Rain-on-snow events impact soil temperatures and affect ungulate survival

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[1] Field data from Spitsbergen and numerical modeling reveal that rain-on-snow (ROS) events can substantially increase sub-snowpack soil temperatures. However, ROS events have not previously been accounted for in high latitude soil thermal analyses. Furthermore such events can result in widespread die-offs of ungulates due to soil surface icing. The occurrence of Spitsbergen ROS events is controlled by the North Atlantic Oscillation. Globally, atmospheric reanalysis data show that significant ROS events occur predominantly over northern maritime climates, covering 8.4×10^6 km^2. Under a standard climate change scenario, a global climate model predicts a 40% increase in the ROS area by 2080–2089. *INDEX TERMS:* 1823 Hydrology: Frozen ground; 1863 Hydrology: Snow and ice (1827); 3322 Meteorology and Atmospheric Dynamics: Land/atmosphere interactions; 3349 Meteorology and Atmospheric Dynamics: Polar meteorology; 3354 Meteorology and Atmospheric Dynamics: Precipitation (1854). **Citation:** Putkonen, J., and G. Roe, Rain-on-snow events impact soil temperatures and affect ungulate survival, *Geophys. Res. Lett.*, *30*(4), 1188, doi:10.1029/2002GL016326, 2003.

[2] A compelling and growing body of observational evidence, supported by results from climate models and theoretical considerations, shows that the high latitudes are the most sensitive regions of the Earth's climate system [*IPCC*, 2001; *Serreze et al.*, 2000]. Snow covered land surfaces there are largely underlain by thermally-vulnerable permafrost or seasonal frost [*Washburn*, 1980]. Since these areas are also home to delicately balanced ecosystems, an urgent concern is to better understand the impact of climate variability and climate change on boreal and arctic environments. Using field observations from a well-established research site in Spitsbergen (latitude 78°57′N, longitude 12°27′E) [*Dalsbo*, 2002; *Hallet and Prestrud*, 1986; *Hanssen-Bauer et al.*, 1992; *Putkonen*, 1998] and nearby meteorological data, we demonstrate that wintertime rain-on-snow (ROS) events, although infrequent, are capable of exerting a considerable influence on mean wintertime soil temperatures. ROS events are therefore a powerful mechanism through which anthropogenic climate change may impact seasonal soil temperatures and, consequently, the long-term survival of regional permafrost. The land surface components of global climate models do not generally represent the consequences of ROS events (the Genesis climate model is the only climate model we know of that accounts for ROS warming (Gordon Bonan, personal communication, Feb., 2002)) and, to our knowledge, have been left out of all studies which have examined the impact of climate on permafrost [*Anisimov et al.*, 1997; *Budyko and Izrael*, 1993; *Judge and Pilon*, 1983; *Kane et al.*, 1991; *Lachenbruch and Marshall*, 1986; *Lunardini*, 1996; *Nelson et al.*, 1993; *Osterkamp and Gosink*, 1991; *Pavlov*, 1996; *Riseborough and Smith*, 1993; *Smith and Riseborough*, 1996].

[3] Arctic ecologists have long known that ROS events are linked with large-scale ungulate (reindeer, caribou, elk, musk-ox) deaths in Spitsbergen [*Aanes et al.*, 2000; *Solberg et al.*, 2001], Scandinavia [*Kumpula*, 2001], eastern Siberia [*Beltsov*, 2002; *McFarling*, 2002], Canada [*Miller et al.*, 1975], Greenland [*Forchhammer and Boertmann*, 1993] and suggested in Alaska [*Griffith et al.*, 2002], all regions where reindeer herding or ungulate populations are an important part of the economy. ROS events result in soil surface icing, which the animals are unable to penetrate [*Reimers*, 1977; *Reimers*, 1982], and the resulting warmer sub-snowpack temperatures promote growth of fungi and mold leading ungulates to avoid affected areas [*Kumpula et al.*, 2000]. A climate-change induced increase in the frequency and spatial coverage of ROS events may therefore have significant physical and ecological consequences precisely where permafrost is most vulnerable at its southern boundary, and where large herds of reindeer and caribou sustain native populations. Furthermore, ROS events are also known to be important triggers of avalanches in mountainous areas [*Conway and Benedict*, 1994; *Conway and Raymond*, 1993].

[4] Over the past eighteen years we have monitored soil temperatures, soil thermal properties and micro-meteorological forcing at our field site near Ny-Ålesund, Spitsbergen [*Putkonen*, 1998](The records are not continuous over this period, but they are extensive enough to give us a good indication of the soil thermal behavior in response to climate forcing. The program was initiated in the summer of 1984 at a patterned ground site [*Hallet and Prestrud*, 1986]). Automated observations revealed episodes of significant and rapid soil warming under a thick (∼1m) snow pack (Figure 1). The warmings cannot be driven by changes in near surface air temperature alone. Temperatures at the soil surface showed neither a decrease of amplitude away from a source (i.e., the snow surface), nor an increasing time lag with depth, both of which are requirements for a pure thermally-conductive system. It is apparent that a significantly more effective mode of heat transfer is required between atmosphere and permafrost to explain the observations. Examination of the local meteorological record showed that a nearby research station received rain or mixed snow and rain during the warming episodes. The anomalous

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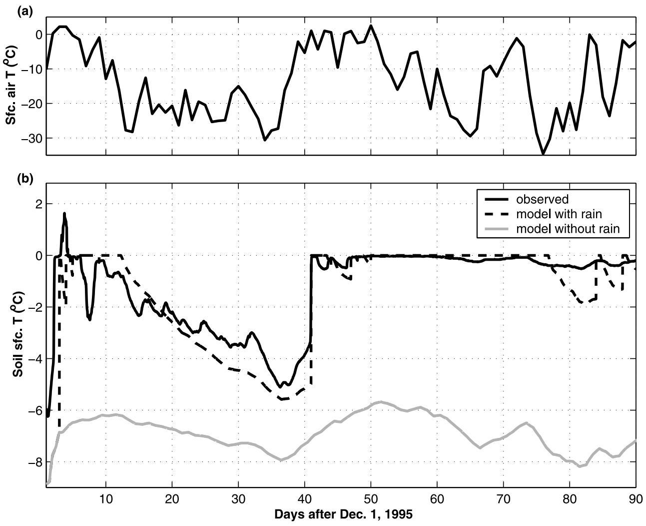

Figure 1. (a) Air temperature measured at 1.6 m above the soil surface. (b) Observations (solid line) and modeling (dashed and gray lines) of soil surface temperatures [*Putkonen*, 1998] at our field site near Ny-Ålesund, Spitsbergen, winter 1995–1996. The sharp upward spikes in the observed record (solid dark line) show the impact and timing of the two major rain events during this period. The gray line is integration of a permafrost evolution model that does not include the impact of rain events. The dashed line is the integration of the permafrost model including rain events [*Putkonen*, 1998]. Using meteorological data from the nearby (10 km) Ny Ålesund station, and summing the totals of the reported rain events and half the totals of reported mixed rain/snow events, around 180 mm of rainfall was reported over the winter. Because of local-scale variations the input of liquid water at the site is not always certain. In this figure the magnitude (but not timing) of rain added to the model was varied to optimize the match to the observations. The integration shown (dashed line) used a total of 173 mm, which therefore compares favorably to the observations. The snow and soil thermal parameters in the model were held fixed. Snow depth ranged between 0.3 and 1.7 m (mean 1.3 m) during the period.

warmings described above could theoretically also result from melting the snow, as is typically observed in the spring. However, we can rule this out because the warmings occurred during the Arctic polar night (no shortwave radiation available for melting) and the near surface air mass of a few degrees above freezing point cannot melt the snow at a sufficient rate. Rainfall, if in sufficient quantity, percolates through the snowpack [*Conway and Benedict*, 1994] and pools at the soil surface (If the rain percolates into the soil the thermal difference between thermal conduction and water advection and related release of latent heat is even larger as the latent and thermal energy bypasses larger domain of thermal inertia), because of the typically low infiltration capacity of the soil. As the water slowly freezes at the soil surface it gives up latent heat and warms the soil beneath and the snow above. The resulting ice/water bath constrains the near-surface temperature of the soil to 0°C. A simple calculation illustrates the importance of ROS on seasonal soil temperature. The latent heat given up by the freezing of 50 mm of water is 1.7×10^7 Jm^{-2}. Calculations from a permafrost model, described below, show that typically about 25% of this energy goes to heating the underlying soil. Now assuming an overlying snowpack of 1 m [*Putkonen*, 1997] (representative thermal conductivity 0.3 Wm^{-1}K^{-1} [*Sturm et al.*, 1996]), and mean winter air temperature of −15°C, it takes about 33 days for the remaining amount of heat to be conducted through the snowpack, during which time the soil surface temperature must remain at 0°C.

[5] In early 1996 several large winter storms traversed the region near Spitsbergen and over the course of 45 days produced rainfall totaling 180 mm over the existing snowpack. Because of this rainfall the soil surface temperature, which would otherwise be around −7 to −8°C, was constrained to be at 0°C for most of the season by a few (in this case just two major) ROS events. A standard soil permafrost thermal model [*Putkonen*, 1998], representing the full suite of thermodynamic processes in the snow and soil, captures the essence of these episodes and allows us to explore the effect of the rain events on the soil temperatures at the site (Figure 1). The permafrost thermal model is a standard 1-dimensional finite difference approximation of the heat diffusion equation. In the model the snow pack densifies through weight of overlying snow mass and destructive metamorphism. The thermal properties of the snow depend on the snow density. Heat transfer is either by conduction or advection (the latter occurs only in the snow). The frozen soils typically contain various amounts of unfrozen water, depending the soil grain size distribution and salt content. The model is modified to allow soil heat capacity, soil thermal conductivity and freezing/thawing related phase change to occur over a wide range of temperatures, however, the vast majority of the water is freezing within 1 degree of 0 deg C. Soil thermal parameters and moisture content are measured in situ and in laboratory (soil thermal conductivity 2.3–3.2 W/m K, dry soil bulk heat capacity 1.7–1.8e6 J/m^3 K, soil moisture content 150–350 kg water/m^3 soil). Over this period, in a model simulation without rain, the top 1m of soil is an average of 4°C colder than in the control simulation in which the observed ROS is included. No other heat transfer mechanism can warm the soil under a snow pack at the observed rate and magnitude. The fact that models, theory and observations agree well regarding the timescale and amplitude of these events is a strong support of our understanding of the physics involved. It is important to emphasize that ROS can be a very direct connection between the atmosphere and a surface insulated by a thick snowpack. Model simulations for the field site show that a single 50 mm ROS event increases the mean wintertime (December, January, and February) soil surface temperature by the same amount as an increase in mean wintertime surface air temperature of 7°C.

[6] The results in Spitsbergen are robust to a wide range of model parameters (the most important is snow depth, which affects the rate of water freezing). An interesting extension of this modelling will be to understand how, in other regions, the interplay of frequency and amount of ROS, snow depth, and snow timing affect the evolution of soil temperatures.

[7] The frequency of significant ROS events in Spitsbergen is linked directly to the North Atlantic Oscillation (NAO), a large-scale pattern of variability in the Northern Hemisphere atmospheric circulation [*Hurrell*, 1995]. An examina-

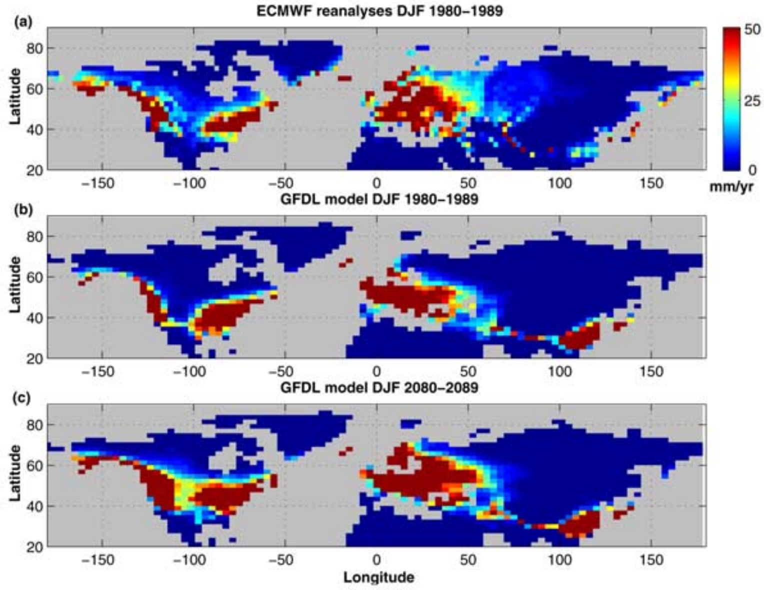

Figure 2. (a) Average wintertime ROS amounts for 1980–1989, calculated using daily reanalysis data from the European Centre for Medium Range Forecasting (ECMWF) [*Gibson et al.*, 1996]. Only data from December, January and February are used. To make the plots clearer, the color scale maximizes at 50 mm/yr. (b), as for panel (a), but using the output from the GFDL global climate model. (c), as for panel (b) but for GFDL climate model predictions for 2080–2089 under a standard anthropogenic climate forcing scenario of a 1% per year increase in CO_2. For the GFDL model monthly-mean model output was used as daily output was not available. ROS was calculated from the model output fields of snow depth, snowfall, and total precipitation. Note that the model grid size in the GFDL and ECMWF output are slightly different.

tion of daily weather maps shows that the ROS events occurred when large storms resulted in incursions of warm air into the region. Such storms have associated frontal passages and large-scale horizontal convergence, which can result in prolonged rainfall lasting upwards of a day. After the passage of the storm, climatologically cold temperatures reassert themselves over the region. These synoptic conditions are preferentially favored during the positive phase of the NAO, which corresponds to a northward displacement of the local jet stream (bringing warmer air into higher latitudes), and a significant increase in storminess in the region near Spitsbergen [*Hurrell*, 1995; *Hurrell and Loon*, 1997]. Using a 25 year-long record of four times daily observations from Longyearbyen in Spitsbergen, and a daily index of the phase of the NAO, we find that ROS events occur approximately five times more often during the extreme positive phase (defined as greater than plus one standard deviation) of the NAO index than during the extreme negative phase (less than minus one standard deviation) which, following the methodology of *Thompson and Wallace* [2001], is an association that is significant at above the 95% level. Taking four-times daily data from Longyearbyen between 1976 and 2001, and considering the months November through March, we find 297 6-hr periods when rain was reported. Of those 125 occurred during days when a daily index of the NAO [*Baldwin and Dunkerton*, 2001] exceeded plus one standard deviation, and 24 on days when the daily index exceeded minus one standard deviation. Including reports of mixed rain/snow or using a daily index of the Arctic Oscillation [*Hurrell and Loon*, 1997] did not change the significance of the association.

[8] Global atmospheric reanalysis data from the European Centre for Medium Range Forecasting [*Gibson et al.*, 1996; *Stendel and Arpe*, 1997] show that wintertime ROS events occur across the northern high latitudes (Figure 2a). While most areas receive relatively light ROS totals (which nonetheless can affect ungulate populations), maritime-influenced climates in particular can experience significant totals. The largest impact occurs where a deep snowpack overlays seasonal frost or permafrost, notably over southern Alaska and Northwestern Canada, Scandinavia and western Russia. We calculate from the reanalysis data that during 1980–89 the area where wintertime ROS exceeds 50 mm on average (a level which our calculations suggest can have a significant effect on soil temperatures) was 8.4×10^6 km^2. Moreover, twice this area experiences at least one winter with ROS exceeding 50 mm during this period. This illustrates the episodic nature of ROS events, which can result from extreme weather patterns; even a single rare event can be detrimental to ungulate populations [*Reimers*, 1977].

[9] Under anthropogenic climate change scenarios, global climate models show pronounced wintertime warming at high latitudes [*IPCC*, 2001]. Such warming may bring rain to snow covered areas more often than today, and we note further that many global climate models predict a trend towards the positive phase NAO pattern, which correlates closely with the ROS in Spitsbergen. We have therefore examined the output from the model of the Geophysical Fluid Dynamics Laboratory (GFDL) which uniquely archives snow and rain separately from their output, from a standard climate change scenario of an increase of 1% per year in atmospheric CO_2 [*Delworth et al.*, 2002]. The model shows some discrepancies from the reanalysis data for the current climate: in particular in the penetration of ROS events into continental interiors is underestimated, and there are some important differences around southern Green-

land and eastern China (Figure 2b). However, the overall nature of the pattern is quite well represented, and the model can therefore serve as a useful tool for projecting potential large-scale trends in ROS due to anthropogenic climate forcing. The area of the land surface in the model which experiences significant ROS events (i.e., exceeding 50 mm/year) increases 40% from $10.3 \times 10^6 km^2$ in 1980–1989 to $14.5 \times 10^6 km^2$ in 2080–2089 (Figures 2b and 2c). Note the predicted encroachment of significant ROS events further into Alaska, central Canada, Scandinavia, and Western Russia. These regions are underlain by seasonal frost or permafrost, and are also prime areas of vital reindeer and caribou herds and thus are the areas where the environmental and ecological impacts are likely to be most significant.

[10] ROS events are capable of effectively transmitting small changes in the atmospheric circulation into a significant response of soil temperatures in snow covered regions. Notably, more frequent and more intense ROS events occurring along the southern margin of permafrost where it is already close to thawing would significantly enhance its sensitivity to any climate warming. The observations and modeling results presented here suggest that ROS events need to be incorporated into our understanding of permafrost vulnerability as well as the sensitivity of the high latitudes and their ecosystems to climate change.

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