TRENDS IN HYDROMETEOROLOGICAL AVALANCHE INDICATORS IN NORWAY AND SVALBARD IN 1961-2020

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ABSTRACT: Hydrometeorological factors, such as snow depth, length of the snow season, wind speed and direction, air temperature, as well as the amount and intensity of rain and snowfall are closely connected to avalanche activity. As the ongoing climate change affects these factors in several ways, our research question is: "How has avalanche activity in Norway and Svalbard changed during the last 50-100 years along with a changing climate?" While there are long time series of for example air temperature, precipitation and snow depth observations, no long time series of observed avalanche activity are available for Norway. In order to analyze changes in historical avalanche activity, we therefore derive four different avalanche activity "proxy" indicators, calculated on the basis of different hydrometeorological variables (daily values at 1×1 km resolution). We analyze changes and historical trends in our avalanche indicators in Norway and Svalbard over the 60-year period from 1961 to 2020. Moreover, we evaluate the performance of our indicators against time series of daily avalanche problems and danger levels issued by the Norwegian avalanche warning service (NAWS).

KEYWORDS: avalanches; climate change; modelling

1. INTRODUCTION

In Norway, avalanches are common in the mountainous areas during the winter and spring seasons, obstructing roads and railway lines, and sometimes causing fatalities when a house, vehicle or a skier is hit and possibly buried by an avalanche. Moreover, north of Norway, in the Arctic archipelago of Svalbard, the settlements have in recent years had to increasingly cope with avalanches and the danger they pose to the local society and tourists.

Although a majority of the fatal avalanche accidents in Norway (on average 7 casualties per year in 2008–2021) happen in connection with winter sport activities (skiing, snowboarding, winter-climbing, snow-mobiling etc.), most of the avalanche activity is, however, triggered by natural causes without any direct human interaction, i.e. due to hydrometeorological, snow- and weather-related factors. It is these naturally triggered avalanches that cause damage on infrastructure (roads, railways, houses, powerlines). Typical causes for naturally triggered avalanches are (i) heavy snowfall or wind-blown snow which increases the weight-load on the existing snow pack; (ii) a lot of rain and/or snow melt water which weaken the bonding between snow grains in the snowpack, and in the case of rain, increases also the weight load; (iii) rapidly increasing air temperature which increases the creep and internal shear forces in the snow pack.

It is obvious that hydrometeorological factors, such as snow depth, length of the snow season, wind speed and direction, air temperature, as well as rain and snow precipitation are closely connected to avalanche activity. Moreover, the ongoing climate change may have affected these factors in several ways the recent decades. For example, the air temperature and precipitation have been generally increasing in Norway by ca. 1° C and 18 %, respectively, in 1900-2014 (Hanssen-Bauer et al., 2015). Also the snow conditions in Norway have been changing the last decades and show a general reduction in the maximum yearly snow depth and a shortening of the snow season (i.e. starting later and ending earlier; Hanssen-Bauer et al., 2015). On Svalbard, the climate has been changing even more rapidly during the recent decades (Hanssen-Bauer et al., 2019). Consequently, a natural question to ask is: "how has avalanche activity in Norway and Svalbard changed during the last decades along with a changing climate?"

While there are many 50-100 year long time series of air temperature, precipitation, snow depth, etc. observations in Norway, there are very few, if any, similarly long time series of observed avalanche activity. Therefore, it remains still uncertain how avalanche activity may have changed during the last 50-100 years.

Since water, in form of snowfall, rainfall and meltwater, is one of the main drivers of avalanche ac-

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tivity, one can speculate that the increased precipitation and water input to the snow pack during the last decades may have contributed to increasing the avalanche activity. However, the snow amounts have generally diminished and this can counteract the potential increase in avalanche activity due to less snow available for avalanches and due to shortening of the avalanche season in both ends, as indicated by studies from the French Alps (Castebrunet et al. 2014; Giacona et al. 2021).

In order to provide some answers to our research question on changes in historical avalanche activity, we derive four different avalanche activity indicators, based on hydrometeorological variables, and analyze historical trends in these indicators. In other words, since no long time series of direct observations of avalanche activity exist, we use indirect but physically-based "proxy" avalanche indicator time series, which are likely to be significantly correlated to avalanche activity. This correlation is evaluated against time series of daily avalanche danger levels and avalanche problem types issued by the Norwegian avalanche warning service (NAWS) since 2017. By using gridded daily hydrometeorological data sets over Norway dating back to 1957, and over Svalbard dating back to 1991, we can obtain several decades long historical proxy time series for avalanche activity covering the whole of Norway and Svalbard. Avalanche indicators with good predictive power are useful to assess both past and projected future changes in avalanche activity. Good avalanche indicators can also aid and increase the precision in daily avalanche forecasting.

2. DATA AND METHODS

We derive four different hydrometeorological avalanche indicators to be analyzed in our study, namely: (i-ii) accumulated new snowfall indicators over one and three days (NS1, NS3), (iii) new wet snow indicator (NWS) and (iv) wind-blown snow accumulation indicator (WBS). Our avalanche indicators have four classes, where class 1 corresponds to a baseline class (low probability of avalanches) and classes 2, 3 and 4 correspond to consecutively higher avalanche probabilities. When illustrated as maps (Figure 1), a color coding is applied for the indicator classes, so that 1=green, 2=yellow, 3=orange, 4=red. The indicator classes thus resemble, but are not directly relatable to the international avalanche danger scale (1-5, green to black) used by operational avalanche forecast services in many countries (EAWS, 2024). A set of three threshold values are required to divide the continuous space of one or more input variables into the four discrete indicator classes (Figure 1). Expert judgement is used in our case to define the threshold values for the avalanche indicators.

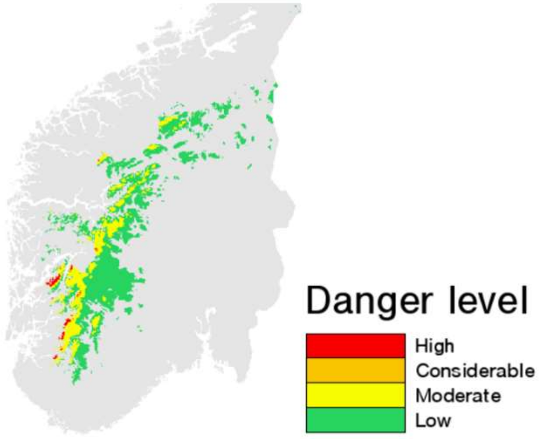

Figure 1: An example map illustration of a natural hazard indicator with four classes from green to red.

The input data for our avalanche indicators in Norway are based on daily hydrometeorological grid data with 1x1 km resolution available since 1957 (seNorge_2018 grid data archives; Lussana et al., 2019). The applied grid data variables are daily air temperature (*Ta*) and precipitation (*P*), as well as snow depth (*Hs*) and runoff to ground from rain and snow melt (*Qrs*) from the seNorge snow model (Saloranta, 2016) as well as wind speed (*U*) data from KliNoGrid grid data archives (C. Lussana, pers. comm).

For Norway we consider only avalanche-susceptible grid cells where the fraction of avalanche terrain is at least 5 % of the grid cell area. We calculate indicators for four different regions (eastern, western, middle and northern Norway) and also make a division between grid cells below and above the tree line in our analyses (referred to as "forest" and "mountain" subregions, respectively). Our main output variable of interest is the daily area covered by the specific indicator classes (yellow, orange, red levels).

For Svalbard we use hydrometeorological data from the "The Copernicus Arctic Regional Reanalysis" (CARRA: see www.ecmwf.int) data set available since 1991 at daily 2.5 x 2.5 km resolution. The CARRA dataset is related to the ERA5 reanalysis, but provides more spatial and temporal details, and is in general in better agreement with in-situ observations than ERA5. The avalanche indicator analysis focusses on the Nordenskiöld Land region, where the main settlements and most of the tourism activity are located. Avalanche danger forecasts are issued daily for the Nordenskiöld Land region by NAWS.

2.1 Avalanche indicator definitions

The new snowfall indicators NS1 and NS3 are related to avalanche activity due to heavy loads of new snow on existing snowpack, known to trigger dry loose snow avalanches as well as dry and wet slab avalanches. These indicators are calculated by using *Ta* and *P* as input data, and by defining the new snowfall amount as sum of all precipitation occurring when $Ta \leq 0.5°$ C (threshold temperature separating solid and liquid precipitation) over the last 1 and 3 days. The threshold values separating the NS1 and NS3 indicator classes 1-4 were set to 30, 50 and 70 mm/d and 40, 70 and 100 mm/3d of new snowfall in water equivalent units (w.e.), respectively.

The new wet snow indicator NWS is related to avalanche activity due to the first wetting of a snowpack, when previous wetting episodes have not yet stabilized the snowpack by destructing the potential weak layers within the snowpack. Such first wetting episodes of the snowpack are known to trigger wet avalanches. This indicator is calculated by using *Ta*, *P*, *Hs* and *Qrs* as input data. The NWS indicator sums up the daily rainfall and snow surface melt water amounts and calculates an indicator value if the existing snowpack has at least 40 mm w.e. of new snow accumulation since it was last water-saturated. If these conditions are not met, or if $Hs < 40$ cm, the NWS indicator is set to its baseline value of 1 (green). The timing of the last water-saturated snowpack is defined by searching the latest day when runoff has occurred from the bottom of the snowpack (i.e. $Qrs >$ 1mm/d). Rainfall is defined as precipitation occurring when $Ta > 0.5°$ C and snow melt water is here estimated by a simple degree-day model (i.e. melt = $3.0 \cdot Ta$ mm/d, if $Ta > 0°$ C). The threshold values separating the NWS indicator classes 1-4 were set to 20, 40 and 60 mm/d of rain and snow melt water.

The wind-blown snow accumulation indicator WBS is related to avalanche activity due to wind-transported snow, especially accumulating and piling up on mountain faces and slopes on the leeward-side opposite to the prevailing wind direction. Such wind accumulation of snow is known to cause dry slab avalanches. This indicator is calculated by using *Ta*, *P*, *Hs* and *U* as input data. The WBS indicator estimates the magnitude of locally wind-accumulated snow depth by an exponential function $a \cdot U^b$ (Föhn, 1980), where *U* is the daily wind speed (truncated at 20 m/s). The coefficient and exponent values are based on Föhn (1980), but adjustments are made for the older dry snow case. The counter for dry snowfall (i.e. the snow assumed to be available for wind transport) is reset to zero whenever rain or moist snowfall (i.e., $P >$1 mm/d at $Ta > -0.5°$ C) or snow surface melt (i.e., $Ta > 0°$ C) occurs. Moreover, if $Hs < 20$ cm, the WBS indicator is set to its baseline value of 1 (green). The threshold values separating the WBS indicator classes 1-4 were set to 5, 20 and 50 cm/d of locally wind-accumulated snow depth.

2.2 Evaluation against avalanche forecast data

In order to evaluate the performance of the avalanche indicators, we compare the daily area-normalized indicator time series (i.e. total indicator area extent divided by the whole (sub)region's area) to the avalanche warning data issued by the NAWS in five December-May seasons in 2017-2022. The NAWS data applied here consists of the overall issued avalanche danger level, priority ranking of actual avalanche problems (seven different avalanche problems used), the sensitivity of releasing the avalanches, as well as their expected size and frequency of occurrence in the terrain.

By using the NAWS data, we construct daily time series of an "avalanche severity index" (K. Müller and A. Widfors, pers. comm.) for 19 of the 23 avalanche warning regions that have 5-year time series of data available. This severity index can obtain values from 0 to 1 and weights and combines the size, frequency and release sensitivity information of the human-forecasted avalanche hazard. Severity index values ≥0.05 are interpreted to signal a significant avalanche danger (corresponding approximately to a danger level of 3 or higher). If an avalanche problem is not present for a particular day and region, severity index is set to zero.

In the evaluation of avalanche indicator time series against the NAWS avalanche warning data (severity index) we use binary classification statistics. The relationship between our avalanche indicators and the NAWS data are defined as follows:

(a) The maximum of NS1 and NS3 (max(NS1, NS3)) indicators is compared to severity index calculated for (i) new snow loose, (ii) new snow slab and (iii) wind slab avalanche problems (highest value of these three is applied).

(b) The NWS indicator is compared to severity index calculated for (i) wet snow loose and (ii) wet snow slab avalanche problems (highest value of these two is applied).

(b) The WBS indicator is compared to severity index calculated for wind slab avalanche problem.

3. RESULTS

The results from the indicator performance evaluation in mainland Norway showed that:

(1) All the four avalanche indicators in mainland Norway have a modest performance, where the new snow related indicators (max(NS1, NS3)) show the best performance while the wet snow and wind-blown snow related indicators (NWS and WBS) have somewhat lower performance. Moreover, the indicator performance varies significantly between the 19 different avalanche regions.

(2) When an indicator does indicate a significant avalanche danger, it correctly does so (according to severity index) on average in 43-52 % of the cases, depending on the indicator.

(3) When an indicator does not indicate a significant avalanche danger, it correctly does so (according to severity index) on average in 89-93 % of the cases, depending on the indicator.

(4) When there is a significant avalanche danger according to severity index (on average 12-21 % of the days in December-May, depending on the avalanche problem type), the avalanche indicators indicate this on average in 38-74 % of the cases, depending on the indicator.

For the max(NS1, NS3) indicator there are on average almost three times more indicator false alarms than misses, while for the two other indicators NWS and WBS there are on average approximately equally many false alarms and misses.

Trends for the avalanche indicator time series are calculated by the non-parametric, rank-based Mann-Kendall trend estimate method. For the input variables, which are generally following better the normal distribution, linear trends are calculated. In addition, the relative changes (%) in the indicators' mean value between two climatological periods 1961-1990 and 1991-2020 are calculated (1991-2005 and 2006-2020 for Svalbard).

Figure 2 shows an example of avalanche indicator time series. The main results of the long-term changes and historical trends in the avalanche indicators in mainland Norway in 1961-2020 can be summarized as the following:

(1) A general increase is detected in the number of high wind speed days (*U*) and in runoff to ground from rain and snow melt (*Qrs*), while a general decrease is detected in average seasonal snow amounts, especially below the tree line.

(2) Despite of the marked changes in the hydro-meteorological input variables, the changes in the avalanche indicators are more variable and often not statistically significant.

(3) In the spring season below the tree line (forest grid cells) most of the indicators show negative decreasing changes, ranging from +3 to -20 %, in all regions except northern Norway. None of the trends are found statistically significant.

(4) When considering the avalanche indicators above the tree line (mountain grid cells), the indicators show mostly positive, increasing changes in all regions, ranging from -1 to +83 %. In addition, 8 out of the 32 trends are found statistically significant at 5 % level.

The main results for Svalbard in 1991-2020 can be summarized as the following:

(1) The new snow indicators NS1 and NS3 show positive trends, even though the number of days with temperatures above 0° C are also increasing in Nordenskiöld Land.

(2) Below 500 m.a.s.l. runoff from snow pack has increased by over 300 % from 1991-2005 to 2006-2020 in both winter and spring. The NWS indicator has increased correspondingly by 68-79 %. Above 500 m.a.s.l. there is almost no days with runoff in the winter and spring seasons.

(3) Both the wind speed days above 9 m/s and the WBS indicator show a decrease from 1991-2005 to 2006-2020.

The climate in Svalbard is affected by the marginal sea ice zone and the North Atlantic storm track. It is therefore worth bearing in mind that our change estimates based on the two relatively short 15-year periods may be "noisy" due to the high interannual variability.

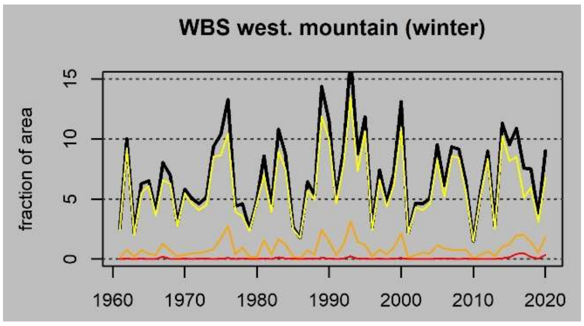

Figure 2: Wind-blown snow accumulation (WBS) avalanche indicator time-series in western Norway above the tree line (mountain) in the winter season (Dec-Feb). Yearly 1961-2020 time series of the area-normalized sum (area) of the grid cells with indicator levels 2, 3 and 4 are shown with yellow, orange and red lines. The black line shows the weighted sum of levels 2-4. This figure is an example from our total set of 56 different time series of avalanche indicators.

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