indices' relevance for assessing the potential for avalanches and difficult driving conditions, and linking these to other hazards in the Discussion only. There is some inconsistency in the naming of the variables: for instance, in the text you refer to WM-FSW1d, in the figure titles to maximum FSW-1d. FSW is a rather unusual abbreviation for fresh SWE / changes in total SWE. Could you use $\Delta SWE_{1d/\Delta SWE5d \text{ or } SWE1d/SWE5d}$ or something similar instead?

We have now harmonized the figure titles and the abbreviations used in the text. We chose to stick to FSW as it is the variable name from the seNorge snow model, and used in e.g. some NVE reports.

p7 l2-6: «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.» - From my perspective, these lines could be deleted, as these sentences more or less repeat the introductory sentence before.

Yes, we agree. This section has been rewritten.

Parameter water supply: It took me some time to get used to this term. Could you use melt-rain, or similar, as a variable name?

I suspect this would be more intuitive for readers. Please explain in more detail how water supply is calculated? Is it melt water produced in the snowpack, or melt-water run-off from the snowpack together with liquid precipitation?

As mentioned above, we low look at winter rain events > 10 mm instead of water supply.

p5l16/p6l9: I suggest changing «daily snow water equivalent» to daily total snow water equivalent to avoid misunderstandings with FSW.

OK, thank you for the suggestion. We have changes accordingly.

Parameter zero crossings (p7l21-26): «Another potential trigger of snow avalanches, and even rockfall, are zero-crossing events.» and «Frequent zerocrossings can lead to difficult road conditions and destabilize the snowpack.» - Add the respective references.

We have shifted the focus of zero-crossings somewhat towards slippery road conditions. References to snow avalanches are removed, and a paragraph has been added to Chapter 3.3

Concerning the latter statement, note that what you introduce here somewhat contradicts what you say in the Discussion (p13l11-13: «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.»). Concerning wet-snow avalanche release mechanisms, I suggest you refer to more general research as well (for instance, in his PhD Mitterer (2012) provides a good overview on literature regarding wet-snow mechanics and wet-snow avalanche prediction).

We have chosen to not focus on different types of snow avalanches, so the distinction between slab avalanches, loose snow avalanches and wet snow avalanches is removed.

Sometimes you refer to the variable maximum snow amount, other times as winter maximum SWE or WM-SWE. I suggest being more consistent which term is used.

5 Section Methods

Please provide briefly some information on the statistical software and libraries/packages used to calculate the Mann-Kendall trend test.

We have added: "(R-package Kendall)"

The reference periods differ between the historical analysis, and the comparison to the future. Could you provide this information in Table 2, together with the derived indices?

We now provide mean values for the reference period 1981-2010.

p9l6-8: Why do you explore only WM-SWE at different elevations, and not all the parameters? Is there a reason why you don't explore the very near future (2011-2040)? It would be the logical sequence following your reference period 1981-2010?

We explore this index in more detail, because it is a good proxy for changes in snow amounts, and a way of showing the development of the snow as an element. We also wanted to answer the question of when snow becomes a rarity, and when the increase in precipitation might turn from increasing snow amounts to decreasing snow amounts in different elevation bands.

We have not studied the very near future because natural variability dominates over the climate signal in the next decades.

6 Section Results

A remark, already addressed before, which applies to 4.1 and 4.2:

As a reader, I would appreciate some absolute values rather than just percent changes. For instance, I could picture a result described like «Heavy 1-day snow fall precipitation changed in focus region 1 at sea level from x to y events per winter, which represents a xy% change.» more visually than just percent changes. I therefore recommend to provide the reader with such results. As summary statistics calculated for the entire region will be little informative, you could exemplary describe these for different elevation levels and/or the two focus regions. Furthermore, this information could also be added in Table 3.

We think this is a good suggestion and have included some examples of absolute changes.

Table 3: highlight that the reference periods differ, either in the caption or the column title. - Column «Past change (1958- 2017)» should probably be changed to «Past change (1988-2017)» with the reference period being 1958-1980? - Why is water supply giving as absolute change for the past, and in percent values for the future?

Not relevant anymore, as we removed water supply. For winter rain we report on percentage changes.

For reasons, which you explain, the thresholds used to assess changes in water supply and FSW are much lower than those suggested by NVE or Jaedicke. Would it be possible to indicate the expected number of events using higher thresholds? As outlined in Dyrrdal et al. (2012) or in Jamieson et al. (2017), such extreme events are probably a better indicator for periods with increased natural avalanche activity, than small precipitation events of more than 5 mm.

We find the trend analysis difficult to perform when using a higher threshold. We do agree that some of the chosen thresholds are rather low, but given that the focus of the paper is to study weather than may lead to road closures, either as a consequence of an event, but also due to a forecast on difficult weather, we believe the selected indices are relevant. We also believe that the pattern of changes for low-threshold events can be transformed to higher-threshold events. We have clarified this in the description of our aims in the manuscript and when introducing the climate indices.

p10l31: When is the turning point from increasing to decreasing snow amounts (=WM-SWE?) reached?

This depends on the elevation, but in our results we already see an increase in elevations of low WM-SWE by 2040, meaning that the turning point has already occurred prior to 2040. As we do not study future periods before 2040, it's hard to suggest the actual period then this happens. We have included a sentence stating that it likely happens between now and 2040.

p11l3-6/Fig13a-b: I would interpret the trend lines becoming closer with time not with a decrease in variability, but actually as a more pronounced elevational gradient in WM-SWE at about 300 m in the Inland region and between 500 and 600 m at the Coast. In fact, in the Inland region this gradient goes from about <100 mm at 250 m to <400 m at 350 m. Is this plausible? Can you discuss potential reasons?

You are right. One plausible reason is the expected increase in precipitation, which in the higher elevations will mainly come as snow, while in lower elevations will come as rain and contribute to snow melt. We have rewritten the sentence as follows: "The narrowing range between smaller and larger snow amounts indicates a stronger elevation gradient for WM-SWE as winter precipitation increases, particularly in low elevations and inland regions. This might be explained by the fraction of rain and degree of snow melt in lower versus higher elevations will differ more in the future, giving a stronger decrease in the low to medium elevations."

P11l27-34: This paragraph first introduces the two focus regions (l27-29), which should be moved to Study Area section. It then discusses past (l29-31) and future (l31-34). These results should either be divided into the respective subsections 4.1 Past development and 4.2 Future development, or the results for the two focus regions should be put into a subsection of their own, together with Table 3.

We have restructured this Section according to your suggestions. See our answer to your comment further up.

p11l29: «largest change in snow variables» is not very specific

This sentence is removed.

7 Section Discussion and Conclusion

This section would benefit from restructuring, maybe splitting into subsections and/or potentially also by splitting discussion and conclusions into two sections. Currently it sometimes mixes how changing weather may influence avalanche activity and how weather/climate indices compare to other studies.

We agree on this and have rewritten these sections where we try to meet these suggestions.

Please discuss potential uncertainties or bias, which may be caused by data and/or methods, and how these were addressed. What is the general uncertainty associated with such future climate predictions?

We have rewritten large parts of these sections.

We have added a paragraph in Section 5, where we discuss the uncertainties associated with data and methods, and specifically the climate projections including hydrological modelling.

Concerning the parameter snow melt and rain (water supply), you state (p12l20-21) «As snow amounts have mainly increased in the past ... the amount of snow melt has likely not changed much» which «will change quite dramatically» in the future. You suspect that this may be caused by more rain during winter (p13l3-4). An alternative, or additional, explanation could be, that the melt season so far has been primarily outside of the defined winter (at least at higher elevations). What is the temporal distribution of the days with high water supply now and in the future? Does this change (for instance earlier onset of warming and melt in spring?) Do you have numbers on how many of the water supply days were in fact rain on snow or just melt? (this would be a very interesting point for discussing wet snow avalanche release) - Please discuss.

This is a good point, we now discuss this question in more detail in Section 5. We include numbers on projected changes in snow season and expected later onset of snow melt season (with reference), and argue that this indeed stretches into our definition of winter.

As mentioned above, we low look at winter rain events > 10 mm instead of water supply.

p12l14 and p12l18: first you state that wet-snow avalanches may increase, then that a general reduction is realistic - I suggest you group such contradictory statements closer together, highlighting the hypothetical nature of avalanche predictions in the future (see also Sinickas et al. (2016) in this regard).

Thank you for this suggestion. We have restructured the manuscript accordingly.

p13l2: what are «snow melt avalanches»?

Thank you for pointing out this mistake. It is now changes to slushflows.

p13l5: «actual areas of Troms» - actual could be deleted

We have removed "actual".

Parameter zero-crossings: could you discuss the temporal distribution within the winter? Are the changes primarily expected at the beginning and end of the season, or throughout the winter?

The following paragraph is added to the Discussion:
"Changes in zero-crossings indicate shifts in slippery road conditions. Although our definition a zero-crossing refers to the fluctuation of air temperature across zero, and additional information about the surface temperature would have given a better representation of slippery conditions, the change pattern shown here would likely be close to a change pattern of surface temperatures. For the low-lying seaside regions of Troms, with several access roads, we primarily expect changes in zero-crossings in the beginning of winter (Oct–Nov) and the end of winter (Apr–May). These seaside regions have mean temperatures close to 0 °C in the shoulder months in the present climate, and even a small temperature increase will therefore lead to large changes in zero-crossings. Fewer zero-crossings are expected both prior to and after the winter season, with the strongest change expected in October and May. In these shoulder months, the change signal of fewer crossings is expected to reach far inland, while for other months, it is limited to the coast. Increases in zero-crossings are limited to regions far inland, at altitudes above approximately

600–700 AMSL from November to April."

We added a reference to Gustafson (1983) in Chapter 3.3, who studied relationships between low surface temperatures and the development of slippery conditions.

You selected rather low thresholds for WM-FSW1d and water supply (a factor ten lower than NVE). - Discuss interpretation of these low thresholds in regard to avalanche activity and road conditions.

See our answer further up. We have also added a short discussion of this in the manuscript, Section 5.

There is a strong decrease in WM-FSW1d and WM-FSW5d in the two focus regions (more or less at sea level I presume)? At higher elevation (typical starting zone elevation or even higher?), the change is less pronounced, although from the maps it is hard to judge what WM-FSW1d / WM-FSW5d amount is predicted in the future. Again, some absolute numbers for different elevations would help the reader to understand the elevation pattern better.

Yes, we have added some absolute numbers in the text.

p13l28-34/p14l1-3 (Wind): Results confirm the statements made in the introduction with no further new findings, as wind predictions were not available for the future scenarios. Therefore, and as already suggested before, consider removing wind as a parameter entirely or providing this information in the supplementary material, and focusing on the other variables instead.

Wind projections for future, based on downscaling and bias-adjustment of a ten model EURO-CORDEX ensemble, is now ready. We are using that in combination with snowfall to compute changes in snow drift in the most exposed locations in the focus areas. The same analysis is done for past climate. See Section 3.1. We have removed the analysis of wind speed alone.

p14l8: as before «an increase in snow variables has occurred» is not very specific

Changed to: "In both areas an increase in all studied snow-related variables has occurred in the last decades, more so in higher elevations, while a decrease is expected towards the end of this century and particularly in low elevations. "

p14l11: it is not the weather indices which might become a larger threat

Thank you. this is changed to: "... weather described by the studied indices might become a larger threat as potential triggers of avalanches and challenging road conditions"

p14l5-15: A more in-depth discussion of changes at different elevations in the focus areas (road level, starting zone conditions) would be nice.

We have now computed changes of all selected climate indices in the highest elevation band known to be avalanche starting zones (between 1000 and 1300 masl in Jøvik/Olderbakken and > 700 masl in Senjahopen/Mefjordvær), and for a low elevation band (< 200 masl) where roads are located in the two focus areas. These numbers are discussed in the text.

As you can only explore weather indices, with their influence on actual avalanche activity remaining hypothetical, I suggest to discuss this point in more detail (see also Sinickas et al. (2016) who concludes: «It is highly unlikely that 'clear' results will ever become available that prove some kind of avalanche change due to climate change in the near future.»). Outlook: maybe add a few points which you would consider important to address in future studies.

This is a good suggestion. We discuss this in more detail in Section 5. We have, for instance, included the following: "As we, in the current study, have focus on only a few selected weather indices, future studies might include other relevant indices. We note that reported avalanche activity has become more detailed the last years, and new avalanche monitoring stations are in operation closer to typical run-out zones. This will provide new insight into triggering weather conditions, which can be used to study the link between weather and avalanche release."

8 Literature

Overall, the cited literature seems appropriate, with an understandable larger proportion of Norwegian publications. However, I suggest you also refer to the publications by Jamieson et al. (2017), who - although for Canada - explored the impact of climate change on snow avalanches in transportation corridors in western Canada, and Sinickas et al. (2016), who explored occurrence rates of avalanches in a changing climate (again for Canada), and discusses uncertainties linked to climate projec- tions. Furthermore, both papers provide additional references, which might be of interest (e.g. publications by Eckert et al. on run-out distance in a changing climate).

Thanks for these suggestions. We have included Jamieson et al. (2017) and Sinickas et al. (2016).

We now discuss uncertainties associated with the climate projections in Section 5, including uncertainties associated with the hydrological modelling.

9 Figures

Generally very informative and of good quality. Some minor remarks:

Sometimes figures have titles, subtitles, sometimes none. While I personally like titles highlighting the figure and sub-figure content, check with the journal guidelines and be consistent throughout. Fig. 1: the scale indicating 10 km and 50 km is rather small. Maybe enlarge, showing several increments of 10 km and 50 km.

Fig. 2: a and b are missing. The colour bar for (b) should probably read [mm] as unit rather than %?

This is now fixed. Thank you.

Fig. 12: axis title for the elevation bands is missing.

If you mean y axis, the title ("masl"; now changed to AMSL [m]) is above the upper panel. For the x-axis the exact numbers are not considered that important, as one can visually conceive the fractions of different changes.

Fig. 13: check with journal guidelines whether masl is a correct abbreviation. %-sign is missing on colour bar. While I like this figure, as it shows absolute changes in elevation, I would appreciate if it would additionally show the mean value for the reference period 1981-2010 to emphasize the changes between now and the future.

Thank you. We have changed to AMSL [m], a common abbreviation for "Above Mean Sea Level").

The 1981-2010 values are included in the figures.

As outlined before, potentially some figures could be merged.

Maybe some of the figures could be presented as supplementary material to highlight key findings.

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Interactive comment on "Present and future changes in winter climate indices relevant for access disruptions in Troms, northern Norway" by Anita Verpe Dyrrdal et al.

Markus Eckerstorfer (Referee)

Dear Markus Eckerstorfer (Referee #2)

We greatly appreciate the time and effort you have put into reviewing our manuscript, and for the very detailed and valuable suggestions. Thank you for pointing us towards interesting and relevant literature. We have responded to each of your questions and suggestions below, and hope to have clarified some of the major issues raised. In particular, we better explain the choice of climate indices and their link to avalanche release, which as you point out is a complex process. We have cleaned up the use of terms and focus the manuscript more towards snow avalanches, including slushflows, and challenging road conditions. In this regard, we have also made our aims more focused. The manuscript has undergone a major restructuring and all sections have been rewritten.

General comments:

I highly welcome this study on future changes of winter climate indices relevant for snow avalanche release. I especially appreciate that this study focusses on Northern Norway, as this is the area I am also working in. There is certainly a lack of studies focusing on future snow avalanche activity in a warming climate. At a first glance, this is rather astounding given the potential geohazard implications.

However, there are mainly two things that prevent the majority of studies from being made: 1) Avalanche release is very complex and not fully understood yet. A combination of snowpack and meteorological factors at different spatial and temporal scales lead to their release. 2) Knowledge of avalanche activity over time at regional scale is not available in many regions.

This manuscript focusses on triggering meteorological factors and studies how they change over time under a climate warming scenario. I think this is a great idea, however, this study falls short on a number of major things. I would like to point these shortcomings out to the authors and ask them to consider my suggestions:

1) Appropriate choice of winter climate indices: I do not think that all indices and/or their thresholds chosen in this study are relevant for snow avalanche release. The problem might be that the authors are not completely familiar with snow avalanche literature and the concepts of prescribing meteorological thresholds to avalanche release. You are mainly studying direct action avalanching and as a starting point, I would suggest looking into Hendrikx et al. 2005 in CRST, or Davis et al. 1999 in CRST, or Floyer and McClung, 2003 in CRST.

Thanks for the comments and suggested literature. We agree that not all the presented indices are relevant for snow avalanche release. However, the indices presented are relevant and potential triggers of both snow avalanche and slushflow, or/and in a wider context, weather induced access disruptions, which is the main focus in this study. The choice of selecting the final indices was also based on the availability of the parameters as gridded data, both for historical and future data.

We made several edits and additions (including the new suggested literature) to make this more

clear.

You will find both meteorological variables, their rates and time scales at which we need to forecast them. I do not think it makes any sense if you are for example neglecting thresholds cited from an NVE report and instead use a 4 times lower threshold only because it gives you more data to work with. If you do so, you would have to argue for it and explain the uncertainty associated. I also think you would for example gain from deriving a snowdrift factor instead of looking at precipitation and wind separately.

Thanks for the suggestions. We agree that snowdrift factor is important. Such factors rate among the top indices for avalanche activity (Davis et al. 1999: Hendrikx et al. 2005; Kronholm et al. 2006b). We created and added in the text and got new results based on a snow drift factor presented by Davis et al. (1999). They use the expressions from Pomeroy and Gray (1995) to derive the wind drift factor as the product of the 24-hour snowfall and wind speed to the fourth power.

We have removed the analysis on wind speed alone.

I would also like to suggest rewriting the introduction after studying the literature on statistical avalanche forecasting and by also considering climate change studies on avalanche activity. There are a few studies from Switzerland (e.g. Schmucki et al., 2014, Marty & Meister, 2012) or France (e.g. Eckert et al., 2013, Castebrunet et al., 2014).

Thanks for this suggestion. We have rewritten part of the introduction, and paid more attention to literature on statistical avalanche forecasting and climate change studies related to avalanche activity.

2) Past winter climate indices: I am not quite sure why the past development of the chosen winter climate indices is of interest. In its current form, what do we learn from this exercise? These results would certainly be of great interest if you could compare them to past avalanche activity. One could then calculate an avalanche activity index and look if meteorological values were different between avalanche / non avalanche days. There is a database of avalanche accidents from NGI, there are road closure databases from Statens Vegvesen and there are regobs.no observations from recent years to work with. Finally, there is NVE's skrednett database of avalanche observations that could be used. I would like to suggest rereading Jaedicke et al., 2008 for inspiration.

As concluded by Jaedicke et al. 2008 the study showed that the limitations of inhomogeneous data collection of landslide and avalanche events in Norway can be bypassed by combining the event database with a homogeneous meteorological dataset. This allows then statistical analysis to find the most important meteorological trigger elements for the various types of landslides and avalanches. Development of a robust model to compare meteorological values to past avalanche activity is beyond the scope of this study. However, the work done by Jaedicke et al., 2008 forms a central background of our study. For Troms most important trigger for snow avalanche release was 1-day precipitation and maximum wind speed during the event day, according to Jaedicke et al. 2008 (see Figure 2.2). Our three indices "Maximum snowfall intensity", "Heavy snowfall frequency" and "Snow drift factor" are highly relevant for this.

3) Mixing of terms and geohazard focus A lot of times you are talking about different types of slope processes or you talk about slides and avalanches, snow avalanches, slushflows and so on. There is a lot of intermixing of terms describing the same process. I would suggest you are clearly focusing on one slope processes – snow avalanches and for that matter, the closure of roads by snow avalanches.

Thanks for this comment. We have clarified the terms. Our main focus is typical winter climate indices known to potentially cause access disruptions in Troms, northern Norway. <u>Snow avalanches</u> are among the natural hazards that most frequently lead to highway blockages. Also <u>slushflows</u> are among the winter hazards that may lead to dangerous road situations and sometimes also road outages. The frequency of both snow avalanches and slushflows are expected to change with climate change. Finally the selected climate indices for the two above hazards are also associated with access disruptions in general. Indices for the latter also include freeze-thaw cycles (zero-degrees Celsius -crossings) which may lead to slippery road conditions.

Note that we now refer to "climate indices" instead of "weather indices" throughout the paper.

4) Two communities Since there are large differences between coastal and inland regions, wouldn't it be more interesting to look at communities from these two different regions?

Very true. But since this study is part of a larger project on winter weather induced natural hazards and access/highway disruptions, we would like to stick to the selected focus areas of the project. These areas are selected because they have experienced many avalanches, road closures and isolation due to such events. However, we now report numbers for two elevation bands in higher and lower elevations (see Section 3.2 and Table 2).

5) Aim of this study As I mentioned above, I find this study very interesting. However, I feel like your aim of this study is rather thin and very wage. What does it mean to 'go deeper' into selected indices? What do you mean by 'somehow' generating life interruptions and so on? I think you could present a clear research question or even better a hypothesis (maybe based on the literature you presented) and then go on and test it.

Thanks for this valuable comment. To make this more clear we have rewritten the aim of our study as follows: "This study presents past and future changes in selected winter climate indices known to potentially cause access disruptions in northern Norway. We have focused on the most common access disruptions and selected climate indices which in literature are known to be potential triggers of snow avalanches and slushflows, or somehow generate lifeline interruptions and difficult and risky road/transport conditions in exposed coastal and fjord areas in Troms, northern Norway"

6) Discussion and conclusion In many studies, reports and fact sheets on the climate change – avalanche relationship, very general statements are given that in my opinion do not have much value. Simply because

there is always a second or third alternative scenario that is probably as likely as the one proposed.

Let me give you two examples:

You start by stating that areas with heavy snowfall and large snow amounts saw a high potential of dry snow avalanches. This can be true (you could check by comparing with skrednett.no). However, there is a different scenario, like we see in Japan every winter, that very frequent snowfall produces a snowpack that is increasingly harder towards the bottom, preventing avalanches of noteworthy size from releasing. We rather see frequent, very small avalanches, called sluff. You then go on by stating that there might be a decrease in dry snow avalanching before 2040 due to a decrease in maximum snow amounts and heavy precipitation. An alternative scenario would be that we suddenly introduce more favorable conditions for weak layer development and get an increase in dry snow avalanche activity before it might decrease due to shorter winters and less/no snow at low elevations.

I think you are getting my point. The solution to this problem might be to first carefully compare the modelled winter indices to past avalanche activity (skrednett.no) in order to quantify which meteorological triggering factors release which type of avalanches. Then one could pick two/three interesting cases (e.g. dry snow avalanches triggered by snow storms, wet snow avalanches triggered by rain on snow) and play through possible future scenarios.

Thank you for this insightful comment. There is indeed a complex, and hard to define, relationship between weather and avalanches. We have attempted to focus on only snow avalanches and slushflows, and more on difficult road conditions which is also a major reason for road closures in the study area. We believe the revised manuscript is more focused. As for carefully comparing winter indices to past avalanche activity, we rely on former studies on the subject.

7) Language and typos I am not an English native speaker, so I do not comment on language and typos. However, I found quite a lot typos in the text.

Thank you for this information. We have looked for and corrected typos more carefully.

Specific comments: 1 Introduction Is the reference to Platt, 1991 relevant here? This reference is neither very recent, nor from Norway.

The reference is removed.

After I googled the reference to Jacobsen et al. (2016) I feel like that the first part of your introduction is uncomfortably close to the introduction written by Jacobsen et al. Could you consider change your introduction to make it more your own!

The first part of the introduction is rewritten.

Your reference to PRA Hordaland is from 1995. Could you please find some newer numbers that certainly exist?!

The reference is removed.

What is a ‘debris avalanche’ that you are mentioning here?

Changed to landslide.

The paper by Hestnes & Jaedicke (2018) is not a study really, but much more a discussion paper. They do not present any data that supports their claims, but rather discuss different scenarios of what is likely to happen.

Changed the wording to “in their recent paper Hestnes & Jaedicke (2018) discussed….”

2 Study region Being entirely above the Arctic circle, I would say that the entire county of Troms lies in the Arctic.

Changed from Sub-Arctic to Arctic. However, the climate in most of Troms is not Arctic: most of the lower seaside areas have temperate rainy climate. Thus we added this sub-sentence: “, but with a partly sub-Arctic climate”.

Please consider to be a little bit more accurate with the term ‘avalanches’. You are using different terms describing the same process as well as the same term to describe different processes.

In the revised paper, we use snow avalanches as a common term for all kinds of snow avalanches and slushflows, which also is a major natural hazard in Norway (cf. Hestnes 1998, Annals of Glaciology 26). We also refer to landslides as a common term for rock avalanches (including rock fall) and debris avalanches (debris flows, mudflows), unless where a specification into type is needed. We have stated this in the Introduction and refer to the classification from Kristensen et al. (2015): http://publikasjoner.nve.no/rapport/2015/rapport2015_90.pdf.

The fatality statistics by Walberg and Devoli, 2014 is from 5 years ago. You could look at NVE’s varsom.no site for updated numbers. Especially since there were quite some fatalities in recent years.

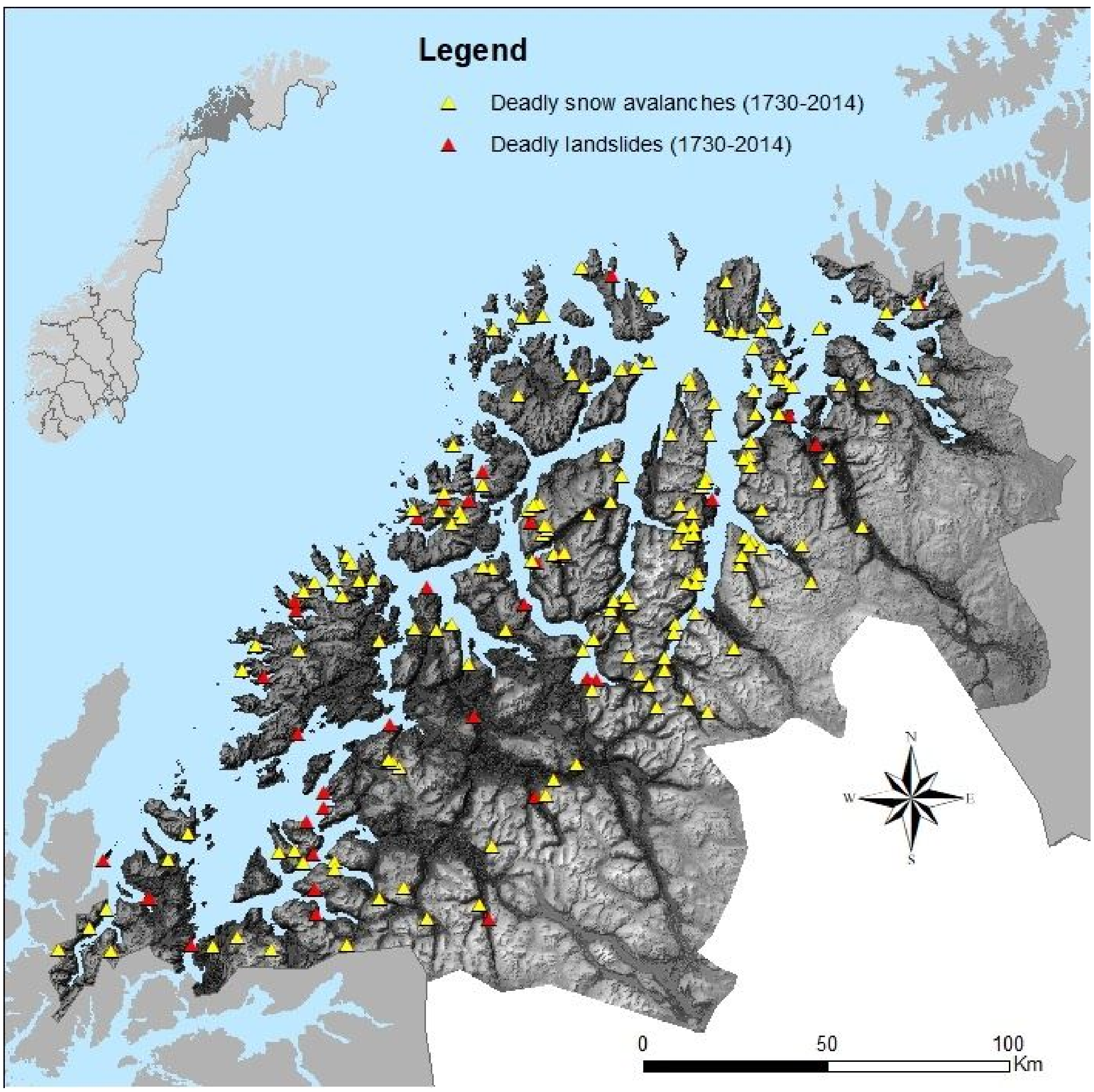
The database skredregistrering.no contains 5815 events from year 900 until 2019. There were 213 events that had one or more casualties cover the period 1730–2014. For snow avalanches, the most updated numbers are available to the winter 2018/2019 (from NGI and varsom.no). We consulted Graziella Devoli at NVE, who extracted all registered casualties in Troms from 1730 from skredregistrering.no. This database is updated until 2. December 2019, but suffers from not being regularly updated. We found that casualty numbers for snow avalanches after 2014 are not complete. There are no registered landslide fatalities in Troms since 2014.

We have looked up the numbers and have changed the text in the Introduction to:

"Both snow avalanches and landslides have led to fatalities in Troms. An analysis of the Norwegian mass movement database http://skredregistrering.no/ (database version December 2019) shows that for the period 1730-2014, 376 casualties were registered in Troms. Snow avalanches resulted in 295 casualties, whereof 121 people were hit in buildings and 9 on roads. Since 2014, an additional 12 casualties are registered, according to varsom.no (all were skiing or driving snow mobile). For other landslides, 81 casualties are registered, whereof 57 in buildings and two on roads."

This database provides a minimum estimate of historical casualties related to mass movements in Norway. Note that this database is incomplete and many of the entries have poor quality, for example, snow avalanche casualties in a database compiled by the Norwegian Geotechical Institute (https://www.ngi.no/Tjenester/Fagekspertise/Snoeskred/snoskred.no2/Ulykker-med-doed) amounts to 183 for the period 1972-2014, compared to 165 in http://skredregistrering.no/ for the period 1730-2014.

This figure summarises casualties registered in Troms.



Is it two or three municipalities you are studying? You are presenting confusing numbers.

Thanks for pointing out this mistake. We have changed to two municipalities throughout the document.

The link to the avalanche hazard map is not working. It is called 'susceptibility map'.

This link is now removed as we restructured and rewrote the section.

What is the difference between a 'slide' and an 'avalanche'?

We have changes slides to "landslides".

When you talk about numerous stretches of roads having steep slopes on their sides, I feel like this statement is not really supported. How many roads, on either sides or just one side, how steep, steep enough for avalanches to occur or maybe too steep?

We have now added two references to this sentence, and modified it to: "In parts of Troms, as much as 50% of roads are located within susceptibility maps for snow avalanches and rock fall (NGI et al., 2013). Numerous stretches of roads in the study region go along alpine mountain sides prone to snow avalanches (Statens vegvesen, 2014), thus also to closures and damages, as well as representing a threat to people's safety. Only along Mefjorden there are 18 known avalanche tracks with runout zones encompassing the access highway for the fishing villages Senjahopen and Mefjordvær (Sjømatklyngen Senja 2017)."

You are presenting data from two weather stations; however, the place names are not known to other readers. Could you mark them in Figure 1 for example?

The station TROMSØ is marked. We have removed the station LYNGEN - GJERDVASSBU from the text, according to suggestion from reviewer 1.

Figure 2 The color bars make it difficult to understand in detail which temperature and precipitation certain parts of the region experienced. In particular as the tick marks with the numbers are not aligned with the borders of each color. Could this be changed so one can not only understand the overall spatial trend, but get a little bit more detailed picture of what is going on?

We have changed to continuous color bars instead of sharp intervals, as in the other figures.

You are defining winter as the period October – April. Is this an officially used definition of the period or is it arbitrary chosen by you? If the second is true, could you argue for it?

The October-April season is often used as the winter/snow season in Norway.

Figure 3 I wonder if the graph would be more readable if you stretch them out horizontally across the entire page? Maybe also changing to a bar chart would help understanding the trends that are going on. Right now, the graphs appear very cluttered and are difficult to read.

Thanks for this suggestion. We have changed the graphs as suggested.

3.1 Gridded observation-based data To make sure, you are talking about daily average temperature (T) and daily amount of precipitation (P).

Yes, changed to "daily mean temperature (T) and daily precipitation sum (P)".

3.2 Future projections (you number it falsely 3.1) What does HBV model stand for?

HBV stands for Hydrologiska Byråns Vattenbalansavdelning (in Swedish), but HBV is mostly used. We added the following sentence and reference for more information: "Datasets of precipitation, temperature and hydrological variables described here contribute to the natural scientific basis for climate adaptation in Norway, as described in Hanssen-Bauer et al., 2017)."

Gridded wind data is used from the past, but no projections are made? Why use it then? And what about a wind drift factor?

Now, projections of wind is also available. See section 3.1 for description. We use this in combination with snowfall to compute changes in snow drift in the most exposed locations in the focus areas.

Table 1 I am not a climate modeler, so this table does not make much sense to me. What are all the acronyms stand for? Why are there ten combinations of these things and what does that mean? Could you try and explain the table better?

We have changed the numbers to crosses and explained the table in more detail in the caption. We also moved the table to the Appendix. We also explain how the projections are made in more detail in Section 3.2, and discuss the uncertainties in Section 5.

3.3 Weather indices You could shorten the first paragraph to two sentences since you are explaining both the literature search and potential triggering factors twice. The transition from dry to wet snow is decisive of the release of wet snow avalanches. The statement by Lied & Kristensen (2003) is certainly true, however, I believe not really relevant for your study. Your last paragraph citing the study by Eckerstorfer et al. (2018) reads like study area description. Please consider moving it there.

We have removed the statement by Lied & Kristensen (2003).

We have moved the part from Eckerstorfer etal. (2018) to Section 2.

4 Results Figures Could you underly these maps with a hillshade so high and low-lying areas are better visible for interpretation?

We believe that underlying the maps with a hillshade would make it difficult to see and disturb the colors of the results. The topography is shown in Figure 1. We have increased the contrast to make the topography more clear.

Isn't it counterintuitive to color negative change in warm colors and vice versa?

This seems to be a recurring subject of discussion. We agree that red is often used to show positive changes. Our reason for using blue as increasing is the fact that most of our indices are related to precipitation, which is associated with the color blue.

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

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Formatted: English (United States)

Abstract. ~~In s~~~~Some~~A number of seaside communities in Troms in northern Norway ~~the~~ are vulnerab~~ility~~le to sudden 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 challenging road conditions~~landslides and rockfall~~. In this paper we study changes in ~~typical~~ selected indices describing winter weather ~~indices~~ known to potentially cause such access disruptions in ~~the region~~Troms. A gridded observation-based dataset is used to analyse changes in present climate (1958–2017), while an ensemble of ten~~10~~ EURO-CORDEX climate model simulations are used to assess expected future changes in the same indices, towards the end of the twenty-first~~present~~~~is~~ century. We focus on climate~~weather~~ indices associated with snow avalanches~~,~~ (such as maximum snow amount~~ and~~, snowfall intensity and frequency~~ and,~~ and strong snow drift)~~,~~ and~~but also~~ ~~for~~ slushflows where ~~total water supply~~rainfall during winter ~~from melting and liquid precipitation~~ is highly relevant. All ~~these~~ climate~~weather~~ indices are also associated with access disruptions in general, including freeze-thaw cycles described as zero-crossings ~~in terms of temperatures crossing zero degrees Celsius~~ (temperature crossing ~~zero~~ 0 °C ~~degrees Celsius~~ ~~crossings~~) ~~which~~ that may lead to slippery road conditions. ~~, total water supply and the frequency of high wind speed~~~~from melting and liquid precipitation, and snow drift~~ ~~isare studied.~~ Our results show that there are large climate gradients in Troms ~~c~~County and also in detected changes. In ~~both~~ our two focus areas, Senjahopen/Mefjordvær in Berg municipality~~(Mefjorden)~~ and Jøvik/Olderbakken in Tromsø municipality ~~however~~, we find that the ~~an increase in~~ studied snow indices have become more frequent in present climate, while ~~a strong decrease is~~they expect to become less frequent~~ed~~ in near and far future, particularly in low elevations where snow cover during winter might become a rarity by 2100. Events of~~Heavy water supply~~ heavy rain during winter ~~is~~are rather infrequent in the present winter climate of Troms, but we show that these events are likely to occur much more often in all ~~inland~~ regions~~areas~~ in the future~~.~~. Although the likelihood~~risk~~ of dry snow-related access disruptions might decrease, wet ~~a warmer and wetter winter climate may increase the risk~~ ~~frequency of wet~~ snow avalanches and slushflows may become more probable ~~likely~~ in a warmer and wetter climate. However, there are contradicting arguments related to the development of snow avalanches in a changing climate due to the complexity of avalanche release. We find more~~that~~ zero-crossings~~, known to destabilize the snow pack and cause rockfall,~~ ~~have increased~~ in most parts of Troms during the last few decades, and ~~a further increase is expected~~this trend is expected to continue for

inland regions and high elevations~~regions~~ in the future, while coastal and low-lying regions can expect fewer ~~less~~ zero-crossings. Strong snow drift, as a combination of snowfall and wind speed, have slightly increased in the two focus areas, but a strong decrease is expected in the future due to less snow. The higher likelihood~~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 additional guidance and training of local authorities~~, especially~~ in ~~exposed and remote~~ regions with highways exposed to such natural hazards. At the same time, research into the complex relationship between weather and different types of hazards, especially wet snow avalanches and slush-flows, is needed.

1 Introduction

Since the turn of the century, there has been a considerable increase in the number of rapid mass movements that affect highways in Norway, according to registrations by the Norwegian Public Roads (Statens vegvesen, 2014).
It has been estimated that one fourth of Norway's public roads are vulnerable to snow avalanches and rockfalls (Frauenfelder et al., 2013~~: 36, 57~~). Small communities in Troms, northern Norway, are among the most vulnerable to weather induced access disruptions. Both snow avalanches and landslides have led to fatalities in Troms. An analysis of the Norwegian mass movement database http://skredregistrering.no/ (database version December 2019) shows that for the period 1730–2014, 376 casualties were registered in Troms: Snow avalanches resulted in 295 casualties, whereof 121 people were hit in buildings and nine on roads. Since 2014, an additional 12 casualties are registered, according to varsom.no (all were skiing or driving snow mobile). For other landslides, 81 casualties are registered in Troms, whereof 57 in buildings and two on roads.

Quite a few highway stretches along alpine mountainsides in Troms are sporadically closed nearly every winter due to climate-induced incidents such as blizzards, heavy snowfalls, strong winds, and avalanches. Several highways in Troms are also being closed in times with imminent avalanche danger, such as polar low pressure alerts. Snow avalanches are among the natural hazards that most frequently lead to highway blockages, in numerous instances for longer periods of time. Also slushflows and ice-fall are among the winter hazards that may lead to dangerous road user situations and sometimes also road outages. Access highways have been regarded as lifelines; connections that health, safety, comfort, and social and economic life depend on (Holand, 2014). Social science studies have revealed that roadside avalanches and winter weather-induced road closures commonly lead to worries about 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 such recurrent lifeline disconnections during the winter (Jacobsen et al., 2016), there might be negative long-term impacts for communities that have been repeatedly isolated and often exposed to risky cold season road travel (Hovelsrud et al., 2018).

The Arctic region, which Troms ~~County~~ is part of, has experienced a major change in climate over the past few decades, driven by increasing temperatures (AMAP, 2017; Vikhamar-Schuler et al., 2016; Hanssen-Bauer et al., 2019). For instance, Vikhamar~~-~~Schuler et al. (2016) found that five indices describing winter warming events in the Nordic arctic region have increased significantly during the past 50 years. This trend, being stronger in autumn and winter months, is significantly larger than the global average (Cohen et al., 2014), and is expected to continue in the future (e.g. AMAP, 2017). 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.

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Whether increasing temperatures and precipitation will lead to lower or higher probability of snow avalanches is much debated, and depends on avalanche type, slope, wind conditions etc. Studies performed using historical data and projections in western Canada did not suggest a substantial increase in avalanches reaching transportation corridors (Jamieson et al. 2017). Results by Sinickas et al. (2016) suggested that natural avalanche occurrence rates over the past 30 years in western Canada had decreased or stayed constant. However, the results were associated with a very high level of uncertainty. On the other hand, Ballesteros-Canovas et al. (2018) states that the transformation of dry snow packs into wet snow packs is decisive for the release of snow avalanches, which explains an increase in wet snow avalanches in Western Himalayas as winters have become milder. Hestnes & Jaedicke (2018) have discussed that global warming altogether will reduce the impact of slushflows and avalanches on humans globally. 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.

Castebrunet et al (2014) shred some light on these contradicting arguments, as they projected a general decrease in mean and interannual variability of avalanche activity in the French Alps, with an amplified decrease in spring and at low altitudes. While in winter and at high altitudes they projected an increase because conditions favourable to wet snow avalanches comes earlier in the season. Similarly, Hanssen-Bauer et al. (2019) stated that an increase in heavy snowfall or heavy rain on snow may increase the occurrence of snow avalanches (including wet snow avalanches and slushflows), while a shorter snow season and reduction in the maximum annual snow amounts may decrease the probability of dry snow avalanches. Hanssen-Bauer et al. (2019) and Hanssen-Bauer et al. (2017) still conclude that the probability of wet snow avalanches and slushflows is expected to increase in Norway.

The current study presents past and future changes in selected winter climate indices known to potentially cause access disruptions in Troms, northern Norway~~northern Norway~~. We have focused on the most common access disruptions and selected climate indices which in literature are known to be potential triggers of snow avalanches and slushflows (thus focusing on natural avalanche occurrences), or somehow generate difficult road/transport conditions in exposed coastal and fjord areas in Troms. First, we present the study region and climate (Section 2), we describe the data and method, and identify relevant climate indices (Section 3), before presenting results (Section 4), and wrapping up with discussion and conclusions (Section 5). The study will supplement social science investigations and advance natural hazard understandings by providing an overview of historical development and projected future changes in climate indices associated with winter season road travel safety and lifeline disruptions in Troms~~ County~~.

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~~According to Schweizer et al. (2003), precipitation, wind and temperature are the weather factors that contribute most to snow avalanche danger. Precipitation (as snow) is the strongest forecasting parameter related to large, new snow avalanchesWind contributes to loading and is often considered the most active contributing factor after new snow. Changes in air temperature affect snow stability in various ways and the rate of change is important (Schweizer et al. 2003). In Norway soften Snumerous County but few of them on the roads, despite the regional road system's exposure to such natural hazards :,two on roads, run-out distanceerrun-outnLandslides 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~~

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~~longer term possibly not appeal to prospective residents (Hovelsrud et al., 2018; Leiren & Jacobsen, 2018) and perhaps also cause relocations of people and businesses.~~

~~C~~

~~Given unclear perceptions of future climate-induced hazards, the present study will scrutinize climate change in Troms CCounty 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 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).~~

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~~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.~~

~~This~~ ~~e present study will go deeper into selected winter climate indices~~ ~~known to potentially cause access disruptions in northern Norway. We have focused on the most common access disruptions and selected weather indices which in literature are known to be potential triggers of snow avalanches and slushflows, or somehow generate difficult road/transport conditions.~~ ~~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 was until 1st January 2020 ~~is~~ the second northernmost county in Norway (see map in Fig.~~ure~~ 1)~~,~~ ~~located between 68.3° and 70.3~~ ~~°degrees~~ N~~orth~~, but was merged with the neighboring county of Finnmark to form the new *Troms og Finnmark* county. Troms~~thus~~ forming a part of the Arctic region, but with a partly sub-Arctic climate. ~~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 larges~~st~~ and mountainous islands, meets steep mountains further inland, resulting in a complex topography (see map in Fig.~~ure~~ 1). Large parts of the population and infrastructure in Troms are located in narrow zones along the seaside~~hore~~, ~~particularly~~ partly in fjords surrounded by steep mountain slopes. The topography, along with geological and meteorological conditions, make~~s~~s ~~the county~~many roads 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).~~ ~~S~~Several small but enterprising communities ~~there~~ in Troms have recurrently been cut off from the rest of the ~~county~~region. According to Jacobsen et al. (2016), many communities in Troms experience sudden access interruptions nearly every winter due to snow~~/slush~~ avalanches and slushflows, heavy snowfall, and/or strong winds and drifting snow in these areas. Eckerstorfer et al. (2017) concluded that Tamokdalen in Troms (about 50km south of Focus area 2; see below) 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) compared avalanche activity and

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forecasted avalanche danger during the two winters of 2014-2016, and 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. ~~or their study in Troms, (2014–2016), forecasted coincidedwithIn January 2019, four skiers were hit by an avalanche in Tamokdalen,~~

In ~~T~~the present study w~~ill~~e focus particularly on t~~hree~~wo areas/communities; Focus area 1: Senjahopen/Mefjordvær next to the ~~fiord~~fjord Mefjorden in Berg municipality, and Focus area 2: Jøvik/Olderbakken next to the ~~fiord~~fjord Sørfjorden in Tromsø municipality (see ~~Jøvik/Olderbakken in Tromsø municipality and Senjahopen and Mefjordvær in Berg municipality, (SeeRefer to~~ Fig. 1~~ure 1~~, for the location of the two focus areas)~~)~~. Both areas~~h 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/). In parts of Troms, as much as 50% of roads are located within susceptibility maps for snow avalanches and rockfall (NGI et al., 2013). Numerous road stretches ~~of roads~~ ~~in the study region~~ in Troms go along alpine mountain ~~-~~sides and escarpments prone to snow avalanches (Statens vegvesen, 2014), thus also ~~have steep slopes on one side, making them prone t~~o closures and damages ~~due to slides and avalanches, -~~ as well as representing ~~representing~~ a threat to people's safety. Only along Mefjorden there are 18 known avalanche tracks with runout zones encompassing the access highway for the fishing villages Senjahopen and Mefjordvær (Sjømatklyngen Senja 2017). In our gridded data, Focus area 1 covers 416 grid cells (1x1 km²), ranging from 0 to slightly more than 800 meters AMSL. Real elevation might be higher due to smoothing in the gridded elevation data. Focus Area 2 is smaller with 162 grid cells, but with ste~~pe~~eper topography ranging from 0 to almost 1800 meters AMSL.

~~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/~~fiord~~fjords and inland regions. During the winter season, Troms is characterized by a relatively mild and wet climate in coastal and ~~fiord~~fjord areas, while the inner parts ~~of the county~~ are cold and dry (see Fig.~~igure~~ 2). Mean winter temperatures range from slightly above zero along the seaside ~~coast~~ to around -12 °C ~~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 sudden periods with 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~~

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~~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.~~

According to a report on projected climate-related changes, "Troms climate fact sheet" (Hisdal et al., 2017, based on results from Hanssen-Bauer et al., 2017), from the Norwegian Centre for Climate Services (NCCS; klimaservicesenter.no), annual mean temperature in Troms is expected to increase by about 5 °C as approaching the end of the present century (compared to the historical period 1971–2000) under a high emission 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 landslides, debris flows, 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. From the development of snow amounts alone, we might expect that the probability of both dry and wet snow avalanches in these regions will increase during the first decades, followed by reduction of dry snow avalanches towards the end of the century (Hisdal et al., 2017). How the effects of these changes on local communities and different sectors could play out, is not much studied.

In northern Norway, wind induced hazards represent significant challenges along the coast and some 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. (2017~~5~~). However, some studies have shown a change in cyclone density in the region~~,~~; 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 in the Barents region in the far future (Parding & Benestad, 2016).

~~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~~

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~~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.~~

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 computed 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, the Norwegian Meteorological institute (MET Norway) provides gridded datasets of daily mean, minimum and maximum temperature (T, Tmin, Tmax) and daily precipitation sum (P) for the Norwegian mainland. The dataset, referred to as “seNorge”, is based on observations interpolated to a 1x1 km grid ~~of daily temperature (T) and precipitation (P)~~covering the period 1957–~~-~~present. ~~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 analysed seNorge1 (e.g. Tveito et al., 2002) as it includes minimum (Tmin) and maximum temperature (Tmax) from which we calculated 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 total snow water equivalent (SWE) and~~,~~ fresh snow water equivalent (FSW; change in SWE from one day to the next),~~water equivalent of last day's snowfall) and snow depth (SD),~~ was~~are~~ computed from seNorge1 T and P using the seNorge snow model v1.1.1 (Saloranta, 2014). This uses a precipitation/degree-day snow model with a snow routine similar to the HBV model (Bergström 1992), which is described in Engeset et al. (2004). In seNorge snow model v1.1.1 a temperature-independent melt term is added to the temperature-dependent degree-day term, while the melt threshold temperature is kept at 0 °C~~degrees Celsius~~. The new melt term is proportional to the potential solar radiation, thus varying with the combination of latitude and time of the year. Saloranta (2014) found that the average station-wise median bias for snow depth from the seNorge snow model v1.1.1 lies between –~~-~~12 to +17 % all the way from January to the end of April. Since~~, but as~~ precipitation from seNorge2 is~~ now~~ used as input in the snow model, 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.~~.~~ seNorge is an operational product updated every day, and available on www.senorge.no, and provides important input to the avalanche forecasting in Norway presented on www.varsom.no.

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 ~~evaluating~~es~~ 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.

3.2~~1~~ Future projections

To assess expected future climate development, we used projections from climate models. The model chain starts with low-resolution General Circulation Models (GCMs) covering the entire earth, which output is used into Regional Climate Models (RCMs) that simulates climate on a finer grid over a region. Finally, a~~A~~n ensemble of ten simulations from the EURO-CORDEX project (Jacob et al., 2014), representing different combination of GCMs and RCMs, ~~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).~~.~~ Due to the systematic biases in the climate model output and their mismatch in scale with impact models data requirement, a post-processing is necessary to obtain plausible time series for use in local impact studies. The downscaled EURO-CORDEX ensemble for the entire period 1971–~~-~~2100 was ~~further~~ bias-adjusted towards ~~an earlier version of~~ seNorge version 1.1 for daily mean temperature and daily precipitation sum (Wong et al., 2016)~~ using an empirical quantile mapping method, for the entire period 1971–2100~~, while for daily mean wind speed the KliNoGrid dataset described above was used as reference for the bias-adjustment. An empirical quantile mapping method was used in the bias-adjustment of precipitation and wind. For mean temperature the same method was used on the anomalies, while for minimum and maximum temperature a quantile delta mapping method (Cannon et al., 2015) was used on the projections.~~.~~

We refer to the corrected datasets of temperature, ~~and~~ precipitation and wind 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~~Temperature and precipitation were then used to force~~d with~~ a spatially distributed, gridded hydrological model (~~version of~~ the HBV model) (Wong et al., 2016) to generate daily time series of different hydrological components. Here we focused on daily SWE, from which we also computed daily FSW~~ (change in SWE from one day to the next)~~. The Norwegian government recommends, as a precautionary principle, using the high emission scenario when assessing the effects of climate change (Norwegian Ministry of Climate and Environment, 2013), thus we only analysed projections from the RCP8.5 emission scenario. Datasets of precipitation, temperature and hydrological variables described here contribute to the natural scientific basis for climate adaptation in Norway, as described in Hanssen-Bauer et al., 2017). Some of them (precipitation, daily mean, maximum and minimum temperature and SWE), are available through the Norwegian Climate Data Store: https://nedlasting.nve.no/klimadata/kss. ~~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 A1 in the Appendix~~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.~~ In the results, we report on the ensemble mean of the ten simulations, not individual model simulations. ~~We use the ensemble 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.~~ ~~These bias-adjusted data (Tmax, Tmin, SWE) are available through the Norwegian Climate Data Store: https://nedlasting.nve.no/klimadata/kss.~~

~~**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~~			

	~~ECMWF~~	~~CCLM~~	~~CLM-Community~~	~~EC-EARTH-CCLM~~	
~~EC-EARTH~~	~~ECMWF~~	~~HIRHAM~~	~~Danish Meteorological institute, DMI~~	~~EC-EARTH-HIRHAM~~	
~~EC-~~	~~ECMWF~~	~~RACMO~~	~~Royal Netherlands Meteorological~~	~~EC-EARTH-~~	

~~EARTH~~			~~Institute (KNMI)~~	~~RACMO~~	
~~EC-EARTH~~	~~ECMWF~~	~~RCA~~	~~SMHI~~	~~EC-EARTH–RCA~~	
~~HadGem~~		~~RCA~~	~~SMHI~~	~~HadGEM–RCA~~	
~~IPSL~~		~~RCA~~	~~SMHI~~	~~IPSL–RCA~~	
~~MPI~~	~~Max Planck-Institut~~	~~CCLM~~	~~CLM-community~~	~~MPI–CCLM~~	
~~MPI~~	~~Max Planck-Institut~~	~~RCA~~	~~SMHI~~	~~MPI–RCA~~	

3.3 Climate~~Weather~~ indices

~~To connect weather variables to road closures, w~~We identif~~y~~ied indices describing weather elements which in literature are known to be potential triggers of snow avalanches and slushflows, ~~rapid mass movements such as slides and avalanches,~~ or somehow generate difficult ~~road/transport~~ conditions for road users~~.~~. For frequency indices, we pragmatically selected the thresholds to facilitate a trend analysis, but we believe that the pattern of changes for low-threshold events can be transformed to higher-threshold events. The final choice of selecte~~ding these~~ indices was also influenced by~~based on~~ the availability of the parameters as gridded data,~~ both~~ for both historical and future periods~~data~~. Of~~For~~ rapid mass movements the ~~I~~indices analyzed here are mostly relevant for snow ~~and slush~~ avalanches and slushflows. For~~,~~ weather induced access disruptions in general ~~but have also~~we ~~have~~ chose~~n~~ indices that often lead to difficult road and driving conditions. The derived indices were~~are~~ identified from literature referred to in the following text, and presented in Table 1~~2~~ below.

In this paper, we use snow avalanches as a common term for all kinds of snow avalanches (including slushflows), and landslides as a common term for rock avalanches (including rockfall) and debris avalanches (debris flows, mudflows), unless where a specification into type is needed. We have followed the classification from Kristensen et al. (2015).

~~fresh depth~~ Jaedicke et al. (2008, 2009) ~~studied~~ coupled 20 000 historical landslide and avalanche events in Norway. Combining avalanche and meteorological data for the period 1961 to 2005 to ~~the correlation between certain~~ 41 meteorological elements. These data sets were then used in a classification tree analysis to identify the most relevant meteorological elements causing avalanches and landslides. ~~, such as 1-day precipitation, temperature, wind speed and direction, and the occurrence of snow avalanches and mudflows in Norway.~~ Results showed that snow avalanches had the highest correlation with meteorological elements such as wind and precipitation, while rockfall~~s~~ showed the lowest correlation (Jaedicke et al. 2008). The study also revealed that the most important elements triggering landslides or avalanches varied spatially over Norway. While 1-day precipitation was the most important trigger for snow avalanches in the coastal south-western part of the country, both wind and precipitation played an important role in northern Norway~~precipitation is the most frequent cause of avalanches, and in nNorthern 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 flow~~slushflows in Norway are often initiated at times of ~~heavy~~ high water supply~~water supply~~ from intense rainfall and/or rapid snowmelt. NVE (2014) indicated a critical threshold of 40 mm/day of total ~~water supply~~rain+melt, given by field experience and measurements. Here we studied winter rainfall events (precipitation amount on days with T > 0°C)~~In the current study, a threshold~~ exceeding a threshold of 10 mm/da~~yy for water supply is~~. During such rainfall events one can expect an extra contribution to water supply through melting. In addition to potentially leading to slippery road conditions due to low surface temperatures and/or freezing at night, such winter rain events can lead to the formation of thick internal ice layers in the existing snowpack, which again inhibits for instance reindeer from foraging and limits vegetation growth (e.g. Vikhamar-Schuler et al., 2016; Pall et al., 2019). ~~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~~has stated 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. This is in agreement with Schweizer et al. (2003) who stated that about 30–50 cm of accumulation of a new snow is critical for naturally released avalanches. ~~We decided to analyze winter maximum snow amount and snowfall intensity, frequency of heavy snowfall and frequency of strong wind~~snow drift factor ~~separately.~~ The combination of wind speed and fresh snow can be defined as a so-called snow drift factor, which have proven high skill in avalanche prediction. Davis et al. (1999), Hendrikx et al. (2005) and Kronholm et al. (2006b) all used classification trees to show that snow drift factors rate among the top indices for avalanche activity. Davis et al. (1999) used the expressions from Pomeroy and Gray (1995) to derive the wind drift factor as the product of the 24-hour snowfall and wind speed to the fourth power (see Equation 1 below):

$$snow\ drift\ \left[mm\left(\frac{m}{s}\right)^4\right] = precipitation\ [mm] * (wind\ speed)^4\ \left[\frac{m}{s}\right] \qquad (1)$$

Here we adopted this definition of snow drift, using 1-day snowfall (FSW-1d) and daily mean wind speed (FF).

Due to the large uncertainties associated with wind, and particularly the high influence from local conditions, we selected the grid cells of highest wind exposure in each focus area (6/8 grid cells in Focus area 1/2, respectively). We computed the snow drift factor according to Equation 1 above, calculated the number of events where the snow drift factor exceeds the 90^{th} percentile (p90), and averaged over all selected grid cells within the focus area before computing the percentage change.

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It is accepted that the most high-risk temperature when it comes to slippery roads is when the road surface is around or just below 0 °C (~~Thornes, 1991;~~ Andersson and Chapman 2011; ~~Crossings of the zero degree threshold can lead to slippery road conditions (~~Gustafson, 1983; Thornes, 1991). ~~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 (Geiger et al., 2012; Kerguillec, 2015), meaning ~~that we move~~ a fluctuation between freezing and thawing conditions. A better index for slippery road conditions could have included surface temperature and humidity (Gustafson, 1983), but these variables were~~are~~ not available as gridded fields. Besides, surface temperatures on roads depend on the thermal conductivity of the road pavement, which is not known. In lieu of surface temperatures, we decided to use maximum and minimum temperatures taken at 2 m height as a proxy. ~~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 1~~2~~: Description of selected climate~~Weather/climate~~ indices.

Climate~~Weather~~ index	**Dataset Present climate**	**Dataset Future climate**	**Details / Abbreviation**	**Associated hazard**
Maximum snow amount	seNorge SWE	EUR11-Nor1-SWE	WM-SWE	Snow ~~A~~avalanche
Maximum snowfall intensity 1 and 5 days	seNorge FSW	EUR11-Nor1-SWE	WM-FSW-1d WM-FSW-5d	~~......~~Snow avalanche, slippery roads and difficult driving conditions
Frequency of	seNorge FSW	EUR11-Nor1-SWE	FSW-1d > 5 mm	Snow avalanche, slippery

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h~~H~~eavy snowfall ~~frequency~~				roads and difficult driving conditions
Frequency of z~~Z~~ero-crossings	seNorge Tmin/Tmax	EUR11-Nor1-T	Tmax > 0 and Tmin < 0 on the same day, abbr: zero-crossings	Slippery roads and difficult driving conditions
Frequency of winter rain events~~Snowmelt + rainfall (water supply)~~	seNorge T~~FSW~~ seNorge P	EUR11-Nor1-T~~SWE~~ EUR11-Nor1-P	~~Water supply~~Winter rain > 10 mm~~/day~~	Slushflows, snow avalanches, slippery roads and difficult driving conditions
Frequency of ~~Strong wind frequency~~strong snow drift	KliNoGrid FF seNorge FSW	EUR11-Nor1-FF EUR11-Nor1-SWE	Snow drift > p90~~Mean daily windspeed > 6 m/s~~	Snow avalanche and~~,~~ ~~slippery roads and~~ difficult driving conditions

3.4 Method

Past trends in winter maxima and peak-over-threshold events were~~are~~ assessed through the rank-based nonparametric Mann-Kendall trend test (R-package Kendall) 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 computed 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~~snow drift which is only computed for selected grid cells in the two focus areas, no trend analysis is performed. ~~(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 computed the percentage 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 extracted mean spatial statistics over the whole of Troms and for the two focus areas~~region~~s and present these in a separate table.~~in a separate table.~~ Within each focus area we additionally identified two elevation bands representing likely snow avalanche release zones (> 700 meters AMSL in focus area 1 and between 1000 and 1300 meters AMSL in study area 2) and likely avalanche run-out zones (< 200 meters AMSL), and report on changes computed for grid cells falling into these elevation bands. All roads in the study areas are located below 200 meters while the high elevation band is defined a collaboration with local avalanche experts.

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 investigated the past and projected development in maximum snow amounts for different elevations. We also analysed~~ze~~ 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~~ cCounty~~, the latter analysis is performed for separate inland and coastal/seaside regions as defined in Fig.~~ure~~ 1.

4 Results

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In Fig.3 we show how winter temperature and precipitation has varied over the last 150 years at a meteorological station in Tromsø, the administrative center of the municipality. Winter temperature fluctuates between ~~-~~–5 and 0.5 °C~~degree Celsius~~, and winter precipitation typically fluctuates between 250 and 950 mm. The temperature time series indicate multi-decadal variability, with a relatively cold period between the 1910s and the 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 a similar pattern (e.g. Polyakov et al. 2003, AMAP 2017). 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.

Further, we present results for each climate index separately, starting with historical and future changes the whole of Troms. We proceed with results from the who focus areas as presented in Table 2, including changes in elevations relevant for avalanche release zones (high elevations) and run-our zones (low elevations), for the historical period and the two future period. In Table 2 we also report on the mean values for the period 1981–2010 for reference.

4.1 Changes in maximum snow amount~~Past development~~

Fig.~~ure~~ 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 Fig.~~ure~~ 1) near the coast and along the fjords, while decreasing towards the Swedish border to the east (Fig.~~ure~~ 4a). In Fig.~~ure~~ 4b, significant positive trends are seen inland and in the north-eastern part of ~~the county~~Troms, with an increase of 20–60% from the first to the last

30-year period (Fig.~~ure~~ 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).

Fig.5 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 (Fig.5a) and 80–100% for far future (Fig.5b).

Fig.6 shows the same change in WM-SWE for past and future climate, but for different elevation levels. 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 and near future, the temperature in these region will, however, reach levels that give declining snow amounts also here. This is further investigated in Fig.7, showing the median elevation where maximum snow amounts stay below certain thresholds (100, 200 and 400 mm). Due to the strong gradients in Troms ~~cCounty~~, we analyze projected changes in WM-SWE for coastal regions (Fig.7a) and inland regions (Fig.7b) separately (see map in Fig.1), thus elevation on the x-axis differs. Median elevation in both regions increase as approaching the end of the century, more so in the coastal region and particularly for WM-SWE < 100 mm, meaning that we need to go to higher and higher altitudes to find snow in the future. Since the elevations are strictly increasing as of 2040, it is likely that the turning point from increasing to decreasing snow amounts occur prior to 2040, at least in terms of WM-SWE. This is supported by the 1981-2010 mean values (indicated as triangles in Fig.7) being lower than values in 2040, except in lower elevations inland where 1981-2010 values are higher. As shown in Fig.4, WM-SWE has increased in the inland region during 1957-2017, and this trend has likely continued longer and/or been stronger in lower elevations. The narrowing range between smaller and larger snow amounts indicates a stronger elevation gradient for WM-SWE as winter precipitation increases, particularly in low elevations and coastal regions where winters are comparatively mild. . This might be explained by the fraction of rain and degree of snow melt in lower versus higher elevations differing more in the future, giving a stronger decrease in the low to medium elevations.

In focus area 1 we compute a 17% increase in WM-SWE (Table 2), with significantly higher values (30%) in the high elevation band, and lower values (4%) in the low elevation band. This is similar for study area 2, but with a mean increase of only 10%. In the future, Focus area 1 is expected to have much less snow-related challenges, with nearly 70 (90)% decrease in the maximum snow amount in near (far) future. This will reduce maximum snow amounts from about 363 mm in the current climate (1981–2010) to only 36 mm by the end of the century. Focus area 2 shows a decrease of 47 (70)% in near

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(far) future. While decreases are similar for high and low elevations in Focus area 1, a decrease of 85% is expected in low elevations of Focus area 2 towards the end of the century, versus only ~~–~~57% in high elevations.

~~The mean, trends and changes in winter maximum fresh snow water equivalent (FSW; change in SWE from one day to the next)for 1 and 5-day durations (WM-FSW-1d, WM-FSW-5d), are shown in Figure 5 for 1 -day durations (WM-FSW-1d) and in Figure 6 for 5-day durations (WM-FSW-5d), 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 events (far inland) to about 50 events (at 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 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~~Changes in maximum snowfall

The mean, trends and changes in winter maximum fresh snow water equivalent (WM-FSW), are shown in Fig.8 for 1-day duration (WM-FSW-1d) and in Fig.9 for 5-day duration (WM-FSW-5d), where FSW is the change in SWE from one day to the next. 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 (Fig.8c). These areas of weak negative trends become smaller with the longer duration; for WM-FSW-5d only islands north of the city Tromsø inhibit weak negative trends (Fig.9b). 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% (Fig.8c) and 30–50% (Fig.9c) are seen for WM-FSW-1d and WM-FSW-5d, respectively, except a small area of even stronger increase in the far north-east.

~~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.~~

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WM-FSW-1d and WM-FSW-5d in the future (Figures 10~~4~~–11~~5~~) 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.~~

The largest change in the past is seen for WM-FSW-5d with an increase of 31%, and similar numbers for both low and high elevation bands. Focus area 2 only had an increase of 15%, but with 24% increase in high elevations and only 5% in low elevations. By the end of the century Focus area 1 can expect a decrease of 57% and 68% for WM-FSW-1d and WM-FSW-5d, respectively, while Study area 2 can expect a smaller decrease of 30% and 36%

4.3 Changes in heavy snowfall events

The frequency of heavy snowfall events (FSW-1d > 5 mm) is presented in Fig.12, showing a similar spatial distribution of trends as WM-SWE but with smaller areas of significant trends. Mean values for the extended winter season (Fig.12a) range from about 10 events (far inland) to about 50 events (at some high-elevated areas near the coast). Significant negative trends are found in and around Ringvassøya (Fig.12b), an island encompassing Tromsø municipality, with decreases of around 20% from the first 30-year period to the last (Fig.12c). 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.

The frequency of heavy snowfall events is expected to decrease in the whole region in the future (Fig.13), similar to other snow indices, by up to 60–70% in near future and up to 100% in far future along the coast. 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.

From Table 2 we find that a 17% and a 4% increase in FSW-1d > 5mm has occurred in 1958–2017 in Focus area 1 and 2, respectively. However, in both near and far future these events are expected to decrease by up to 89% in Focus area 1 towards the end of the century. Comparing to mean values for the reference period 1981–2100, this means a decrease from 38 to about 4 events on average. A smaller decrease of 64% towards the end of the century is expected in Focus area 2.

4.4 Changes in zero-crossings

Fig.14 shows a clear increase in the number of zero-crossings in the entire ~~county~~Troms during 1958~~-~~–2017, with large parts being dominated by significant positive trends (Fig.14b), reflecting increasing temperatures over the period. 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 (Fig.14a). The percentage increase between the first and the last 30-year period ranges from about 10% to 40%, with no obvious spatial pattern (Fig.14c), apart for a smaller change in valley bottoms.

Similar to the frequency of zero-crossings in the present climate, projected changes in zero-crossings (~~Figure~~ Fig.15~~7~~) also show an increase in many areas, reflecting that ~~increasing~~ temperatures will rise to~~in a relatively cold region approach~~ the zero degree threshold for a ~~larger part of the time~~longer period. However, in the mildest areas along the coast, where mean winter temperatures are already close to zero in the present climate, these crossing events will become less frequent. Both increases and decreases are expected to become stronger towards the end of the century. ~~For the low-lying, coastal regions of Troms where roads are present, we primarily expect changes at the beginning of the winter (Oct-Nov) and the end of the winter (April-May). These coastal regions have mean temperatures close to 0 degrees in the shoulder months in today's climate, and even a small temperature increase will therefore lead to large changes in zero-crossings. Fewer zero-crossings are expected at both sides of the winter, and the strongest change is expected in October and May. In these shoulder months, the change signal of fewer crossings are expected to reach far inland, while for other months, it is limited to the coast. Increases in zero-crossings are limited to regions far inland, at altitudes above approximately 600-700 AMSL from November to April.~~

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In Focus area 2 zero-crossings have become more frequent, with an increase of 24%, as opposed to only 5% in Focus area 1 (~~far future~~1981–2010). However, high elevations of Focus area 1 have experienced an increase of 18%. These events are expected to decrease in Focus area 1 in far future (~~-~~–18%), while an increase of 52% is expected in Focus area 2. Numbers for high and low elevations differ significantly in this area, with almost a doubling of events in higher elevations and a slight decrease in low elevation in the far future. A decrease of 39% is expected in the lower elevations of Focus area 1, meaning that slippery road conditions will become less frequent ~~road conditions might improve~~ in these areas during winter.

4.5 Changes in winter rain events

Fig.16 shows changes between the first and the last 30-year period of 1958~~-~~–2017 for mean number of days per winter with rainfall exceeding 10 mm. Mean values of winter rain > 10 mm range between 0 (far inland) to about 30 events on the southeast coast (Fig.16a). There has been an increase of such events in the whole of Troms, with significant positive trends in many coastal regions (Fig.16b).

Winter rain events have been rare in Troms in the past, but ~~Figure~~ Fig.17~~8~~ shows that the frequency of ~~heavy~~ winter rain > 10 mm~~water supply (rainfall and/or snow melt)~~ is projected to increase everywhere in Troms~~ significantly in the future, as compared to 1981-2010~~. I~~ 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., 20175), higher temperatures giving more precipitation as rain instead of snow, and increasing snow melt due to longer periods of temperature above zero degrees.~~ncreases of up to 400% are expected in some inland regions (Fig.17b), while in coastal regions show increases of up to 100% towards the end of the century.

Focus area 1 (2) experience about 70% (42%) more heavy winter rain events today compared to the first 30-year period (Table 2). Approaching the end of the century the largest change is expected in Focus area 2, with a 361% increase in high elevations. However, in these areas there were only 1–2 events with rain > 10 mm/day in the period 1981–2010, meaning that an increase of 361% would result in 6–7 events by the end of the century.

4.6 Changes in snow drift

For changes in the snow drift factor we only have numbers for the two focus areas as means over selected grid cells particularly exposed to wind. Events of snow drift > p90 have increase by 16% and 10% in Focus area 1 and 2, respectively. Focus area 2 can expect slightly larger changes in the future, with a decrease of 89% towards the end of the century. With a mean number of strong snow drift events of 21 in the current climate, an average of about two events each year is expected in 2071–2100.

~~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 Senjahopen, but increase by up to 39% in Jøvik in far future. Although changes in heavy water supply have been~~

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~~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 ~~2~~3: Estimated changes in climate ~~weather~~ indices between two 30-year periods in the two focus areas, based on spatial mean values. In parenthesis we present the change in the lower and higher elevation bands, respectively. Values for snow drift are only based on selected grid cells in high and wind exposed elevations. All values are in %~~*Absolute change~~. Past change refer to the change between the first and the last 30-year period during 1958–2017 (for wind: 1958–2015). Change in near (far) future refers to change between 1981–2010 and 2041–2070 (2071–2100).

Climate~~Weather~~ index	Past changes Whole region (low, high) Reference value (1981–2010)~~Past change (1958-2017)~~		Changes in near future Whole region (low, high)		Changes in far future Whole region (low, high)	
	~~Senjahopen~~Focus area 1	~~Jøvik~~Focus area 2	~~Senjahopen~~Focus area 1	~~Jøvik~~Focus area 2	~~Senjahopen~~Focus area 1	~~Jøvik~~Focus area 2
~~Maximum snow water equivalent~~ (WM-SWE)	17 (4,30) 363 mm~~13.9 %~~	10 (0,12) 426 mm~~11.3 %~~	-69~~70~~ (-71, -60)~~.6 %~~	~~-52.0 %~~-47 (-63, -32)	~~-90.5 %~~-89 (-91, -85)	-70 (-85, -57)~~4.8 %~~
~~Maximum 1-day snowfall (~~WM-FSW-1d~~)~~	26 (28, 27) 24 mm~~27.8 %~~	12 (9, 16) 27 mm~~13.5 %~~	-30 (-34, -21)~~-30.7 %~~	-16 (-31, -4)~~-18.8 %~~	-57 (-66, -38)~~-59.4 %~~	-30 (-55, -11)~~-34.9 %~~
~~Maximum 5-day snowfall (~~WM-FSW-5d~~)~~	31 (32, 34) 56 mm~~31.6 %~~	15 (5, 24) 61 mm~~13.5 %~~	-37 (-44, -23)~~-38.5 %~~	-19 (-35, -7)~~-22.0 %~~	-68 (-77, -48)~~-70.6 %~~	-36 (-64, -16)~~-42.4 %~~
~~Frequency of 1-day snowfall > 5 mm (~~FSW-1d > 5 mm~~)~~	17 (15, 22) 38 events~~16.4 %~~	4 (-1, 7) 37 events~~3.8 %~~	-65 (-73, -48)~~-67.6 %~~	-39 (-60, -24)~~-43.2 %~~	-89 (-94, -76)~~-90.7 %~~	-64 (-85, -48)~~-69.1 %~~
Zero-crossings	5 (0, 18) 79 events~~3.8 %~~	24 (20, 28) 67 events~~23.2 %~~	7 (-13, 38)~~1.4 %~~	43 (9, 60)~~36.2 %~~	-18 (-39, 23)~~-25.0 %~~	52 (-4, 90)~~39.1 %~~
~~Water supply~~Winter rain > 10~~10~~	70 (75, 36) 13 events~~9.9~~	42 (37, 36) 5 events~~5.7~~	43 (30, 68)~~26.9 %~~	88 (42, 123)~~59.8 %~~	62 (39, 125)~~34.1 %~~	207 (69, 361)~~65.4 %~~

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mm/~~day *~~						
~~Wind speed > 6m/s *~~Snow drift > p90	**16** 22 events~~0.8~~	**10** 21 events~~2.3~~	**-61**	**-67**	**-85**	**-89**

5 Discussion and conclusions

Our analyses of past development point~~s~~ to areas in T~~h~~roms c~~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 in some 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~~of Troms, particularly in low altitude regions, indicating that the transition from increasing to decreasing dry snow avalanche likelihood~~risk~~ takes place before 2040 even in the highest~~highest elevated~~ and coldest areas. ~~However, the probability of wet snow avalanches and slushflows may increase as milder winters and rain to high elevation may significantly restrict snow transport (Hendrikx et al., 2005) and 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 avalanche~~d~~s might be realistic in a warmer climate with a shorter winter season and less snow. ~~As stated in the introduction, the complexity of avalanche release lead to contradicting arguments related to the development of snow avalanches in a changing climate.~~

~~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 and/or+ snow melt). Actually,~~Events of winter rain > 10 mm ~~these events~~ occur relatively seldom in ~~today's~~the present~~'~~ climate, still, they have already become more frequent in Troms in the last decades. This is in line with findings by Pall et al. (2019), who showed that rain-on-snow events were more frequent during winter months in 1981~~–~~–2010 compared to 1961~~–~~–1990.~~.~~ Over the next few decades, our results indicate that heavy ~~this will change the relative change will increase quite dramatically, and events of water supply exceeding of 10 mm/day~~winter rain events are likely~~expected~~ to increase ~~significantly~~ in all regions~~.~~, although high percentage increases are partly explained by low relative numbers, thus absolute changes are restrained to 8~~–~~–10 more events by the end of 2100~~except along the coast and in deep valleys. As stated in Hisdal et al. (2017), snow melt avalanches~~slushflows ~~will occur earlier in the spring and become less frequent towards the end of this century~~ ~~.~~ ~~A~~thus ~~a~~ likely explanation of more frequent ~~heavy water~~winter rain events

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~~supply~~ is obviously milder winters, but the amount of water vapor available is also likely to be higher in a warmer atmosphere. ~~the projected increase in winter precipitation coming as rain.~~ Another plausible contributor to more water supply is the lengthening of the snow melt season into the winter season defined in current climate. In the period 1971~~-~~–2000, mean number of snow days ~~lies~~ were between 180 and 270 in Troms, thus covering the whole winter season (Oct~~-~~–Apr) of 212 days. A decrease of 60~~-~~–180 days by 2071~~-~~–2100 under emission scenario RCP8.5 is expected, depending on elevation (Hanssen-Bauer et al., 2017). Consequently, very few or no areas will have a full snow season and the snow melt season will start earlier and contribute more to water supply during winter, as long as snow is available. More rain~~rain~~ during winter and more snow melt may ~~also~~ point to increased likelihood~~risks~~ of wet snow avalanches and slushflows in the ~~actual~~ areas of Troms~~,~~. ~~h~~However, Hisdal et al. (2017) states that slushflows will occur earlier in the spring and become less frequent towards the end of this century due to less snow available~~s~~. In addition, other studies show that an 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~~)~~). The contradicting arguments pointed out here~~,~~ underline~~s~~ the complexity of avalanche release and the large uncertainties associated with the future development of such hazards under climate change. In this regard, we would like to urge further studies on expected future avalanche activity covering different avalanche types. ~~In the areas of no change or decrease, there might not even be much snow available for melting during winters in the future.~~

Changes in zero-crossings indicate shifts in slippery road conditions. ~~Gustafson (1983) found a "very clear relationship between low surface temperatures and the development of slippery conditions".~~ ~~With~~ Although our definition~~,~~ a zero-crossing ~~occurs when~~refers to the fluctuation of air temperature ~~fluctuates from~~across zero, ~~below zero to above zero, not and surface temperatures. 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 ~~Although~~ additional information about the surface temperature would have given~~give~~ a better representation of slippery conditions, the change pattern shown here would likely be close to a change pattern of surface temperatures~~duration of thawing and freezing may be required to better represent the potential trigger of snow avalanches~~. ~~We regard uncertainties related to climate emission scenarios, measurements etc. to be larger than the difference a 2m TmaxTmin index and a surface temperature index. Even changes in rockfall frequency, which are triggered by stresses created when water freezes or by water pressure when ice thaws, could be informed by the change maps in zero-crossings, although values of change are uncertain.~~ For the low-lying~~,~~ seaside~~coastal~~ regions of Troms, with several~~where many~~ access roads ~~are present go~~, we primarily expect changes in zero-crossings a~~in~~t the beginning of ~~the~~ winter (Oct~~-~~–Nov) and the end of ~~the~~ winter (Apr~~il~~–May). These seaside ~~coastal~~ regions have mean temperatures close to 0 °C ~~degrees~~ in the shoulder months in ~~today's~~the present climate, and even a small temperature increase will therefore lead to large changes in zero-crossings. Fewer zero-crossings are expected both prior to and after~~at both sides of~~ the winter season, ~~and~~ with the strongest change ~~is~~ expected in October and May. In these shoulder months, the change signal of fewer crossings ~~are~~ is expected to reach far inland, while for other months, it is limited to the coast. Increases in zero-crossings are limited to regions far inland, at altitudes above approximately 600~~-~~–700 AMSL from November to April.

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 border between Norway and Sweden~~the Swedish border~~. Their analysis was based on daily mean temperature and ended in 2010~~.~~. ~~T, thus~~Thus ~~our~~ the results here are more robust and the pronounced positive trends in the entire ~~county~~ Troms 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, including two stations in ~~Troms county~~Troms ~~County~~. For these two stations, the frequency of zero-crossings increased during the periods 1970–1979 and 1990–1999 but decreased in the 1980s. ~~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~~Kerguillec (2015) claims that a strong negative NAO (North Atlantic Oscillation) index generally increases zero-crossings in ~~coastal~~ seaside regions, particularly those ~~of central Norway including two stations~~ in ~~Troms county~~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~~ seaside areas, while inland areas and mountains are expected to have more zero-crossings in the future compared to present climate. These are the coldest areas ~~today~~in the present, and an increase in temperature will bring winter temperatures closer to zero.

Our two focus areas, Senjahopen/Mefjordvær (Mefjorden) and Jøvik/Olderbakken, have and will experience many of the same changes in climate indices relevant for access disruptions. However, as Focus area 1 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 Focus area 2. In both areas an increase in all studied snow-related variables has occurred in the last decades, more so in higher elevations, while a decrease is expected towards the end of this century and particularly in low elevations. This means a potential for less dry snow-related access disruptions in the future, ~~but~~ while wet snow avalanches and slushflows may increase. In the far future, we have shown that zero-crossings and events of winter rain > 10 mm are projected to increase, and more so in Focus area 2. In areas where there is still a significant amount of snow in 2071~~-~~–2100, weather described by the studied indices might become a larger threat as potential triggers of avalanches and challenging road conditions. Our findings support to a large degree the Troms climate fact sheet of Hisdal et al. (2017), which states that slushflows will become an increased threat in ~~Troms county~~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~~ while reduced snow amounts in the long run will decrease the risk for snow avalanches.

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We have shown that strong snow drift, computed from snowfall and wind speed, have slightly increased in the two focus areas, but that a strong decrease is expected in the future. There is no evidence for large changes in wind activity in our regions and wind projections are associated with a high degree of uncertainty, of which a large part is related to their positioning of storm tracks (e.g. Zappa et al., 2013). ~~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. Wheather 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 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. However, an obvious reason for fewer strong snow drift events is the lack of snow when approaching 2100, as discussed above.

~~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.~~

Although observation based datasets are associated with uncertainty, especially due to relatively sparse measurements in a complex terrain, future projections have a number of uncertainty aspects. As ~~this~~ table A1 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. Other sources of uncertainty associated with future climate projections of temperature and precipitation include emission scenario, natural climate variability, shortcomings in our understanding of the climate system, which results in climate models reproducing certain processes incorrectly, and limited capacity of supercomputers (Hanssen-Bauer et al., 2017). ~~for instance although~~ Kotlarski et al. (2014) report that for instance the RCA model seems to have a cool and wet bias over the Scandinavian region during the winter (DJF) season, meaning that future projections in the current study could be biased towards larger snow amounts. Projections for Norway are bias-adjustment (see Section 3.1), thus systematic biases are removed. Still, only one method of bias-adjustment is used. Further, uncertainties in the hydrological modelling, mostly related to parameterization and the fact that only one hydrological model is used, affects snow parameters.

In a changing climate it is particularly important to identify areas of increased vulnerability and risk of weather-induced hazards. As we, in the current study, have focused on only a few selected climate indices, future studies might include other relevant indices. We note that reported avalanche activity has become more detailed during the last years, and new avalanche monitoring stations are in operation closer to typical run-out zones. This will provide new insight into triggering weather conditions, which can be used to study the links between weather and avalanche release.

~~Remote s~~Seaside communities with access highways exposed to natural hazards, such as ~~Senjahopen~~Focus area 1 and ~~Jøvik~~Focus area 2, 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~~ several municipalities~~, who~~ that, by Norwegian law, are responsible for preventive measures and risk management~~,~~ associated with ~~e.g.~~ weather-induced ~~landslides~~ hazards. 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 likelihood~~risk~~ of water and rainfall-induced hazards and more frequent freeze-thaw conditions in certain inland areas, a better coordinated climate adaptation, cooperation between different sectors, as well as guidance and training of local authorities ~~is~~ will be 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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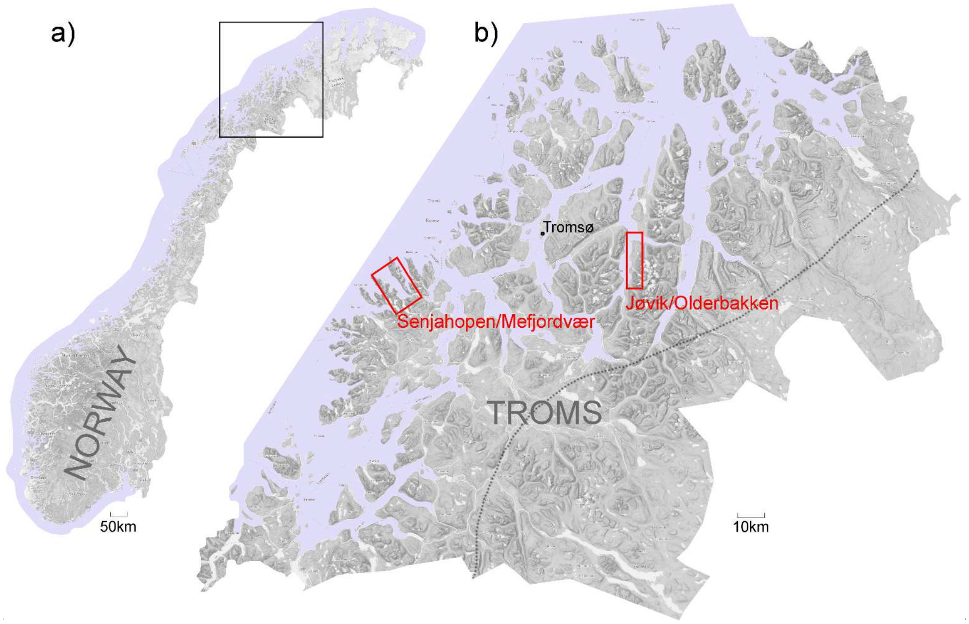

a)
b)
NORWAY
50km
Tromsø
Senjahopen/Mefjordvær
Jøvik/Olderbakken
TROMS
10km

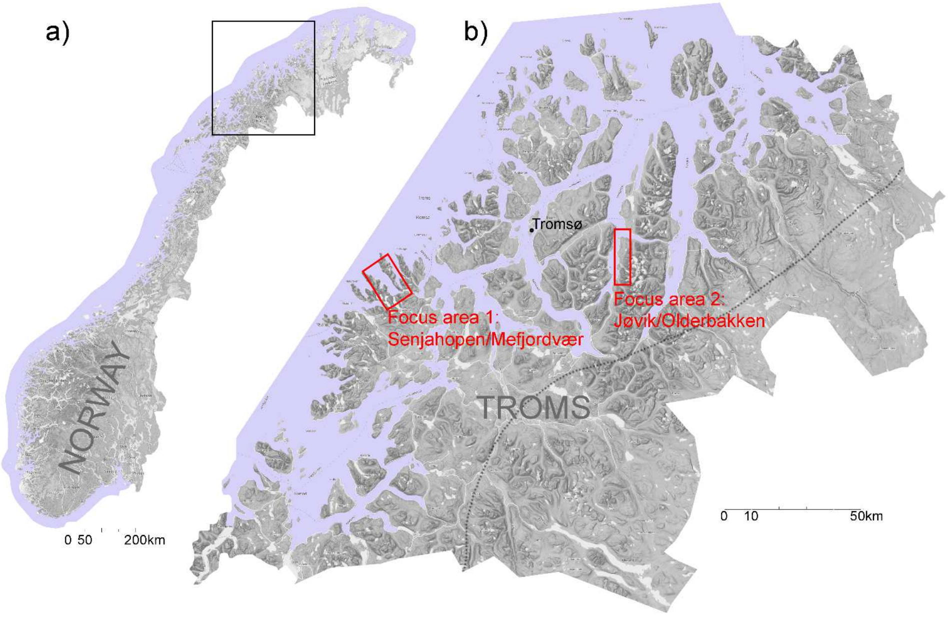
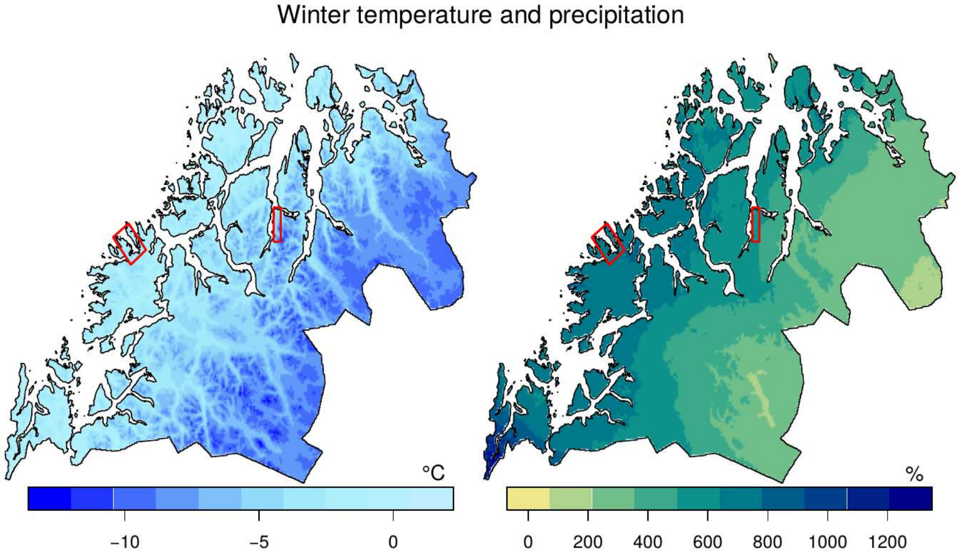


Figure 1: Map of Norway (left) and ~~Troms county~~Troms ~~County~~ (right), with inland and coastal regions separated by the stippled line, and our two focus areas, ~~Senjahopen~~Focus area 1 and ~~Jøvik~~Focus area 2 in red squares.



Winter temperature and precipitation
°C
−10
−5
0
%
0
200
400
600
800
1000
1200

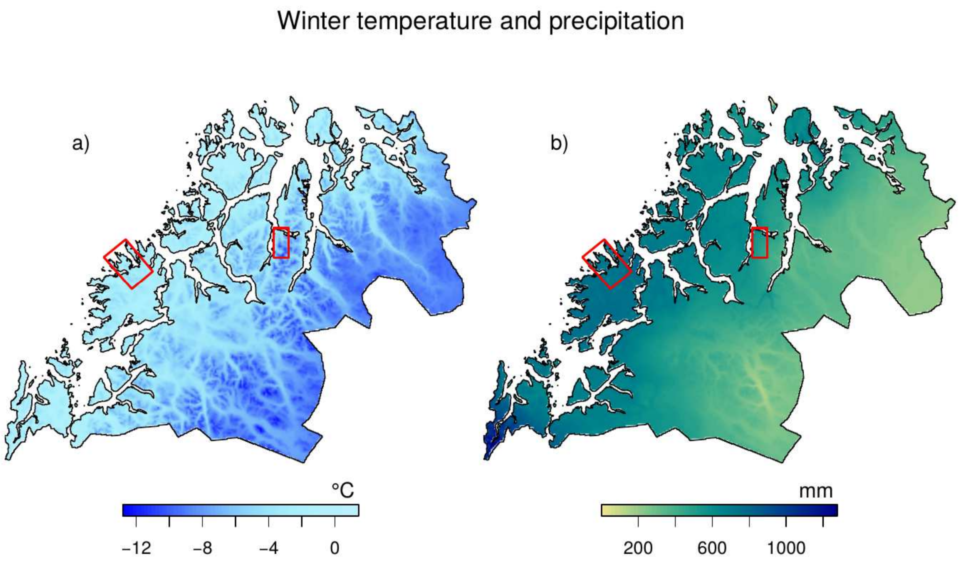
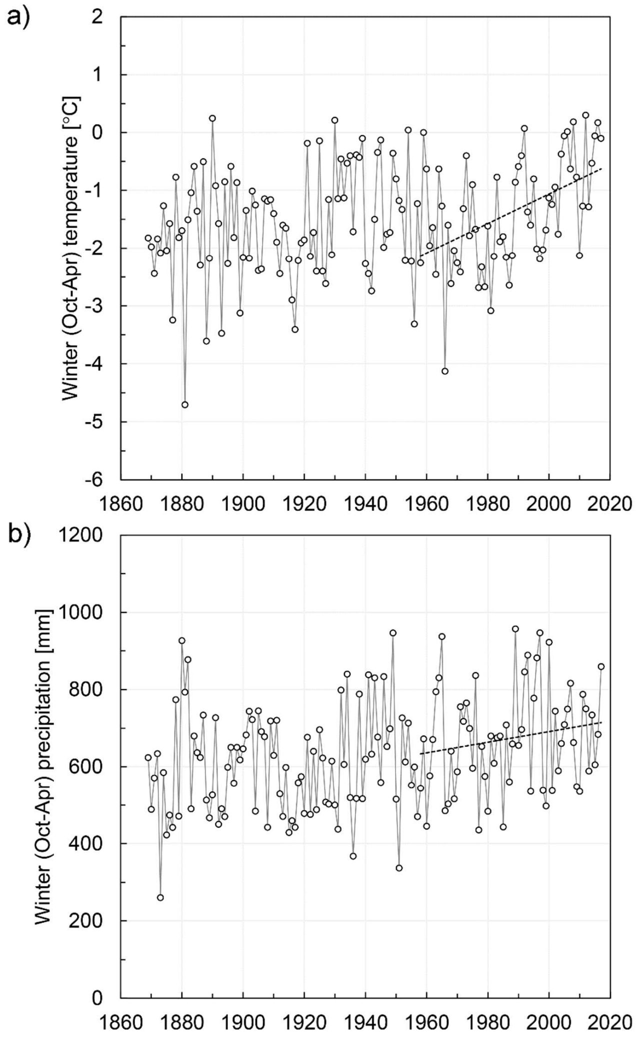


Figure 2: Mean winter temperature and total winter precipitation averaged over the period 1981–2010.


a)
Winter (Oct-Apr) temperature [°C]
2
1
0
-1
-2
-3
-4
-5
-6
1860
1880
1900
1920
1940
1960
1980
2000
2020
b)
Winter (Oct-Apr) precipitation [mm]
1200
1000
800
600
400
200
0
1860
1880
1900
1920
1940
1960
1980
2000
2020

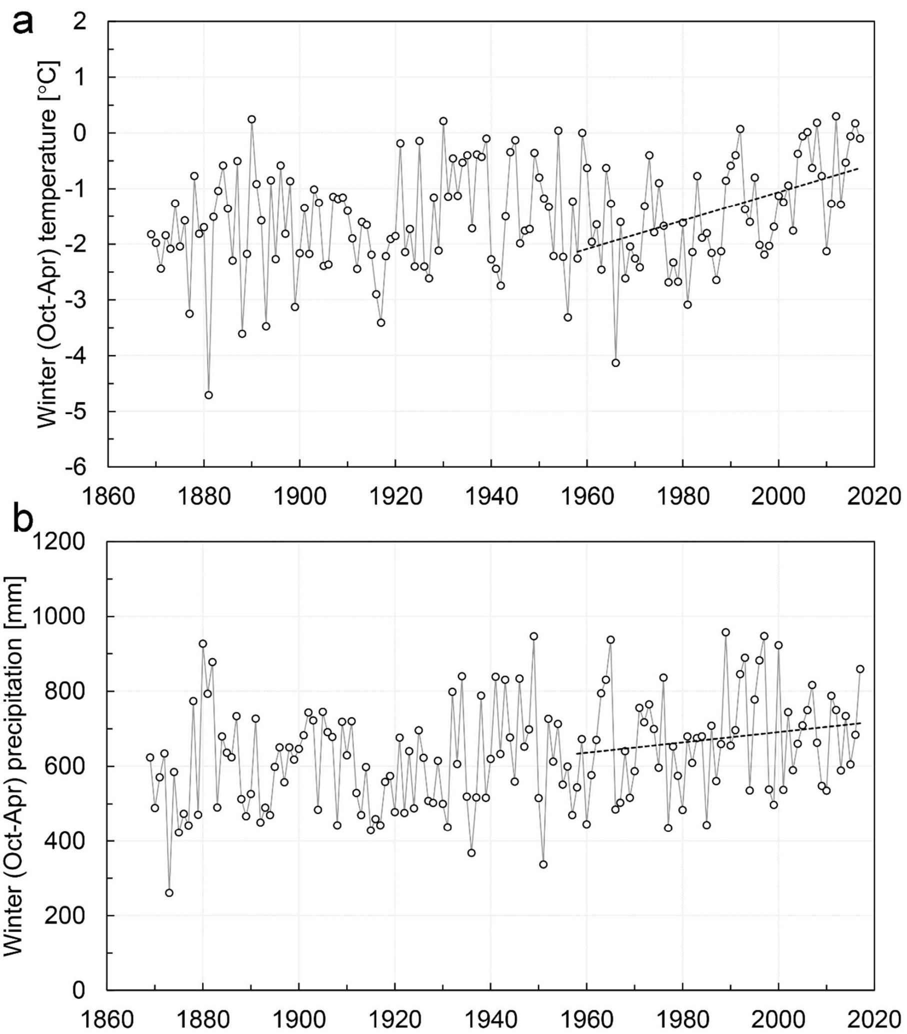
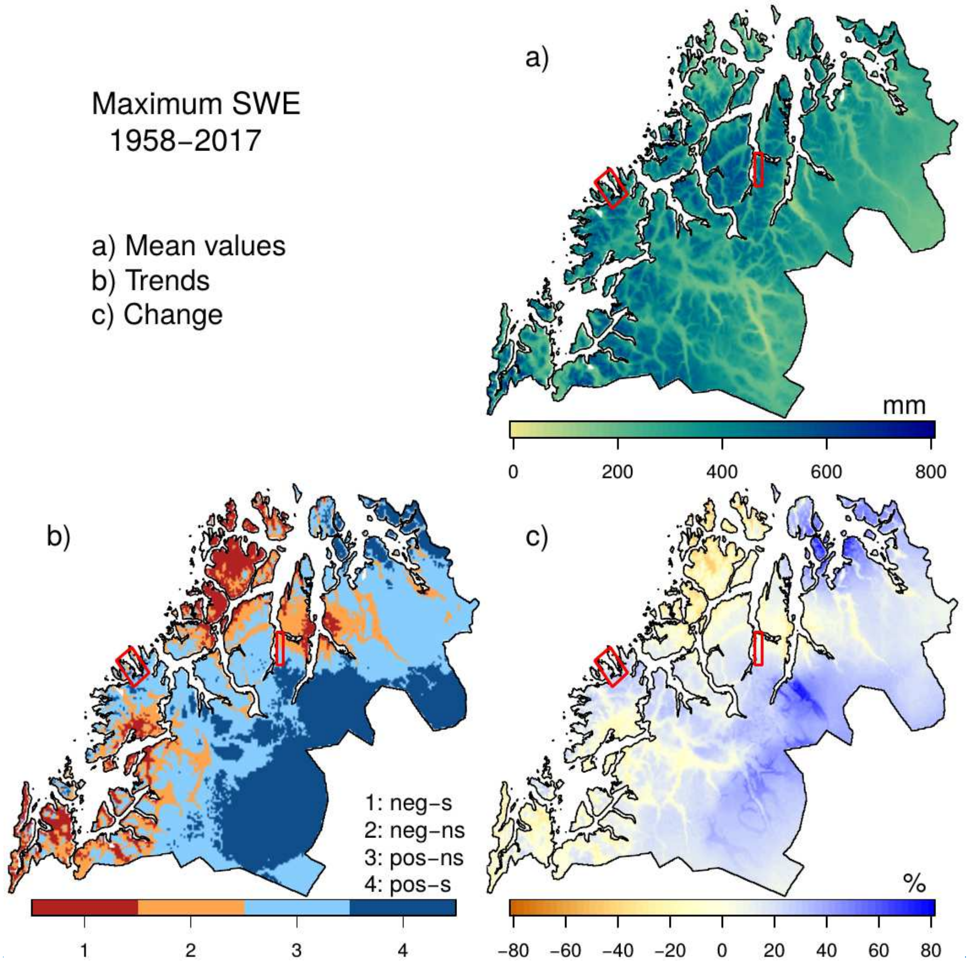


Figure 3: Mean winter temperature (a) and total winter precipitation (b) measured at Tromsø meteorological station in the period 1867-2017. The stippled line indicates the trend in the period 1958-2017.



Maximum SWE
1958−2017
a) Mean values
b) Trends
c) Change
a)
mm
0
200
400
600
800
b)
1: neg−s
2: neg−ns
3: pos−ns
4: pos−s
1
2
3
4
c)
%
−80
−60
−40
−20
0
20
40
60
80

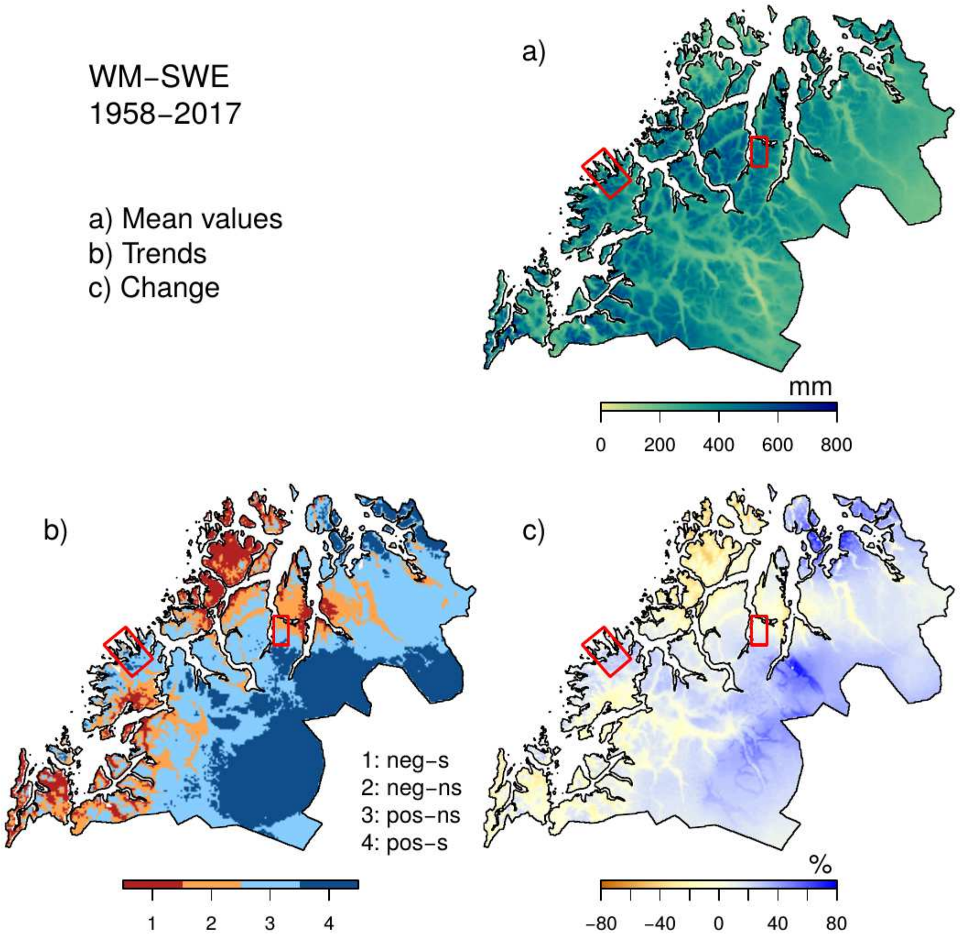
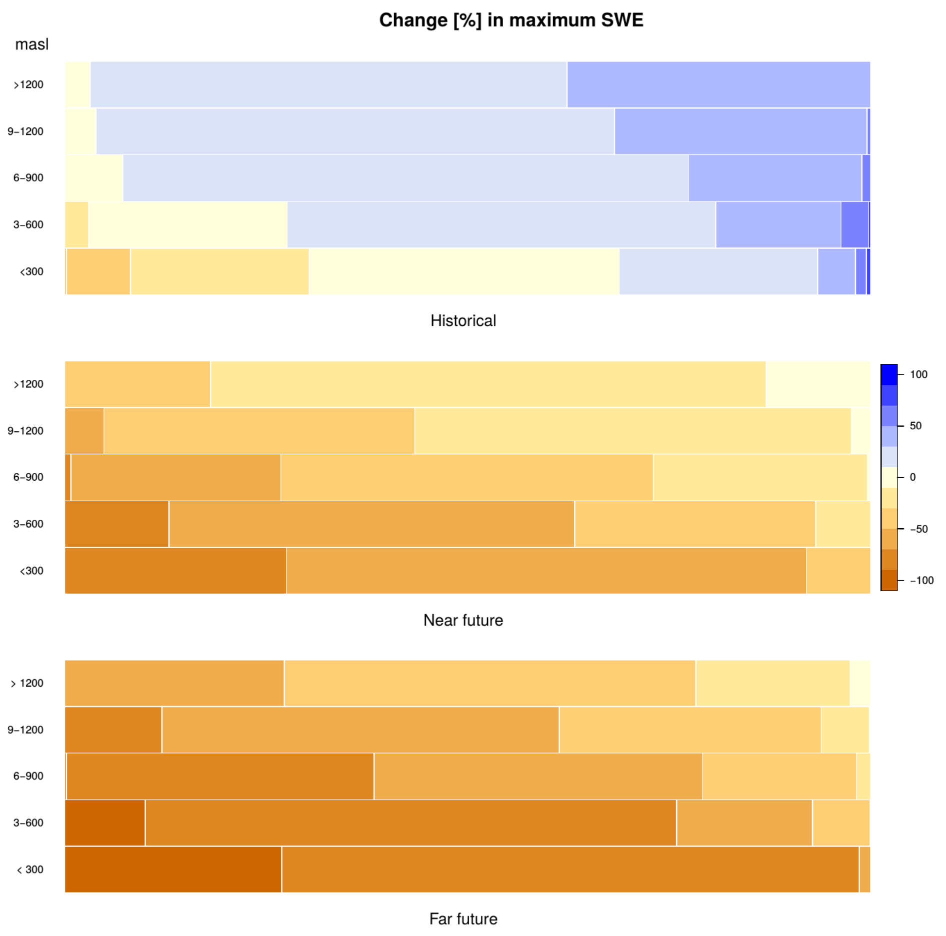


Figure 4: Mean values (a), trends (b) and changes (c) in winter (Oct–Apr) maximum snow water equivalent (SWE) for the period 1958–2017. In b), positive trends are illustrated in blue and negative trends in red; dark red and blue colors represent statistically negative and positive significant (s) trends, 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.



Change [%] in maximum SWE
masl
>1200
9–1200
6–900
3–600
<300
Historical
>1200
9–1200
6–900
3–600
<300
Near future
100
50
0
−50
−100
> 1200
9–1200
6–900
3–600
< 300
Far future

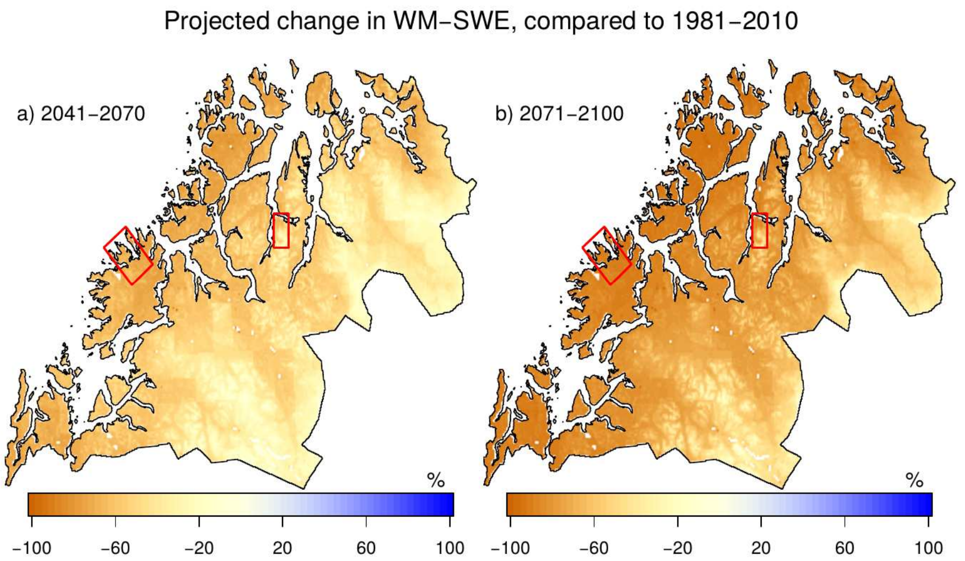


Figure 5: Projected change in maximum snow water equivalent (SWE) during winter (Oct–Apr) between 1981-2010 and a) near future (2041-2070); b) far future (2071-2100.

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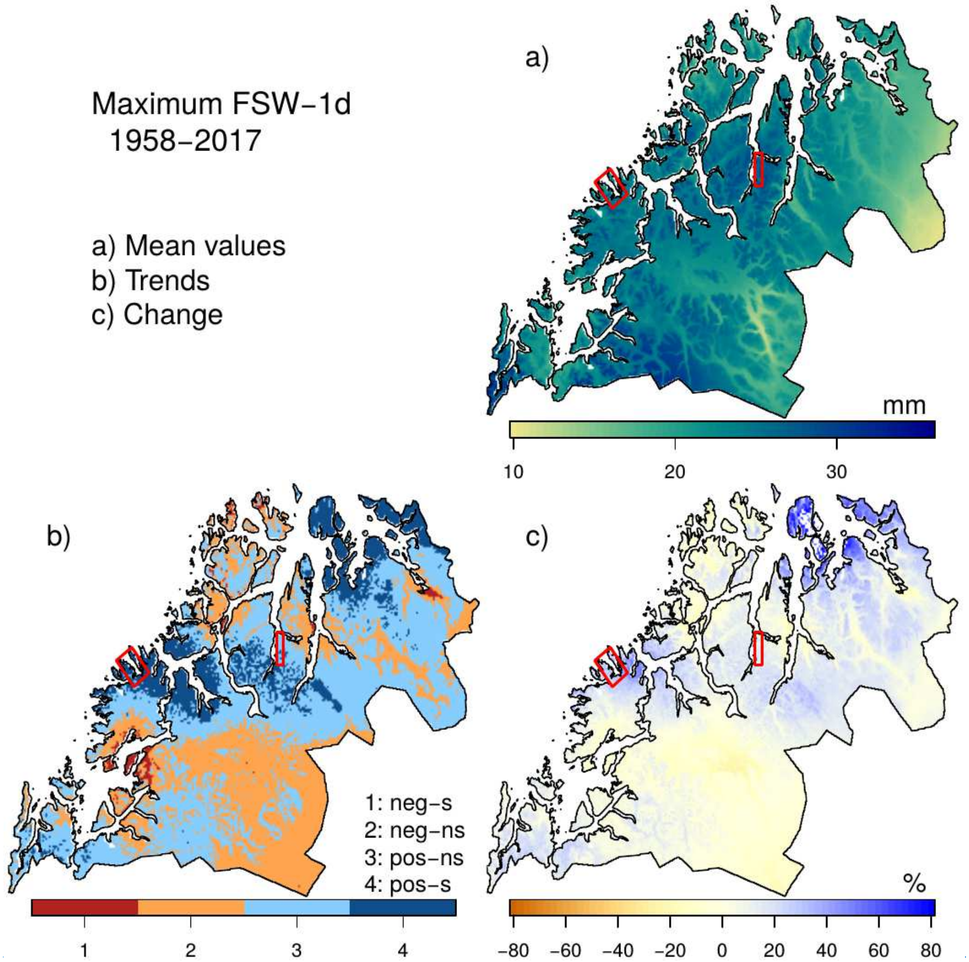
Maximum FSW−1d
1958−2017
a) Mean values
b) Trends
c) Change
a)
mm
10
20
30
b)
1: neg−s
2: neg−ns
3: pos−ns
4: pos−s
1
2
3
4
c)
%
−80
−60
−40
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0
20
40
60
80

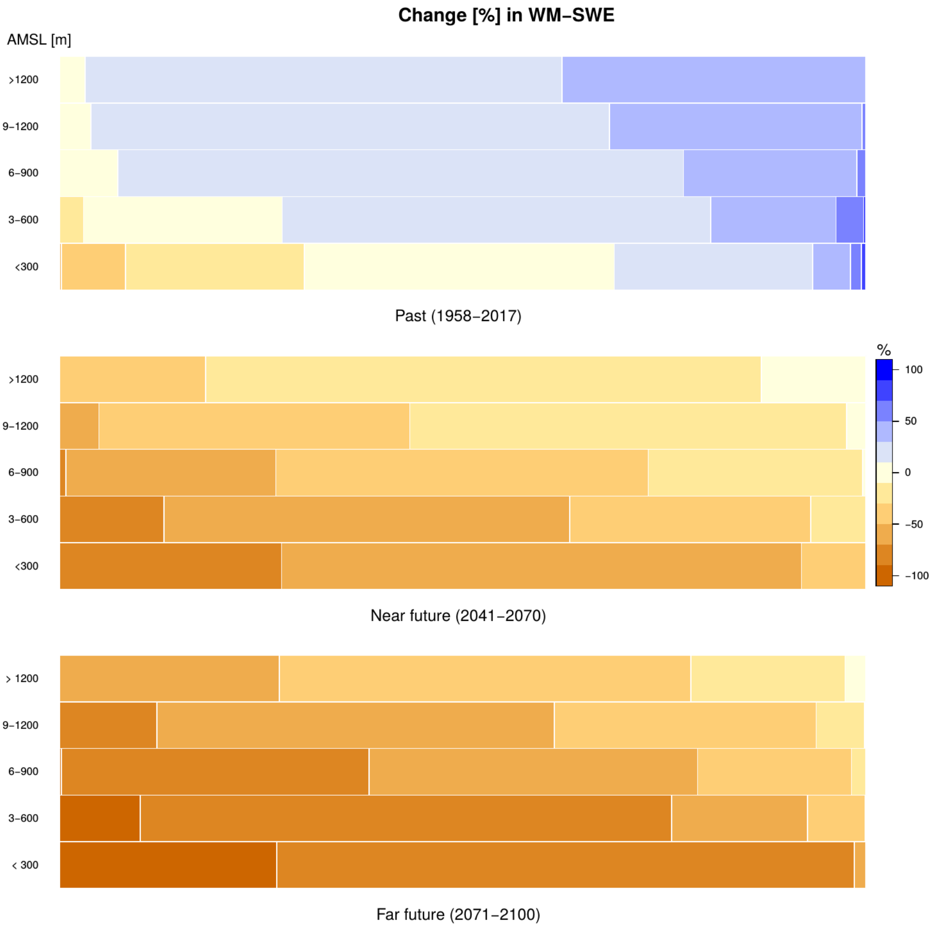
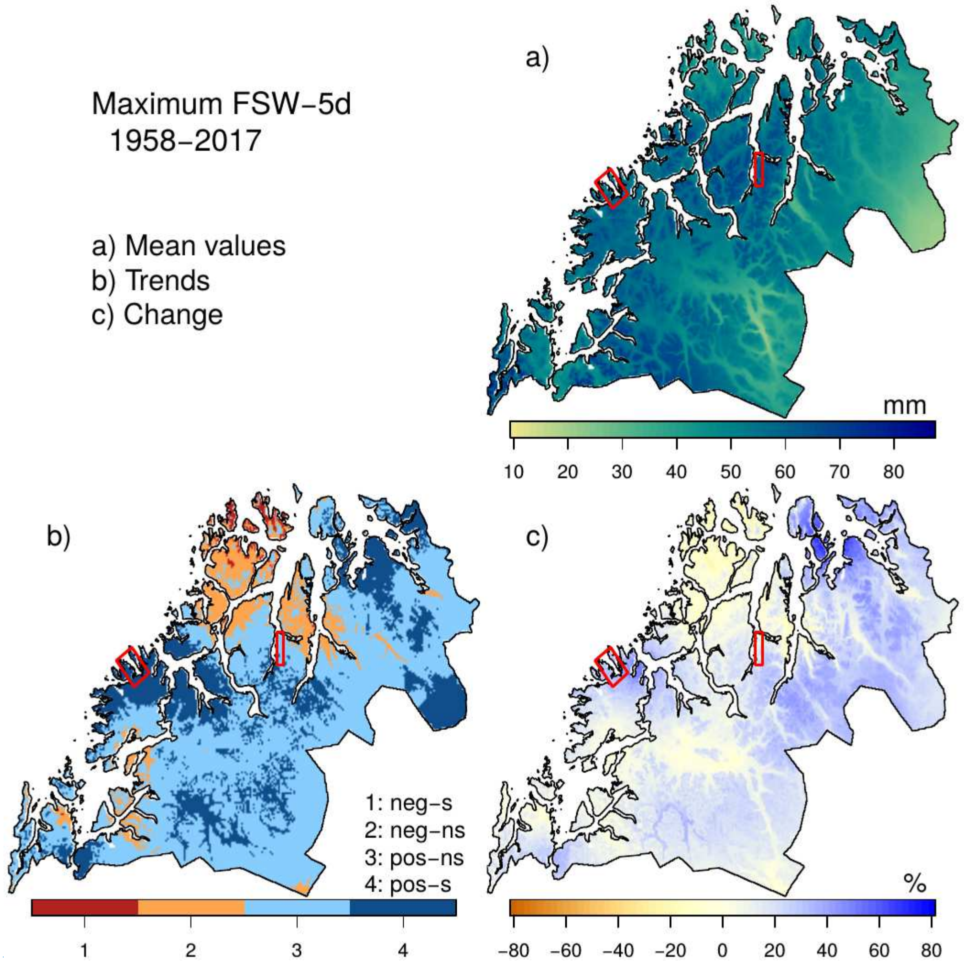


Figure ~~6~~5: Percentage change in winter maximum SWE in different elevation levels for: historical period (change between 1958-1987 and 1988-2017; upper panel), near future (change between 1981-2010 and 2041-2070; middle panel) and far future (change between 1981-2010 and 2071-2100; lower panel). The length of the colored bars represent the fraction of grid cells within the different intervals given by the legend.

~~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.~~


Maximum FSW−5d
1958−2017
a) Mean values
b) Trends
c) Change
a)
mm
10 20 30 40 50 60 70 80
b)
1: neg−s
2: neg−ns
3: pos−ns
4: pos−s
1 2 3 4
c)
%
−80 −60 −40 −20 0 20 40 60 80

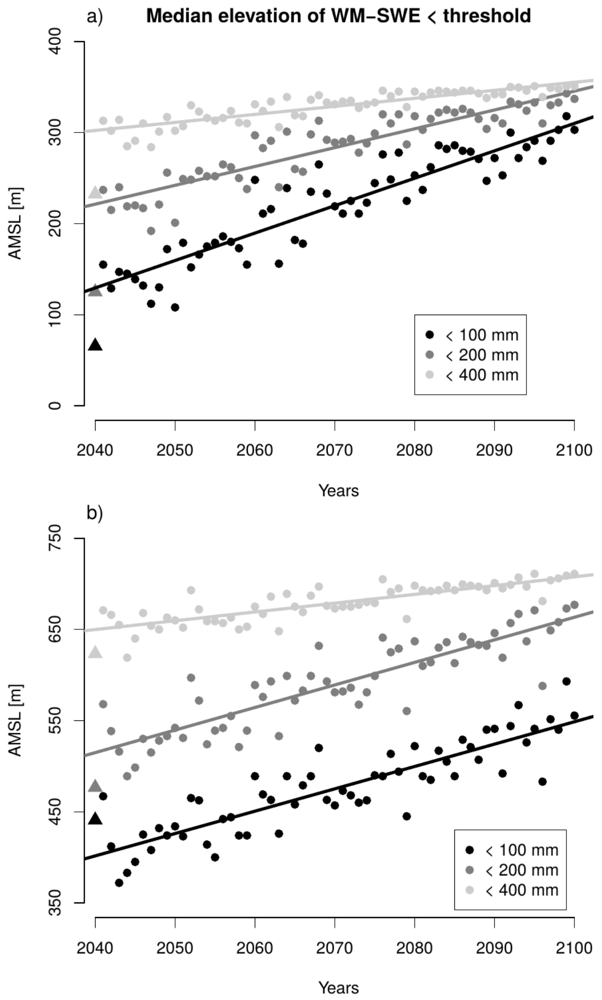
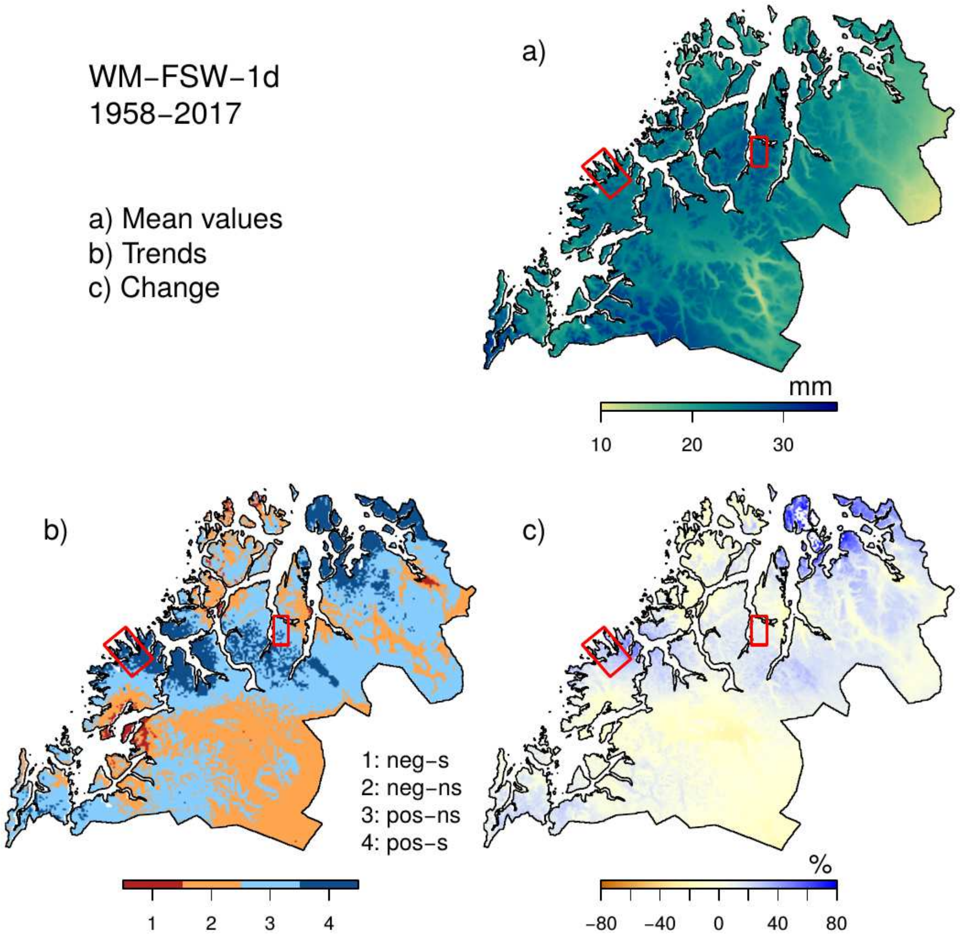


Figure 76: Projected future development in median elevation where winter maximum SWE is below 100 mm (black), 200 mm (dark grey) or 400 mm (light grey). a) Coast and b) inland (see map in Fig.1). Mean values for the period 1981-2010 are indicated as triangles.

~~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.~~


WM−FSW−1d
1958−2017
a) Mean values
b) Trends
c) Change
a)
mm
10
20
30
b)
1: neg−s
2: neg−ns
3: pos−ns
4: pos−s
1
2
3
4
c)
%
−80
−40
0
40
80

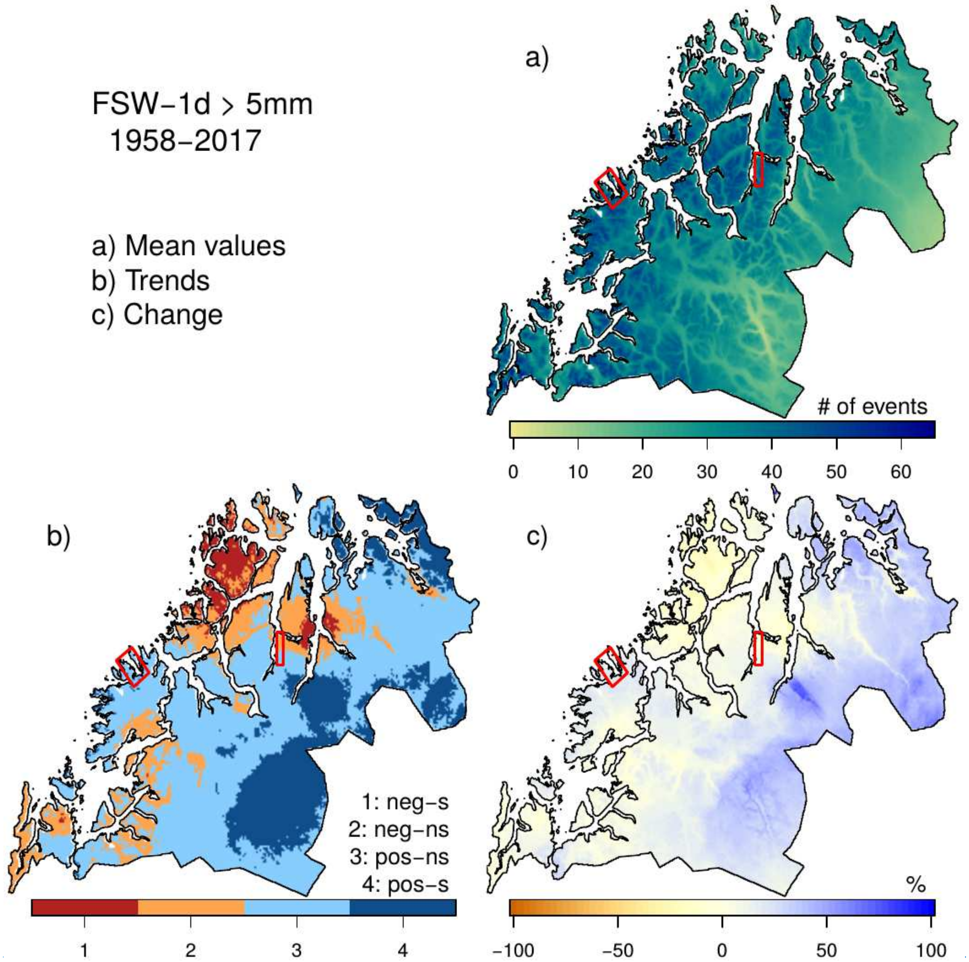
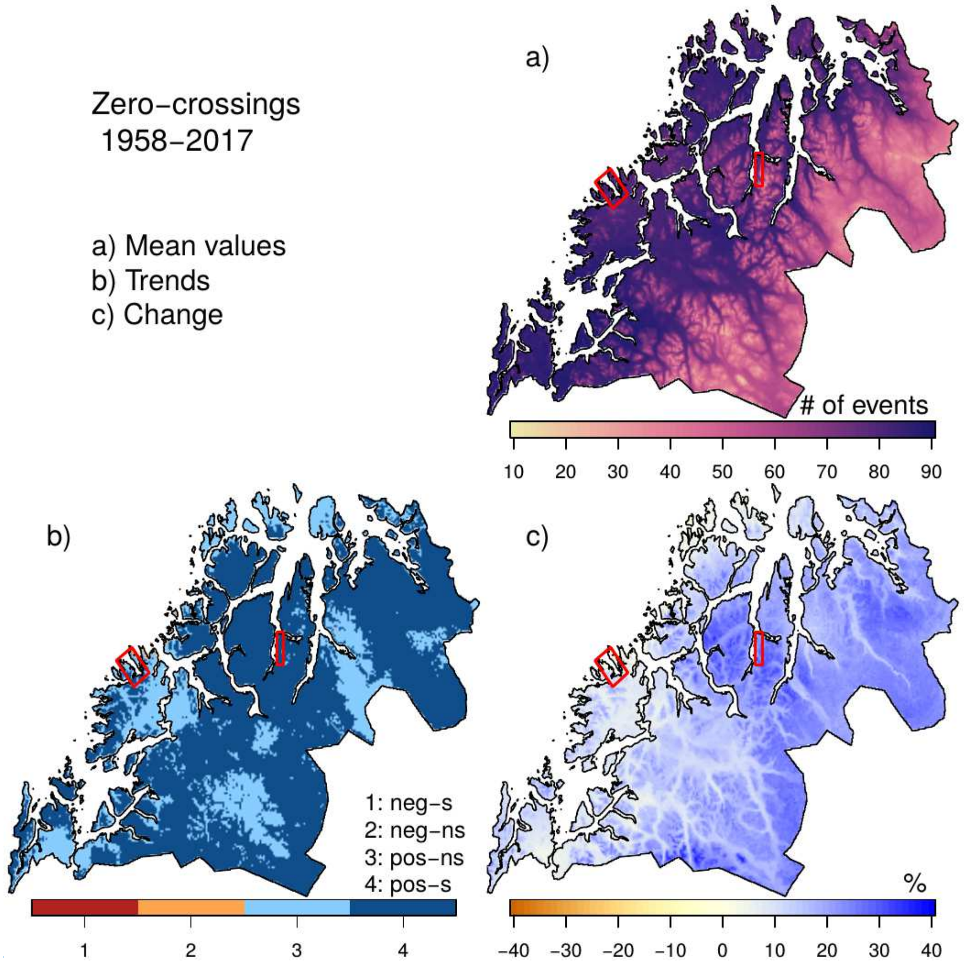


Figure ~~7~~8**: Maximum 1-day snowfall during winter (Oct–Apr) for the period 1958-2017, based on maximum fresh snow water equivalent for 1-day duration (WM-FSW-1d). Mean values (a), trends (b) and changes are shown in the same way as in Fig.4.**

~~**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.**~~



Zero−crossings
1958−2017
a) Mean values
b) Trends
c) Change
a)
# of events
10 20 30 40 50 60 70 80 90
b)
1: neg−s
2: neg−ns
3: pos−ns
4: pos−s
1 2 3 4
c)
%
−40 −30 −20 −10 0 10 20 30 40

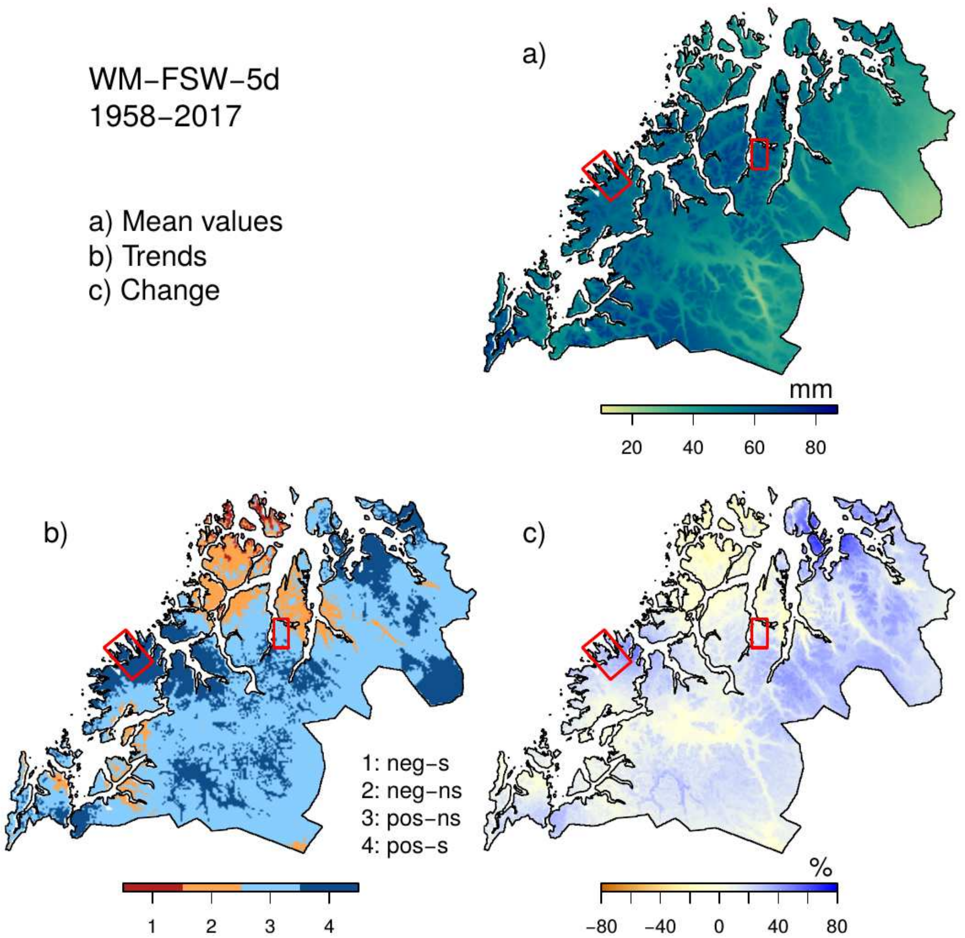
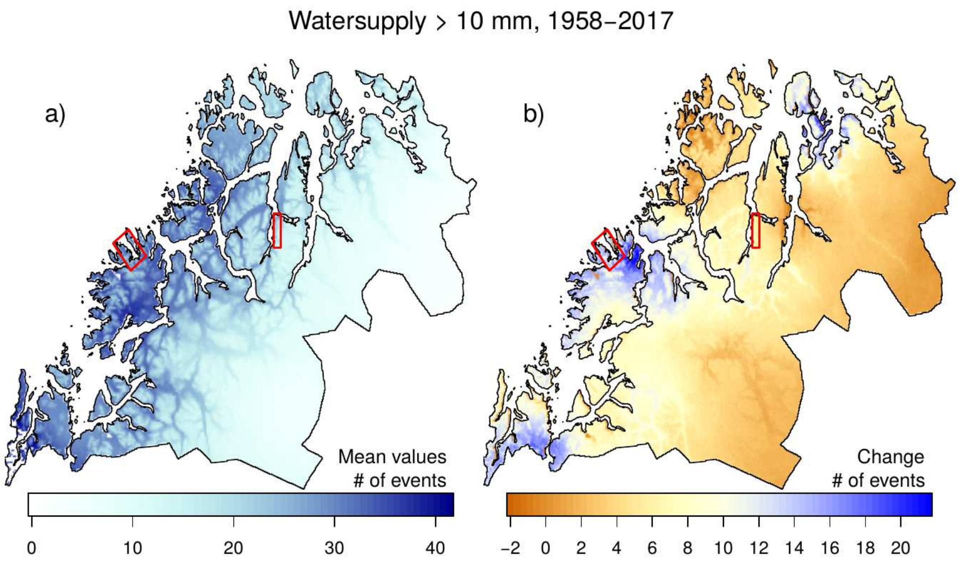


Figure 9~~8~~: Maximum 5-day snowfall during winter (Oct–Apr), based on maximum fresh snow water equivalent for 5-day duration (WM-FSW-5d). Absolute mean values (a), trends (b) and changes are shown in the same way as in Fig.4.

~~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.~~



Watersupply > 10 mm, 1958−2017
a)
b)
Mean values
# of events
0
10
20
30
40
Change
# of events
−2
0
2
4
6
8
10
12
14
16
18
20

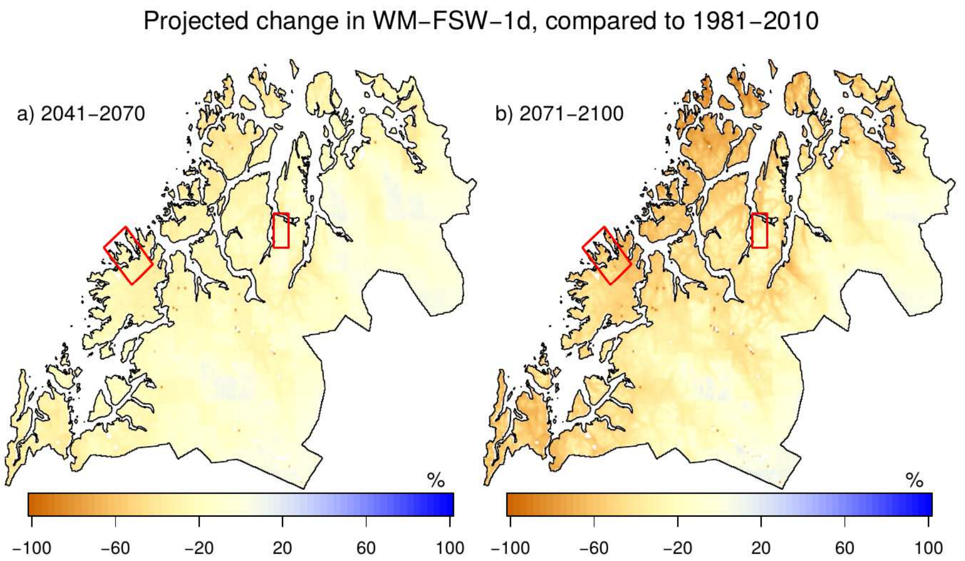
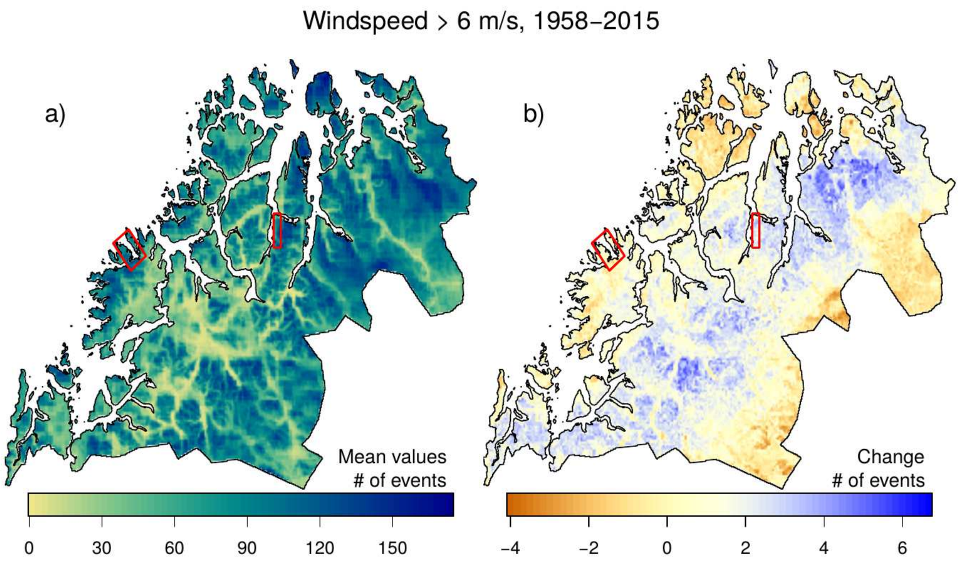


Figure ~~9~~10: Projected change in maximum 1-day snowfall during winter (Oct–Apr) between 1981-2010 and a) near future (2041-2070); b) far future (2071-2100, based on maximum fresh snow water equivalent for 1-day duration (WM-FSW-1d).

~~**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.**~~



~~**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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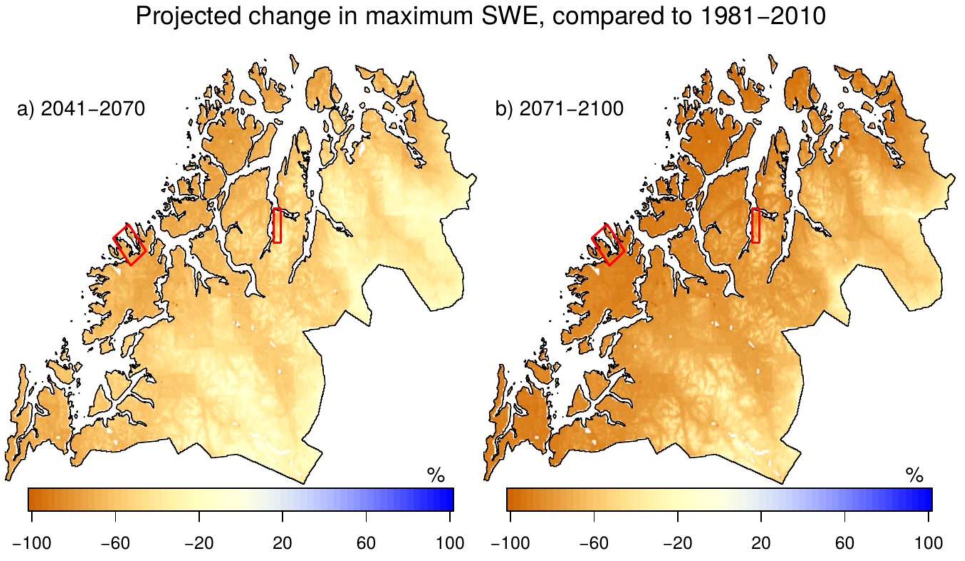

Projected change in maximum SWE, compared to 1981−2010
a) 2041−2070
b) 2071−2100
%
−100
−60
−20
20
60
100
%
−100
−60
−20
20
60
100

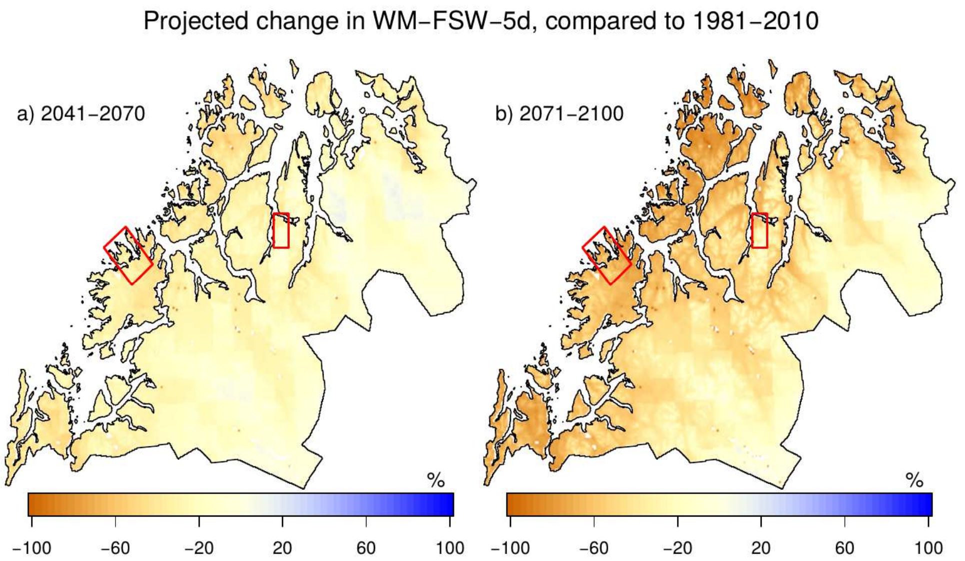
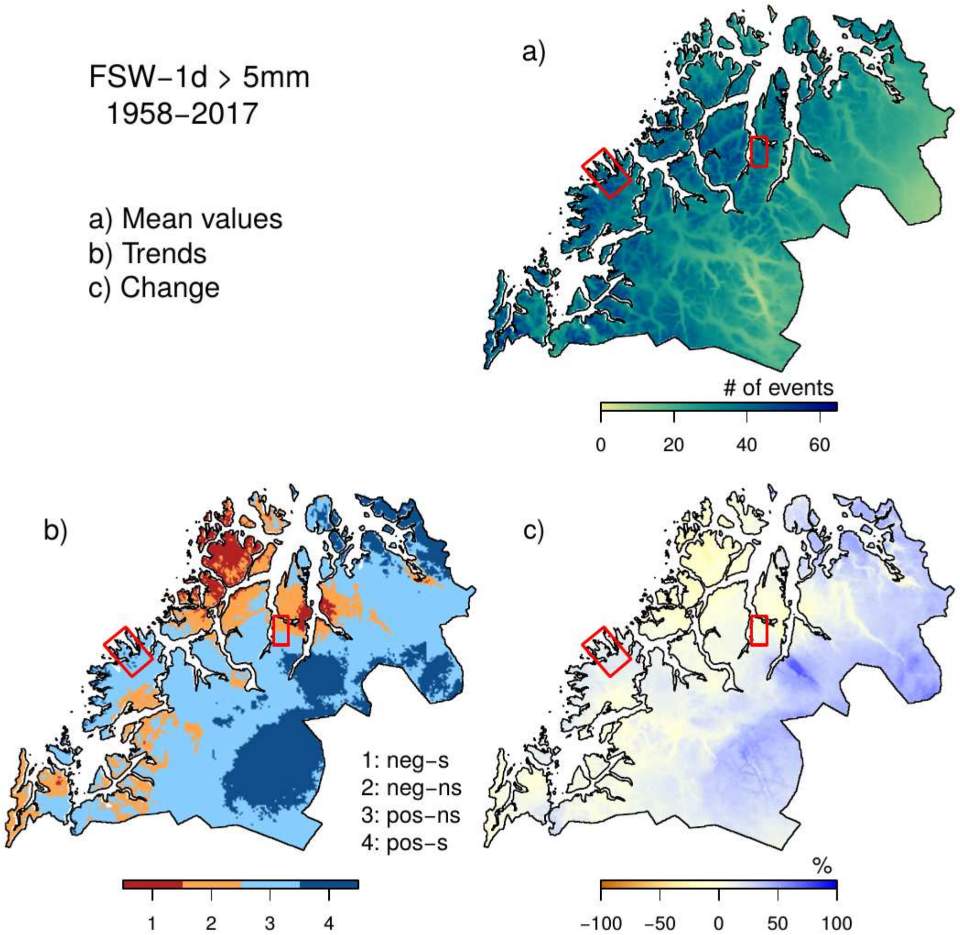
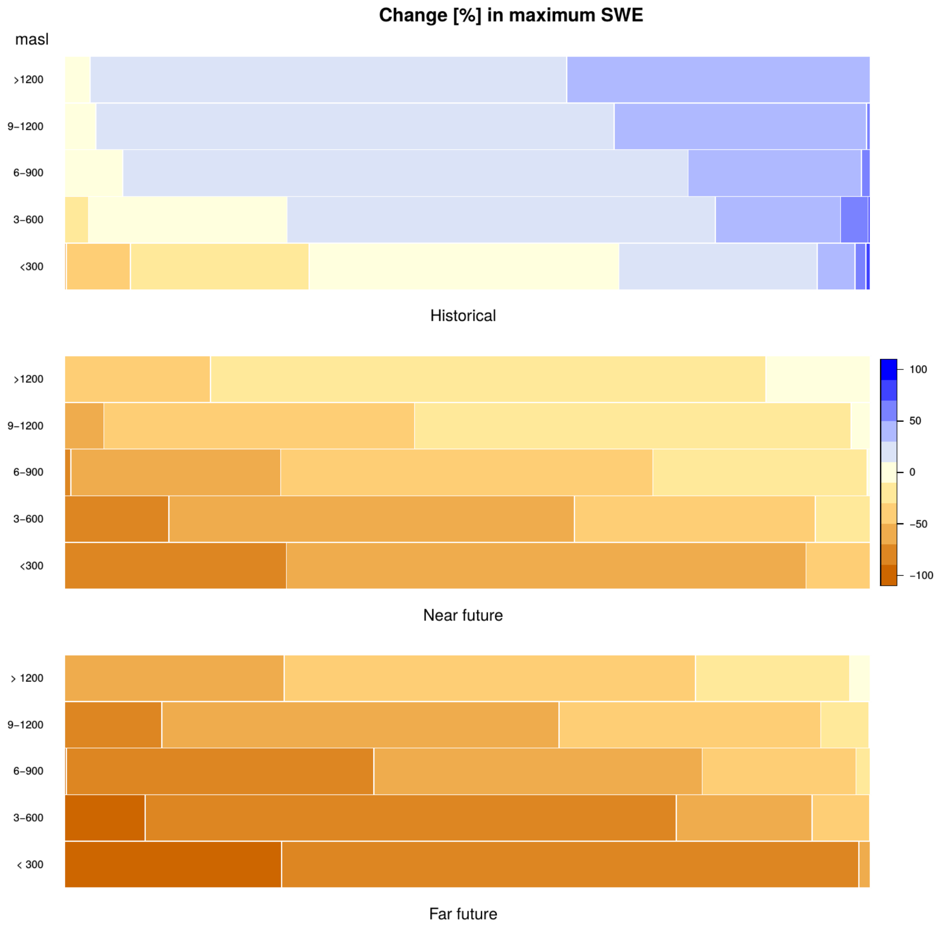


Figure 11~~1~~: Projected change in maximum 5-day snowfall during winter (Oct–Apr) between 1981-2010 and a) near future (2041-2070); b) far future (2071-2100, based on maximum fresh snow water equivalent for 5-day duration (WM-FSW-5d).~~Projected change in maximum snow water equivalent (SWE) during winter (Oct–Apr) between 1981-2010 and a) near future (2041-2070); b) far future (2071-2100.~~


FSW−1d > 5mm
1958−2017
a) Mean values
b) Trends
c) Change
a)
# of events
0
20
40
60
b)
1: neg−s
2: neg−ns
3: pos−ns
4: pos−s
1
2
3
4
c)
%
−100
−50
0
50
100



~~**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.**~~

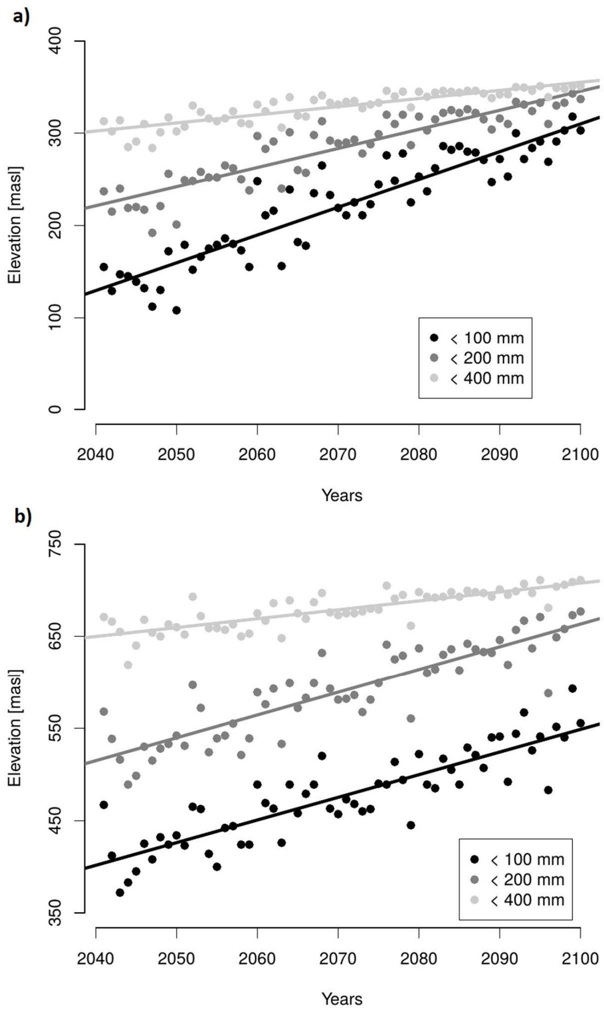
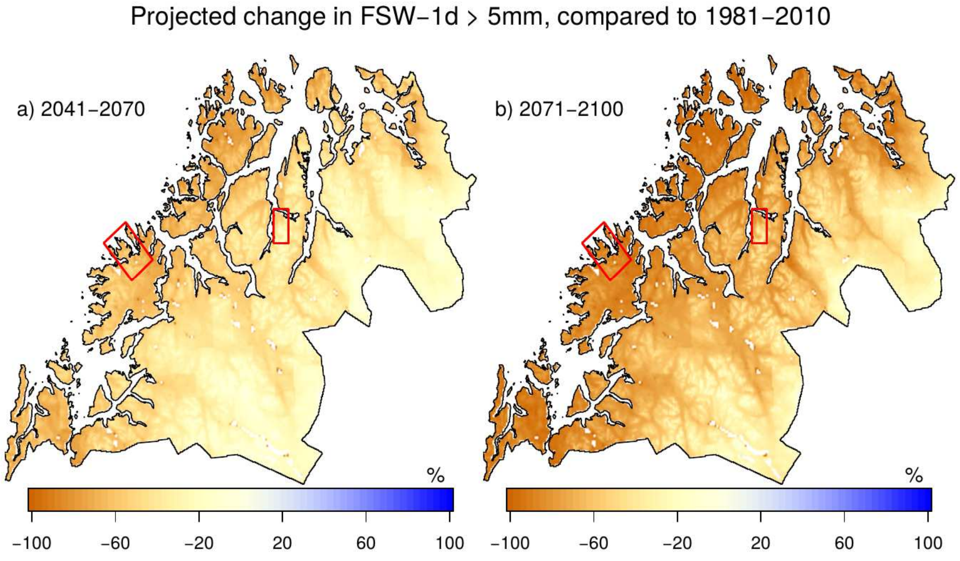


Figure 1~~3~~2: Frequency of 1-day snowfall exceeding 5 mm during winter (Oct-Apr) for the period 1958-2017, based on fresh snow water equivalent for 1-day duration (FSW-1d > 5 mm). Mean values (a), trends (b) and changes are shown in the same way as in Fig.4.

~~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).~~



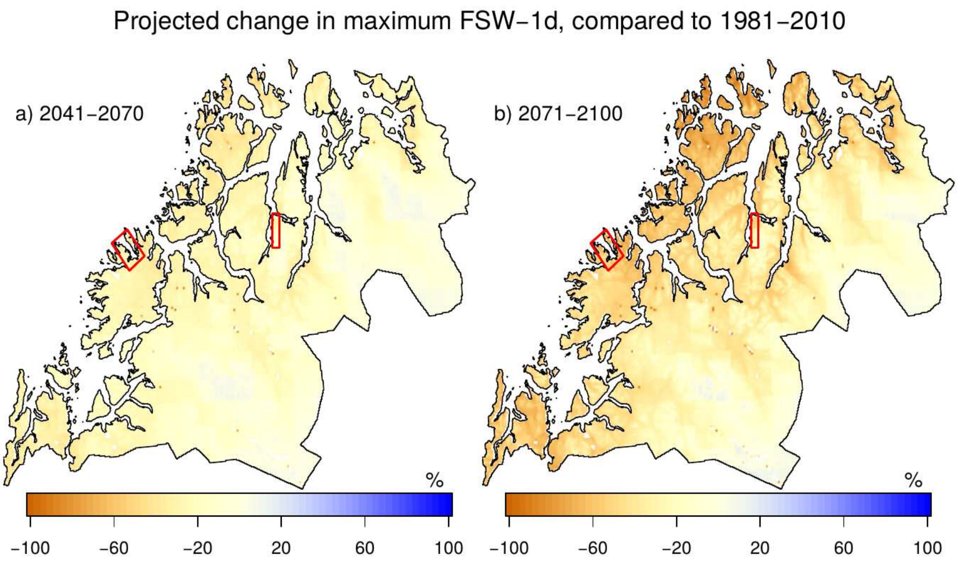
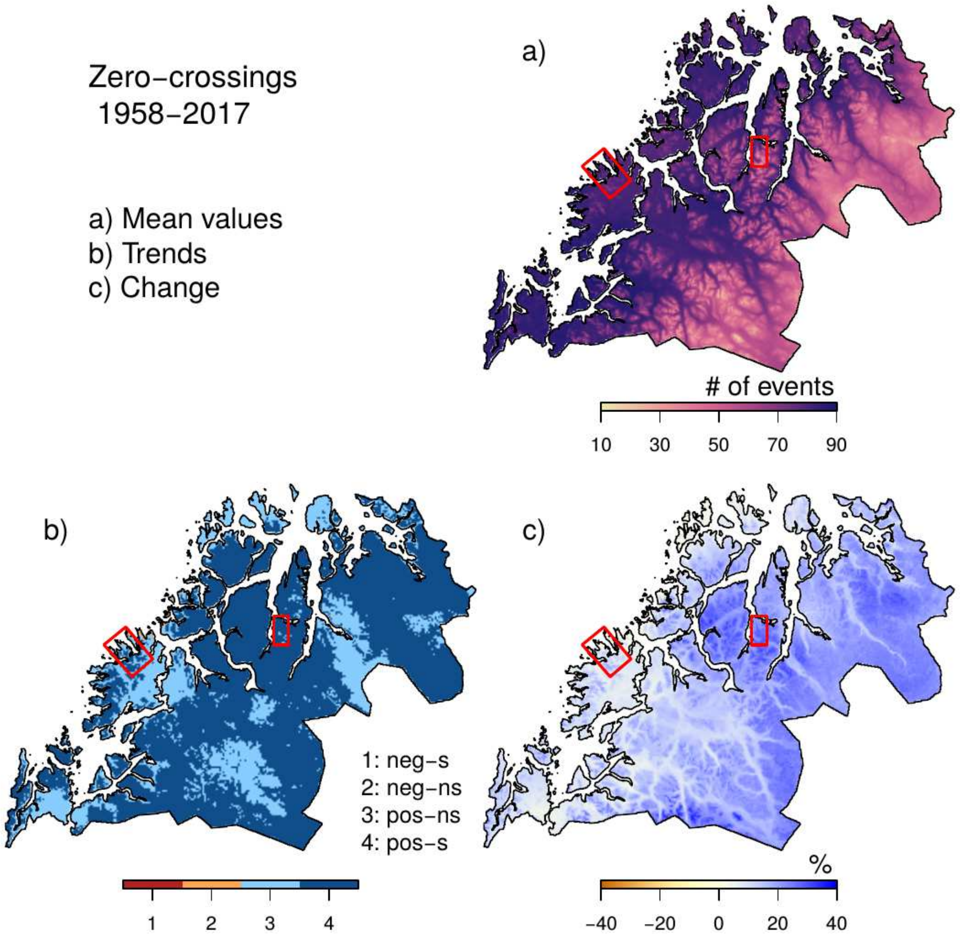


Figure 1~~3~~4: Projected change in the frequency of 1-day snowfall exceeding 5 mm during winter (Oct-Apr) between 1981-2010 and a) near future (2041-2070) and b) far future (2071-2100), based on fresh snow water equivalent for 1-day duration (FSW-1d > 5 mm).~~Projected change in maximum 1-day snowfall 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).~~



Zero−crossings
1958−2017
a) Mean values
b) Trends
c) Change
a)
# of events
10
30
50
70
90
b)
1: neg−s
2: neg−ns
3: pos−ns
4: pos−s
1
2
3
4
c)
%
−40
−20
0
20
40

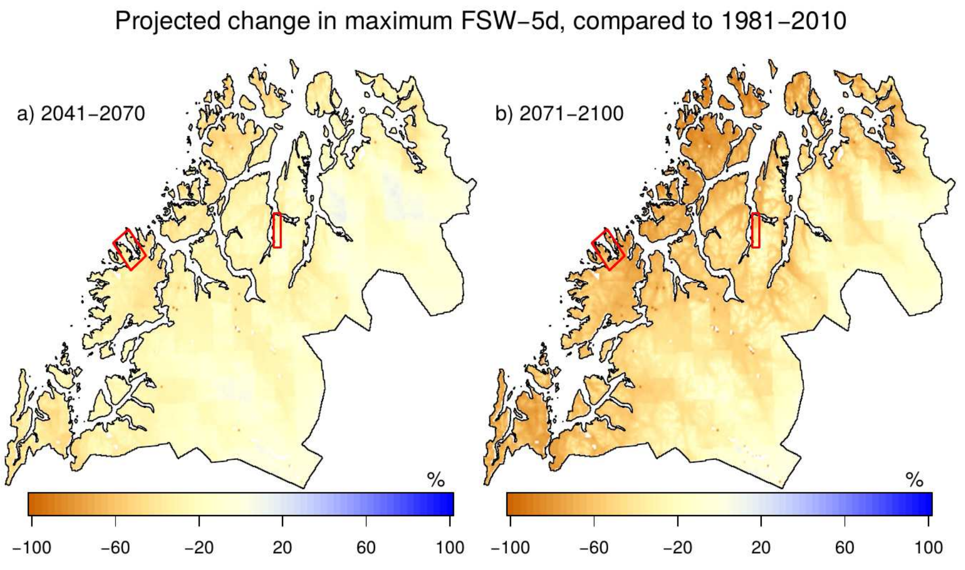
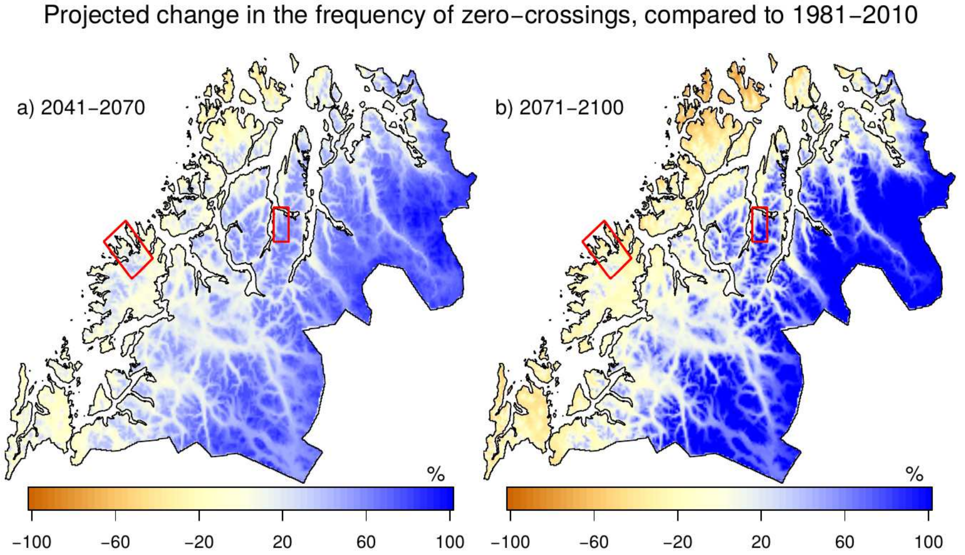


Figure 14~~5~~: Frequency of zero-crossings during winter (Oct-Apr) for the period 1958-2017, based on minimum and maximum daily temperature. Mean values (a), trends (b) and changes are shown in the same way as in Fig.4.

~~**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).**~~


Projected change in the frequency of zero−crossings, compared to 1981−2010
a) 2041−2070
b) 2071−2100
%
−100
−60
−20
20
60
100
%
−100
−60
−20
20
60
100

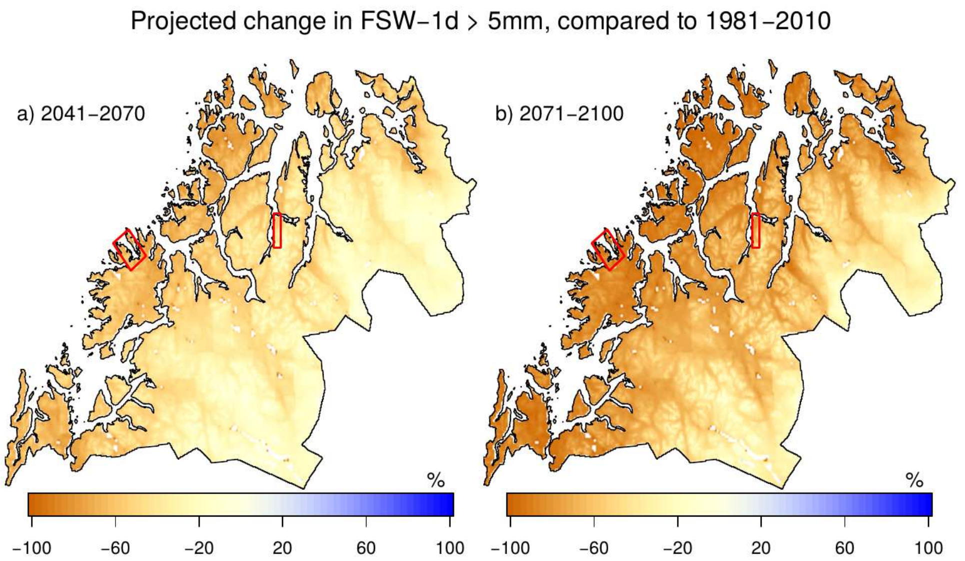
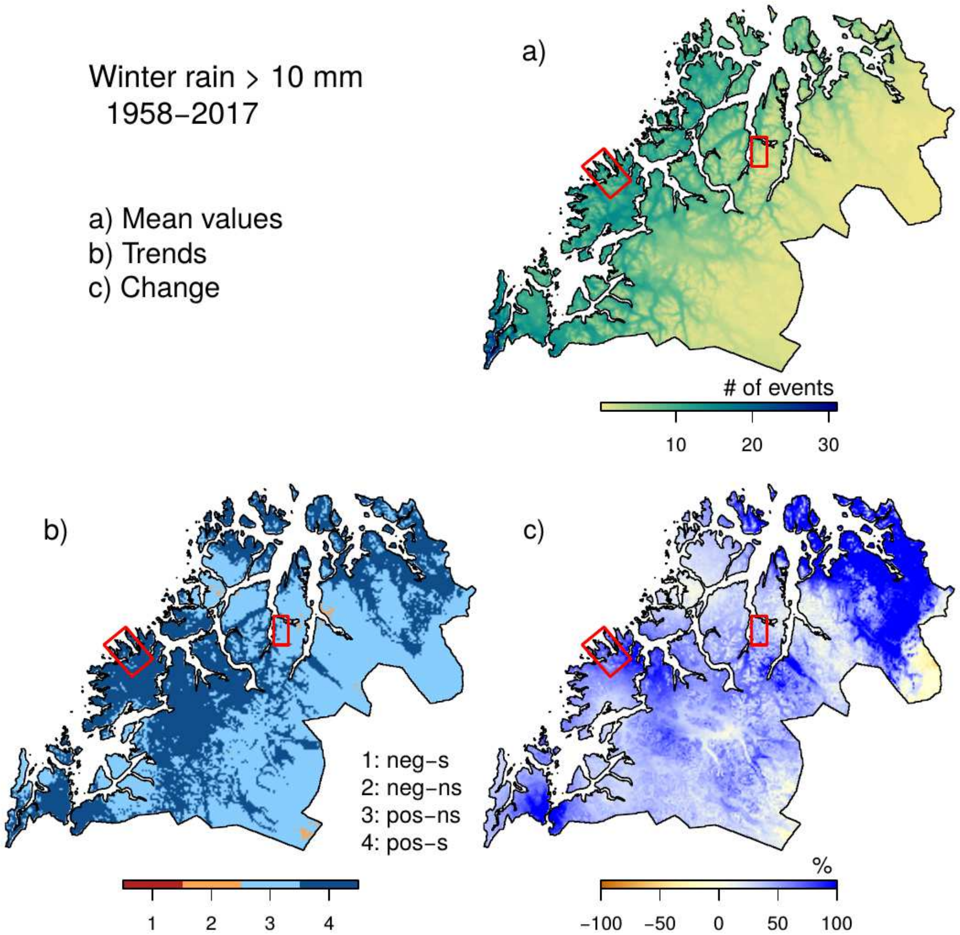


Figure 1~~6~~5: Projected change in the frequency of zero-crossings during winter (Oct-Apr) between 1981-2010 and a) near future (2041-2070) and b) far future (2071-2100), based on minimum and maximum temperature.~~Projected change in the frequency of 1-day snowfall exceeding 5 mm during winter (Oct-Apr) 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).~~



Winter rain > 10 mm
1958−2017
a) Mean values
b) Trends
c) Change
a)
# of events
10
20
30
b)
1: neg−s
2: neg−ns
3: pos−ns
4: pos−s
1
2
3
4
c)
%
−100
−50
0
50
100

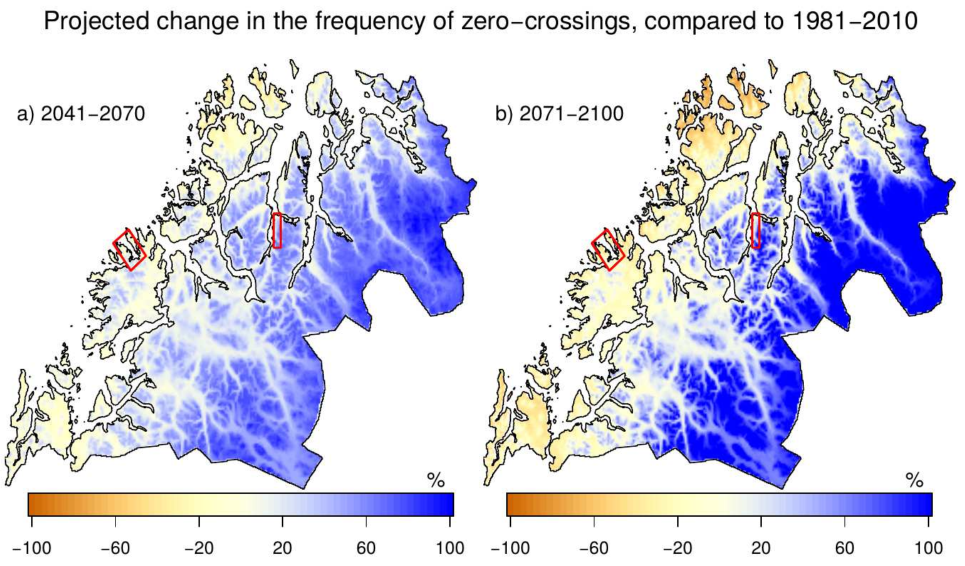
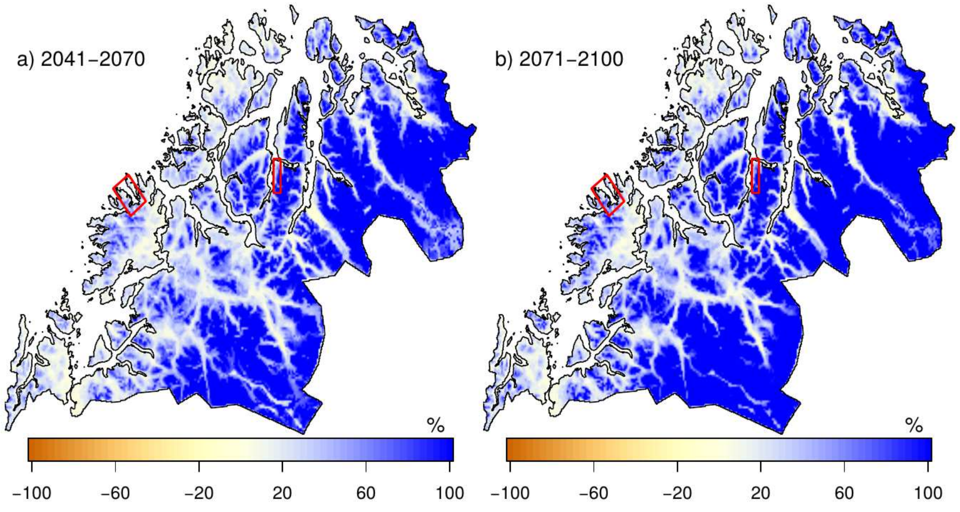


Figure 1~~7~~6: Frequency of rainfall events exceeding 10 mm during winter (Oct-Apr) for the period 1958-2017, based on minimum and maximum daily temperature. Mean values (a), trends (b) and changes are shown in the same way as in Fig.4. ~~Projected change in the frequency of zero-crossings during winter (Oct-Apr) between 1981-2010 and a) near future (2041-2070) and b) far future (2071-2100), based on minimum and maximum temperature.~~

Projected change in watersupply > 10mm compared to 1981−2010



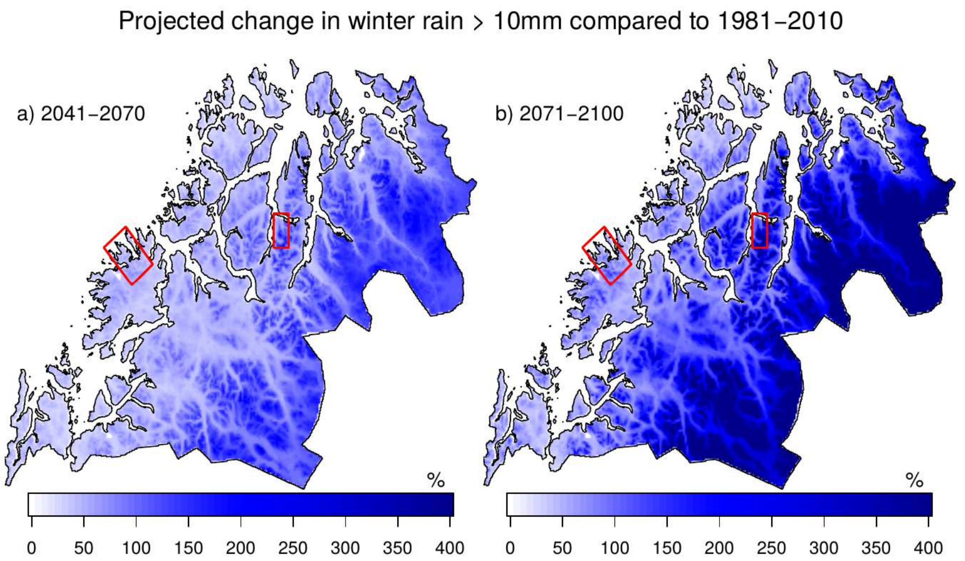


Figure 178: Projected change in the frequency of rainfall events exceeding 10 mm during winter (Oct-Apr) between 1981-2010 and a) near future (2041-2070) and b) far future (2071-2100). Note that the legend differs from other figures, going from 0 to 400%. ~~Projected change in the frequency of water 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.~~

Appendix

Table A1: GCM/RCM combinations in the EURO-CORDEX ensemble, where the first column indicates the name of the GCM and the first row indicates the name of the RCM.

GCM/RCM	CNRM	EC-EARTH	HADGEM	IPSL	MPI
CCLM	x	x			x
RCA	x	x	x	x	x

HIRHAM		x			
RACMO		x			

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