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Key Points:

- Climatology of rain-on-snow events
- Observed trends of rain-on-snow events
- Associated variability of rain-on-snow events

Supporting Information:

- Text S1 and Figures S1–S9

Correspondence to:

J. Cohen,
jcohen@aer.com

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Trends and variability in rain-on-snow events

Judah Cohen¹, Hengchun Ye², and Justin Jones¹
¹Atmospheric and Environmental Research, Lexington, Massachusetts, USA, ²Department of Geosciences and Environment, California State University, Los Angeles, Los Angeles, California, USA

Abstract We analyzed rain-on-snow (ROS) events in two reanalysis products. ROS events are a relatively rare phenomenon outside of a few regional maxima including western Eurasia, the higher elevations of western North America, the northeastern United States, and southeastern Canada. ROS events occur at the high latitudes, especially away from the continental interior, and no robust trends were found in the frequency of ROS events. We also explored the variability of ROS events with dominant large climate modes. The most robust relationship was found with the Arctic Oscillation or North Atlantic Oscillation (AO/NAO). The most notable variability associated with the AO/NAO was a northeast/southwest dipole feature across western Eurasia. More ROS events were found for northeastern Europe for the positive phase of the AO/NAO due to the increased frequency of rainfall. However, more ROS events were found for Central Europe for the negative phase of the AO/NAO due to the increased frequency of snow cover.

1. Introduction

Across cold, high-latitude regions like the Arctic, precipitation falls in multiple forms—rain, snow, and mixed precipitation. One of the less frequent precipitation events at higher latitudes is rain-on-snow (ROS). For a ROS event to occur there must be an accumulation of snow on the ground, and the frequency of ROS events is dependent on the number of rain days in a particular location [McCabe *et al.*, 2007].

The majority of ROS events occur in the Arctic and northern maritime regions such as Scandinavia, Canada, Greenland, Spitsbergen, and Solberg [Putkonen and Roe, 2003]. These high-latitude locations are one of the most sensitive regions of the climate system. The study of these events is complex because meteorological station data are sparse and uncertain, as many of them are not manned [Rennert *et al.*, 2008]. The actual measurement of ROS events is difficult due to ambiguity in distinguishing rain, snow, and mixed precipitation [Conway and Raymond, 1993].

Although infrequent, only occurring a few times throughout the year, ROS events have a large impact when they do happen. ROS events constrain surface soil temperatures close to 0°C in regions that would otherwise be well below freezing [Putkonen and Roe, 2003]. Besides temperature, ROS events impact the hydrological cycle by accelerating melting of snow. This can result in warming of the soil temperature and water seeping through the snow and produce an icy crust on snow or the ground when it refreezes. When rain falls on top of snow, it melts some of the snow and also has the potential to seep through and warm the ground. This causes a decrease in the snowpack when it begins to melt in the spring. Rainfall on snow that has not started to melt only penetrates the upper 5–10 cm in the first hour, while when rain falls on wet snow, it can penetrate the whole snowpack immediately [Groisman *et al.*, 2006a]. With a smaller snowpack, melting can begin earlier and last for a shorter duration. Therefore, since ROS events result in a smaller snowpack with lower water content, this in turn can lead to drier soils during the summer months. Between 1956 and 1991, in the former Soviet Union, snow cover decreased by 3%. The most significant decrease occurred over Siberia in the late spring [Groisman *et al.*, 2006b], which would lead to drier soils in the summer.

The impact of ROS events on climate is dependent on depth of the snowpack and the temperature on days when precipitation takes the form of rain. More frequent ROS events have the greatest physical and ecological consequences where the permafrost is most vulnerable, i.e., at the southern boundary [Putkonen and Roe, 2003]. These regions include southern Alaska, northwestern Canada, Scandinavia, and western Russia [Ye *et al.*, 2008]. Light ROS events are most harmful to regions with foraging animals and ungulates while heavier events have a major impact in regions of permafrost [Rennert *et al.*, 2008].

Temperature is critical for ROS events, and changes in temperature mean and variance could impact the frequency of ROS events. Scientific consensus indicates that Earth is warming and that it will continue to

warm, and human activities are a primary driver [Solomon *et al.*, 2007]. Nowhere on the globe has the impact of climate change been greater than in the higher latitudes of the Northern Hemisphere, including the rapidly declining sea ice, especially in late summer and early fall, and snow cover in the spring [Derksen and Brown, 2012], which has resulted in the greatest warming observed around the globe [Holland and Bitz, 2003; Serreze and Barry, 2011; Orsolini *et al.*, 2012].

However, little is known about how a warming climate might affect the frequency and form of precipitation. Typically, as the air temperature rises, regions will receive more rainfall and less snowfall. Ye and Cohen [2013] found that warmer temperatures across Eurasia are resulting in a shorter snowfall season. Warmer winters bring more rain than snow, increasing the amount of moisture in the soil and the amount of runoff [Trenberth, 1998]. Changes in the frequency of solid precipitation while the climate warms necessitate more attention because snowfall and ice regulate the energy budget and hydrological cycles [Ye, 2008]. The type of precipitation falling when the temperature is close to the freezing point can vary from rain, snow, and mixed precipitation.

In Russia, both the temperature and the amount of precipitation are increasing, creating more winter precipitation mostly in the form of snow as temperatures remain below the freezing point during the cold season [Ye *et al.*, 1998]. Outside of the Arctic where winter temperatures are closer to freezing, more ROS events in winter are possible [Ye *et al.*, 2008]. However, in the Arctic where winter temperatures are well below freezing, increases in precipitation in the fall and spring provide greater opportunities for ROS events in the Arctic. And the area affected by ROS events is expected to increase by 40% by the 2080s over Northern Eurasia [Ye *et al.*, 2008]. Therefore, an increase in the frequency of these events is expected to surpass the effects of air temperature warming on soil temperatures, which could cause an acceleration of global warming on sub-surface temperatures [Putkonen and Roe, 2003].

Little is known about the large-scale characteristics of ROS events and their relationship with large-scale climate modes. Here we present a climatology analysis of trends and relationships with the dominant mode of climate variability. A better understanding of the variability associated with ROS events is needed to anticipate future changes in the frequency and location of ROS events with climate change. ROS events in the fall and winter season differ from those in the spring. In the fall and winter, ROS events impact soil and snow properties prior to the snowmelt season, while in the spring, ROS events amplify, snowmelt, runoff, and flood risk. Here we analyze hemispheric patterns, trends, and relationships of ROS events with large-scale climate modes. We focus on the cold season (boreal fall and winter) when same signed climate anomalies are most extensive and relationships between surface weather and climate modes are strongest. Also, during the fall and winter hemispheric snow cover, extent has been relatively stable, with no significant trends over the reanalysis time period (<http://www.ncdc.noaa.gov/snow-and-ice/extent/>), and is ideal for studying interannual variability; however, for completeness a climatology for spring is provided in the supporting information. In contrast over the same period, spring snow cover has undergone strong declines, even greater than summer sea ice [Derksen and Brown, 2012] that makes linear analysis difficult to interpret. Though imperfect, we have analyzed ROS events in state-of-the-art reanalysis products, which are optimized for hemispheric scale studies.

2. Data and Methods

Observational temperature and precipitation data originate from the Modern Era Retrospective-Analysis for Research and Applications (MERRA) [Rienecker *et al.*, 2011] for the period January 1979 through February 2014. Linear regression analysis and linear trend analysis are the two statistical techniques employed throughout the study. Significance was determined using a two-tailed *t* distribution.

ROS events were determined using MERRA daily averaged surface snow cover and precipitation fields. When the snow cover fraction was 0.5 or greater in the model gridbox, that gridbox was considered snow covered. Where the snow cover was determined to be present in the reanalysis model at each grid point for each day, the total snowfall flux was subtracted from the total precipitation flux to obtain the total liquid precipitation. If the total liquid precipitation was greater than 1 cm, then a ROS event was identified as having occurred at that grid point. The results were not sensitive to the extent of snow cover in each grid cell where the total snow cover extent exceeded a majority of the grid cells. We repeated the analysis with different thresholds of liquid precipitation, and the 1 cm threshold did not materially alter the results and had the advantage of eliminating many spurious counts of ROS events.

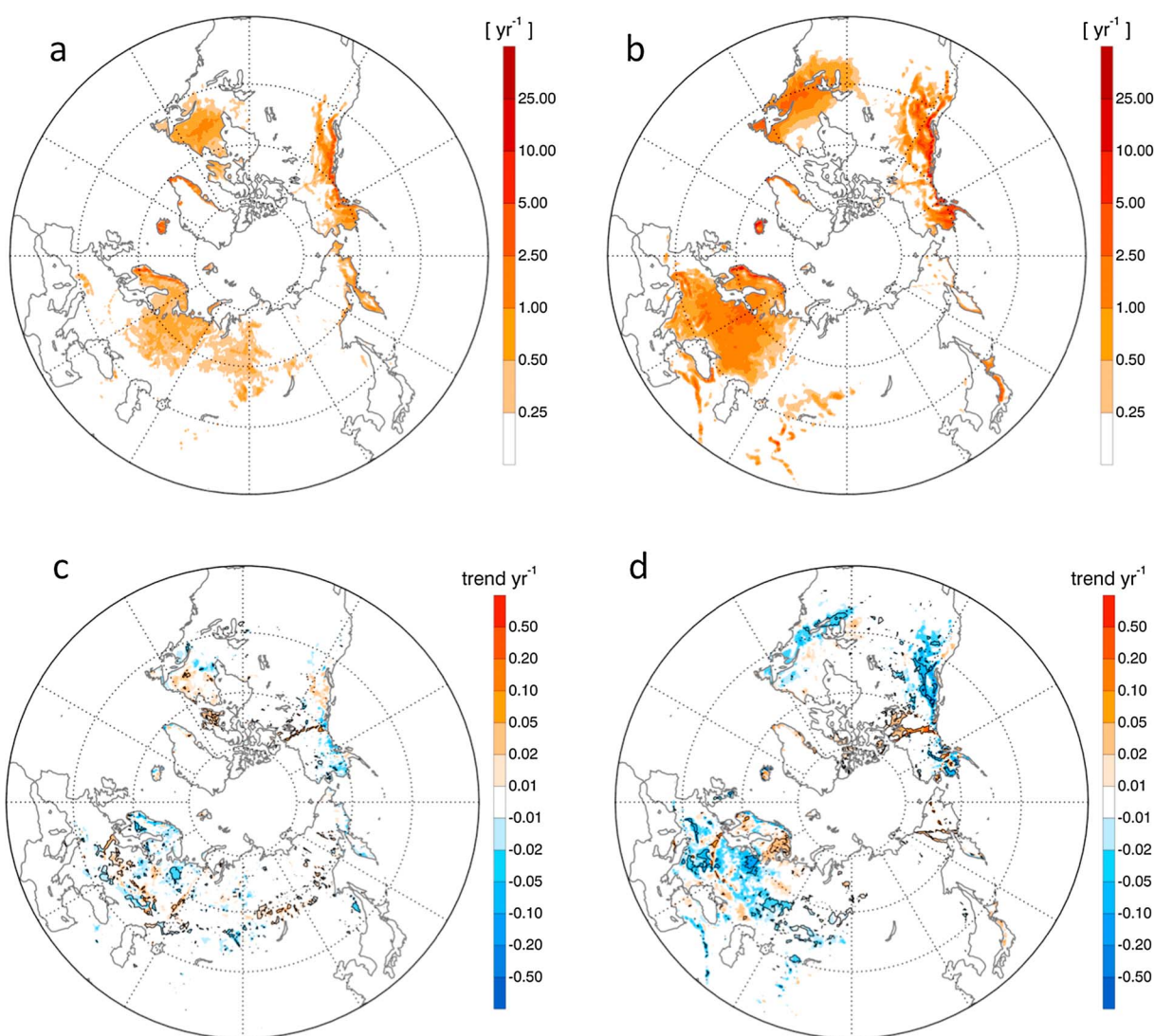


Figure 1. The number of ROS events across the Northern Hemisphere (see text for definition) for (a) September–November (SON) and (b) December–February (DJF) for the period 1979/1980 to 2013/2014. Also shown is the linear trend of ROS events based on least squares regression for (c) SON and (d) DJF. Black contour delineates those correlations that are significant at the 90% confidence level or higher.

In models, precipitation in general is problematic and especially for snowfall. Therefore, in the supporting information we provide some comparisons with both observations and with another reanalysis data set, ERA-Interim [Dee *et al.*, 2011]. Discussion of how ROS events were computed in order to complete the comparison is also provided in the supporting information.

3. Results and Discussion

Previous research on ROS events is sparse, so we begin our analysis by presenting a climatology of ROS events across the Northern Hemisphere.

3.1. Climatology and Trend

Figure 1 shows the number of annual ROS event individual seasonal totals for fall (September–November) and winter (December–February). Shown in Figure S2 is the climatology for Eurasia based on station data, and comparison of the climatology between MERRA and ERA-Interim is presented for fall and winter in Figure S3 and spring in Figure S4. ROS events occur at high latitudes where snow cover is found on the ground and can be generalized as occurring in the northern corners of the Northern Hemisphere continents

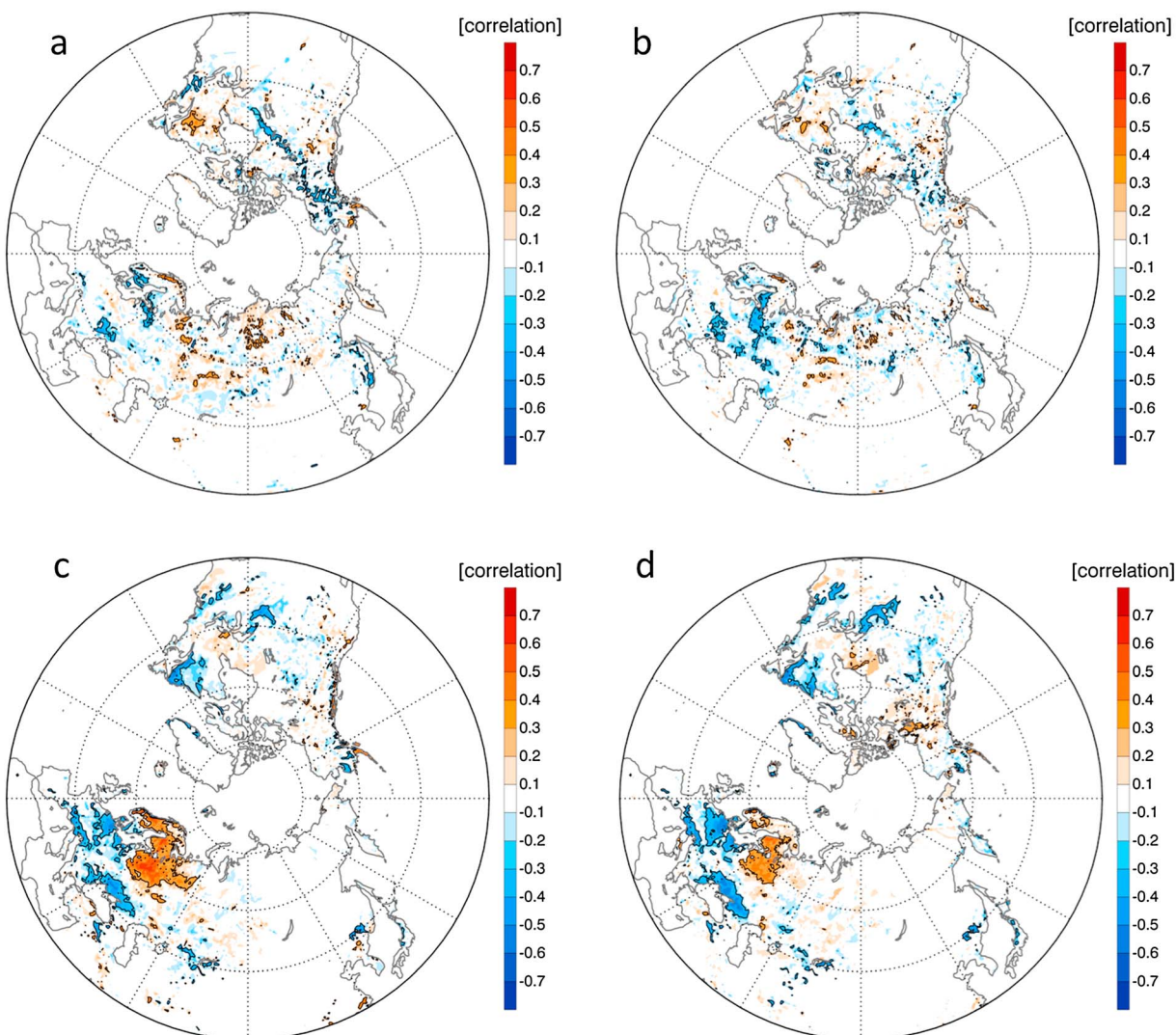


Figure 2. Correlation of the SON (a) AO and (b) NAO with the ROS events for SON across the Northern Hemisphere for the period 1979–2013. (c and d) Same as Figures 2a and 2b except for DJF. The AO/NAO values are calculated as a weighted average of the monthly values. Correlation coefficients at 0.28, 0.33, and 0.43 or higher are statistically significant at a confidence level greater than 90%, 95%, and 99%, respectively, in Figures 2–4. Black contour delineates those correlations that are significant at the 90% confidence level or higher.

and away from the interior. In fall, ROS events mainly occur in northwestern Eurasia and North America, the Kamchatka Peninsula, and northeastern Canada. In winter, ROS also occurs over northwestern Eurasia but over a much greater area—Japan, the west coast of North America, southeastern Canada, and the northeastern United States. In spring, ROS events occur mostly in eastern Canada and the coastal mountain ranges of western Canada and Norway. Based on Figures 1, S2, and S3 we have more confidence in the location of ROS events than in the actual frequency, which shows a large spread in Figures 1 and S3.

Next we explore trends in ROS events. It has been widely reported that surface temperatures have been warming for the entire globe over the instrumental record [Intergovernmental Panel on Climate Change, 2013] and that the region of the globe that is warming the fastest is the Arctic [Cowtan and Way, 2013]. An overall warmer surface and lower troposphere should translate into a decrease in frequency of snowfall events and an increase in the frequency of rainfall events. An increasing ratio of rain versus snowfall events could translate into an increase of ROS events [Ye *et al.*, 2008]. However, warmer temperatures also favor bare ground versus snow-covered ground, and less snow cover could translate into fewer ROS events. Therefore, there are likely competing impacts of warming temperatures on the frequency of ROS events that cancel each other out.

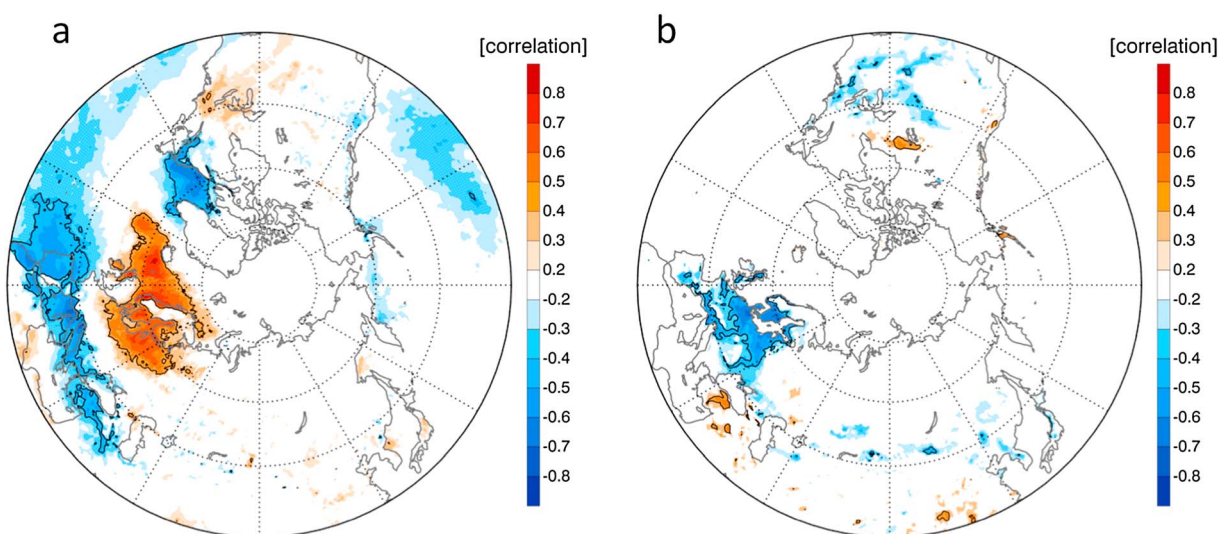


Figure 3. (a) Days with rainfall greater than 1 cm for DJF correlated with the DJF AO across the Northern Hemisphere for the period 1979–2013. (b) Snow-covered days for DJF correlated with DJF AO across the Northern Hemisphere for the period 1979/1980 to 2013/2014. Snow-covered grid cells are those with at least 50% coverage based on NASA MERRA surface data. Black contour delineates those correlations that are significant at the 90% confidence level or higher.

Also, in Figures 1 and S5 we plot the trend in ROS frequency for the fall and winter seasons. The trend in ROS events across the Northern Hemisphere continents is mixed. In fall, the trends seem somewhat more coherent with decreasing trends in western Eurasia but increasing trends in eastern North America. This may be explained by whether decreasing snow cover or increasing rainfall is the dominant factor. In winter, trends appear to be more regionally dependent with little coherency in trends on continental scales, though decreasing trends in ROS events in the coastal mountains of western North America seems to be consistent between the two reanalysis data sets. It is worth noting that the ROS increases over the southwestern coast of Greenland in both seasons where the ground cover is glacier, and increased rainfall directly contributed to more ROS events.

3.2. Variability Associated With Teleconnection Patterns

Other than temperature trends, teleconnection patterns could alter the frequency of ROS events. Given that the majority of ROS events occur in western Eurasia and eastern North America, the atmospheric teleconnection pattern that explains the greatest variance in the climate of both regions is the Arctic Oscillation (AO) or North Atlantic Oscillation (NAO). We correlate both the September, October, and November (SON) AO and NAO indices with ROS event frequency in Figures 2 and S6 (only the AO is shown in the reanalysis comparison). We also show the correlation of the AO with ROS events for SON using the observations in Figure S7. Probably, because temperatures are marginal in the fall throughout the continental regions, the correlations are widespread and mixed. No coherent patterns dominate but possibly one generalization is that the positive AO/NAO results in higher frequency of ROS events to the north (poleward of 60°N across Eurasia and northeastern Canada) and the negative AO/NAO results in higher frequency of ROS events to the south (equatorward of 60°N across Eurasia and western Canada). The increased frequency of ROS events when the AO/NAO is positive is probably due to anomalous rainfall at higher latitudes, and the increased frequency of ROS events when the AO/NAO is negative is probably due to positive anomalous snow cover at lower latitudes, though the relationships are not strong.

Also, in Figures 2 and S6 we correlate both the December, January, and February (DJF) AO and NAO (only shown in Figure 2) indices with ROS event frequency. We also show the correlation of the AO with ROS events for DJF using the observations in Figure S7. In winter across western Eurasia, a coherent dipole is observed with positive values to the north and east in the colder continental air and negative values to the south and west in the milder maritime air. In North America the pattern is not as well defined, with the most robust signal being negative values dominating the northeastern United States and the Canadian Maritimes. There are some positive values across interior eastern Canada, but none are statistically significant.

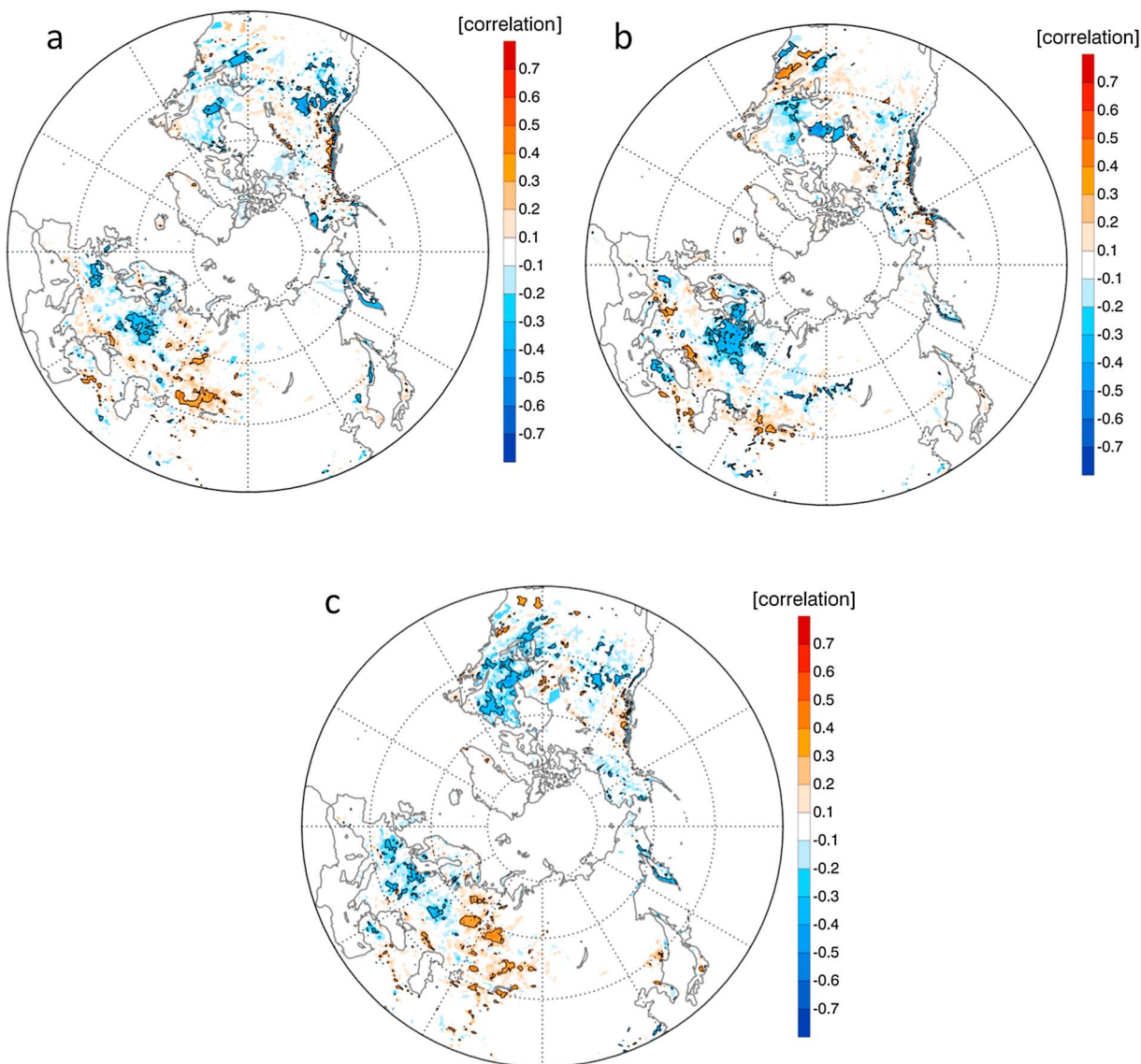


Figure 4. Correlation of the DJF (a) Pacific–North American pattern (PNA), (b) Pacific Decadal Oscillation (PDO), and (c) October–November multivariate ENSO index (MEI) with the ROS events for DJF across the Northern Hemisphere for the period 1979/1980 to 2013/2014. The PNA/PDO values are calculated as a weighted average of the monthly values. Black contour delineates those correlations that are significant at the 90% confidence level or higher.

In Figures 3 and S9 we plot the correlation of the AO with the frequency of rainfall and snow cover in winter. Across Europe the pattern of both matches up well with the pattern of increased frequency of ROS events for both phases of the AO. When the AO is positive, rainfall is increased across Northern Europe, which contributes to increased ROS events where snow cover is common in winter. When the AO is negative, much of Europe experiences increased number of days with snow cover, even in regions where snow cover is less common, increasing the possibility of ROS events when rainfall does occur. Similarly, across the northeastern United States, snow cover is more frequent when the AO is negative, again leading to increased chances of ROS events. To the north, across southern Canada, snow cover is greater when the AO is positive, possibly leading to an increased frequency of ROS events, but in the Canadian Maritimes, rainfall frequency is decreased favoring fewer ROS events. This is consistent with an earlier study using station records over Northern Eurasia that suggested NAO is positively correlated with increased ROS events over Northern European Russia due to higher frequency of both rainfall and snowfall in winter [Ye *et al.*, 2008]. However, the reduced snowfall events associated with the positive phase of NAO limited the ROS events over Southern European Russia.

Finally, in Figures 4 and S8 we correlate dominant teleconnection patterns from the Pacific sector, which include the DJF Pacific/North American pattern (PNA), the DJF Pacific Decadal Oscillation (PDO), and the October–November multivariate El Niño–Southern Oscillation (ENSO) index (MEI) with the frequency of winter ROS events. No strong relationships are seen, but in general when the Pacific teleconnection patterns are positive, ROS events are less frequent in eastern North America and northern Europe, but more frequent across Asia east of 60°E. Also, when the PDO is positive, ROS events increase in the Mid-Atlantic States of the United States.

4. Conclusions

ROS adversely impacts humans, vegetation, hydrology, and wildlife and further impacts the local climate by altering snowmelt, runoff, and soil temperatures. ROS events are relatively rare but occur more frequently in regional maxima in western Eurasia and northeastern and northwestern North America. Based on the comparison between two different reanalysis products and station data, we have more confidence in the regions of ROS events maxima more so than in the frequency.

Trend analysis mostly exhibits weak trends of both signs, despite that, temperatures are warming across the globe, especially at the higher latitudes of the Northern Hemisphere. This is likely because even if warmer temperatures result in an increase in rainfall frequency or an increase in the ratio of rain to snow events, warmer temperatures also result in disappearing snow cover and a decreasing frequency in ROS events.

Variability in atmospheric patterns or teleconnections does show identifiable regional signatures in the frequency of ROS events. The most robust pattern that we identified is a northeast-southwest dipole across western Eurasia associated with variability in the AO/NAO. The positive AO results in higher frequency of ROS events across northwest Eurasia as milder maritime air penetrates anomalously deep into the Eurasian continent resulting in an increased number of rainfall events over the persistent snow cover. The negative AO results in higher frequency of ROS events across much of central and eastern Europe as snow cover expands westward as cold air flows west from Siberia and a more southerly storm track supports an expansion of snow cover that becomes increasingly vulnerable to rainfall. Similarly, the negative AO results in an increased frequency of ROS across the northeastern United States as snow cover expands southward with colder temperatures and a more southerly storm track that is similarly more vulnerable to rainfall.

Various indices of variability in the North Pacific sector do not show as a robust signature with ROS events as the AO/NAO. However, their positive phase is associated with a decrease in ROS event frequency across northern Europe and eastern North America (with the possible exception of the PDO across the Mid-Atlantic), but an increase across western Asia.

Previous studies have argued that as temperatures warm ROS events, a relatively rare event will become more common. However, our analysis reveals strong regional variability in ROS events with trend analysis and correlations with large-scale modes of variability, which preclude any gross assumptions about future trends due to climate change or projected changes in atmospheric modes. The lack of robust trends in ROS events is likely due to the competing consequences of warmer temperatures—more frequent rainfall relative to snowfall but also less snow cover.

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