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

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).

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).

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 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/.

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.

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.

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.

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).

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.

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

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).

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

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.

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.

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

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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.

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

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.

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 30 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.

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?

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.

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?).

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

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?

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.

5   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.

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

10 is potentially influencing results, it could also briefly be discussed in the Discussion section.

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

15 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.

p7l1: it is not the *indices* which are potential triggers of rapid mass movements, but the indices describe weather elements

20 which may cause such event.

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

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.

25 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 $\Delta SWE_{1d}/\Delta SWE_{5d}$ or SWE_{1d}/SWE_{5d} or something similar instead?

p7 l2-6: «Indices analyzed here are mostly relevant for snow and slush avalanches, but have also often lead to difficult road and

30 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.

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

35 produced in the snowpack, or melt-water run-off from the snowpack together with liquid precipitation?

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

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. 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).

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.

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?

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?

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.

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?

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.

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

5 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?

P11l27-34: This paragraph first introduces the two focus regions (l27-29), which should be moved to Study Area section. It
10 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.

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

7   Section Discussion and Conclusion

15 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.

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?

20 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

25 would be a very interesting point for discussing wet snow avalanche release) - Please discuss.

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).

30 p13l2: what are «*snow* melt avalanches»?

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

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?

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.

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.

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.

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

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

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

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.

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 projections. 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).

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 %?

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

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.

As outlined before, potentially some figures could be merged.

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

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References

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