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 weather 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 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. The frequency of both snow avalanches and slushflows are expected to change with climate change. 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.

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/climate 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 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"

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.

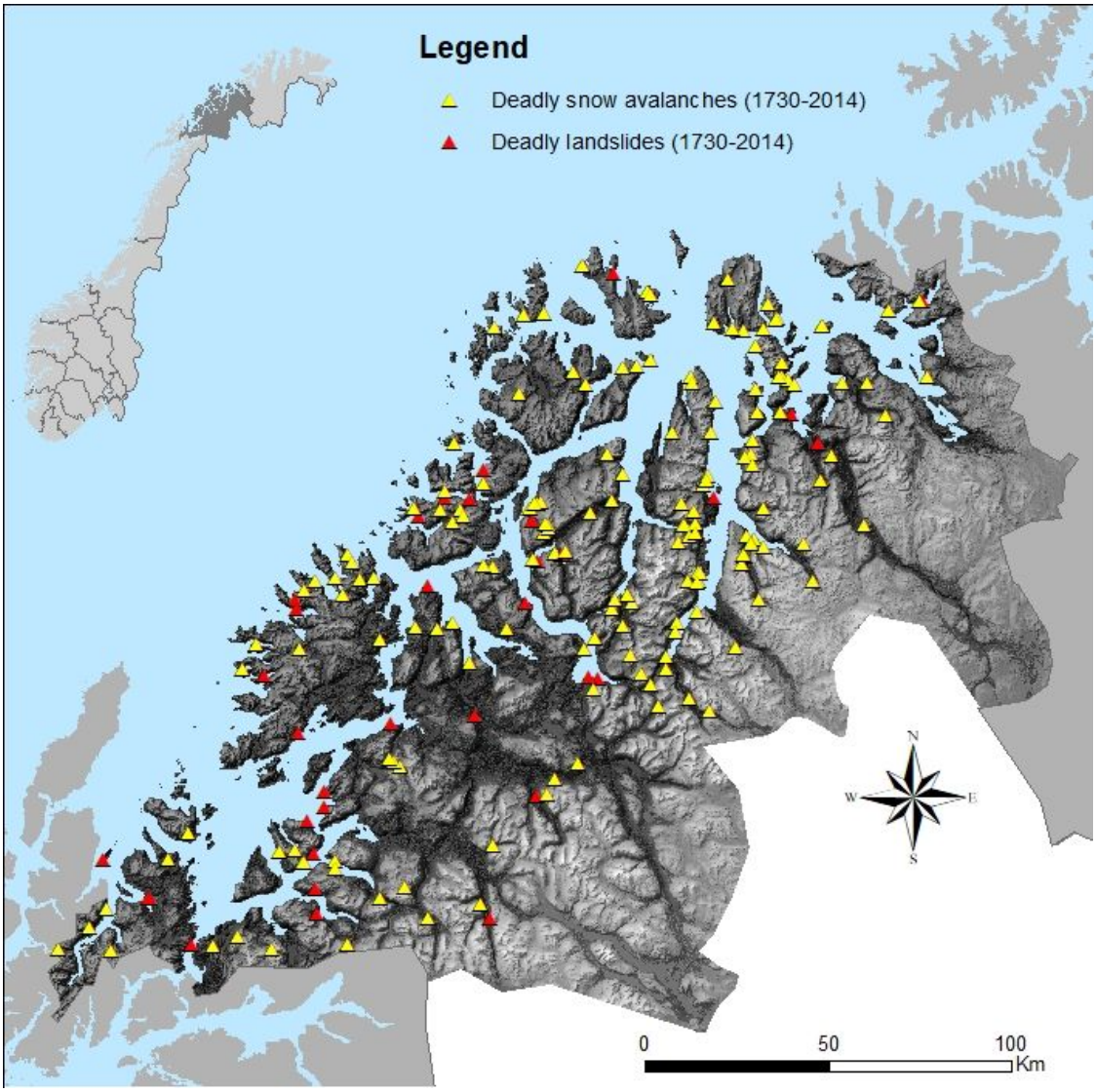
The database skredregistrering.no contains 5815 events from year 900 until 2019. There were 213 events that had one or more casualties cover the period 1730–2014. For snow avalanches, the most updated numbers are available to the winter 2018/2019 (from NGI and varsom.no). We consulted Graziella Devoli 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.