Soil Thermal and Ecological Impacts of Rain on Snow Events in the Circumpolar Arctic

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ABSTRACT

Rain on snow (ROS) events are rare in most parts of the circumpolar Arctic, but have been shown to have great impact on soil surface temperatures and serve as triggers for avalanches in the midlatitudes, and they have been implicated in catastrophic die-offs of ungulates. The study of ROS is inherently challenging due to the difficulty of both measuring rain and snow in the Arctic and representing ROS events in numerical weather predictions and climate models. In this paper these challenges are addressed, and the occurrence of these events is characterized across the Arctic. Incidents of ROS in Canadian meteorological station data and in the 40-yr ECMWF Re-Analysis (ERA-40) are compared to evaluate the suitability of these datasets for characterizing ROS. The ERA-40 adequately represents the large-scale synoptic fields of ROS, but too often has a tendency toward drizzle. Using the ERA-40, a climatology of ROS events is created for thresholds that impact ungulate populations and permafrost. It is found that ROS events with the potential to harm ungulate mammals are widespread, but the large events required to impact permafrost are limited to the coastal margins of Beringia and the island of Svalbard. The synoptic conditions that led to ROS events on Banks Island in October of 2003, which killed an estimated 20 000 musk oxen, and on Svalbard, which led to significant permafrost warming in December of 1995, are examined. Compositing analyses are used to show the prevailing synoptic conditions that lead to ROS in four disparate parts of the Arctic. Analysis of ROS in the daily output of a fully coupled GCM under a future climate change scenario finds an increase in the frequency and areal extent of these events for many parts of the Arctic over the next 50 yr and that expanded regions of permafrost become vulnerable to ROS.

1. Introduction

The vast lands of the Arctic are a place of meteorological extremes and extraordinarily harsh winter conditions. The Arctic exhibits some of the largest interannual climate variability on the earth and has also undergone systematic alterations to its landscape and ecosystems in recent decades (Serreze et al. 2000). These changes underscore the controlling role that positive trends in surface temperature, particularly during the winter season, play in the Arctic system. Rain on snow (ROS) events represent a different type of extreme event in the Arctic that can have equal or even greater impact on the physical and ecological systems. The ROS event itself is typically short lived (order of days), but the effects on the ecosystem (herd decline) and soil temperatures may last for years. Rainwater carries latent heat that heats snow and the underlying soil as it freezes within the snowpack or at the soil surface. In turn, the frozen layers within the snowpack can affect the ability of ungulates to travel and forage, and in extreme cases can cause die-off through starvation and impact herds for generations (Aanes et al.

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2000; Miller et al. 1975). In mountainous regions, ROS events can also destabilize the snowpack and act as precursors for avalanches, as has been shown in midlatitudes by Conway and Raymond (1993) and Conway and Benedict (1994). The mechanisms for the impacts of ROS are well understood, but the synoptic conditions causing these events have never been characterized for the Arctic.

The mechanism by which ROS can impact the heat budget of the permafrost was investigated by Putkonen and Roe (2003, hereafter referred to as PR2003). Their work showed that the large rain events effectively short-circuit the insulative role of the snowpack on permafrost, and provide a direct link between transient atmospheric events and the soil surface. Heavy rain can percolate through the entirety of the snowpack to pool at the soil surface, and the water releases latent heat directly to the soil surface and to the overlying snowpack as it freezes. Their results showed that a single large ROS event can constrain the soil surface temperature to 0°C for months during the winter as the liquid water slowly freezes. This process is an extremely effective means of warming the soil surface at a time when it is typically insulated from the atmosphere by the snowpack. Large and long-lasting surface air temperature anomalies would be required to cause an equivalent heating of the permafrost. For example, estimates of conductive heat transfer at the soil–snow surface for a 1-m snowpack show that latent heat from freezing 100 mm of liquid water over a 50-day period results in a 6 $\mathrm{W\ m^{-2}}$ decrease in heat drawn from the soil, 3 times the decrease attributed to an increase in mean atmospheric surface temperature of 5°C (κ_{snow} is assumed to be 0.3 $\mathrm{W\ m^{-1}\ K^{-1}}$).

Ice layers formed at the surface and throughout the snowpack from ROS can also have a detrimental effect on Arctic ecosystems. In particular, ungulates such as caribou, reindeer, and musk oxen forage throughout the winter to survive, and can have difficulty penetrating through ice layers to reach nutrient-rich surface lichens and other forage. Pooling water from large ROS events can also cause these lichens to spoil (Kumpula 2001). Both situations can force the animals to increase their range greatly to find sustenance, and impose a cumulative energetic penalty over the course of a winter (Thing 1977; Skogland 1978; Fancy and White 1985). This energetic penalty can increase winter depletion of body fat and protein reserves (Allaye-Chan 1991), increase mortality and late-term abortion, and decrease calf birth weights. The timing of ROS events therefore plays a critical role in determining the severity of the impacts on ungulates; events that occur in the early part of winter have more time to exact energetic costs from the animals. The ungulate calves are most susceptible to direct mortality due to starvation, and malnourishment among pregnant cows also leads to a low calf survival rate the summer following the ROS event. These two factors may combine to remove several years of calves from a herd. This in turn leads to a subsequent population crash several years after the ROS event as the adults age without replacement. In this way, ROS events can have both a near-term impact through animal starvation, and a long-term impact by disrupting the ability of the herd to recover through reproduction. Icing events such as those caused by ROS have been shown to be the single best predictor of variability of the size of the Svalbard reindeer population (Kohler and Aanes 2004), and implicated in the 70% decline in Peary caribou over the last three generations (Harding 2003).

Incidents of ROS as unusual weather events have gone relatively untreated in the atmospheric literature. The most relevant study of Arctic ROS is that of Groisman et al. (2003), in which they considered 50-yr trends in small ROS events in the Arctic winter and spring. They found an increasing trend in ROS events in western Russia and a decrease in western Canada. The decreasing trend in western Canada was attributed to a decreasing snowpack. McCabe et al. (2007) examined ROS in the western United States and found decreases in ROS events in this region due, in part, to changes in ENSO, as well as a decreased number of days with snow on the ground due to warmer surface temperatures.

The apparent omission of ROS from the atmospheric literature is largely attributable to the difficulties inherent in characterizing these particular types of weather events with the data available for the region. Meteorological station coverage in most regions of the Arctic is sparse, and many of these stations are automated and have limited means for accurately measuring or discerning rain from snow. Even where staffed and properly equipped stations exist, the measurement of ROS is still difficult due to cold conditions, and there is some ambiguity in reporting mixed rain and snow. Global circulation models tend to underestimate rain amounts and, like reanalysis products, these amounts are most commonly evaluated for the midlatitudes and tropics. This implies caution is necessary when using either type of product to determine Arctic rain. Finally, there is often a strong scale mismatch between the size of the area impacted by ROS and the resolution of the dataset used to represent it. For example, in our case study of the 2003 ROS event on Banks Island, we find that the impacted area was less than half the size of a single grid point in the European 40-yr reanalysis.

In summary, ROS has important impacts on the land surface and ecosystems of the Arctic, and we seek to characterize their extent, frequency, and magnitude across the region. To do this, the aforementioned difficulties in the datasets must be addressed. Sections 2 and 3 begin this study with a general discussion of the station and reanalysis datasets used, and an intercomparison between the two to determine the consistency in their results. Climatological ROS is discussed in section 4, allowing for an assessment of the nature and relative size of the impacts from ROS across the Arctic. In section 5 two case studies in which ROS was observed to have dramatic impacts are presented. The first case involves a series of drizzly ROS events that led to the deaths of 20 000 musk oxen on Banks Island during the winter of 2003 and spring and early summer 2004. The second features a pair of large ROS events that occurred on the Norwegian island of Spitsbergen during the winter of 1995/96 and had a significant warming effect on the permafrost. Compositing analysis is utilized in section 6 to gain an understanding of the typical synoptic conditions that lead to ROS for four disparate regions of the Arctic, and the projection of these conditions onto large-scale modes of atmospheric variability is discussed. The study concludes with the exploration of the future occurrence of ROS under a future climate change scenario. Predictions from this model indicate that the areal extent of regions affected by ROS will likely increase, and that regions of permafrost that are not impacted today may become vulnerable.

2. Data

The primary dataset used for the climatological analysis of ROS events is the 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40; Uppala et al. 2005). The ERA-40 dataset was chosen over the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis dataset as it is believed to provide a superior precipitation product (Serreze et al. 2005; Bromwich and Wang 2005; Bromwich et al. 2007). The data are provided at a 6-hourly temporal resolution and on a 2.5° latitude × 2.5° longitude grid for the years 1957–2002. Daily average snow depths were created by averaging the 6-h snow depth field. Daily totals for accumulated snowfall were calculated by summing up the 6-hourly snowfall field, and daily rain totals were then created by subtracting the daily total snowfall from the daily sum of the convective and large-scale precipitation fields. The winter season for the Arctic as it relates to rain on snow is taken to be October–March.

Precipitation data from meteorological stations in Canada were provided by Environment Canada in a processed format that had been binned into rain and snow categories (Mekis and Hogg 1999). In their raw format, station operators recorded precipitation amounts to a precision of 0.2 mm, and categorized the conditions and types of precipitation using standard World Meteorological Organization (WMO) data flags. These flags were then postprocessed by Environment Canada and binned into daily rain and snow totals, which we used in our analysis. Only stations that had been recording for at least 1957–2002 were used, to match the period of ERA-40. Figure 1a shows the locations of the stations used. To provide context for the impacts discussed in this study, Figs. 1b, c show the herd ranges of caribou and reindeer generated by the CircumArctic Rangifer Monitoring and Assessment Network (CARMA; information retrieved from http://www.rangifer.net/rangifer/herds/index.cfm on 11 January 2008), as well as the type and extent of Arctic permafrost based on soil data described by Brown et al. (1998).

The case study of the Banks Island event in October 2003 is outside the period of the ERA-40 data, so atmospheric fields from the NCEP North American Regional Reanalysis (NARR) product (Mesinger et al. 2006) were used. The NARR produces 3-hourly output for all of North America on a Lambert projection. It is an unusual reanalysis product in that it assimilates actual precipitation measurements, and therefore, in principle, NARR should generate a superior precipitation product. Unfortunately for our purposes, the assimilation of precipitation over the oceans only occurs south of 35°N, so it is a less useful natural constraint for the high latitudes. It is not possible to properly distinguish rain from snowfall in the output of the NARR, so we examined the total precipitation field, allowing us to place an upper bound on rainfall. As will be explained in the case study, this was adequate for the conclusions drawn for this case.

3. Data intercomparison

An issue central to the study of ROS in the Arctic is the suitability of the datasets for analyzing them. As discussed in the introduction, each of the two forms of data for the Arctic (sparse meteorological stations and reanalysis products) have their own disadvantages. Given that the ROS events themselves tend to be infrequent and their measurement difficult, it is unrealistic to expect these datasets to provide an accurate representation of rain amounts for an area as large as the Arctic. In light of this, rather than attempting to obtain

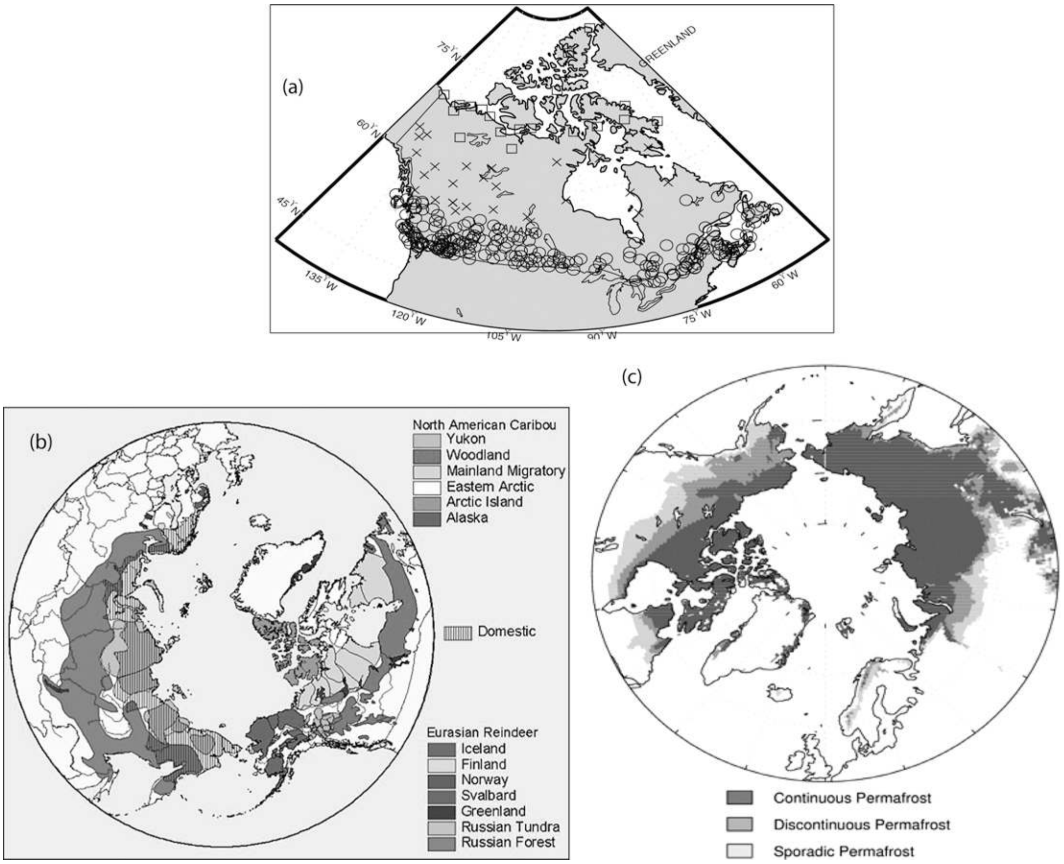


FIG. 1. (a) Locations of Canadian station data used for data intercomparison. (b) Caribou and reindeer herd ranges. (c) Regions and types of Arctic permafrost.

exact amounts of liquid precipitation that have fallen, the data are utilized to obtain the general characteristics of ROS and their uncertainties. Comparing the datasets allows for their consistent characteristics to be used to obtain a plausible characterization of ROS for the historical record.

Climatological daily rainfall and total precipitation for the Canadian stations were compared with the output from the ERA-40 grid cell that encompasses that station's location. Figure 2a provides a scatterplot of the mean climatological daily rainfall for our defined winter season of October–March. Comparing sparse point measurements to a 2.5° × 2.5° grid-cell average is a demanding comparison, so it is reassuring to see an approximately linear relationship between climatological amounts of rain for the two datasets, especially at the middle latitudes. Of note at the higher latitudes in the Canadian interior are both the miniscule amounts of rain recorded at the stations and the apparent overestimation by the ERA-40. The reason for this discrepancy can be understood by repeating the analysis for the total precipitation field rather than just for rain (Fig. 2b). The scatterplot of the total precipitation fields is much more linear than for the rain fields at more northerly latitudes. Therefore, each dataset is producing a comparable amount of mean precipitation, but recording it in different forms. The ERA-40 often produces more rain than is reported at these stations. This could either indicate a slight bias toward comparative raininess in the ERA-40, or a potential issue with the reporting and postprocessing of the station data into precipitation categories performed by Environment Canada.

An examination of histograms of rain magnitude in the two datasets (not shown) further shows that the ERA-40 has a tendency to generate drizzle. The ERA-40 was found to generate more frequent, smaller rain events of less than 2 mm day^{-1}, and seldom generated rain events as large as the largest events recorded in the station data. This suggests caution in using the ERA-40 to look at very small events in the climatological record.

Days with poor agreement between the two datasets were also examined on a case-by-case basis. On days in which individual stations recorded large rain events but

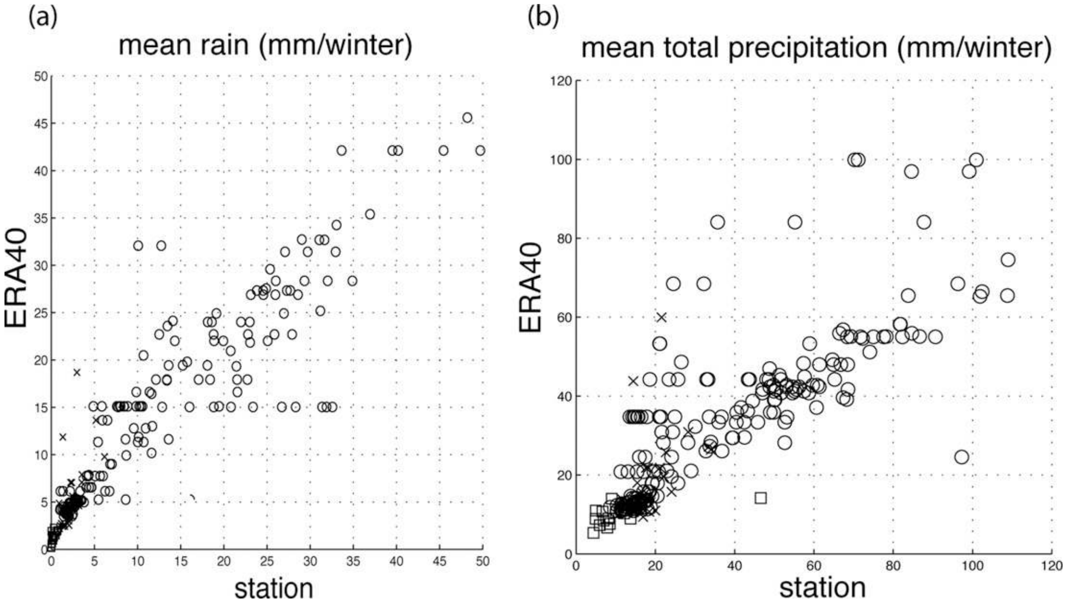


FIG. 2. Scatterplot comparisons of (a) mean winter total rain and (b) mean winter total precipitation (all forms) between the Canadian meteorological station data and the ERA-40 value for the overlying grid cell. Units are mm per winter. Marker types correspond to those used for station location in Fig. 1a. Mean amounts of winter rain in the station and ERA-40 datasets are comparable for the lower latitudes. At higher latitudes, the ERA-40 data show higher rain amounts than the stations report. Total precipitation amounts at these latitudes are much more comparable, potentially indicating either relative raininess in the ERA-40 or issues in the reporting or postprocessing of the station data.

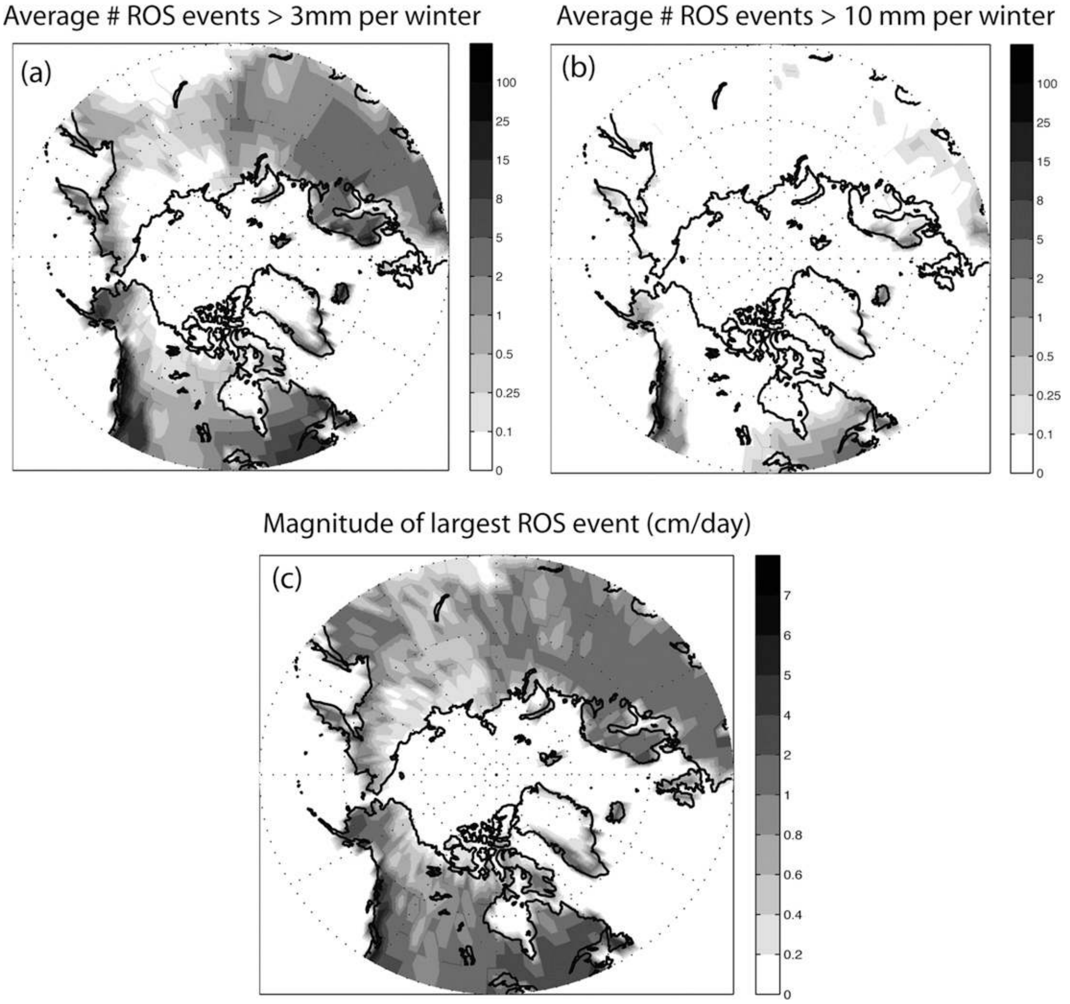
the ERA-40 did not, the synoptic fields of the ERA-40 were examined. In almost all cases, the ERA-40 synoptic fields were consistent with a pattern that could have generated rainfall. This suggests that, for the purposes of characterizing ROS, the deficiency in the reanalysis is not in the large-scale synoptic fields, but in the actual production of rain. There is further evidence for this in the two case studies examined in section 5, and it is an important result for the discussion of the synoptic conditions that favor ROS for different areas of the Arctic in section 4. Due to the characteristics of the data discussed in this section, we believe they are best used to estimate the spatial coverage of ROS and for exploring the large-scale synoptics of these types of events.

The snow product of the ERA-40 was evaluated against the snow extent climatologies from the Global Snow Laboratory (information online at http://climate.rutgers.edu/snowcover/) for general consistency of climatological spatial coverage and timing of the onset of autumn snow cover and spring melt. Snow coverage to a minimum depth is an important component of this study, but accuracy in snow depth above this minimum depth is less critical for the creation of climatologies. More important is that there is a minimum amount of snow present to allow for the formation of ice layers. The ERA-40 was found to adequately represent the timing and spatial coverage of snow for these purposes.

4. Climatological ROS in the circumpolar Arctic

Different magnitudes of ROS events have different impacts on ecosystems and the soil thermal field. Large events, which have the ability to penetrate snow cover to the soil surface, have the potential for the largest impact on the permafrost, ungulates, and for destabilization of the snowpack. However, even light rain, or above freezing air temperatures, can be detrimental to foraging animals. For this reason it makes sense to examine climatological ROS for a pair of minimum thresholds: one set to show even small events in regions of importance to ungulates, and the other set to show only large events in regions of permafrost.

Daily data from the ERA-40 were used to examine past incidents of ROS for large and small rainfall thresholds based on results from section 3. Figure 3a and 3b show the past frequency of October–March ROS for minimum rain thresholds of 3 and 10 mm day^{-1} with a minimum threshold of 3-mm snow water equivalent. ROS is most frequent along coastal margins where the maritime influence can be felt, and even



Average # ROS events > 3mm per winter

Average # ROS events > 10 mm per winter

Magnitude of largest ROS event (cm/day)

FIG. 3. Climatologies of the mean number of ROS events per winter for rain thresholds of (a) 3 and (b) 10 mm day^{-1}, and (c) the magnitude of the single largest ROS event (cm day^{-1}) for each ERA-40 grid cell for the period of record. The winter season is defined as October–March, with a snow minimum of 3-mm snow water equivalent. Small rain events that can impact ungulates shown in (a) occur throughout the circumpolar Arctic, while the larger events that can warm permafrost (b) are exceedingly rare in the ERA-40, and are largely confined to coastal areas.

small events are extremely rare in the deep interior of the Canadian and Siberian Arctic. This picture is consistent with our general expectations for where these events tend to occur. It is expected that the ERA-40 precipitation products are of lower quality for the time period before the advent of satellite-based modern data streams in 1979, but a comparison of the climatologies for the pre- and post-1979 periods finds them to be quite similar (not shown). Figure 3c shows the magnitude of the single largest ROS event for each grid cell in the ERA-40 for the period of record. This shows that even the largest events in the ERA-40 for the Arctic are generally less than 10 mm, and in most regions of the Arctic are on the order of just a few millimeters. In the next section we present case studies of specific ROS events that severely impacted two different regions, neither of which stand out in these maps. It is emphasized that these climatologies yield a general picture of where these events tend to occur, but may not reveal locations with some of the largest and most important events for the ecosystem and soil physics. These climatologies should be viewed as a lower estimate of the impacts of ROS.

Areas of overlap between Figs. 1b and 3a indicate that those animals that have primarily been impacted are caribou and reindeer that range throughout Alaska and northwestern Canada, as well as reindeer on Svalbard, and in Scandinavia and eastern Siberia. It should be noted that the majority of the events represented in these figures occur during the transitional months between fall and winter, and winter and spring (not shown).

For ROS to have a significant impact on the heat budget of permafrost requires large amounts of rain to be delivered to the snowpack. Figure 3b shows the mean number of ROS events larger than 10 mm per winter season. Events of this size are exceedingly rare in most parts of the Arctic, and in the current climate only a few regions with permafrost would appear to be vulnerable. In particular, southwestern Alaska and the island of Svalbard are both within reach of large winter storms that could generate large amounts of rain.

5. Case studies

In this section, case studies of ROS events on Banks Island in the Canadian Arctic and on the Norwegian island of Svalbard are studied. The motivation for this is threefold: to illustrate the differing synoptic conditions that give rise to ROS in different parts of the Arctic, to provide further evidence for the extreme impacts of these events, and finally to highlight the issues in their measurement.

a. Banks Island, October 2003

Banks Island, the westernmost island in the Canadian Archipelago, has a human population of approximately 150 as well as a current population of some 52 000 musk oxen and 2000 Peary caribou. Peary caribou are listed as endangered. There is a small male-only harvest quota (36 males per year). Although this is a small harvest, it is socially and culturally important to the community of Sachs Harbour, Northwest Territories. Musk oxen are harvested for subsistence use and there is also a large-scale commercial harvest for export of meat and qiviut (underwool).

By early October, approximately 6 in. of new snow had accumulated on Banks Island. This was followed by a week of intermittent rains and then a rapid return to subfreezing temperatures. This resulted in the formation of a thick sheet of ground-fast ice on the northern two-thirds of the island. Hunters reported that following the drizzly rain the 6-in. snowpack turned into several inches of ground-fast ice in many places. This ice sheet was too thick for the musk oxen to crater through to forage for food. They reported that by mid- to late winter confused musk oxen were wandering out onto the pack ice in search of food, and drifting out to sea on ice pans (J. Lucas 2007, personal communication). Nagy and Gunn (2004) surveyed the island during July 2004 and found there had been a large die-off of musk oxen on the island. Based on surveys conducted in 2001 and 2005, they estimated that approximately 25% of the entire island's population of musk oxen had died (J. Nagy et al. 2007a,b, unpublished manuscripts). The direct animal mortality due to starvation was largely among the youngest and oldest musk oxen in the population, and there were also few calves born in the summer of 2004 due to the poor condition of the cows because of the ROS events. As discussed in the introduction, this gap in the age structure of the herd by the ROS is expected to cause another dramatic decline in population in 4–5 yr.

Conditions were most severe on northwestern Banks Island. The majority of the musk ox carcasses located during July 2004 were found in this area (Nagy and Gunn 2004). The animals clearly died of starvation as evidenced by emaciated carcasses (skin draped over skeletons). Locals report that the southern third of the island was much less affected, and that icing conditions there were minimal. The caribou population, also vulnerable to these types of events, inhabits the southern part of the island. Although a die-off was not evident, cows on the northern part of the island were in very poor condition and postnatal mortality of calves was likely high. The localized nature of this event highlights the difficulty in using reanalysis products to study ROS; the entire area impacted was approximately 47 000 km^2, approximately the size of a single 2.5° × 2.5° grid cell.

The October 2003 Banks Island ROS event is outside the period of the ERA-40 reanalysis, so the NARR data were used to analyze the synoptic conditions leading up to these events. Climatological conditions for October are shown in Fig. 4a. For approximately a week before the ROS, Banks Island was experiencing strong southwesterly flow, due to a ridge in the 500-hPa height field that stretched almost all the way to the tropics. To facilitate comparison with the climatology, the hemispheric 500-hPa height field from the NCEP Global Forecast System (GFS) 0-h forecast for 3 October 2003 is shown in Fig. 4b rather than the regional fields provided by the NARR; the two products exhibit similar strong features over the domain of the NARR for the relevant time period. This relatively warm, moist flow was lifted at Banks Island by a weak upper-level short wave passing through, resulting in snow followed by rain. Both positive vorticity advection increasing with height and advection of warm air can be identified as contributing to the lift (Trenberth 1978). For the 5-day period of 3–8 October during which the events are estimated to have occurred, the amount of total precipitation (all forms) for Banks Island in the NARR is only 4 mm. There are no nearby precipitation values significantly larger than those reported for

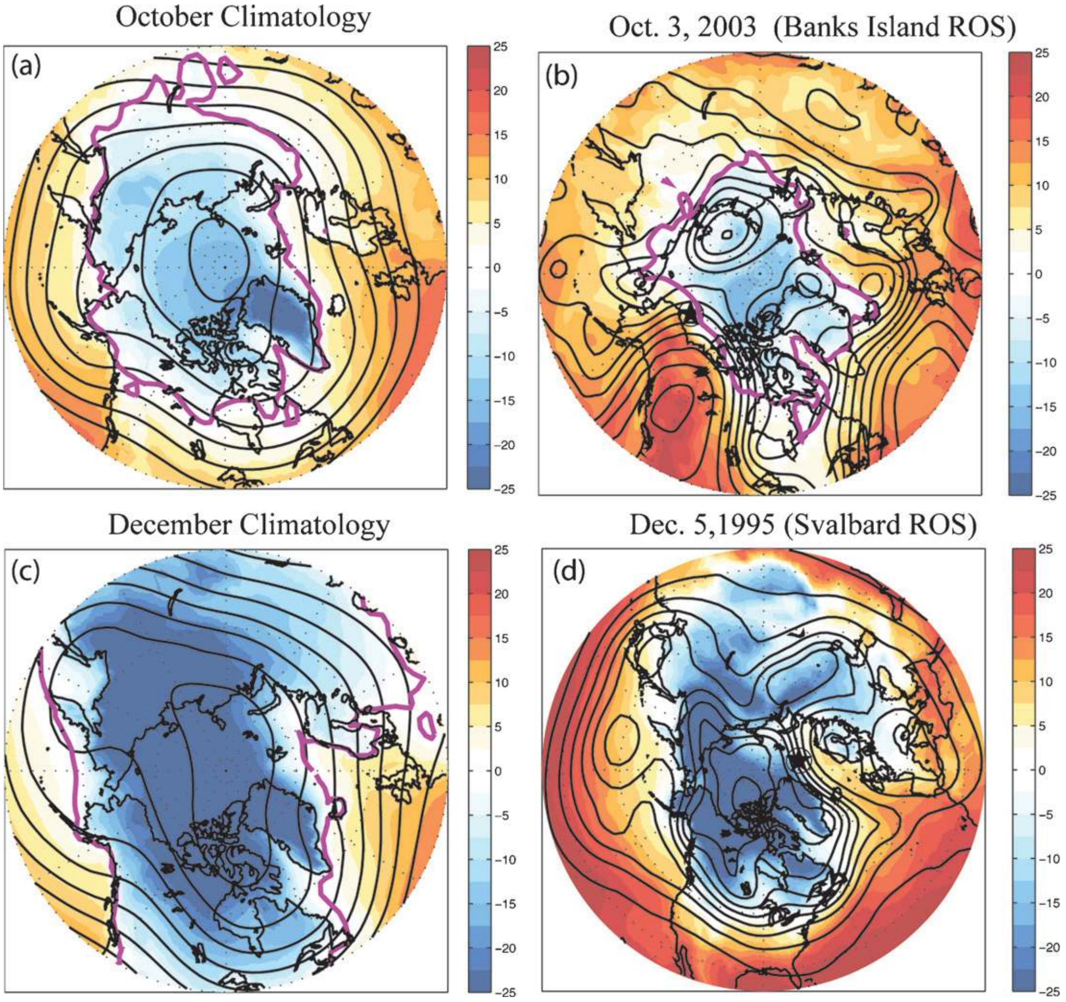


FIG. 4. Climatological conditions for the months of (a) October and (c) December. Colors show surface air temperatures (°C); contours are 500-hPa geopotential heights (contour interval 75 m). Large pink contour is the 0°C line of surface temperature. (b), (d) The synoptic conditions during the Banks Island (3 Oct 2003) and Svalbard (5 Dec 1995) case studies, respectively. Both locations exhibited strong southwesterly flow for several days prior to the rain events, yielding abnormally warm surface air temperatures and setting the stage for rain. Svalbard's exposure to storms coming from across a long fetch of the Atlantic makes it susceptible to large-magnitude ROS events, whereas Banks Island ROS tends to be drizzle.

Banks Island, so it is unlikely that the NARR simply tracked the storm somewhere else. The Sachs Harbour meteorological station on the southern tip of the island is the only station on the island equipped to measure precipitation amounts, and was ill-positioned to record the events. It reported approximately 5 mm of total precipitation for this time period.

This case study illustrates some of the main issues in studying ROS. There is an abundance of evidence in the form of eyewitness accounts and animal mortality that ROS occurred and had a larger magnitude than was recorded. This is not surprising given the relatively small area of impact relative to the resolution of the datasets, but is nonetheless an issue when trying to even qualitatively estimate the impacts of such events. Also, even though firsthand accounts indicated heavier rains occurred than were recorded, it still is unlikely that the rain amounts described were enough to melt a 6-in. snowpack through sensible and latent heat transfer from rainwater alone. The total melting was likely due to a combination of direct warming from the rain as well as radiative warming from a possible low-level inversion. Estimating the relative role of each is made difficult by the lack of upper-level air measurements near the area of impact. The resulting impacts from radiative melting are similar to those from ROS, so for simplicity we have chosen to focus here only on the role of the rainwater itself. Other mechanisms for delivering liquid water to the snowpack will be considered in the conclusions and discussion section.

b. Spitsbergen, December 1995

The Norwegian island of Spitsbergen is inhabited by approximately 3000 people and has a small population of Svalbard reindeer. The long fetch of open Atlantic Ocean to the west and southwest of the island makes it vulnerable to much larger ROS events than occur on Banks Island. During the period of 3–5 December 1995, the island's meteorological station at Ny Ålesund recorded 42.2 mm of precipitation that was classified as rain or mixed snow and rain. This event was followed approximately 40 days later by a slightly smaller event. As documented in PR2003, these two ROS events penetrated the snowpack and caused the soil surface to be constrained to 0°C for the rest of the winter.

Figure 4d shows the surface temperature and 500-hPa height fields during the first large rain event as taken from the ERA-40. These fields show abnormally warm surface temperatures, well above freezing, in Spitsbergen brought about by several days of strong southerly flow over an extremely long fetch of the Atlantic. This is a straightforward case featuring a tremendous source of warm, moist air that was lifted and generated a downpour on the island. The ERA-40 generated only 11 mm of total precipitation and 7 mm of rain on Svalbard for this period, compared with the 42.2 mm of rain and mixed rain and snow recorded at the Ny Ålesund station. The large-scale synoptic setting and surface temperatures in the ERA-40 clearly indicated conditions favorable for generating a large rain event, the magnitude was simply lower than recorded at the reporting station.

These two case studies provide examples of two extremes of ROS that can have Arctic impacts. The Banks Island events were small in magnitude and spatial extent and fell on an area that is poorly instrumented. Svalbard instead had a huge rain signal falling on a very well-instrumented meteorological station. The nature of the each events was quite different, but both led to significant animal mortality. Magnitudes for both cases also appear to have been underestimated in the gridded datasets used, though the upper-level fields appear consistent with the occurrence of extreme weather to the impacted areas. This leads us to emphasize the general upper-level flow over precise rain amounts when characterizing these events with these datasets.

6. Compositing analysis of ROS events

We have argued that the ERA-40 generates plausible synoptic fields for ROS events even when rain magnitudes are underestimated. Compositing analyses can provide a particularly useful way of diagnosing the large-scale picture contributing to ROS in different locations. For this purpose we have used the 500-hPa geopotential height field as being generally representative of the upper-level flow during these events.

Compositing analysis was performed for four locations in the Arctic that are susceptible to different types of ROS. As in the first case study, Banks Island (Fig. 5a) is generally susceptible to rare, drizzly events. In contrast, Spitsbergen (Fig. 5b) is geographically positioned to be vulnerable to winter downpours. In addition to these two locations, composite analysis was performed for a location in southwestern Alaska (Fig. 5c) and western Siberia (Fig. 5d). For all locations, the compositing was performed by calculating the mean 500-hPa height field for days on which rain fell and the minimum snow water equivalent threshold was 1 cm. At each location the minimum rain threshold for compositing was chosen such that a minimum of 20 days were composited.

In examining the four panels in Fig. 5, a straightforward picture emerges, common to all of these locations. ROS at these locations is associated with extended warm air incursions from southerly or southwesterly flow. At Banks Island, the climatological flow, which typically brings air northward out of Siberia and across sea ice, is replaced with relatively warmer southwesterly flow from Pacific waters south of Alaska. Similarly, the climatologically zonal flow in coastal Alaska becomes strongly southwesterly during ROS events. Upper-level flow at Spitsbergen is almost directly from the south during ROS, hugging the eastern coast of Greenland rather than passing directly over the ice mass. At the location in Siberia, a trough upstream of the Urals causes flow to be southwesterly and relatively warmer than the typical zonal flow conditions.

Differences in the synoptic settings for ROS at the different locations emerged after examining the 90+ individual events used in the composites (not shown). In particular, the small events at Banks Island only tend to occur during October, and require a fairly persistent (5–7 days) upstream trough to increase the 1000–500-hPa thickness at the island and set the stage for ROS. Similarly, Spitsbergen ROS tends to occur after a deep upstream trough has been in place for several days, and these events can occur through December. In contrast, the more southerly locations in Alaska and in Siberia are closer to the climatological storm track, and ROS events there can result from disturbances that are much more transient (i.e., the necessary synoptic conditions are set up over a day or two). ROS at these locations was found to occur during all winter months.

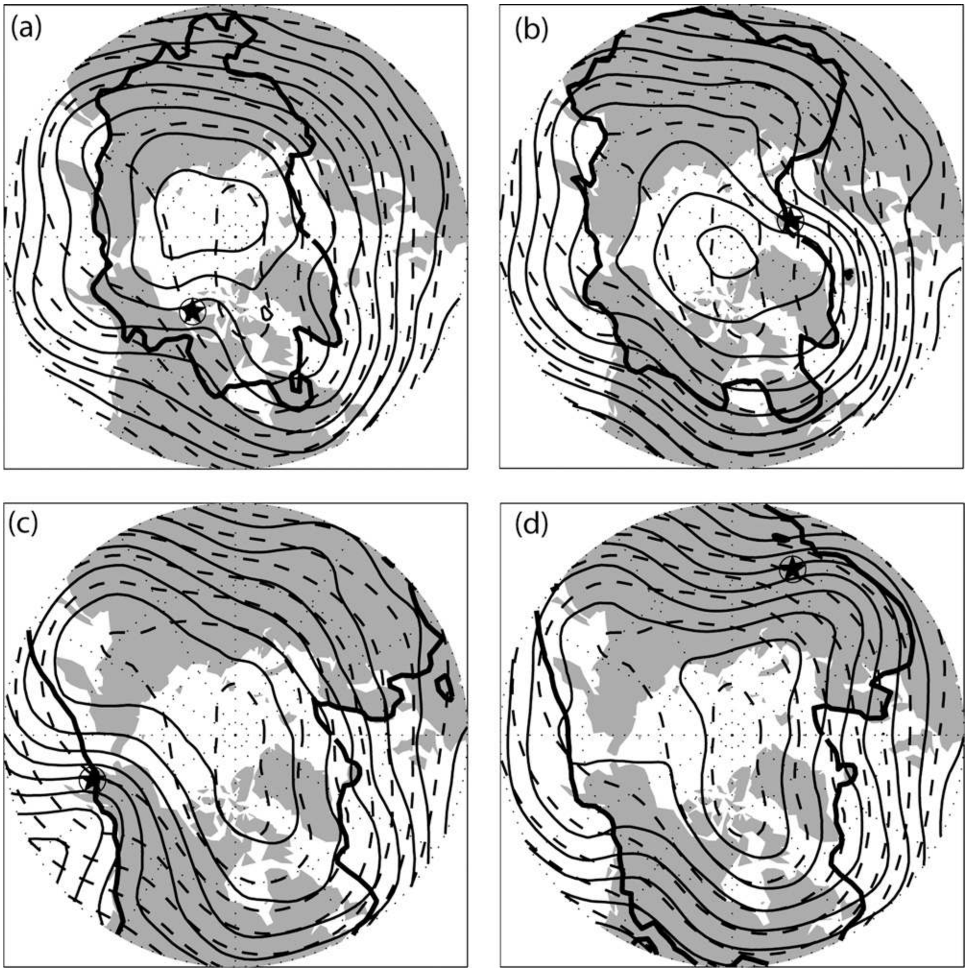


FIG. 5. Composite synoptic setting for ROS events on (a) Banks Island, (b) Svalbard, (c) western AK, and (d) western Siberia. Dashed contours are climatological 500-hPa heights for October–March for 1958–2002. Solid contours are 500-hPa height composites for 20 ROS events of size 1 mm or greater; contour interval is 75 m. Thick contour is the composite 0°C line. Locations of events are marked by a black star in a circle.

Synoptic conditions favorable to ROS at these locations project strongly onto larger modes of atmospheric circulation. ROS in North America is largely associated with variability in the Pacific–North America (PNA) pressure pattern (Wallace and Gutzler 1981). In its negative phase, the PNA features an anomalously weak Aleutian low, providing favorable conditions for ROS events in Alaska. The composite map for ROS at Banks Island projects strongly onto the positive phase of the PNA. This was particularly evident during the October 2003 ROS events featured in our case study. In that case, ROS occurred in the middle of a 21-day positive excursion of the daily PNA index, and just after the index had peaked at over three standard deviations positive. Statistically, an excursion of this magnitude should only happen once every 20 winters. This association of ROS with the PNA is also consistent with our finding that the setup for ROS in this location results from quite slowly varying circulation patterns.

In the Atlantic sector, ROS is associated with variations in the North Atlantic oscillation (NAO; Hurrell 1995). Flow patterns conducive to ROS in Spitsbergen project onto the positive phase of the NAO. PR2003 found that ROS events in Spitsbergen occurred 5 times more often during positive extremes of the NAO index than during negative extremes.

The association of ROS events with these climate patterns provides another useful tool for diagnosing and predicting the likelihood of ROS. Both the NAO and PNA have a greater degree of medium-range predictability than do individual storms (Renwick and Wallace 1995), and also tend to be better represented

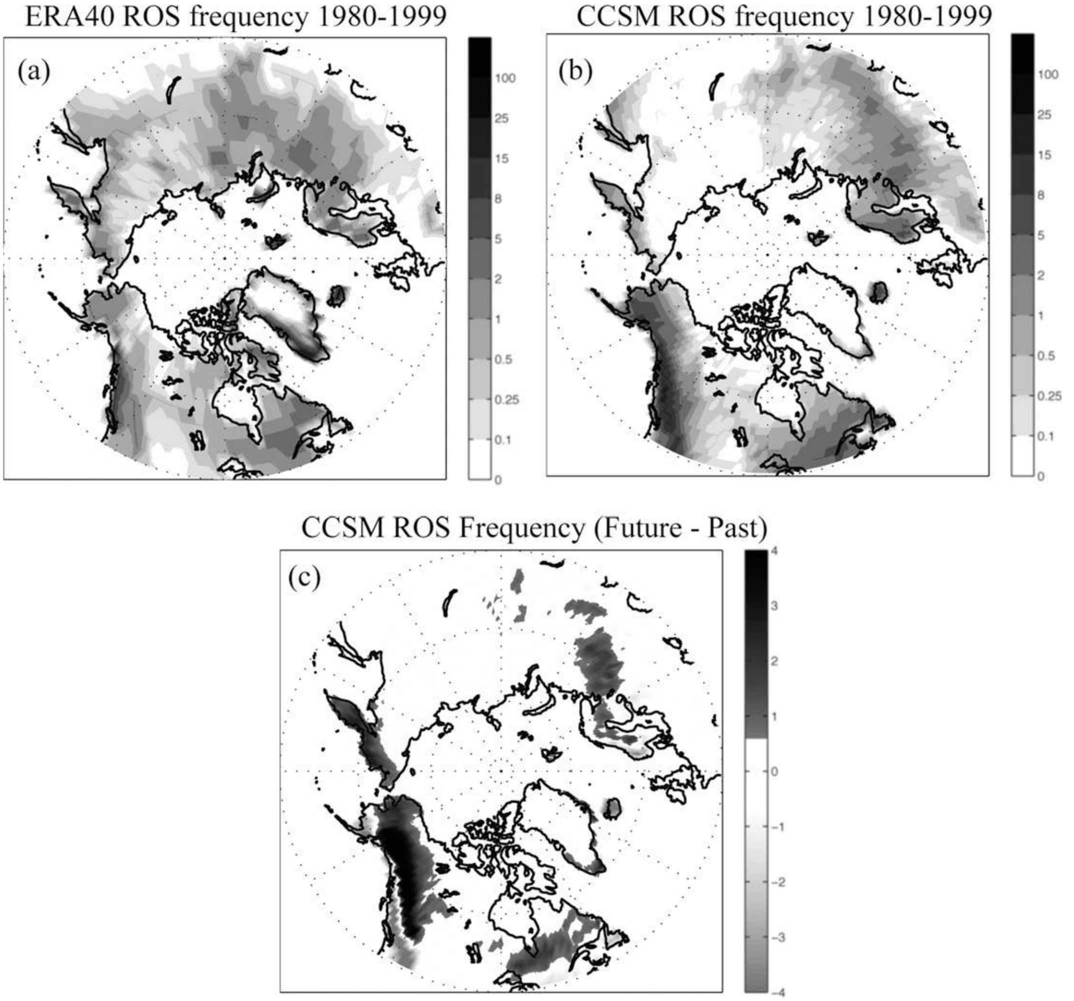


FIG. 6. Number of ROS events per winter in (a) ERA-40 for the period 1980–99 and (b) for the same period in the CCSM3 general circulation model. ROS events are defined as a minimum of 3 mm of rain falling on a minimum of 5 mm of snow water equivalent. (c) The difference between projected ROS events per winter for the same thresholds for the period 2040–59 in the CCSM3 under the A1B SRES climate scenario and the 1980–99 period. The future scenario indicates the increased frequency of ROS in much of northwestern North America, a habitat for several types of caribou. Decreases in ROS shown are broadly due to projected decreases in snowpack in the model, not a decrease in rain events.

than individual weather events in global circulation models. This may also provide a more robust way of interpreting model projections of future changes in ROS.

7. Frequency of future ROS

For a fixed relative humidity atmosphere with all else being equal, it is expected that a warmer troposphere resulting from a warming climate will result in a more active hydrologic cycle (Trenberth 1998; Held and Soden 2006), with an associated higher frequency of ROS in the Arctic. PR2003 examined the wintertime amount of rain in the monthly averaged output of the Geophysical Fluid Dynamics Laboratory's (GFDL's) coupled climate model with rhomboidal 30 truncation (R30) under a doubling of CO_2 and found an approximately 40% increase in the area impacted by ROS by 2080. To refine this estimate, daily data from a five-member ensemble of the more recent Community Climate System Model 3 (CCSM3) was analyzed for the periods 1980–99 and 2040–59. The future climate change scenario is the Intergovernmental Panel on Climate Change's (IPCC) Special Report on Emission Scenarios scenario A1B (SRES A1B; Meehl et al. 2006), which has a doubling of CO_2 by about midcentury. Figure 6a and 6b compare the frequency of ROS events for a minimum of 3 mm day^{-1} rain falling on a minimum of 5-mm snow water equivalent in CCSM3 and the ERA-40 reanalysis for the period 1980–99. The patterns of ROS are broadly similar in the reanalysis and the CCSM3, though the climate model tends to generate larger numbers of events over northwest North America and fewer over central and eastern Russia.

The difference between the numbers of ROS events for 2040–59 and 1980–99 are shown in Fig. 6c. For this rain threshold, ROS becomes more prevalent mainly in northwestern Canada, in Alaska, and eastern Russia, all areas with substantial ungulate populations. This also indicates greater exposure of the underlying permafrost in these areas to winter rain, though the size of the individual events predicted is likely too small to have a substantial impact on soil temperatures. The model output also shows regions with decreasing amounts of ROS along the western coasts of Norway and Canada, and along the southwestern coast of Alaska. Analysis using the snowpack from the control run and the rain output from the future run indicates that this is due to a decrease in the snowpack in the future run, not a decrease in wintertime rain. Further analyses comparing trends in the 500-hPa height field with trends in surface temperatures (not shown) also indicate that positive temperature trends in this scenario are the dominant reason for changes in ROS frequency, not changes in upper-level circulation. To evaluate future trends in ROS properly would certainly require comparing an ensemble of models. The results from this single model, however, appear to be consistent with our hypothesis of larger areal extent and higher frequency of ROS in the future.

8. Summary and discussion

In this paper, rain on snow has been examined as one type of rare meteorological event that can have lasting impacts on both permafrost and ungulate populations in the Arctic. Whereas prior work has provided specific demonstrations of both of these types of impacts and explored their underlying mechanisms, we have taken a broader approach to these events, creating a climatology of them for the circumpolar Arctic. This climatology has shown that only limited areas experience large enough ROS events to impact permafrost temperatures, but that smaller events that can impact caribou and musk oxen are a pan-Arctic phenomenon.

While there are inherent limitations in the datasets available for studying ROS, it is still possible to characterize their occurrence in the Arctic. To more accurately estimate rain amounts falling on snow would require substantial improvements in both the observational network as well as in the model-based reanalysis. As evidenced by the Banks Island case study, important events can occur on a spatial scale that fits between manned stations. To address this would require a significant increase in the density of manned stations as well as a focus in their observations toward careful classification of precipitation type. Even were this to be implemented, it is expected that reanalysis products would still be required to interpolate between stations. The reanalysis product used in this study appears to capture the large-scale synoptic setting fairly well, but an increased density of observations could be used to tune future products to more accurately represent Arctic rain. An increase in Arctic stations measuring precipitation could also allow for assimilation in a manner similar to the current North American Regional Reanalysis scheme for latitudes south of 45°N. Techniques that utilize the passive satellite microwave signature of ROS to detect its occurrence are currently under development, and have been demonstrated for the 2003 Banks Island ROS discussed in the present study (Grenfell and Putkonen 2008). In their work, three distinct stages of the Banks Island ROS event were seen in the satellite data: the initial rainfall event, the accumulation of a liquid layer on the tundra at the base of the snowpack, and the subsequent freeze up of the liquid forming the ice layer that lasted throughout the winter.

The two case studies presented here typify the main varieties of ROS experienced in the Arctic. The geographic location of Svalbard exposes it to storms coming over a long fetch of the Atlantic, and makes it one of the few places in the Arctic vulnerable to ROS events large enough to affect soil surface temperatures. The large magnitude of typical ROS events there combined with the presence of a reliable meteorological station make it the ideal setting for studying ROS. The case study of ROS on Banks Island provides a setting more typical of the rest of the Arctic; the rain events were much lighter, and the stations were sufficiently far from the area impacted as to record negligible amounts of rain. The Banks Island study illustrates that under the proper conditions, even small events can have a devastating impact on ungulates. It also highlights some of the data issues discussed above; despite a preponderance of evidence for the occurrence of the ROS events, an inspection of the data that paid attention only to rain amounts would never have flagged them as significant.

A robust feature of ROS events was the prevailing synoptic conditions under which they occurred. Compositing analysis was used to draw out those synoptic features for four different locations in the Arctic. The picture common to each location chosen was one of the emplacement of warm air from southerly or southwesterly flow, typically for several days. The patterns and time scales of these events project strongly onto slowly varying modes of circulation such as the PNA and the NAO. Such connections could be used to enhance the medium-range predictability of ROS.

Changes in future ROS can be thought of as being determined by a convolution of changes in temperature and circulation. In the results from a climate model presented here, the effect of increasing temperatures dominates that of changes in circulation. Regions of permafrost that were not rained upon during winter months in the twentieth century warm sufficiently in the model to be exposed to more small bouts of winter rain. Coastal areas in western North America and Scandinavia show decreases in the numbers of ROS events due primarily to decreases in the snowpack.

This paper has focused exclusively on ROS as a mechanism for delivering liquid water to the land surface and the formation of ice layers within the snowpack, but it is by no means the only method for this to occur. In particular, thaw–freeze events provide another means for delivering liquid water to the snowpack. The hardening of snow due to strong wind events is another means by which ice layers can be formed in the snow (Benson and Sturm 1993). Though these additional types of events share the same impacts as ROS, they also share in its difficulty of study. Surface temperatures are in general a more robust variable in reanalysis products than are rain amounts, but estimating how they impact the composition of a snowpack over the course of a winter is a formidable challenge. Utilizing those estimates to ascertain the impact on ungulates is an even harder task. The health and survival of Arctic ungulates such as caribou and musk oxen is dependent on a wide array of environmental pressures, of which rain, wind, and melt–freeze events are only a few. This paper has showcased extreme examples during which these pressures rise to dominate all others, but in more typical cases, they are one of many that the animals must adapt to during the course of the Arctic winter. Complex climate stresses also apply in other seasons. For example insect harassment is severe during summer, but can be significantly ameliorated on windy days.

This issue of cascading uncertainties in both the detection and prediction of impact is by no means unique to the study of ROS, and it is common to many climate studies, especially those involving precipitation or ecosystems. We have come to view this research more broadly as a case study in how to address these issues and extract useful information from fairly disparate datasets. In such cases we have found it is important to consciously shift focus away from making quantitative estimates of past and future impacts, and instead to treat the events as environmental pressures with an associated tendency of impact. The intent then must be to find the general circumstances under which this environmental pressure can occur and become more important than others. In our case, this approach involved finding specific examples of known impact, and using lessons from these case studies and the data intercomparison to tie ROS more broadly to larger-scale patterns of flow and variability. It is to be hoped that by highlighting these general regions of vulnerability to ROS, and understanding their connection with unusual flow patterns, the tendencies for future ROS may be more easily diagnosed from climate simulations that are not necessarily focused on this particular set of impacts.

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