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Arctic rain on snow events: bridging observations to understand environmental and livelihood impacts

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Abstract

When rain falls on an existing cover of snow, followed by low temperatures, or falls as freezing rain, it can leave a hard crust. These Arctic rain on snow (ROS) events can profoundly influence the environment and in turn, human livelihoods. Impacts can be immediate (e.g. on human travel, herding, or harvesting) or evolve or accumulate, leading to massive starvation-induced die-offs of reindeer, caribou, and musk oxen, for example. We provide here a review and synthesis of Arctic ROS events and their impacts, addressing human-environment relationships, meteorological conditions associated with ROS events, and challenges in their detection. From our assessment of the state of the science, we conclude that while (a) systematic detection of ROS events, their intensity, and trends across the Arctic region can be approached by combining data from satellite remote sensing, atmospheric reanalyses, and meteorological station records; (b) obtaining knowledge and information most germane to impacts, such as the thickness of ice layers, how ice layers form within a snowpack, and antecedent conditions that can amplify impacts, necessitates collaboration and knowledge co-production with community members and indigenous knowledge-holders.

1. Introduction

There is increasing recognition that Arctic rain on snow (ROS) events, which are projected to become more frequent as the Arctic warms (Rennert *et al* 2009, Bintanja and Andry 2017), can have significant and sometimes even catastrophic impacts on the physical and living environments of the North (figure 1). ROS events are generally associated with short-lived (hours to days) warm spells in autumn and winter, linked to extratropical cyclones that generate rain, followed by a rapid drop in temperature (Hansen *et al* 2014). The rainwater may freeze on the snow surface or percolate through the snowpack and pool at the ground surface. This depends upon the thickness and density of the snowpack, and the intensity of the precipitation event. After refreezing, ice crusts can variously form on the snow surface, as layers within the snow, or at the base of the snowpack.

ROS events can foster slush avalanches when the rain reduces cohesiveness and destabilizes the snow (Hansen *et al* 2014). Alternatively, formation of an ice layer can weaken the snow pack through growth of large faceted grains, providing a hard surface upon which a slab avalanche can slide (Jamieson 2006). ROS events influence snow structure, albedo, density and conductivity, and hence the ground thermal regime (e.g. Mazurkiewicz *et al* 2008, Romanovsky *et al* 2010, Westermann *et al* 2011, Freudiger *et al* 2014, Guan *et al* 2016). If enough water pools at the ground surface and freezes, latent heat release alters seasonally frozen ground, increasing the depth of the

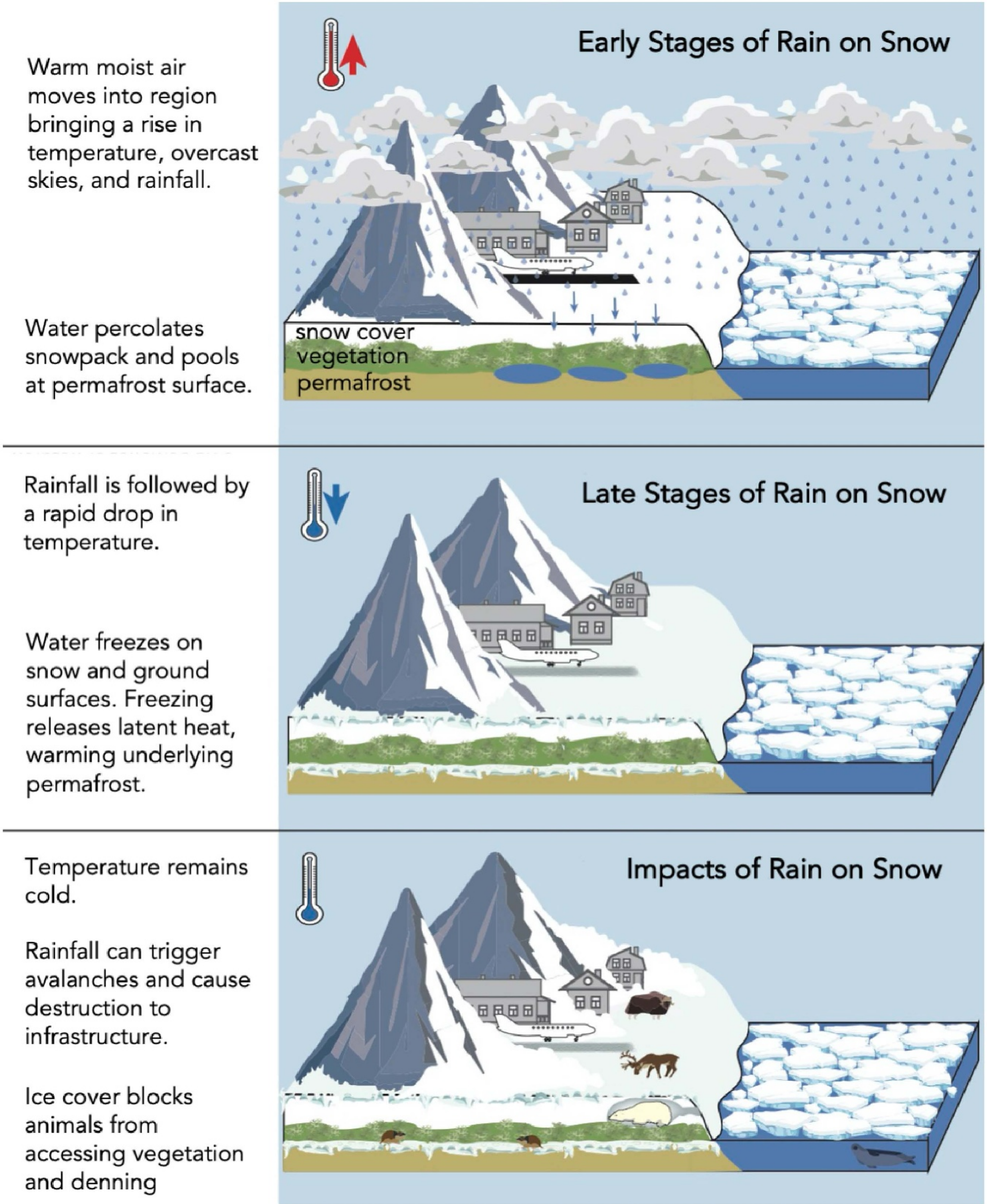

Figure 1. Some impacts of Arctic rain on snow events over Arctic lands and ocean.

permafrost active layer and warming underlying permafrost. Severe rain events can remove the insulating ability of the snowpack (Putkonen and Roe 2003, Rennert *et al* 2009). Impacts have been documented on vegetation (e.g. stress due to ice encasement) and soil organisms (e.g. through altered temperature and drainage conditions) (Bjerke *et al* 2015). ROS events can influence vegetation greenness as detectable with satellite data (Bjerke *et al* 2017) as well as CO_2 fluxes (Treharne *et al* 2020).

On land, ROS events influence population dynamics of lemmings (Kausrud *et al* 2008), voles (Stein *et al* 2012), and bird species that seek shelter in the snowpack, including owls, ptarmigan, and grouse (Mysterud 2016). Notably, icing can foster fading of lemming cycles, causing crashes of Arctic predators such as snowy owls and Arctic fox, which depend on them (Sokolov *et al* 2016). In marine environments, polar bears (*Ursus maritimus*) and ringed seals (*Phoca hispida*) are also impacted—rains early in the breeding season can melt subnivean lairs and increase cub mortality (Stirling and Smith 2003).

Perhaps the most devastating impact of ROS events, however, is that ice layers, in creating barriers that prohibit foraging (figure 2), can lead to massive die-offs of large herbivores, with

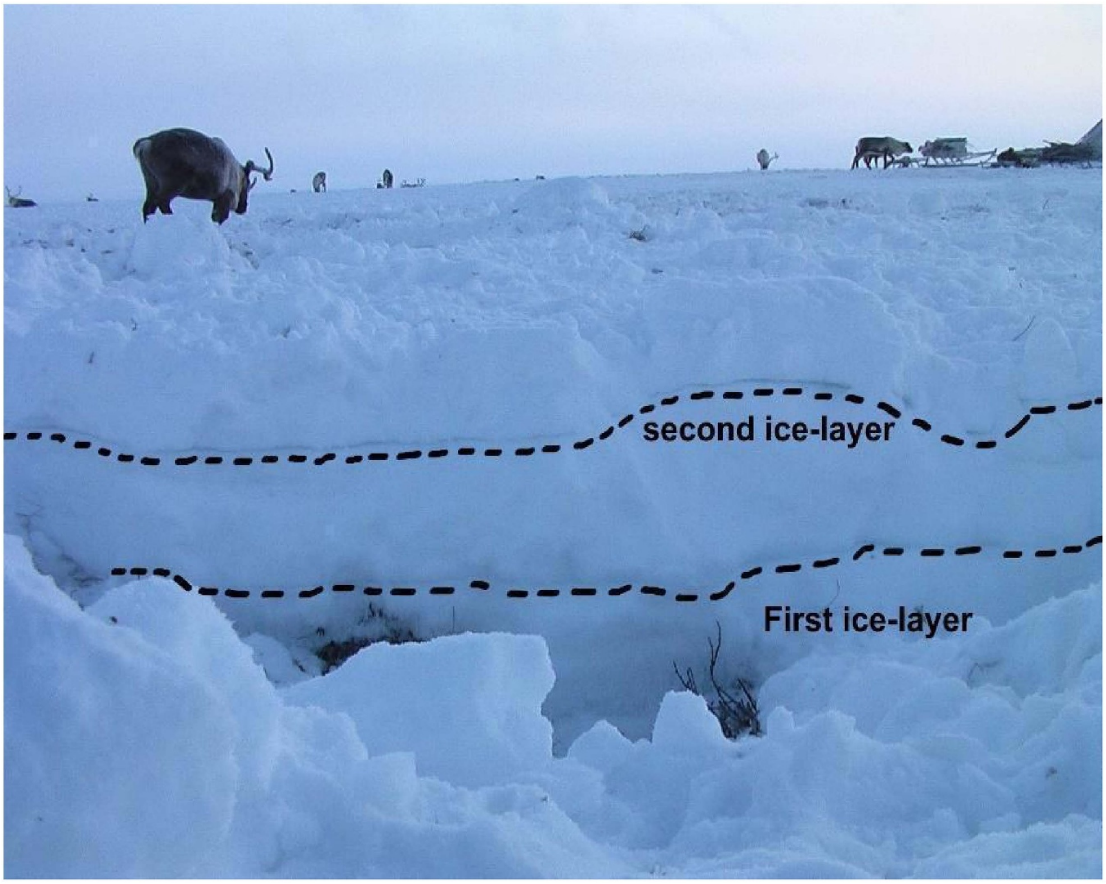

Figure 2. Ice layers within the snowpack associated with two separate ROS events. Photo: Printed with permission from Florian Stammler.

concomitant social-economic impacts, especially in regions where humans depend on either wild or semi-domesticated populations of *Rangifer* species (caribou and reindeer) for food, transportation, and other needs. Such impacts can evolve and cascade, presenting threats to shared food systems, cultural vitality, and other issues identified by communities (Egeland *et al* 2013, Huntington *et al* 2019).

Based on analysis of radar backscatter data (Ku-band QuikScat records) from 2000 to 2009 (Bartsch 2010a, 2010b) and in general agreement with patterns determined from atmospheric reanalysis data (Rennert *et al* 2009, Liston and Hiemstra 2011) (see sections 4.4 and 4.5) as well as local observations (Bartsch *et al* 2010), ROS events are most frequent over northern Europe and southern Alaska (Bieniak *et al* 2018, Crawford *et al* 2020). They occasionally occur over western Siberia, southern Greenland, and parts of Canada but are rare in the cold Canadian Arctic Archipelago (figure 3). Events that do occur in the Canadian Arctic Archipelago (a region classified as a polar desert), have tended to take place in early autumn when it is warmer. Given that reliable detection via radar backscatter is limited to midwinter (see later discussion), taken in figure 3 as November through February, a higher frequency of events can be expected when considering the shoulder seasons.

We provide here a review and synthesis of our current knowledge of Arctic ROS events, emphasizing impacts on reindeer herding livelihoods and wildlife harvesting. We start with an overview of observed impacts on human-environmental relationships, followed by case studies of the meteorology and impacts of three notable events. Attention then turns to data sources and approaches to detect ROS events and their intensity across the Arctic. We then address the growing importance of knowledge co-production (Tondu *et al* 2014, Behe *et al* 2020, Carlo 2020) with Indigenous researchers, hunters, harvesters, and other Arctic residents whose knowledge, lived experiences, and detailed observations of changes in climate and weather are needed for understanding and addressing environmental impacts (e.g. ACIA 2005, Krupnik and Jolly 2002, Gearheard *et al* 2010, Pearce *et al* 2015) and ensuring that research on the physical aspects of ROS events and anticipated changes are relevant and practical for community use. Our paper represents a contribution to the Arctic Rain on Snow Study (AROSS), a project within the National Science Foundation's Navigating the New Arctic (NNA) initiative. It also contributes to CHARTER, a project aimed at comparing the impacts of well-documented events on contrasting social-ecological conditions (e.g. semi-domesticated versus wild ungulates) in

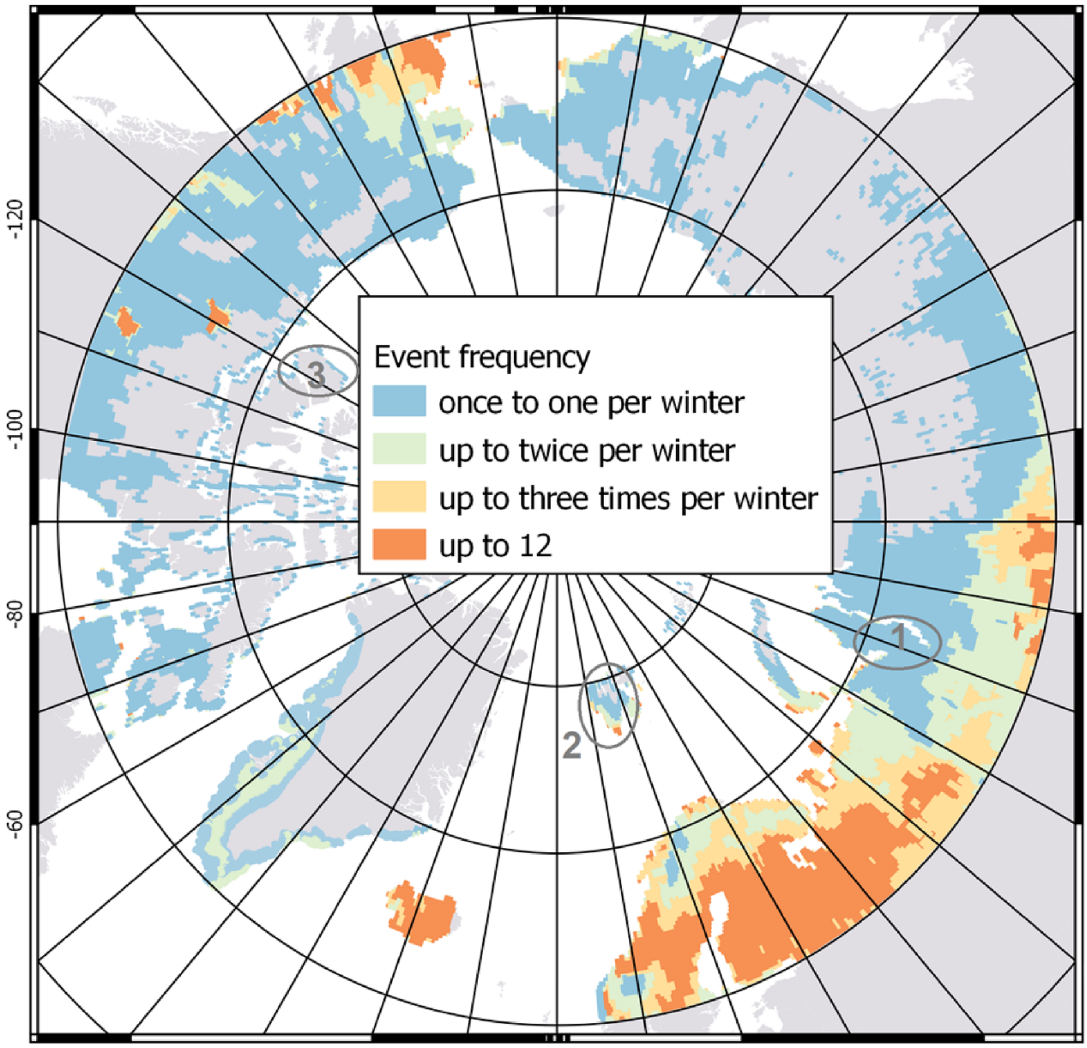

Figure 3. Potential ROS events per year for November through February of the winters 2000/1–2008/9 based on midwinter daily average backscatter increases of more than 1.5 dB as detected with Ku-band QuikSCAT; no masking applied for lakes (Bartsch 2010a, 2010b, Bartsch *et al* 2010, Freund and Bartsch 2020). Also shown are the locations for three ROS case studies: 1—Yamal Peninsula, Russia, 8–10 November 2013; 2—Svalbard, Norway, 30–31 January 2012; 3—Banks Island, Canada, 3–8 October 2003.

Arctic Eurasia and North America. While these projects are underway and full results are pending, this review provides a summary of the state of observations and knowledge of ROS events and their impacts, thus providing a baseline for future efforts to co-develop collaborative observational approaches with Arctic residents.

2. ROS impacts on human-environment relationships

2.1. Reindeer and reindeer herding communities

Reindeer and caribou are the same species, though reindeer have some morphological differences due to semi-domestication. A mature male reindeer can grow to about 100 kg. Females typically give birth in May and June to a single calf. Reindeer herding is practiced across the circumpolar Arctic, but most activity is in Fennoscandia and parts of Russia. Herding is conducted by families, within herding districts, villages, and state-owned collectives. Reindeer are used for food, clothing, as well as transportation (Forbes and Kumpula 2009). Finland has 54 herding districts and approximately 4500 reindeer owners, of which an estimated 900 are full-time herders (RHA 2020). Reindeer husbandry is practiced across northern Russia, by Sámi herders on the Kola Peninsula to the Taimyr reindeer herd of north central Siberia (the largest in the world of at least a half million animals) to the Chukchi herders in north-eastern Siberia. In North America, there are also roughly 10 000 reindeer managed on and around Alaska's Seward Peninsula by approximately 20 herders, who belong to the Kawerak Reindeer Herders Association—a tribal organization that assists in developing a viable reindeer industry for rural Alaska communities (Kawerak Reindeer Herders Association 2020). There are also many thousands of reindeer throughout Alaska's Nunivak Island, St. Lawrence Island, the Pribilof Islands, and parts of the Aleutian

Islands. Reindeer were originally introduced to Alaska in the late 1800s and early 1900s by government officials who worked first with Chukchi and then Sámi herders to introduce reindeer husbandry as a strategy to supplement the food supply of Iñupiaq communities (Andrews 1939).

2.2. ROS impacts on reindeer herding

During spring and summer, reindeer graze on graminoids, herbs and shrubs; in autumn, mushrooms are favored. Once winter sets in, the reindeer diet is largely limited to lichens, typically accessed by digging through the snow. However, in boreal forest regions, arboreal lichen found in old-growth forests becomes important.

The cold season is critical for managed reindeer herds, which consist mainly of pregnant females with high energy demands. Icing for a relatively short period towards the spring melt is part of a typical evolution of the snow cover in Northern Fennoscandia and can be managed by searching for less-affected pastures with softer snow. Herds can also disperse to find more easily available forage, but this necessitates effort and resources to control the animals. If snow is deep or icy, foraging through it in search of lichens consumes considerable energy (Helle 1984). However, especially in the boreal forest zone, if old-growth forests are available, icy snow may actually ease reindeer grazing on arboreal lichen, which often falls in clumps from branches and remains at the surface. Reindeer can also move from tree to tree to reach lichen growing on higher branches.

The situation changes if thick and extensive ice crusts are formed. Impacts depend on many factors, including the timing and intensity of icing events, snowpack characteristics, topography, vegetation, climate, as well as herding culture, traditions, and practices. ROS and other icing events are historically known to cause strong declines in reindeer populations in Fennoscandia (Riseth *et al* 2016, Eira *et al* 2018). Ice barriers, especially in early winter, can force animals to expand their grazing range, depleting body fat and protein reserves as they travel in search of soft snow. Starvation can occur quickly or drag on for many months and even longer (Bartsch *et al* 2010, Forbes *et al* 2016). Spring weight, calf production, calf size, and adult survivability are all lower when reindeer are unable to satisfy their energy needs. Cumulative energy loss can lead to late winter-/early spring abortion of calves and low calf survival rates in late spring and early summer (Tveraa *et al* 2003, Helle and Kojola 2008). On the Seward Peninsula, weather related stressors, including ROS events, can be one of multiple drivers leading caribou to expand their range onto the peninsula, causing competition with other reindeer for food, often resulting in reindeer being pulled away from their herd (Project Jukebox 2001).

Impacts can be mitigated by supplementary feeding, but this is time consuming and costly (Turunen *et al* 2016, Rasmus *et al* 2020). Population crashes have sometimes occurred even with supplementary feeding (for example, arboreal lichen supplied by felling old-growth trees, cf Berg *et al* 2011a, 2011b) or when reindeer were moved to alternative pastures (Helle and Jaakkola 2008). Die-offs have also been triggered by difficult conditions of previous seasons, causing reindeer to be in poor condition before the winter. If ROS events occur too frequently, herders may not have enough time to recover the size, demography, and health of their herds (Stammler and Ivanova 2020), illustrating the cumulative impact of ROS events beyond individual episodes or seasons to across annual cycles.

Another challenge is that in a globalizing North, reindeer husbandry shares the same operational space with other land uses, leading to fragmentation, deterioration, and shrinking of pastures (Landauer *et al* 2021). When other land use and infrastructure hinders the mobility and flexibility in pasture use, supplementary winter feeding occurs either in the pasture areas or in enclosures near the settlements, increasing working hours and expenses (Turunen and Vuojala-Magga 2014, Turunen *et al* 2016) and ultimately reducing the adaptive capacity of herders to climate change.

2.3. Beyond reindeer

ROS impacts on human-environment relationships extend far beyond challenges related to reindeer herding. Mass starvation of reindeer, caribou, and musk oxen can lead to trophic cascades as predators and scavengers (e.g. red foxes and corvids) move north to exploit abundant carrion. These predators in turn have a negative impact on medium-sized game species such as ptarmigan and hare, which are also valuable food resources for local people (Sokolov *et al* 2016). Turning to the marine environment, Furgal *et al* (2002), in documenting details of seal hunting at Arctic Bay, Nunavut, note how unusual weather conditions such as ROS events can affect local ringed seal populations. A local hunter described how a February rain created a thick ice cover over seal breathing holes, leading to fewer seal harvests. Cree hunters in the eastern James Bay region observed that increased autumn and winter precipitation had weakened inland lake ice through changing its composition (e.g. less black ice, more white ice, lack of columnar ice crystals) (Royer *et al* 2013). The variation and instability of the ice conditions created hazards for Cree who use frozen rivers and lakes for hunting, fishing, trapping, and travel. Communities in the region reported an increase in ice travel-related accidents among both novice and experienced hunters (Royer *et al* 2013).

Rain events during freeze-up and early winter can also lead to break-up of river ice, delaying use of

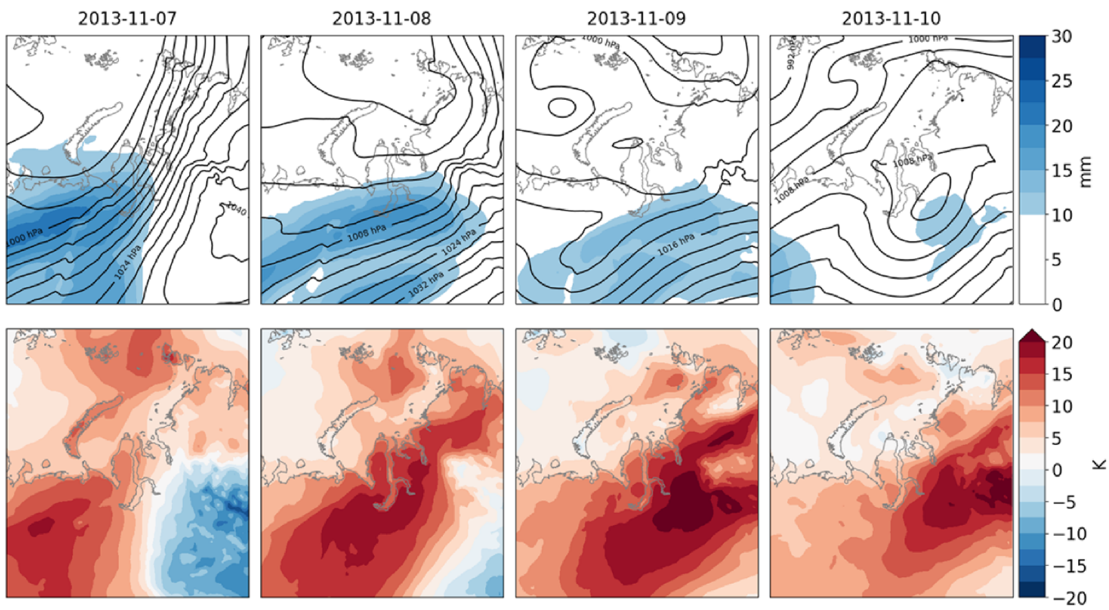

Figure 4. Daily average sea level pressure and precipitable water (top row), and anomalies of daily average 2 m air temperature (bottom row) from ERA5 over the Yamal Peninsula between 7 November and 10 November 2013. Regions with precipitable water less than 10 mm, considered very dry air, are shown in white. Air temperature anomalies are calculated with respect to 1979–2020 daily average fields, with a 30 days boxcar averaging filter applied.

rivers as travel routes via snow machines. While this is caused by a sudden increase in river volume, rather than icing from rain, such events add to the cumulative effects of ROS events on Arctic communities. As one more example, climate extremes in the winter of 2010–2011, including late winter rainfall, decreased sea ice coverage, and high temperatures affected the traditional food system in Iqaluit, Nunavut (Statham *et al* 2015). Caribou moving further inland for forage after vegetation iced over, together with the shortened sea ice hunting season, posed a key threat to food security, exacerbated by existing socioeconomic conditions in this coastal community (Statham *et al* 2015).

3. Notable ROS events

3.1. Yamal Peninsula, Russia, 8–10 November 2013

In early November 2013, an ROS event affected most of the southern Yamal Peninsula (Forbes *et al* 2016), as well as coastal portions of neighboring regions (Sokolov *et al* 2016, Staalesen 2016). Following 24 h of rain, air temperatures rapidly dropped and remained below freezing throughout autumn and winter. While analysis of radar backscatter data (see section 4.4) suggests that this region tends to see approximately one ROS event per year (figure 3, region 1), as noted earlier, the satellite record is short (ends 2010) and reliable detection is limited to midwinter. A higher frequency can be expected considering the shoulder seasons. Indeed, several Yamal events have been recorded by local observers in recent years (see below). The salient meteorological feature linked to the 2013 event was a low-pressure system moving from the northern North Atlantic into the Yamal Peninsula on November 8. Based on data from the ERA5 atmospheric reanalysis (Hersbach *et al* 2020), anomalously high near-surface air temperatures and positive anomalies in precipitable water (column integrated water vapor) were found over inland Eurasia before the event and then over the Yamal Peninsula (figure 4). While local herders reported a severe icing of pastures following the event, starting on November 10, 2 m temperature anomalies shown by ERA5 are positive even after this date, possibly reflecting limitations of the snow parameterization (Arduini *et al* 2019). Ice covered an area of approximately 27 000 km^2 and completely blocked reindeer from foraging, leading to the death of 61 000 animals between November 2013 and June 2014 (Forbes *et al* 2016).

Socioeconomic impacts unfolded over a period of several years. Nenets nomads in Arctic Russia were particularly affected by the event (Stammler and Ivanova 2020), with many herders losing most or all of their animals. This left some families stranded on the tundra without viable transportation (Forbes *et al* 2016). Additionally, the ground icing made large portions of migration routes inaccessible. In response, nomadic Nenets had to adjust their migration routes and the timing of migration. Nenets were forced to adapt by finding new food sources and breeding techniques in an attempt to rebuild their livelihoods.

During the 5 year period following 2013, several additional significant ROS events occurred on the Yamal Peninsula (Laptander 2020), resulting in a situation where tundra Nenets nomads reported not having enough time between events to regenerate the size, demography and health of their herds (Stammler and Ivanova 2020). By the spring of 2019, some herding communities were still subsisting entirely on fish and trying to rebuild their stock of animals.

3.2. Svalbard, Norway, 30–31 January 2012

Figure 3 suggests that the Svalbard Archipelago, located between 78° N and 80° N latitude, experiences up to one event per year over the central and northern parts of the largest island of Spitsbergen and coastal regions of the more northerly Nordaustlandet. A greater number of events are detected on the west and east coasts of Spitsbergen. This reflects the region's proximity to open water and its location along the terminus of the North Atlantic cyclone track, yielding a relatively warm winter climate with respect to latitude (Serreze *et al* 2015). During a two week period in late January and early February 2012, a remarkable event brought above-freezing air temperatures to the entire archipelago and record-breaking precipitation.

Key meteorological aspects are summarized in figure 5. A blocking pattern over northern Fennoscandia fostered the migration of low-pressure systems up into the Arctic and the influx of warm and moist air towards Svalbard (Hansen *et al* 2014). The stream of moist air was part of an atmospheric river (Serreze *et al* 2015). Many previous studies have documented links between atmospheric rivers and extreme precipitation events, such as along the coasts of California and Greenland. Positive anomalies in precipitable water moved into the area on 27 January and persisted throughout the course of the warm spell. On 30 January, record breaking precipitation was recorded at the Ny Ålesund meteorological station, with 98 mm of rain (Serreze *et al* 2015). On this day, there was strong high pressure over northern Fennoscandia and Eurasia and low pressure over Svalbard that originated in the North Atlantic. The low-pressure movement was paired with positive precipitable water anomalies directly over the archipelago, with the largest positive air temperature anomalies located just to the northeast.

Temperatures then dropped, and Spitsbergen became covered in 10–20 cm of ice (Hansen *et al* 2014), covering the low growing tundra vegetation and blocking reindeer from grazing. Despite favorable feeding conditions prior to the ROS event, there was a large starvation induced mortality episode. The number of reindeer carcasses counted in the summer 2012 census was among the highest ever recorded (Hansen *et al* 2014).

In Longyearbyen, a slush avalanche destroyed a pedestrian bridge and forced roads to shut down for several days. Ice formation on the Svalbard airport runway forced the airport to shut down on 29 and 30 January. The impacts that avalanches and ground ice had on transportation, including transportation by snowmobile, dogsled, and pedestrian transport, resulted in massive income losses for the local tourism industry. After the event, local permafrost experienced warming down to at least 5 m. At several monitoring sites, the ground surface temperature stayed at 0 °C for weeks after the warm spell had passed (Hansen *et al* 2014).

3.3. Banks Island, Canada, 3–8 October 2003

Banks Island, in the western Canadian Arctic Archipelago (figure 3, region 3), has a cold and very dry environment, classified as polar desert. ROS events from November through February appear to be uncommon. However, in early October 2003, the climatological flow that usually brings dry air from Siberia briefly shifted, and warmer, moister air from the Pacific invaded the region (Rennert *et al* 2009). The weather system initially brought approximately 6 inches of new snow, but from 3 to 8 October, the precipitation fell as drizzly, intermittent rains. This event was the first to be documented with satellite observations (Grenfell and Putkonen 2008).

In the days before the event, the southwesterly flow was attended by a strong low-pressure system centered in the Bering Strait. As the event began, the low tracked along the Alaskan coast towards Banks Island and was attended by positive anomalies in both air temperature and precipitable water. Slightly positive anomalies of both existed over Banks Island prior to the main ROS event, most notably during 3–4 October (figure 6). On 7 October, high pressure moved over Banks Island, bringing colder and drier air. According to reports from hunters in the area at the time, following intermittent rains and falling temperatures, the former 6 inches of new snow was turned into a thick sheet of ice on the northern two thirds of the island (Rennert *et al* 2009).

The surface icing had severe impacts on Banks Island's ungulate populations, especially musk oxen; approximately 20 000 animals died. In addition to the physical barrier created by ice, water that had percolated through the snowpack and pooled at the ground surface caused vegetation to spoil. This forced musk oxen to expand their grazing range. After the event, in mid- to late-winter, some animals wandered onto the sea ice in search of food and were left stranded at sea (Rennert *et al* 2009).

Significant ungulate mortality events in the western Canadian Arctic date back several decades (Parker *et al* 1975, Gunn *et al* 1989, Miller and Gunn 2003), but as noted, the October 2003 ROS event was the first that could be documented via satellite data. Rennert *et al* (2009) conclude that the severe impacts of the event can be traced to it having occurred early in the cold season so that food sources were blocked for the entire winter. The direct mortality from starvation was most prevalent within the youngest and oldest age groups. Only a few musk oxen were healthy enough to maintain pregnancy, and there were very few calves

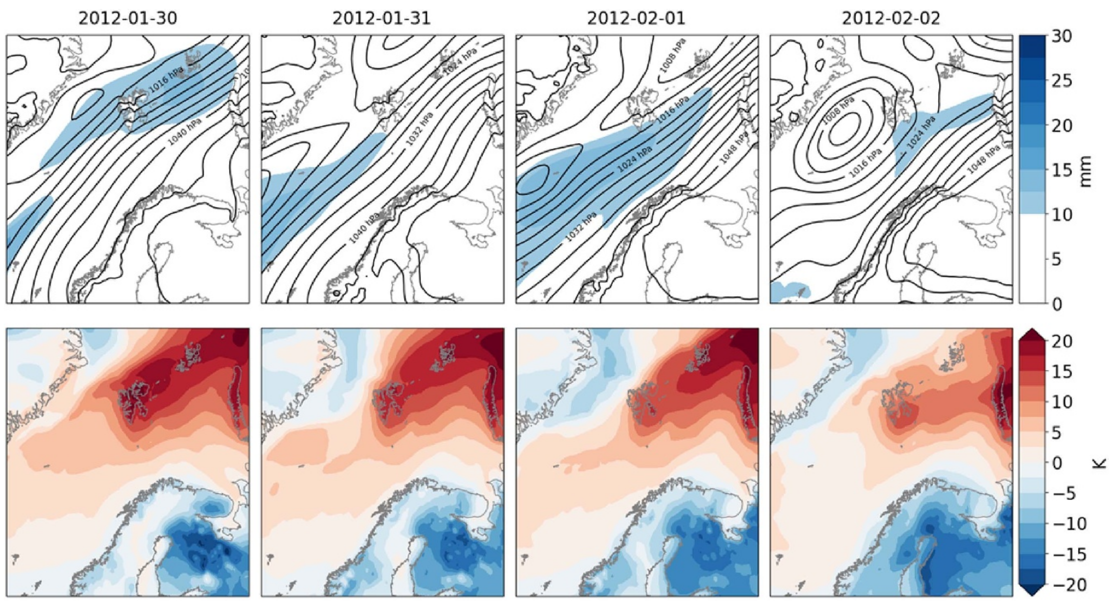

Figure 5. Daily average sea level pressure and precipitable water (top row), and anomalies of daily average 2 m air temperature (bottom row) from ERA5 over the North Atlantic and Svalbard Archipelago between 30 January and 2 February 2012. Regions with precipitable water less than 10 mm, considered very dry air, are shown in white. Air temperature anomalies are calculated with respect to 1979–2020 daily average fields, with a 30 days boxcar averaging filter applied.

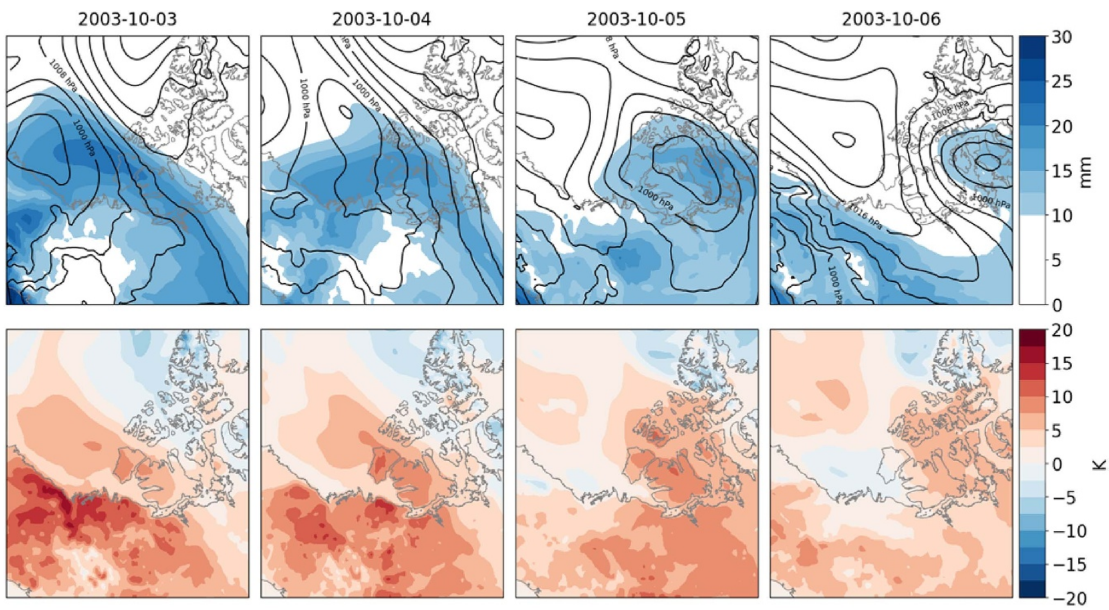

Figure 6. Daily average sea level pressure and precipitable water (top row), and anomalies of daily average 2 m air temperature (bottom row) from ERA5 over the Banks Island between 3 October and 6 October 2003. Regions with precipitable water less than 10 mm, considered very dry air, are shown in white. Air temperature anomalies are calculated with respect to 1979–2020 daily average fields, with a 30 days boxcar averaging filter applied.

born the following summer. Rennert *et al* (2009) also argues that, as has been observed for reindeer, the lack of new calves coupled with the decline of overall herd health can remove multiple generations of calves from a herd, leading to a population crash years after the ROS event. For this particular event, there were few calves born in summer 2004 with another population decline expected 4–5 years later as the adults aged without replacement (Rennert *et al* 2009).

4. ROS detection and characteristics

4.1. Overview

Event detection plays a key role in advancing our understanding of ROS events, their characteristics, changes in their frequency and severity, and their varied impacts. As we make clear below, event detection is imperfect, evolving and requires combining different approaches, each with their merits and shortcomings. Moving forward will require combining information from meteorological station records, local and Indigenous knowledge holders, satellite remote sensing and atmospheric reanalyses. Surface observations provide ground truth for developing detection algorithms and combining multiple information sources. It is only from local observers that one can obtain critical information bearing on impacts such as how ice layers form, how thick they become and whether they form at the snow surface, within, or at the base of the snowpack. In turn, data from satellite retrievals and atmospheric reanalyses addresses the spatial scale of events, which can range from local to widespread. Given the importance of ROS detection and characteristics, we give this topic special emphasis in this paper.

4.2. Meteorological records

An ongoing challenge with station meteorological records is that records span many individual sources. A series of Environment and Climate Change Canada sites are accessible across the Canadian Arctic (Mekis *et al* 2018). A number of archives are available through the National Oceanic Atmospheric Administration (NOAA) National Weather Service (NWS). Some records from NOAA/NWS consist of automated surface observation stations and Cooperative Observer Network records, mainly for sites located in Alaska. An additional data source for Alaska and some parts of Canada is snow telemetry sites maintained by the Natural Resources Conservation Surface (e.g. used for ROS detection in Semmens *et al* 2013, Wilson *et al* 2013, Pan *et al* 2018). Other sources include the Norwegian Meteorological Institute, the Finland Meteorological Institute and the Swedish Meteorological and Hydrological Institute. Some information over the Arctic Ocean is available from the Russian North Pole series of drifting stations (ongoing) and field campaigns. The World Meteorological Organization's Observing Systems Capability Analysis and Review Tool provides information on data sources across the globe. While station records of air temperature, precipitation and snow height serve only as indicators of ROS, SYNOP (present weather codes) made by observers at the station (codes 20–29 corresponding to precipitation and type) can be highly valuable.

Spatially, as well as temporally, extensive snow profile observations exist only in rare cases. A so-far unique dataset, a collection of more than 500 snow profiles during the period 2010–2017 in Central Spitsbergen, was used to analyze long term patterns directly (Peeters *et al* 2019).

4.3. Local observers

Observations of ROS events from reindeer herders, harvesters and others can greatly augment station records, but more importantly, can provide detailed information on event characteristics, key to understanding impacts. Reindeer herders move over wide areas during the year, communicate across herding families on topics related to weather and herd health, and pay close attention to conditions limiting reindeer foraging in winter pastures. Such observations, however, have seldom been systematically collected, one exception being Rasmus *et al* (2018), who compiled data on annual icing events from 1948 to 2016 for the reindeer management area of Finland, based on archival sources (annual management reports of herding districts). Rasmus *et al* (2018) focused on the formation of basal ice layers on the pastures. They found that rain and subsequent freezing of the liquid precipitation in the basal layer of the snow cover (or in the whole of a thin snow cover) was reported in 27% of cases. Icing was also found to be regularly attended by mold formation on pastures during early winter, which can have severe negative effects on the condition of reindeer (Kumpula *et al* 2000).

Another exception is a collection of 17 interviews with reindeer herders from Alaska's Seward Peninsula, a collaborative effort between the Reindeer Herders Association in Nome, Alaska and the University of Alaska Fairbanks Oral History Department. These interviews, accessible online, discuss herding practices, the generational passing-down of herder knowledge, and how climate and environmental change impact herder livelihoods and the reindeer themselves. As gleaned from these interviews, herders nowadays observe more thawing events interlaced between snowfalls during freeze-up, resulting in a snow pack that is icy and consolidated from top to bottom once the winter cold season sets in, making it more difficult for reindeer to access feed (Project Jukebox 2001).

A potentially rich information source is organized observer networks. Generally, observer networks focus on qualitative information such as photos and videos that may be posted on specific observer web-platforms or social media, and first-hand narratives from 'on the ground' experience. Some networks are broad in their focus, and the observers that participate are necessarily generalists. However, other observer networks may be highly knowledgeable in specific aspects of their local places and community activities. Observers with the Alaska Arctic Observatory and Knowledge Hub (AAOKH) specialize in observing seasonality, focusing on the snow, ice, weather, coastal processes, and related community travel and hunting activities. The AAOKH observers' database (https://eloka-arctic.org/sizonet/), maintained by the Exchange for Local Observations and Knowledge of the Arctic, contains some detailed observations of winter rain events, often in the context of local travel or hunting

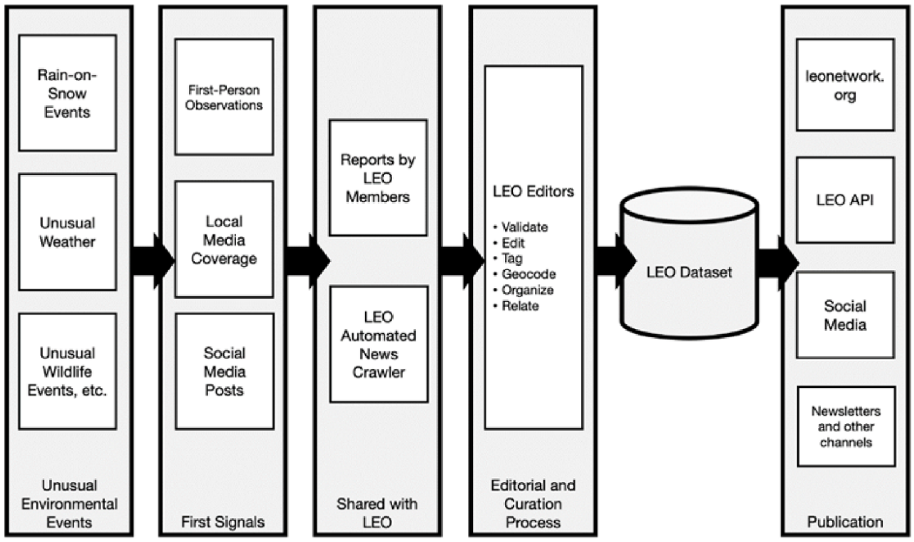

Figure 7. Schematic information sources and information flow in the LEO network.

activities. For example, an observation from Point Hope in November 2019 described how a rain event led to the break-up of a foot of ice on the Kukpuk River, leaving a wall of ice along the riverbank (Adams 2013a). An observer from Toksook Bay noted in late December 2009 that glare ice, resulting from a freezing rain event, prevented planes from reaching the village (Adams 2013b). An event that resulted in a change of migration patterns in 2006–07 on Yamal was documented by an anthropologist traveling with reindeer herders (Bartsch *et al* 2010). A more extensive event during winter 2013–14 on Yamal similarly triggered substantial reorganization of migration patterns, which were mapped using a participatory approach with reindeer herders, administrators and scientists (Forbes *et al* 2016).

Also notable is the Local Environmental Observer (LEO) Network, with observers concentrated in North America and growing membership around the circumpolar North. The LEO Network provides an online platform for sharing information about significant environmental events. Local knowledge experts share observations and engage with topic experts as co-authors on LEO Network posts. Members can also post news articles as another local source for these events. The LEO Network has roots in the Indigenous communities of Alaska, but has grown greatly. As of June 2020, the LEO Network has over 3500 members from over 50 countries (including all Arctic nations). The LEO editorial process involves validating observations, geocoding, time stamping, sharing them with subject matter experts, organizing them by topic and geography, and publishing them to the online platform (figure 7). Two of the most common event categories are *Weather,* and *Ice and Snow*. Much less common, but still numerous, are events further categorized as *Rain on Snow*, with 47 events in the LEO database as of November 2020. While many of these ROS entries discuss impacts on animals, other impacts are also noted, such as diminished recreational opportunities, public safety issues from icing and infrastructure issues involving power and telephone lines, and flooding.

4.4. Satellite retrievals

ROS detection from satellite microwave retrievals (both passive and active) shows considerable promise for providing a pan-Arctic view (e.g. Bartsch *et al* 2010, Dolant *et al* 2016, 2017, Langlois *et al* 2017) (table 1). This is because microwave emission or backscatter from the surface is strongly affected by liquid water and snow cover structure, as well as the strength of impact depending on microwave frequency and polarization.

In passive microwave radiometry, the energy detected by the satellite is the measured emission intensity, converted to a brightness temperature that is a function of the physical temperature of the target and the emissivity. The emissivity of the snow cover is determined by its dielectric properties and its surface roughness. When there is liquid water in the snow, emissivity sharply increases because of the much higher dielectric constant of water, leading to a sudden increase in passive microwave brightness temperature. In this case, absorption processes dominate over scattering, and consequently only the topmost snow layers contribute to the measured brightness temperature. The response is larger at higher frequencies because of the change in emission depth associated with melt. The response is

Table 1. Overview of remote sensing and reanalyses studies of ROS events.

Source/Method	Sensor(s) or parameter	Study	Analyses period	Season	Region
Passive microwave: Gradient ratio/polarization ratio Method: wet snow detection	SSMI	Grenfell and Putkonen (2008)	2003/4	Single event	Banks island, Canada
	AMSR-E/2	Semmens *et al* (2013)	2003–2009	All	Yukon basin
	AMSR-E/2	Dolant *et al* (2016)	2010/11	All	Nunavik
	SSMI + AMSR-E/2	Langlois *et al* (2017)	1979–2011	October–May	Canadian Arctic Archipelago
	AMSR-E/2 + Modis	Pan *et al* (2018)	2003–2016	November–March	Alaska
Active microwave: Single band backscatter Method: snow structure change detection	Quikscat	Bartsch *et al* (2010)	2000–2009	November–February	Russia
		Bartsch (2010a)	2000–2009	November–February	Circumpolar
		Wilson *et al* (2013)	2000–2009	April–May	Alaska
		Semmens *et al* (2013)	2003–2009	All	Yukon basin
	ASCAT	Forbes *et al* (2016)	2013	Single event	South Yamal
Reanalyses—MERRA	Rain and temperature	Liston and Hiemstra *et al* (2011)	1979–2009	All	Circumpolar
Reanalyses—ERA-40	Rain	Rennert *et al* (2009)	1957–2002	—	Circumpolar
Reanalyses—seNorge	Rain and snow water equivalent	Pall *et al* (2019)	1957–2016	At least 3 mm of snow water equivalent	Norway

also polarization dependent (Anderson 1997). The response of emissivity to liquid water is the basis for snowmelt onset detection from microwave brightness temperatures on land (Frei *et al* 2012, Alimasi *et al* 2018) as well as on sea ice (e.g. Markus *et al* 2009, Wang *et al* 2013) and ice sheets (Abdalati and Steffen 1995).

As for active microwave, microwave energy transmitted by a radar is reflected and scattered by the snowpack. The unit of measure is called the backscatter, and depends on the surface area illuminated, and the distance from the receiver to the target. During the transition from dry to wet snow, absorption is the main mechanism, driven by increased dielectric loss from the snowpack, causing the radar backscatter to decrease (Ulaby *et al* 1982). Volume scattering occurs under dry snow conditions in the case of short wavelengths.

The strategy of wet snow detection is applicable when measurement intervals are shorter than the ROS events themselves. Given that event duration can be limited to a few hours (Bartsch *et al* 2010) It is thus very likely that events are missed. Satellite observations from polar orbits (as is the case for relevant active and passive microwave missions) are usually limited to certain time windows, in the morning and afternoon. An alternative is to focus on ROS impacts on snow structure. The resulting ice layers change the interaction of the microwave radiation with the snowpack. In case of (for example) active microwave techniques, the backscatter response increases when the snow grain size increases and specifically when crusts are present. Such changes can occur as part of seasonal snow metamorphosis (grain size increases with snow age). These are, however, gradual changes, compared to ROS impacts. The determination of sudden changes can, therefore, reveal potential ROS events. This has been so far mostly applied to Ku-band radar for monitoring larger areas as in figure 3 (Bartsch *et al* 2010, Bartsch 2010a, 2010b, Wilson *et al* 2013, Semmens *et al* 2013) although passive microwave data are suitable as well to identify changes (Grenfell and Putkonen 2008, Langlois *et al* 2017). C-band radar is also promising (Forbes *et al* 2016) and offers potentially high resolution (down to 10 m). This is based on the synthetic aperture radar technique. Such detail cannot be achieved with passive microwave to date. What also needs to be considered for this technique is that multiple events lead to stepwise increase of backscatter and the magnitude of change decreases throughout the season. In extreme cases, a maximum level (similar to backscatter levels of ice sheets) is reached, and detection of further events is impeded. The presence of vegetation also leads to volume scattering and increases the backscatter minimum at the beginning of the snow-covered season, reducing sensitivity to snow structure change (Bartsch *et al* 2020).

A challenge with longer wavelengths such as C-band is the sensitivity to the soil beneath the snowpack. Changes in midwinter, which are related to the evolution of frozen state dielectric properties (driven by ground temperature), can also lead to high backscatter response similar to snow crusts, and saturate the signal (Bergstedt *et al* 2018). Recent fire events can also alter soil wetness and temperature, which impacts the snowpack structure for several decades (Bartsch *et al* 2020).

In general, retrieval algorithms use threshold values that require tuning with respect to observations and are unlikely to hold everywhere as weather effects and snowpack properties influence the retrievals. Furthermore, the detection of liquid water does not necessarily mean that a ROS event occurred. It can also not be directly inferred if snow is present on the ground. A combination with snow cover datasets based on multi-spectral observations is, therefore, useful (Pan *et al* 2018). A further strategy is limiting analysis to mid-winter when warm spells are less likely. The definition of this period does, however, strongly differ between different studies (table 1), which complicates comparing results. An alternative is the combination with reanalysis data, such as applied by Semmens *et al* (2013) and described in section 4.5. To date, the only study for the entire Arctic land area which is based on satellite records is Bartsch (2010a), derived from Ku-band QuikScat records from 2000 to 2009 (figure 3). The algorithm has been initially based on local observations by reindeer herders (Bartsch *et al* 2010).

The use of satellite data allows for the determination of spatial patterns. The extent of events is crucial, such as with respect to the migration possibilities of ungulates. Wilson *et al* (2013) analyzed event sizes for the first time and found differences with respect to distance from coast for Alaska. Events in proximity to the coast tend to be comparably small and frequent compared to further inland where they are larger and less frequent. Such types of investigations, characterizing events apart from their mere detection, are, however, still lacking across the Arctic.

4.5. Atmospheric reanalyses

Atmospheric reanalyses, the most recent example being the European Center for Medium Range Forecasts ERA5 effort, represent retrospective forms of numerical weather prediction (NWP) models. A great advantage of reanalyses (and operational NWP systems) is the provision of forecasts of precipitation amount and phase along with information on the vertical temperature and humidity structure. In an operational setting, forecasts of precipitation type and amount are made in a post-processing step using information from NWP systems about the vertical structure of temperature and humidity, as well as other variables (Elmore *et al* 2015). All of the modern generation of atmospheric reanalyses provide data from 1979 or 1980 onwards (1979 represents the start of the modern satellite era). ERA5 provides data from 1950, and the Japan Meteorological Agency JRA55 provides data from 1958. A national specific dataset used in this context is seNorge, a high-resolution gridded hydrometeorological dataset covering mainland Norway (Pall *et al* 2019).

The quality of NWP precipitation forecasts (for both operational systems and reanalysis) depends on both the physics in the model and the amount and quality of observations that can be assimilated to produce the analysis from which forecasts are generated. It is commonly thought that NWP forecasts in the Arctic are limited by sparse observational data. This is true, only to an extent—while the radiosonde network is suboptimal, polar orbiting satellites provide a wealth of data. Uncertainties and biases in reanalysis outputs in the Arctic region have been widely addressed. All reanalyses have biases in Arctic precipitation relative to observations (e.g. Wang *et al* 2019, Barrett *et al* 2020).

Output from the North American Regional Reanalysis has been employed in a number of ROS studies, serving as a basis for evaluation of satellite-based retrievals (Semmens *et al* 2013, Wilson *et al* 2013). Precipitable water (total column water vapor) from reanalysis data also serves as input for correction of passive microwave observations (Langlois *et al* 2017). Reanalysis records are also useful for assessing the reasons behind snow structure changes detected within satellite records. Near-surface air temperature and dew point temperature, visibility, and relative humidity were used to determine the occurrence of fog by Semmens *et al* (2013). The relatively moist and warm conditions forming fog are considered to affect snow and melting. In some years, more than 60% of snow structure change events over the Yukon basin could be attributed to fog and only a maximum of 35% to ROS events.

5. Paths forward

A key challenge in gaining a greater understanding of ROS events is providing a pan-Arctic view of their frequency, seasonality, and intensity. This will require combining information from multiple data

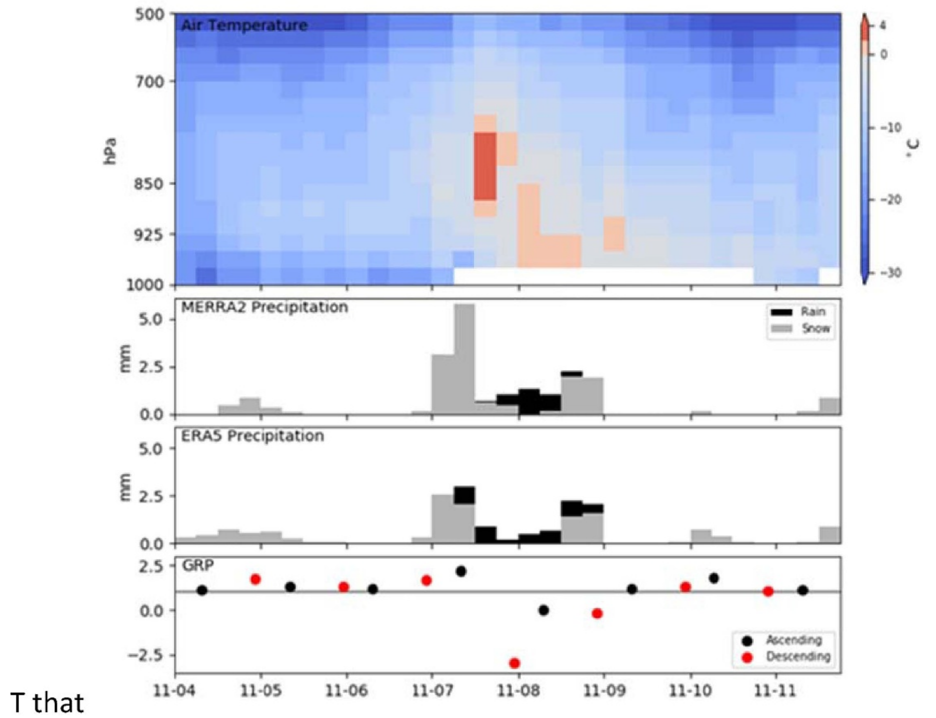

Figure 8. Tropospheric air temperature and precipitation amount and phase for the closest MERRA2 (Gelaro *et al* 2017) grid point to 67.75° N and 68° E on the Yamal Peninsula for 4–11 November 2013 corresponding to the events studied by Forbes *et al* (2016). Also shown is precipitation from the ERA5 and MERRA2 reanalyses at the same location, and the ratio of vertical and horizontal polarization gradient ratios between the 18 GHz and 36 GHz bands from AMSR2, with values <1 indicated liquid water at the surface.

sources that provide regular coverage across the Arctic, notably remote sensing and atmospheric reanalyses. Figure 8 provides an example of using these two data sources in tandem. As part of the developing AROSS effort, passive microwave reanalyses satellite retrievals, output from atmospheric and surface observations are being used together to develop a machine learning algorithm to detect and map ROS events across the Arctic from 1979 present; the surface observations from meteorological stations across the Arctic, are used as the training data (figure 9). Active microwave (radar) observations provide the possibility to significantly improve spatial detail and gradients through combination of with synthetic aperture radar, an approach followed in CHARTER. The step from mere event detection to actual characterization of ROS needs to be made.

However, as is clear from previous discussion, partnering with local observers can convey key information regarding ROS impacts, providing a focus for developing better technologies. For example, while ROS impacts are known to be tied to the formation of ice layers, ice layer formation processes are poorly understood and difficult to model, and ground observations are sparse (Kohler and Aanes 2004, Liston and Hiemstra 2011, Vikhamar-Schuler *et al* 2013, Rasmus *et al* 2014, 2016, Pirazzini *et al* 2018). Having detailed surface observations offers a path for developing better process models and for understanding how the development of ice layers ties into the larger-scale meteorological aspects of ROS events. In addition, there remains much to be gained in furthering our understanding for how ROS events intersect with the livelihoods of Arctic communities. Surface observations made locally by community members may assist in better describing ice layer formation and morphology, yet where, when, and how such observations are made also relate to the context of community activities and movement across the land or ocean where the impacts of ROS are felt. For example, future research is needed to answer key questions, such as how may more frequent ROS events affect food security, infrastructure, and hazards, and what options may exist to mitigate such effects? Existing programs like LEO and AAOKH are laying groundwork in this direction.

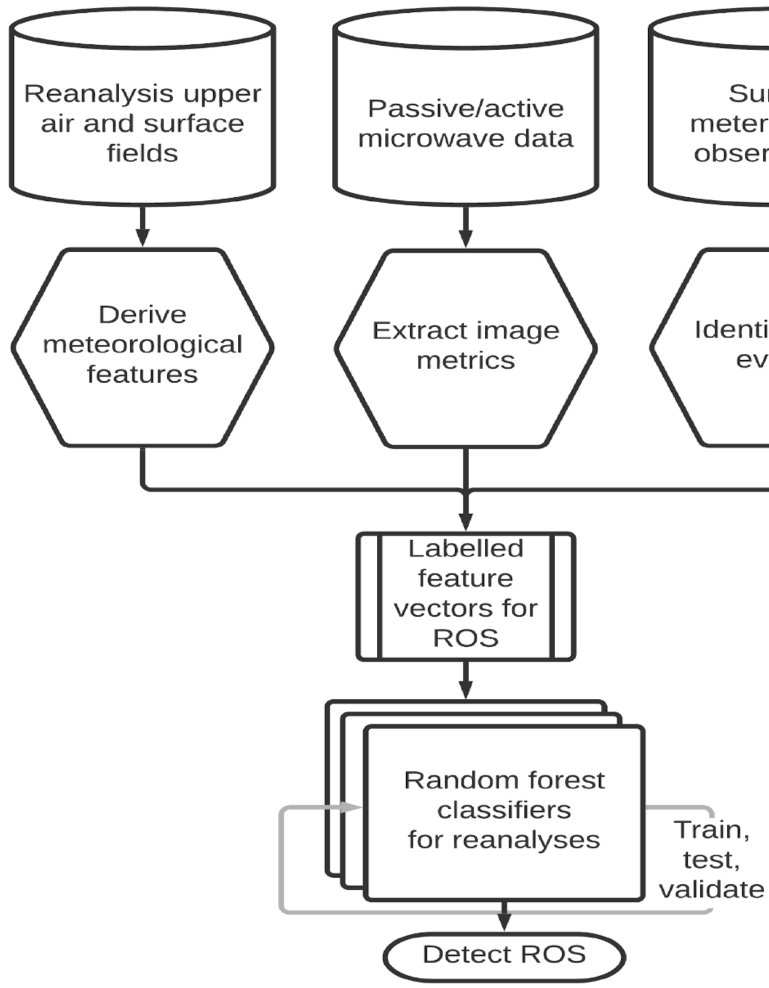

Figure 9. Flow diagram showing potential inputs, and procedure for creating training data and developing the ROS detection algorithm.

6. Conclusions

Despite advances in our understanding of ROS events and their impacts, many gaps in knowledge still exist. These include uncertainties in detecting liquid water on the snowpack from satellite data, detection of ROS events and precipitation amount from atmospheric reanalyses, and the general sparseness of direct surface observations. Another is a lack of understanding of ice layer formation processes.

As the Arctic warms, ROS and winter thaw events are likely to become more frequent and there is growing evidence that changes are already happening (Hansen *et al* 2011, Liston and Hiemstra 2011, Ruosteenoja *et al* 2016, Vikhamer-Schuler *et al* 2016, Luomaranta *et al* 2019). Climate models project a shift toward more Arctic rain events (Bintanja and Andry 2017), with total Arctic precipitation expected to increase by 30%–60% (Bintanja and Selten 2014, Bintanja and Andry 2017). Uncertainties abound, however—projected changes in precipitation amount and type range widely between different models using the same emissions scenario, and future emission rates are unknown. In turn, it is possible that a decrease in the duration of the snow cover season could at least in part counterbalance the effects on more rainfall and the frequency of ROS events (Mudryk *et al* 2020).

It is clear that to understand Arctic ROS events and their impacts, there needs to be a co-production of knowledge approach (Tondu *et al* 2014, Behe *et al* 2020, Carlo 2020), one that bridges scientific disciplines, Indigenous knowledge, local observations and especially ensures equitable Indigenous and local collaboration in the research from the outset. This requires multi-disciplinary and multi-cultural research teams, including atmospheric scientists, harvesters, herders, social scientists, modelers, Indigenous scholars, and others. Advancing new understandings of ROS events and their impacts will support a more adaptive Arctic.

Data availability statement

The data that support the findings of this study are openly available. Data from the ERA reanalysis, the MERRA-2 reanalysis and satellite data from AMSR2 can be found, respectfully, at https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-levels?tab=overview, https://disc.gsfc.nasa.gov/datasets?project=MERRA-2 and https://nsidc.org/data/AU-SI12/versions/1.

The data that support the findings of this study are openly available at the following URL/DOI: https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-levels?tab=overview.

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