A CLIMATOLOGY OF RAIN-ON-SNOW EVENTS IN SVALBARD AND THEIR IMPLICATIONS FOR AVALANCHE HAZARD

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ABSTRACT: Rain-on-snow (ROS) events have become increasingly common in the wintertime across the Arctic as its climate continues to warm at an alarming pace. It is projected that Svalbard will experience a threefold increase in the frequency of winter warming events by 2100 with profound impacts on land and glaciers. Changes in the frequency, intensity, duration and spatial distribution of ROS are important to quantify due to their wide-ranging impacts on the physical environment and on society, which included increased avalanche risk, permafrost degradation, damage to vegetation and difficult foraging conditions for reindeer as ground ice forms following a ROS event. To understand which areas are most vulnerable to ROS impacts at present and in the future, reliable datasets describing the spatial and temporal variations of ROS are crucial. We have used Synthetic Aperture Radar (SAR), which is sensitive to liquid water in the snowpack, to map ROS events for the period 2004-2020. The results are compared against ROS events detected using a reanalysis dataset, which had been calibrated against ground observations. The ROS climatology observed by SAR and reanalysis data were in general consistent with each other, showing that ROS occurs most frequently in the southern and western parts of Spitsbergen and very few, if any, occurrences across the glaciated areas and northeastern parts. Using the reanalysis dataset, we have also estimated the intensity, duration and timing of the ROS events since 1991, and their trends. Statistically significant increases in the frequency, intensity and duration of ROS events were found, with no parts of the archipelago exhibiting a significant decrease in any of the characteristics. Lastly, since SAR is also sensitive to changes in snow surface roughness, avalanche debris can be detected using a change detection approach. We present an overview of a recently published SAR dataset for avalanche activity for Svalbard and show that SAR detects an increase in avalanche activity increases during ROS events. Climate projections may provide an indication of how the spatiotemporal characteristics of ROS events will change in the future, and therefore how wet snow avalanche activity may be affected as a result.

KEYWORDS: Svalbard, rain-on-snow, remote sensing, avalanche detection, climate projections

1. INTRODUCTION

The Arctic is warming at a rate that is three to four times the global average (eg. Rantanen et al., 2022) which is resulting in major changes to the wintertime climate. Interludes of winter warming bringing rain, often referred to as rain-on-snow (ROS) events, are becoming increasingly frequent across the High Arctic archipelago of Svalbard. These events have attracted increasing research attention and have been well documented during the last decade due to their range of impacts on not only the cryosphere, but also on wildlife, terrestrial and coastal ecosystems as well as society, through increased avalanche risk (e.g., Eckerstorfer and Christiansen, 2012; Abermann et al., 2019). As the climate in Svalbard continues to change, the characteristics of ROS events and avalanche activity will be steered by changes in temperature and precipitation patterns that affect the structure and stability of the winter snowpack. To understand which areas are most vulnerable to ROS impacts at present and in the future, reliable datasets describing the spatial and temporal variations in atmospheric and snow variables are crucial. Recent studies of ROS climatology in Svalbard have exploited Synthetic Aperture Radar (SAR) remote sensing, due to its sensitivity to liquid water in the snowpack (Vickers et al., 2022). The dataset showed good agreement with ROS events detected using snow models and atmospheric reanalyses, when the models and reanalysis datasets had been calibrated against ground observations. Specifically, the Copernicus Arctic Regional Reanalysis (CARRA) dataset was able to accurately capture the occurrence of ROS events based on an evaluation against ground observations. Until now the majority of ROS studies have concentrated on documenting ROS frequency but few, if any have paid attention to how their duration, intensity and timing has changed. As the wintertime climate in Svalbard continues to change, it is crucial to quantify how ROS characteristics are influenced by changes in climate, as changes in ROS characteristics will to a large degree determine what impact they have on the snow cover and therefore avalanche danger. The CARRA dataset now spans more than 30 years and in this study, we exploit the full time series to document changes in the characteristics of ROS since 1991. In particular we derive parameters that include the frequency, timing, duration, and intensity. These events could have significant consequences for permafrost and vegetation if ROS characteristics change, such that more frequent or more intense events completely remove snow cover. For reindeer populations, ROS events may no longer leave forage encased in ice, and if vegetation becomes fully exposed as snow cover disappears, forage becomes more easily available. In addition to presenting the averages, we also quantify trends in these characteristics over climate-relevant timescales (1991-2022).

SAR can also be used to detect avalanche debris and has been demonstrated as an ideal tool for large scale monitoring of avalanche activity at high latitudes due to frequent imaging by multiple SAR geometries under all light and weather conditions. Large scale mapping of avalanche activity can assist with identifying changes in avalanche activity steered by day-to-day changes in weather, as well as from season to season and on longer timescales. This kind of monitoring of avalanche activity is needed to better understand the link between the driving meteorological triggers and the snowpack's response, which can assist in providing more accurate avalanche forecasts. SAR is therefore a unique tool for observing ROS and snowmelt-related hazards such as wet snow avalanches. As well as studying changes in ROS characteristics during the most recent three decades, we describe and present a newly produced avalanche activity dataset for Svalbard for the period 2017-2021, produced using Sentinel-1 SAR data. The capability of SAR to detect both wet snow and avalanche debris provides a unique opportunity to study if and how often ROS and wet snow are linked to major avalanche cycles in Svalbard. We show how the recently published wet snow dataset for Svalbard (Vickers et al., 2022) is one application of the avalanche activity dataset to be described here. The results can provide insight into the likely changes in avalanche activity in Svalbard's rapidly warming climate which may lead to increased risk of wet snow avalanches in the future. While we have focused on Svalbard as the study area, the results will have applicability to the entire circumpolar region as well as other mountainous regions of the world affected by a changing ROS climatology.

2. METHODS AND DATASETS

2.1 SAR wet snow dataset

The SAR rain-on-snow dataset used in this study is described in detail by Vickers et al. (2022) and is derived from wet snow maps produced on a grid with 100m x 100m pixel spacing using three different SAR sensors spanning the period 2004-2020, with the latest period (2014 onwards) providing frequent coverage by the Sentinel-1 satellites. The method for wet snow mapping implemented in this work is based on a thresholding approach developed by Nagler & Rott (2000). In this approach, wet snow is detected when the backscatter change in a pixel falls below some threshold value determined by a reference values, usually based on the mean wintertime backscatter coefficient during which the snow conditions are assumed to be dry. For most wet snow applications, a threshold backscatter value of between –2.5 and –3dB is used.

ROS events are detected when the pixel classification in the wet snow maps changes from dry to wet, and the duration of an event is counted until the pixel is classified as dry snow again or in some cases, bare ground.

2.2 CARRA dataset

The East domain of the Copernicus Arctic Regional Reanalysis (CARRA) dataset covers both Northern Norway and Svalbard and provides 3-hourly reanalyses and short-term hourly forecasts of atmospheric and surface meteorological variables at 2.5 km resolution, on 65 vertical levels (Schyberg et al., 2020). For the detection of ROS events, we obtained daily averages of the 2m air temperature and snow water equivalent (SWE) and the total 24-hour accumulated precipitation values calculated using precipitation data at lead times of +6 and +30 hours with initial time 00UT. Observations of 2m air temperature and snow depth are assimilated in CARRA and thereby constrain the dataset in the proximity of observation sites, while observations of precipitation are not assimilated in CARRA. CARRA data are available from 1991 to the present year. ROS events are detected by applying thresholds to the daily mean temperature (-0.5°C), SWE (3mm) and 24-hour precipitation (1mm). The threshold of –0.5°C was obtained by evaluating the ROS detection at different temperature thresholds using ground observations and using the F1 score as a measure for detection accuracy. For full details of this evaluation the reader is referred to Vickers et al. (2024). One ROS event is defined as a sequence of consecutive days where the ROS criteria was fulfilled. Using this definition, the duration is taken as the number of consecutive days where the criteria was fulfilled, the total precipitation is simply the accumulated precipitation fallen over the duration of the event, and the intensity is taken to be the total precipitation divided by the duration. In section 3 we present trends in each of the characteristics for the maximum event. That is to say, we examine the trends in the events with the longest duration, the most precipitation and the highest intensity.

2.3 PCCH-Arctic downscaled climate projections

The PCCH-Arctic dataset provides high-resolution climate projections for Svalbard from 1991-2070 at 2.5 km horizontal resolution. The regional climate model HARMONIE Climate (HCLIM) cycle 43 is used to produce the simulations and features convection-permitting HARMONIE-AROME atmospheric physics and SURFEX land-surface model with ISBA Explicit Snow snow scheme and Simple Ice (SICE) prognostic sea ice thickness. The Norwegian Earth System model (NorESM2-MM) is used to provide boundary conditions, following the SSP5-8.5 scenario.

2.4 SAR avalanche detections

The Sentinel-1A SAR satellite was launched in April 2014 and has been operational since October 2014. The second Sentinel-1B satellite was launched in April 2016 but due to malfunction of the satellite, data from Sentinel1-B has no longer been acquired since December 2021. The Sentinel-1 pair of satellites provide images in two different modes; interferometric wide swath mode (IW) covers a swath of approximately 250 km and is extended often up to 1000 km, whereas the extra wide swath mode (EW) provide data almost daily over Svalbard but does not have sufficient spatial resolution to allow for avalanche detections (Wesselink et al., 2016). EW mode can, however, be used for detecting wet snow (Vickers et al., 2022). The IW mode has 20 m × 5 m resolution (azimuth-ground range), and images are acquired in two polarizations (bands), copolarization (“VV/HH”) and cross polarization (“VH/HV”). We have processed all images from both VV+VH and HH+HV polarizations. IW coverage is approximately 3 scenes per 12 days (6 when S1 A/B are available).

Detection of avalanches was carried out by implementing the method outlined by Vickers et al., 2016, which is based on applying a K-means unsupervised clustering algorithm to SAR backscatter change images. This approach has been operationalized in Norway (Eckerstorfer et al., 2019). The resulting product is a polygon defining the extent of the detected avalanche debris. Due to the frequent imaging over Svalbard, avalanches may be detected multiple times by different imaging geometries, and the operational processing chain described in Eckerstorfer et al. (2019) outlines the approach for identifying and removing repeated detections of the same avalanche debris. Since the detection algorithm can also produce erroneous detections on glaciers and in regions where avalanches cannot occur (mountain plateaus and flat valleys far away from steep terrain it was necessary to perform a manual filtering of the detections.

The dataset of avalanche detections over Svalbard consists of 31899 individual avalanche detections, covering the period from February 2017 to May 2021. Most detections are found in the western parts of Svalbard. To quantify the temporal distribution of avalanches, the Avalanche Detection Density (ADD) parameter has been used as a measure of avalanche activity per day. Each detection corresponds to a top-hat density function spanning the two timestamps corresponding to the satellite images used to form the backscatter change image. Thus, each detection is weighted by the time interval between the two timestamps, with multiple weighted detections per day summed to produce an overall value for the daily ADD.

3. RESULTS

In this section we present the results of the analysis of trends in the ROS characteristics derived from 32 years of CARRA data (1991-2022), as outlined in section 2.2, as well as an overview of the SAR avalanche dataset and its relationship to ROS events.

3.1 ROS characteristics from CARRA

We present only the statistically significant trends in the ROS events with longest duration, greatest accumulated precipitation, and highest intensity, as well as the trend in the number of events over the period. Figure 1 shows that there is an increasing trend in event frequency over large parts of the archipelago. The trend ranges from 0.5-1.5 events per decade, with highest trends in the northwest and in low-lying areas in the central and eastern parts of the archipelago. No areas exhibit a decreasing trend in frequency.

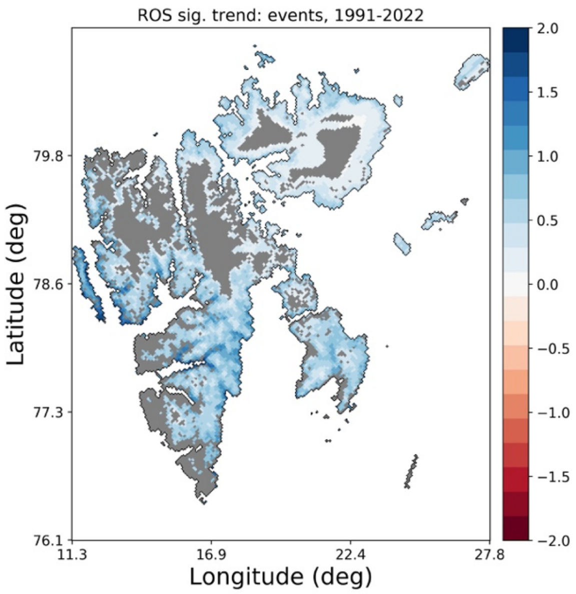

Figure 1. Trend in number of ROS events per decade

Figure 2 shows the significant trend for the maximum precipitation ROS events. While the area with significant trends is not as great as for the ROS frequency, the wettest events are becoming wetter by up to 8mm per decade along the east coast and across Edgeøya. Smaller increases of up to 2mm per decade are exhibited across Nordaustlandet. For the trend in ROS event duration,

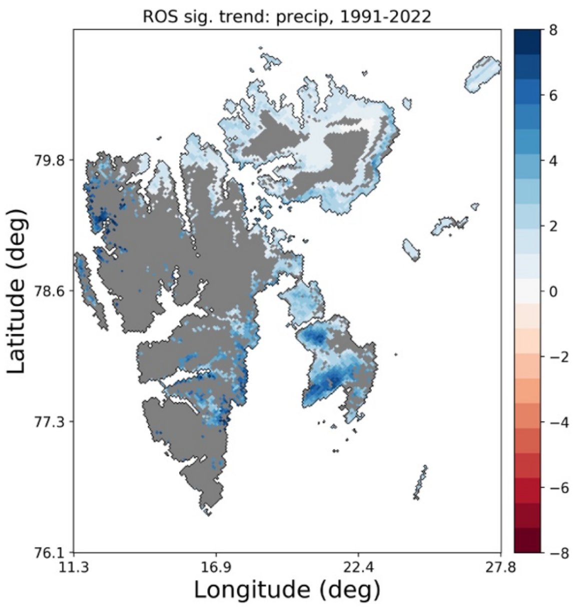

Figure 2. Trend in total precipitation for max precipitation events, given in mm per decade.

Figure 3 indicates that the longest events are also becoming longer by up to 1 day per decade. The highest trends in ROS duration are shown along the northwest coast and in the central parts of Svalbard. Smaller increases in duration of the longest events are found across large parts of Nordaustlandet.

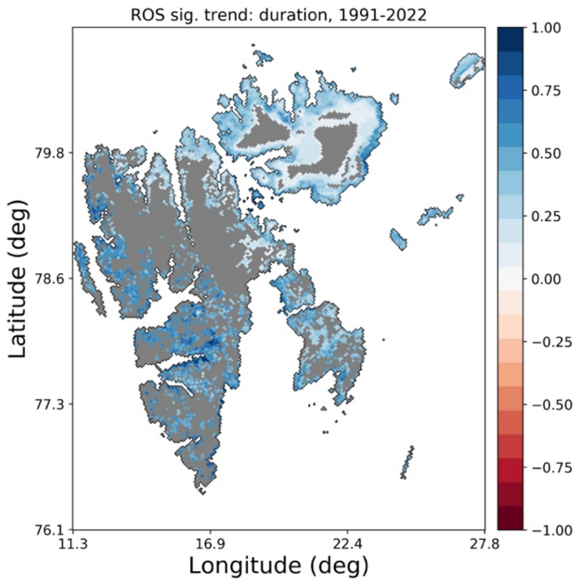

Figure 3. Trend in max duration event (days/decade)

For the trend in maximum intensity ROS event, shown in Figure 4, there are significant and increasing trends across Nordaustlandet as well as across the eastern parts of Spitsbergen and on Edgeøya, typically ranging from 2 to 6mm/day per decade.

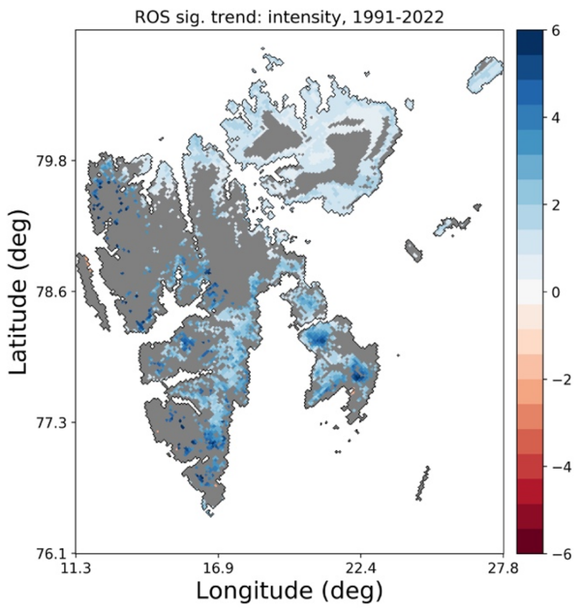

Figure 4. Trend in the maximum intensity events (mm/day per decade)

<u>*3.2 Avalanche detection dataset from SAR*</u>

Figure 5 provides an overview of the avalanche detections mapped from February 2017 through to May 2021. Detections are concentrated on Spitsbergen, especially in the south and central parts, but there is also significant activity in the northern and northwestern parts of Spitsbergen. In contrast, relatively few detections were mapped across Nordaustlandet and Edgeøya.

Figure 5. Geographical distribution of avalanche detection density (ADD) for the winters 2016/2017 through to 2020/2021

In the following Figures 6, 7 and 8 we show examples of the SAR avalanche detection density parameter (upper row) together with the SAR wet snow fraction (lower row, dark blue curve) and measured precipitation at the meteorological stations Ny Ålesund (2016-2017), Hornsund (2017-2018) and Longyearbyen (2018-2019) respectively. The precipitation measurements are shown only for days when the mean daily temperature was above freezing, thus taken as a proxy for rain events. The period shown is 1 November to 31 April in each case. In general, for Figures 6, 7 and 8, there is a good temporal correlation between increases in ADD (and therefore avalanche activity) and increases in wet snow fraction and precipitation as rain. The correspondence between a ROS event, as indicated by increased wet snow and measured rainfall, is particularly evident in Figure showing data from Hornsund during the 2017-2018 winter. All increases in ADD are accompanied by an increase in wet snow detection, even though not necessarily all these increases in wet snow occurred when there was precipitation at temperatures above freezing.

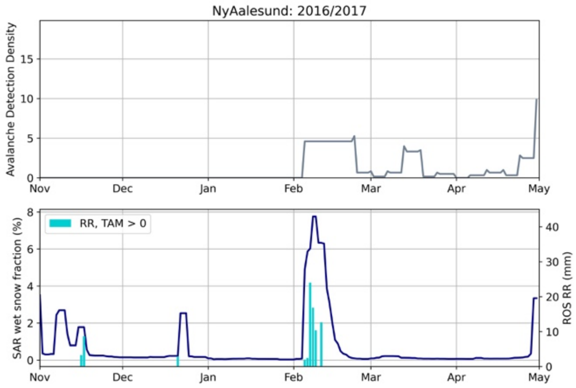

Figure 6. The ADD time series (top) and SAR wet snow fraction and measured precipitation when the daily mean temperature was > 0 for the 2016-2017 winter season at Ny Ålesund.

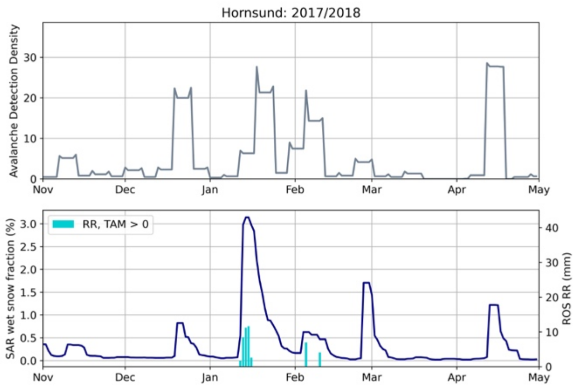

Figure 7. As for Figure 6, but for the 2017-2018 winter season at Hornsund.

Figure 6 shows that there were ROS events in the early part of the 2016-2017 winter at Ny Ålesund, however since the avalanche dataset begins in February 2017, it is not possible to determine if these ROS events led to avalanche activity or not. However, there was an increase in avalanche activity in March 2017 which did not correspond to a ROS event.

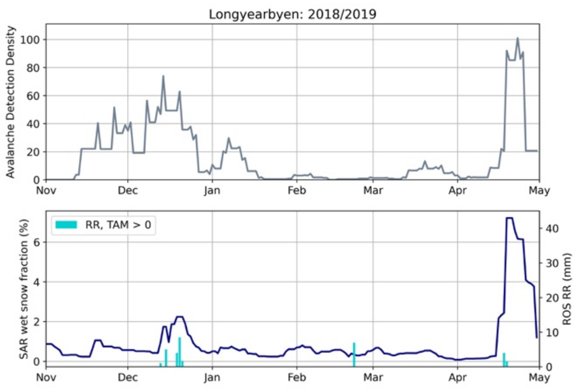

Figure 8. As for Fig.6 and 7, but for the 2018-2019 winter at Longyearbyen.

3.3 Future projections of ROS characteristic

The PCCH-Arctic dataset was analysed in the same manner as the CARRA dataset to detect ROS events, and their characteristics (frequency/number of events, duration, total precipitation and intensity) for the period 2030-2070. We have used the average behaviour for the periods 2000-2020 and compared these to the averages for 2030-2050 and for 2050-2070. Here we show only the difference in number of events, duration, total precipitation and intensity between the periods 2050-2070 and 2000-2020 in Figures 9 to 12 respectively.

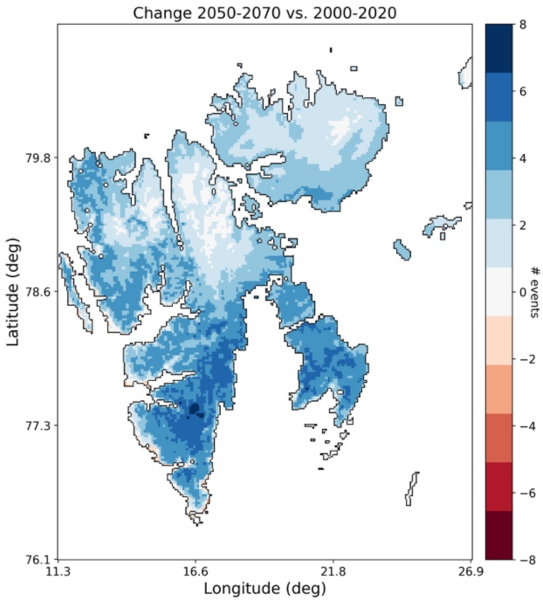

Figure 9. The change in mean frequency of ROS events for 2050-2070 compared to 2000-2020

We have used the means of ROS precipitation, duration and intensity per winter to calculate 20-year averages for the two periods, rather than examining changes in the most extreme ROS events per winter. Figure 9 indicates that ROS in some of the southern and eastern areas of the archipelago can be expected to increase by 8 events on average in the 2050-2070 period, compared to the current climate (2000-2020), with largest increases occurring over eastern areas that in the present climate, experience fewest ROS events. The mean duration (Figure 10) will decrease along western coast by on average 0.5 days between 2030-2050 compared to 2000-2020 but increase in mountainous areas in the northwest and across the eastern parts of the archipelago by around 0.5-1 day on average (2030-2050 results not shown). For the 2050-2070 period, the mean duration will double across the same areas relative to 2030-2050, resulting in an overall increase of 1-2 days in duration over the northern mountain areas and eastern/northeastern parts of the archipelago.

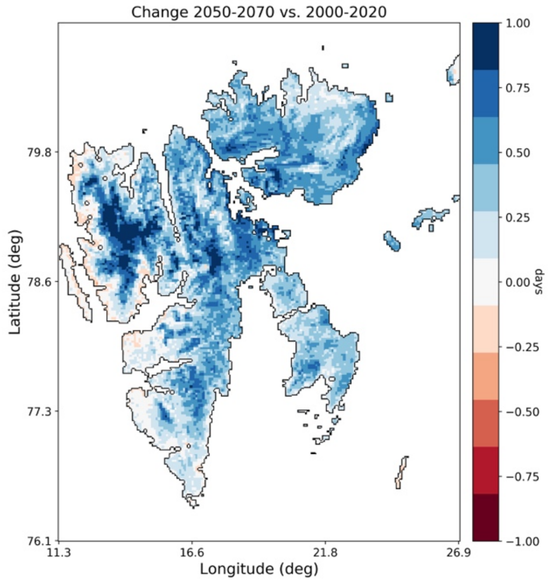

Figure 10. Change in the mean duration of ROS events in the 2050-2070 period compared to 2000-2020

Similarly, the mean total precipitation per ROS event (Figure 11) is expected to intensify over the same areas, with greatest increase over northern mountainous areas of >15mm per event and smaller increases of up to 5mm per event across eastern lying areas in 2030-2050 compared to 2000-2020. The west coast of the archipelago will undergo an overall decrease of to 5mm per event, in line with a reduction in overall duration of ROS events in this period.

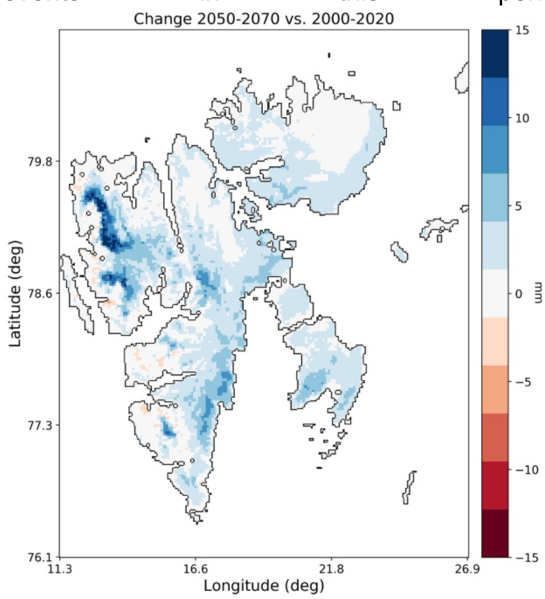

Figure 11. Change in mean total precipitation of ROS events for 2050-2070

By contrast, the change in mean total precipitation for the 2050-2070 does not change much relative to the 2030-2050 period, resulting in an overall decrease in the mean intensity of ROS events between 2030-2050 and 2050-2070, but a small increase in mean intensity of 2.5-5mm per day across eastern and northeastern areas relative to the present climate (Figure 12). There is almost no change in mean ROS intensity over the western regions compared to 2000-2020.

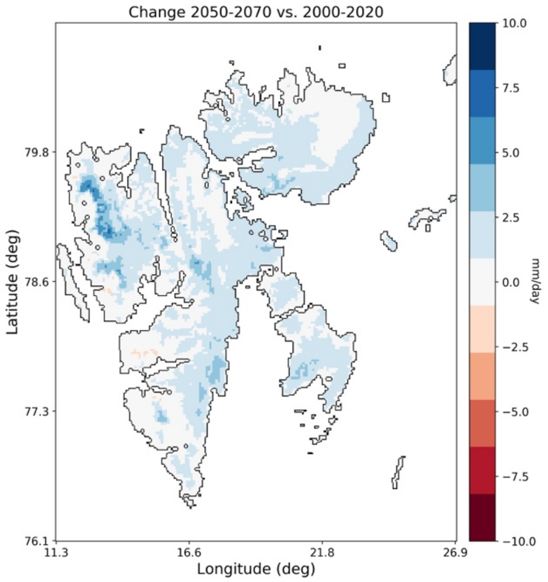

Figure 12. Change in the mean intensity of ROS events for 2050-2070 compared to 2000-2020.

4. DISCUSSION

This study has examined four different characteristics of rain on snow events in Svalbard from 1991-2023 using the CARRA dataset (frequency, total precipitation, intensity, and duration). Increasing trends in all characteristics were found across the archipelago. Nordaustlandet, Edgeøya and some. eastern parts of the archipelago typically exhibited significant and increasing trends in all parameters, while for the western and northwestern parts of the archipelago where ROS events are at present most common, there were only significant trends in events frequency and duration, suggesting that the increase in temperatures across the archipelago in the last few decades have had greater impact on the characteristics of ROS events predominantly in areas that are typically characterized by a colder and drier climate. This contradicts earlier results obtained using only the SAR wet snow dataset from 2004-2020 (Vickers et al., 2022), which indicated that the southern and western parts of Spitsbergen were experiencing greatest increase in frequency of events, while no significant trends were obtained over Nordaustlandet and even decreasing trends in frequency were observed over Edgeøya. Since ROS climatology derived from the CARRA and SAR datasets were found to compare well to each other in a later study (Vickers et al., 2024), the differences in trends are likely to be due to the longer time period of CARRA data available (33 years vs. 17 years) as well as due to inherent differences in the parameters being observed (SAR wet snow vs. CARRA atmospheric variables).

Our analysis of the PCCH-Arctic climate projections comparing changes in ROS characteristics for 2 future periods, 2030-2050 and 2050-2070 indicates similar patterns of change as exhibited by the CARRA dataset for the current climate. For both future periods examined, the greatest changes in frequency and duration of ROS events can be expected to occur over eastern and northeastern parts of the archipelago, where ROS events are at present least frequent, but have been increasing in the last 3 decades as shown in the CARRA dataset. By contrast, the westernmost coastal areas of Svalbard will see a decrease in both frequency and mean duration, resulting in a decrease or no change in the mean total precipitation and intensity of ROS events by 2050-2070. The greatest changes in mean total precipitation will occur in the near future (2030-2050) while the frequency of ROS events will increase most rapidly between 2030-2050 and 2050-2070. The impacts of these changes on the cryosphere will be determined by the overall snow depth across these areas, since ground ice is most commonly formed in association with ROS events acting on thinner snowpacks (Peeters et al., 2019). In contrast, greater total precipitation may completely remove snow cover where the snowpack is thin, while more frequent, short duration ROS events may produce a snowpack with many ice crusts.

A simplistic comparison of the SAR-derived avalanche dataset for Svalbard with the SAR wet snow data indicates that avalanche activity in Svalbard may be driven by periods of mild weather during the winter, where rain is associated with both wet snow and occurrence of wet snow avalanches. However, the avalanche detections from SAR are known to be biased toward detection of wet snow avalanches than dry snow avalanches. Therefore, if dry snow avalanches are missing from the dataset, the correlation between ROS and avalanches could potentially be too strong, but this cannot be determined based on the present dataset available. As more years of data become processed, a deeper and more quantitative analysis of the relationship between ROS events and avalanche activity in Svalbard will become possible.

5. OUTLOOK

Though an in-depth analysis of the relationship between winter rain-on-snow events and avalanche danger in Svalbard has not yet been carried out, there are early indications that ROS events drive increased avalanche activity across the Svalbard archipelago. Long time series of atmospheric and cryospheric variables have been utilised to provide a climatology and trends in four ROS characteristics for the most recent 3 decades (1991-2023). Early analyses of downscaled climate projections at a comparable spatial resolution have been exploited to derive knowledge about how ROS events in Svalbard will change in the future, and thus how avalanche activity may be impacted in different regions of the archipelago. In particular, it is expected that areas that are at present experiencing most ROS events, will see a decrease in ROS frequency during the next 4 decades, while eastern areas that are impacted to a less extent by ROS now, will experience an increase in ROS frequency of up to 3 events per winter by 2050, with the number increasing rapidly by up to 8 more events per winter by 2070 compared to the current climate. However, the present analysis indicates that even though the frequency of events will undergo a large increase, the mean total precipitation and intensity will not change as greatly compared to the 2030-2050 period.

ACKNOWLEDGEMENT

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