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 weather 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 weather 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 weather 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.

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, 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.

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 is are a major natural hazard in Norway (cf. Hestnes 1998, Annals of Glaciology 26). In the introduction 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 weather 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 weather 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 now used rain+melt > 10 mm/day as abbreviation, and explained the term "water supply" in the Abstract, as well as other places in the manuscript.

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: "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 weather 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"

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:

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 Section 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 that describe 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?

We have now used rain+melt > 10 mm/day as abbreviation, and explained the term "water supply" in the Abstract, as well as other places in the manuscript. In Section 3.3 we explain in more detail the derivation of the selected weather indices.

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 3.3. Weather indicators / zero crossings.

We have re-written «Another potential trigger of snow avalanches, and even rockfall, are zero-crossing events.» to «Crossings of the zero degree threshold can lead to slippery road conditions (Gustafson, 1983).»

and removed the sentence «Frequent zero-crossings can lead to difficult road conditions and destabilize the snowpack.»

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?

Changes in water supply in the past is given in absolute values, because there are large areas in Troms where this index gives very low number of events in current climate, and event small changes would give large percentage values. In a future climate, however, these events increase significantly. We have now given the values for the Focus areas as percentage, see Table 2 (former Table 3).

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 weather 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 have not looked at the temporal distribution of heavy water supply, and what fraction comes from rain and snow melt, but 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. The following sentences are included in the Discussion: "A likely explanation of more frequent heavy water supply is the projected increase in winter precipitation coming as rain. Another plausible factor 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 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."

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 results, explaining Figure 17:
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 the 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.

New formulation in discussion: Changes in zero-crossings indicate shifts in slippery road conditions. With our definition, a zero-crossing occurs when air temperature fluctuates from below zero to above zero, even for a short period of time. It is worth noting that such atmospheric zero-crossings do not necessarily capture freeze-thaw cycles in the ground or snowpack. Although additional information about the ground temperature would give a better representation of slippery conditions, the change pattern shown here would likely be close to a change pattern of ground temperatures.

We added a reference to Gustafson (1983), 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, except snow melt, has occurred in the last decades …"

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 weather 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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