Rain on Snow: Little Understood Killer in the North

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In October 2003, a severe rain-on-snow (ROS) event killed approximately 20,000 musk-oxen (Figure 1) on Banks Island, which is the westernmost of the Canadian Arctic islands (approximately 380 kilometers by 290 kilometers in size). The event reduced the isolated herd by 25% and significantly affected the people dependent on the herd's well-being. Because of the sparsity of weather stations in the Arctic and the lack of routinely deployed weather equipment that was capable of accurately sensing the ROS event, its detection largely was based on reports from hunters who were in the affected areas at the time.

Such events can significantly alter a frozen ecosystem—with changes that often persist for the remainder of a winter—by creating ice layers at the surface of, within, or below the snowpack. The water and ice layers are known to facilitate the growth of toxic fungi, significantly warm the soil surface under thick snowpack, and deter large grazing mammals. Although ROS events of the magnitude that was experienced in Banks Island in 2003 likely have reverberations throughout the entire Arctic and subarctic ecosystem, little is presently known about them and their impacts. As understanding of ROS events expands, many ROS-related aspects of the Arctic ecology and hydrology are likely to be discovered. They may include topics such as the fate of small mammals under the snowpack at the iced soil surface, the difficulty of ptarmigans to burrow into the iced snow, the limited infiltration of spring snowmelt into the iced over soil, and the changing drifting patterns of ice-crusted snowpack.

The lack of accurate detection tools combined with model predictions of more frequent ROS events in the future promises uncertain times for the northern native populations whose commercial meat export, subsistence hunting, and cultural identity are closely tied to the fate of northern ungulates (e.g., caribou, reindeer, musk-ox).

ROS is a natural hazard that is well-known to the inhabitants of the northern snow-covered land areas. Despite its significance, however, ROS events north of approximately 60° latitude have received little attention in scientific and policy-making circles. The primary reason for this oversight may be that ROS is inherently challenging to study. ROS events occur with relative rarity at any particular location, and the freezing water and melting snow pose mechanical challenges to the proper

Fig. 1. Musk-oxen in the Arctic tundra on Prince Patrick Island, Northwest Territories, Canada. Prince Patrick Island is located north of Banks Island on the western edge of the Canadian Arctic Archipelago. Photograph by Tom Grenfell.

functioning of conventional rain and snow detection equipment. In lower latitudes, such as the conterminous United States, ROS events are known to induce winter flooding, trigger snow avalanches, and adversely affect infrastructure. This article focuses on the much less understood ROS events north of approximately 60º latitude.

ROS and Ungulates

The impact of ROS events on northern ungulates depends on the magnitude of the rain event and the subsequent surface air temperatures. For the sake of clarity, in this article, ROS events are informally distinguished and named as either minor or major ROS events. No simple universal divide exists between these two categories, though a total of approximately 10 millimeters of water per event could be considered as an informal divide. A minor ROS event may only wet the snow surface and create a thin, icy layer on the surface of the snowpack, which is relatively easy for ungulates to penetrate. In the case of a major ROS event, the rain wets the snow surface and also percolates well into the snowpack, making the snowpack denser and thus harder for animals to penetrate.

If the event is large enough, rainwater can pool at the soil surface and subsequently freeze. The resultant ice layer covers the soil surface, restricting access of grazing animals to lichens and of musk-ox to grasses, the foods on which they feed in winter. The resulting ice layer forces the grazers to spend more energy on feeding, therefore forcing them into a negative energy balance. In extreme cases, the ice layers can make feeding impossible and lead to starvation and death or, as is more common, result in the animals' widespread movement away from affected areas, thus limiting the availability of animals to hunters. Even during a minor ROS event, the additional stress can reduce the productivity (number and survival of offspring) of animals, leading to long-lasting, herd-wide effects [*Russell et al.*, 2005].

Satellite Detection of ROS Events

The most pressing questions related to ROS events are when and where they occur. A major ROS event covering an area of 50 kilometers by 50 kilometers easily can be missed by the sparse weather observation network in the Arctic. Even when manual weather observations are made, the resulting weather records only contain information on the total amount of precipitation and on a single dominant type for the precipitation, though in the case of ROS, there is often mixed rain and snow. The archived observational precipitation record does not specify the actual amounts of either fraction of rain and snow. For these reasons, it is likely that severe ROS episodes currently are underreported.

Satellite observations offer the potential for spatially and temporally continuous observation of ROS events, but until recently, no satellite products were available to meet the task. A recent study by *Grenfell and Putkonen* [2008] reprocessed the archived multifrequency passive microwave data from the U.S. Defense Meteorological Satellite Program's Special Sensor Microwave/Imager (SSM/I) to detect the major ROS event of 2003 on Banks Island. The study identified the physical modifications of the snowpack due to the rainfall and determined the subsequent stages of freezeup of the water in and at the base of the snowpack.

Although the detection of a ROS event was successful in this particular case, considerable additional investigation is needed to produce a robust working ROS algorithm to assess the true frequency and spatial distribution of severe ROS events in northern snow-covered land areas. The existing and planned microwave satellite sensors, such as SSM/I and Advanced Microwave Scanning Radiometer (AMSR/AMSR-E), offer the potential to refine ROS detection and provide analysis of ROS events in near real time, with a delay of only a few days. This capability would provide ample time, for example, to distribute emergency animal feed or to move managed ungulate herds to areas that are unaffected by a particular ROS event.

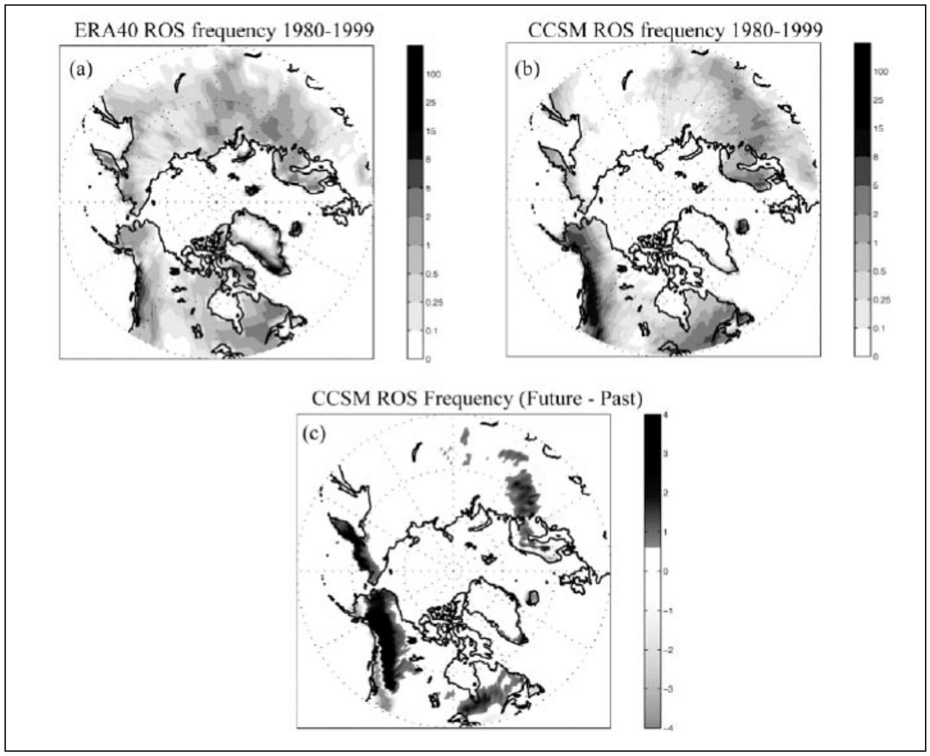

*Fig. 2. Number of ROS events per winter (a) in the European Centre for Medium-Range Weather Forecasts' (ECMWF) Forty-Year European Re-Analysis (ERA40) of the Global Atmosphere for the period 1980–1999 and (b) for the same period using version three of the Community Climate System Model (CCSM3) general circulation model. ROS events are defined as a minimum of 3 millimeters of rain falling on a minimum of 5 millimeters of snow water equivalent. (c) The difference between current and projected ROS frequencies per winter for the same thresholds for the period 2040–2059 in the CCSM3 under the IPCC Special Report on Emissions Scenarios' A1B climate scenario [*IPCC, *2000] and for the 1980–1999 period under ERA40. If a given area is forecasted to receive exactly the same amount of ROS in the future as it receives today, the map shows white in that area; an area forecasted to receive more ROS in the future than today is shown in darker shades of gray, dependent on the magnitude of the increase; and areas forecasted to receive less ROS in the future than today are shown in lighter shades of gray. The future scenario indicates increased frequency of ROS events in much of northwestern North America, which is the habitat for several types of caribou. Decreases in ROS events shown are broadly due to projected decreases in snowpack in the model, not to a decrease in rain events. Reprinted with permission from* Rennert et al. *[2009].*

ROS and Permafrost

If large enough quantities of rain percolate to the base of a snowpack, the soil will be substantially warmed by the latent heat that is released slowly as the water freezes over a period of days, weeks, or months. The ice-water bath at the soil surface effectively maintains the soil temperature at 0ºC when it otherwise would be many degrees colder. It is conceivable that an increase in the frequency of ROS events could surpass the effects of simple air temperature warming on soil temperatures, potentially accelerating the effects of global warming on the subsurface temperatures [*Putkonen and Roe*, 2003].

In much of the Arctic, for which there are minimal historical air temperature records, deep soil temperatures are often used as proxies. ROS-related soil warming would make it more difficult to correlate deep soil temperatures to air temperature.

In currently ongoing Arctic-wide research, there are hints at counterintuitive connections between ROS, snow depth, and resulting changes in soil temperatures.

Future Changes in the Frequency and Magnitude of ROS Events

Much of the Arctic has seen rapid recent environmental changes related to global climate change. Even though our understanding of the frequency, magnitude, and spatial distribution of ROS events is still quite limited, it is possible to estimate how the characteristic climatic conditions that lead to currently detected ROS events will change in the future. Results from a fully coupled global climate model under the Intergovernmental Panel on Climate Change (IPCC) A1B climate scenario [*IPCC*, 2000] suggest a significant increase in the area and frequency of ROS events in the next 40 years [*Rennert et al.*, 2009] (Figure 2).

ROS Research Challenges

The current maps and statistical analyses of ROS events are based on limited detection by a surface weather network that is especially sparse in the north. The existing data lack direct evidence of some of the largest known ROS events [e.g., *Putkonen*, 1998; *Rennert et al.*, 2009], which suggests that many more events may have escaped detection. Currently, the greatest need is to create a database for the frequency and distribution of past and present ROS events. This could be produced by reprocessing the archived satellite microwave data with the aid of the recently developed detection method by *Grenfell and Putkonen* [2008] for ROS events.

One of the most immediate challenges is to develop automated equipment that can reliably detect ROS events in the field without becoming incapacitated or confounded by melting snow or freezing water. Such measurement capability would provide much needed surface observations against which the satellite record could be compared.

Major ROS events strongly affect the lives and fates of wildlife, ecosystem, and people in northern snow-covered regions. Without a clear understanding of the processes that lead to ROS events, and without knowledge of past spatial distributions and frequencies of ROS events, it is impossible to chart the impending changes in ROS characteristics and gauge the implications for the Arctic environment in general. The use of the techniques described in this article, in conjunction with modern global climate modeling, offers the potential to anticipate and alleviate the impact of ROS events on northern ungulates and ecosystems and the people who live there.

References

Intergovernmental Panel on Climate Change (IPCC) (2000), *Special Report on Emission Scenarios: A Special Report of Working Group III of the Intergovernmental Panel on Climate Change, Working Group III*, Cambridge Univ. Press, Cambridge, U. K.

Grenfell, T. C., and J. Putkonen (2008), A method for the detection of the severe rain-on-snow event on Banks Island, October 2003, using passive microwave remote sensing, *Water Resour. Res.*, *44*, *W03425*, doi:10.1029/2007WR005929.

Putkonen, J. K. (1998), Soil thermal properties and heat transfer processes near Ny Alesund, northwestern Spitsbergen, Svalbard, *Polar Res.*, *17*, 165-179.

Putkonen, J. K., and G. Roe (2003), Rain on snow events impact soil temperatures and affect ungulate survival, *Geophys. Res. Lett.*, *30*(4), 1188, doi:10.1029/2002GL016326.

Rennert, K., G. Roe, J. Putkonen, and C. Bitz (2009), Soil thermal and ecological impacts of rain on snow events in the circumpolar Arctic, *J. Clim.*, *22*(9), 2302–2315, doi:10.1175/2008JCLI2117.1.

Russell, D. E., R. G. White, and C. J. Daniel (2005), Energetics of the Porcupine caribou herd: A computer simulation model, *Tech. Rep. Ser. 431*, 64 pp., Can. Wildlife Serv., Ottawa, Ont., Canada.

Author Information

Jaakko Putkonen, Department of Geology and Geological Engineering, University of North Dakota, Grand Forks; E-mail: Jaakko.putkonen@und.edu; Thomas C. Grenfell, Kevin Rennert, and Cecilia Bitz, Department of Atmospheric Sciences, University of Washington, Seattle; Paul Jacobson, Department of Earth and Space Sciences, University of Washington, Seattle; and Don Russell, Canadian Wildlife Service, Whitehorse, Yukon Territory, Canada