

Winter rain on snow and its association with air temperature in northern Eurasia

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Abstract:

This study examines the characteristics of winter (Dec–Feb) rain-on-snow events and their relationship to surface air temperatures to reveal potential changes in rain-on-snow days under a warming climate over northern Eurasia. We found that rain-on-snow events mostly occur over European Russia during winter. Rain-on-snow days increase as air temperature increases and are primarily attributable to the increase in rainfall days. Air temperature is the primary cause for these changes, while the North Atlantic Oscillation has some influence on the rain on snow and rainfall over the northern part of European Russia. The magnitude of rain-on-snow increase ranges from 0.5 day to 2.5 days per degree Celsius increase in air temperature. Higher rates of increase in rain-on-snow days occur in the northern and eastern parts of European Russia where the air temperature is lower, in contrast to rainfall days which have higher rates at locations with higher air temperatures. This suggests that a decrease in snowfall days might be limiting the rate of increase in rain-on-snow events over warmer regions where the temperature is about -8°C or higher. This study also implies that rain-on-snow days will become more common over regions in which it is currently a rare event as air temperatures increase. Copyright © 2008 John Wiley & Sons, Ltd.

KEY WORDS rain-on-snow; northern Eurasia; precipitation characteristics

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INTRODUCTION

Changes in the Arctic hydrological cycle have been studied by focusing heavily on increases in precipitation amount (Nicholls *et al.*, 1996; Ye, 2001a), snow depth (Brown and Braaten, 1998; Ye *et al.*, 1998; Ye, 2001b), and river discharge (Zhang *et al.*, 1999; Peterson *et al.*, 2002; Yang *et al.*, 2002; Serreze *et al.*, 2003; Manabe *et al.*, 2004; Oelke *et al.*, 2004; Ye *et al.*, 2004; Berezovskaya *et al.*, 2005). In addition, reduction in both snow cover and sea ice in recent decades has been in the public spotlight (Robinson *et al.*, 1995; Serreze *et al.*, 1995; Brown and Goodison, 1996; Stroeve *et al.*, 2005). These changes have a significant impact on vulnerable Arctic terrestrial and ecological systems. Equally important, issues regarding changes in precipitation characteristics, such as types under a warming climate, have not been researched very much. For instance, rain-on-snow events, although occurring less frequently than rain or snow events, have had adverse impacts on ungulate population dynamics due to the formation of icy and slippery surface conditions hazardous for migration and preventing animals from penetrating the snow surface to feed (Miller *et al.*, 1975; Reimers, 1982; Solberg *et al.*, 2001; Putkonen and Roe, 2003). A recent study found that rain-on-snow events are related to high mortality of young

ringed seals by the thinning of the snow layer thereby reducing insulation and causing the collapse of snow caves, some of which are inhabited by seals (Stirling and Smith, 2004). However, the impact of changes in the frequency of rain-on-snow events under a warming climate over high-latitude regions has not yet been studied.

Rain-on-snow events outside of the Arctic have been found to trigger flooding (Singh *et al.*, 1997; Sui and Koehler, 2001; McCabe *et al.*, 2007), increase stream acidity (Eimers *et al.*, 2007), and cause avalanches in mountainous regions (Singh *et al.*, 1997; Sui and Koehler, 2001; McCabe *et al.*, 2007). Changes in rain-on-snow frequency is determined by two major factors: rainfall events and ground snow cover days. These two factors have opposite trends in most middle-latitude regions as air temperatures increase: increases in precipitation and decreases in snow cover days. It is well known that type of precipitation is directly determined by near-surface air temperatures (Auer, 1974; Rohrer, 1989; Fassnacht *et al.*, 2001), and that increases in air temperature reduce snowfall days and thereby snow cover days in middle-latitude regions. A recent study of rain-on-snow events over the western United States (McCabe *et al.*, 2007) suggests that the frequency of rain-on-snow events has been decreasing owing to the disappearance of snow on the ground caused by warmer air temperatures.

The impact of increasing air temperature on rain-on-snow events over the Arctic may be different from those over the western United States. Studies over northern Eurasia suggest that snow depth (Ye *et al.*, 1998;

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Ye, 2001b) and snowfall season length have increased in some areas (Ye, 2001c), but little change has occurred in continuous snow cover length (Ye and Ellison, 2003). A recent study by Ye (2008) suggests that increases in rainfall days over northern Eurasia in winter are associated with air temperature increases. These studies suggest that rain-on-snow events may actually become more frequent in this region. However, the question regarding what is the dominant force that is affecting rain-on-snow events over the Arctic under the current temperature range has not been answered.

The purpose of this study is to use historical synoptic observational records to examine the frequency of rain-on-snow events and evaluate its relationship to air temperatures, rainfall days, snowfall days, and atmospheric circulation patterns over northern Eurasia during the winter season.

DATA AND METHODOLOGY

The synoptic weather data are from the Six- and Three-hourly Meteorological Observations from 233 U.S.S.R Stations available at the Carbon Dioxide Information Analysis Center (CDIAC), Oak Ridge National Laboratory, Oak Ridge, Tennessee (ORNL/CDIAC-180, NDP-048/R1; ftp from cdiac.esd.ornl.gov). Each station record consists of six-hourly (1936–1965) and three-hourly (1966–1990) observations of 24 meteorological variables including air temperature, past and present weather type, precipitation amount, cloud amount and type, sea level pressure, relative humidity, wind speed, and wind direction. The data have undergone extensive quality assurance by the All-Russian Research Institute of Hydrometeorological Information-World Data Centre (RIHMI-WDC), National Climatic Data Center (NCDC), and CDIAC (Razuvaev *et al.*, 1995). The changes in observation times through the two different time periods (before and after 1966) have been adjusted on the basis of station time zone.

The weather codes and associated weather types are listed in Table I. The types of current weather coded 50–59 represent 10 categories of drizzle (slight, moderate, heavy, etc.); 60–67 represent 8 categories of rain (intermittent, continuous, slight, etc.); and 80–82 represent 3 categories of rain shower (slight, moderate, heavy and violent). All these are considered to be rain events. Liquid products occurring at the observation time associated with the preceding hour's thunderstorms are coded 91 and 92, which are also included. In addition, rains during the preceding observation hour are coded 21 (rain) or 25 (showers of rain) and are also included as rain events.

For snow events, weather codes of 70–79 are used representing 10 categories of solid precipitation not in shower form (intermittent and continuous slight, moderate, and heavy snow flakes, diamond dust, snow grains, ice pellets). Solid precipitation in the form of showers is coded 85 or 86. Snow and possibly hail associated with thunderstorms are coded 93 (slight) and 94 (moderate)

Table I. Weather codes for liquid and solid precipitation

Codes	Weather
<i>Liquid precipitation</i>	
21	Rain during preceding hour
25	Shower of rain during preceding hour
50–59	Drizzle or drizzle and rain at the time of observation (intensity increases as the code number increases)
60–67	Rain or freezing rain at the time of observation (with different intensity)
80–82	Rain shower (intensity increases as the code number increases)
91–92	Rain at the time of observation, with thunderstorms during preceding hour
<i>Solid precipitation</i>	
21	Snow during preceding hour
70–75	Snow flakes at the time of observation (intensity increases as the code number increases)
76–79	Diamond dust, snow grains, isolated snow crystals, ice pellets at the time of observation
85–86	Snow shower at the time of observation (intensity increases as the code number increases)
93–94	Snow or hail at the time of observation, with thunderstorms during the preceding hour

and are also included as snowfall days. Snow recorded during the hour previous to the observation time is coded 22. All these are considered as snow events. Any types of mixed solid and liquid precipitation are not included in either rain or snow category for this particular study. Also, hail events only are not included as snowfall days.

The ground snow condition data are primarily based on the daily snow depth records from the Historical Soviet Daily Snow Depth CD version II (HSDSD), compiled and quality-controlled by the National Snow and Ice Data Center (Armstrong, 2001). The ground is considered to be snow-covered if there is a measurable record (1 cm or above) for a day. Also, if daily snow depth is indicated as a missing value, the ground condition code (GRND) from the synoptic station record is checked. The ground is considered to have snow cover if the visual observation record code is 5 (ice, snow, or melting snow covering less than one-half of the ground), 6 (ice, snow, or melting snow covering more than one-half of the ground), and 7 (ice, snow, or melting snow covering the ground completely) and the quality flag does not equal 9 which indicates missing. If both data sources of snow depth and ground cover code are missing for a day, the starting date and ending date of continuous snow cover are

used to check to see if that day falls in between to determine if that day has snow cover. The starting and ending dates of continuous snow cover is also derived from the HSDSD data set by examining daily snow depth time series. The details of extracting these dates are found in Ye and Ellison (2003). If the missing ground condition day falls outside of the continuous snow cover time period, the starting and ending dates of the snowfall season (Ye, 2001c) is used to check whether it falls outside of the snowfall season. If it does not, the day is considered as missing for the rain-on-snow event.

To stay consistent with the number of observations per day, only four observations per day are used throughout the study time period. Thus, for the later period starting in 1966, only the four observations that occur closest to the previous years' observation times are used. If there is one observation showing rain or snow, the day is considered as a rain or snow day. Since there are four observations per day using the weather codes, the chance of missing a precipitation event is much less than it would be by using recorded daily precipitation data especially during winter when precipitation is of light intensity due to low air temperatures. Also, this method makes it possible to avoid the data quality problem of under-catching and changes in instrumentations associated with precipitation records. Therefore, the compilation of frequencies of precipitation types is quite accurate.

The number of days featuring rain with snow on the ground is totaled for winter seasons (Dec–Feb). If there is one day missing (either in weather events or ground cover conditions), that season is considered missing. Similarly,

the number of rain days and snow days are totaled for the winter seasons. Among these 223 stations, 80 stations are retained for analyses (the ones that have quality data starting around 1936–1937, no later than 1940–1941). The locations of these 80 stations are shown in Figure 1. The number of missing winters for rain-on-snow days ranges from 1 to 13 and the number of missing rainfall and snowfall winters ranges from 2 to 16 and 2 to 17, respectively during the 53 years of the study period. The slightly higher number of missing winters for rainfall and snowfall days is due to the fact that the weather code is checked for missing for all 90 days or 91 days of each winter instead of just during the snow-on-ground days.

Daily air temperature that was measured at 2 m above the ground is averaged from the same four observation times of the synoptic data set. Winter average values are derived from the daily mean, and if more than 10% of observations are missing, the winter mean temperature is considered as missing.

The major atmospheric circulation pattern, the North Atlantic Oscillation (NAO) index available from Climatic Research Unit, United Kingdom (<http://www.cru.uea.ac.uk/cru/data/nao.htm>) is used to examine atmospheric circulation impacts on rain-on-snow, rainfall, and snowfall days. The NAO is known for its influence on the Arctic region by steering cyclones northward and bringing warm and moist air into the northern region during its positive phases (e.g. Hurrell, 1995; Serreze *et al.*, 1997). This NAO index is calculated from the normalized pressure difference between the two stations at Gibraltar and southwestern Iceland (Reykjavik) (Jones *et al.*,

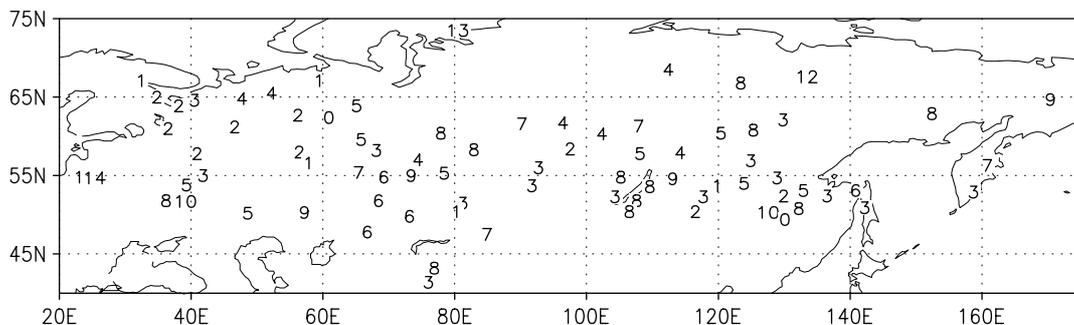


Figure 1. Location of the 80 stations and the number of missing winters during 1936/1937–1989/1990

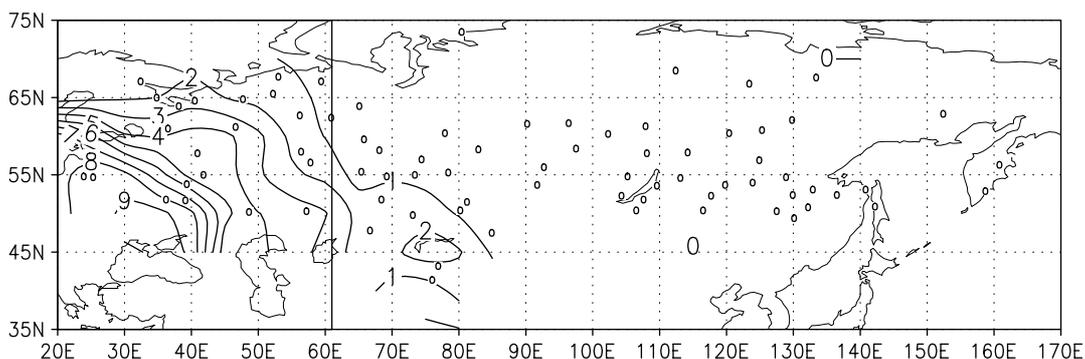


Figure 2. Mean total rain-on-snow days during 1936/1937–1989/1999 winter season. The box on the left indicates the geographical area where this study is focused on

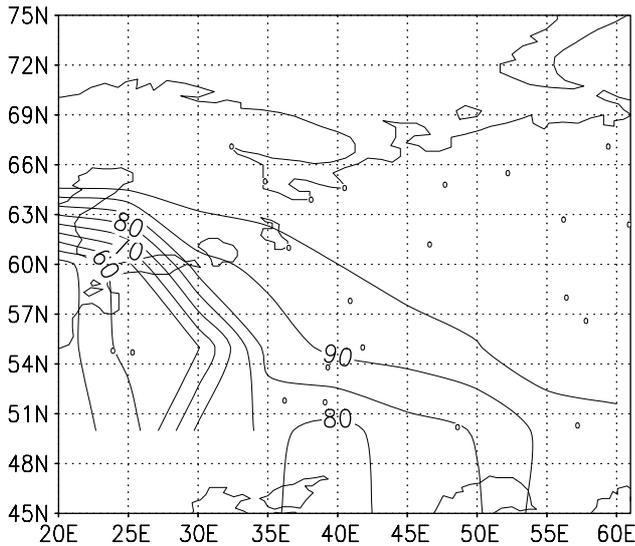


Figure 3. Mean ratio (in percentage) of rain-on-snow versus rainfall days

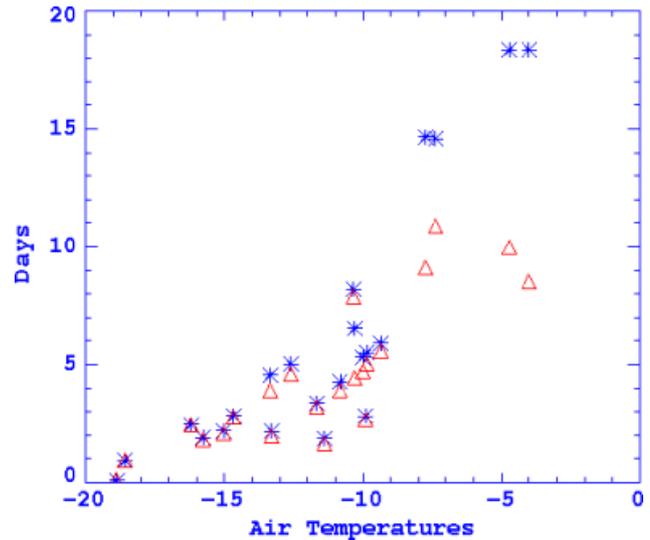


Figure 4. Mean total rain-on-snow days (red triangle) and rain days (blue star) versus air temperature at the 22 stations over European Russia

1997). The winter index is averaged from the three months of December, January, and February.

The rain-on-snow days, rainfall days, and snow days will be correlated to the surface air temperature and NAO index for the winter season during the study period. The rate of change per degree of air temperature increase at each station will be estimated on the basis of a simple linear regression with air temperature as an independent variable and rain-on-snow days as a dependent variable. The rate of change will be plotted against the mean air temperature of each station to reveal any non-linear relationship in the rate of change due to different temperature conditions or geographical regions.

To examine whether rainfall days or snowfall days are affecting rain-on-snow day changes, correlation analysis of each to the rain-on-snow days will be calculated.

In addition, any change in ratio of rain-on-snow versus rainfall days associated with air temperature is revealed by correlating the ratio with air temperature. The ratio is calculated when total rain-on-snow days is divided by total rainfall days and multiplied by 100 for each winter representing the percentage of rainfall as rain on snow at each station. This will reveal whether the proportion of rain-on-snow change is faster or slower than the rainfall day changes associated with air temperature changes.

RESULTS

The average number of rain-on-snow days during winter is shown in Figure 2. It illustrates that rain-on-snow events occur mostly over European Russia (east of the Ural Mountains or about 61°E), ranging from 1 to

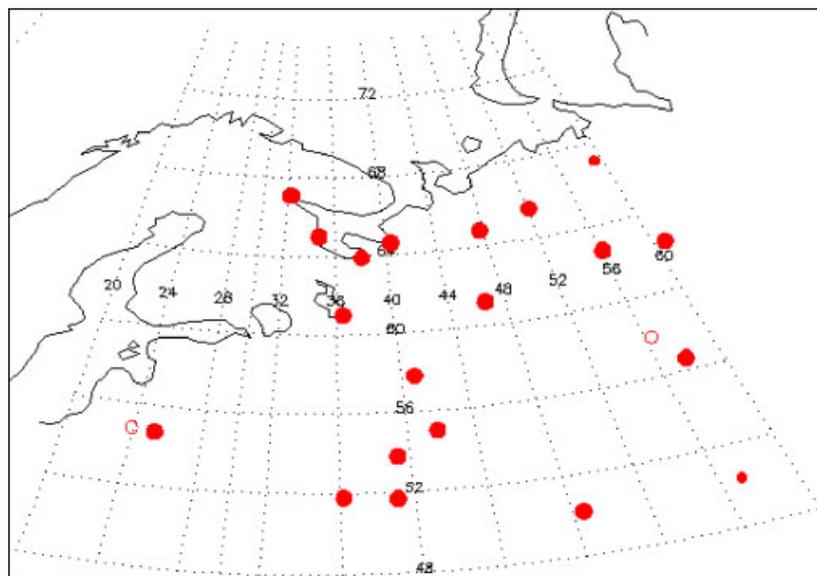


Figure 5. Correlation between rain-on-snow days and mean air temperature at 22 stations located over European Russia. Large shaded circles: positive correlation statistically significant at 99% confidence level and above; small shaded circles: positive correlation statistically significant at 95% confidence level and above. Open circle: positive correlation with no statistical significance

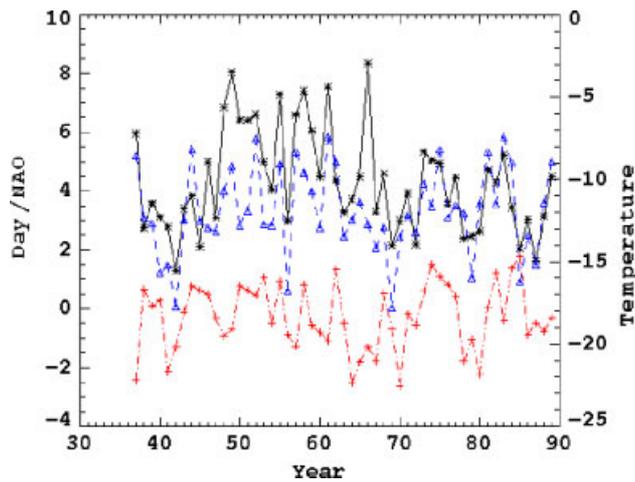


Figure 6. Time series of mean rain-on-snow days (solid), surface air temperature (dashed), and winter NAO index (dots and dash mixed) averaged from all the 22 stations located west of 61°E longitude

9 days per winter with almost no events occurring over central and eastern Siberia. Rain-on-snow days increase in frequency towards the west where warm and moist air occasionally intrudes into the region. This pattern resembles that of total rain days during the winter season except for the number of days that are less

than the total of rain days especially over southwestern European Russia. This indicates that some of the rain days occur with no snow on the ground over southwestern European Russia during winter. Given the distribution of the rain-on-snow days, the rest of the paper will focus on European Russia and therefore only the 22 stations located west of 61°E (indicated by the box on the left portion of the map) will be used in the analysis.

The mean ratio of the percentage of rainfall days occurring as rain on snow is depicted in Figure 3. The ratio ranges from close to 100% over northeastern European Russia to about 65% on the western edge of European Russia owing to the decrease in snow cover days as the air temperature increases towards the west. To reveal the changes in ratio related to the stations' mean temperature conditions, the total number of rain-on-snow days and rainfall days are plotted against the stations' mean surface air temperature in Figure 4. Both rain-on-snow days and rainfall days increase quickly as air temperature increases, while the difference between rain-on-snow days and rainfall days becomes more evident at stations with air temperatures higher than about -8°C. The number of days of difference jumps from about 0–2 days to 5–10 days.

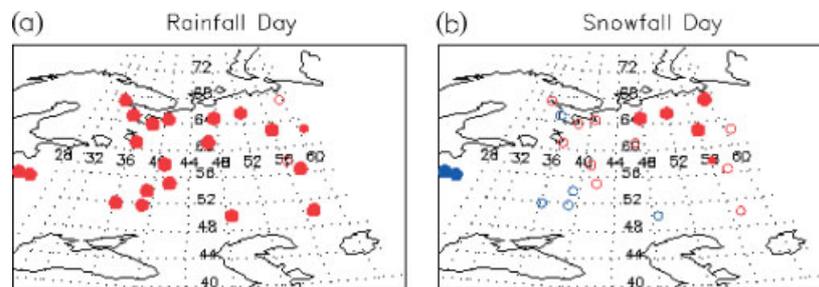


Figure 7. Correlation between surface air temperature and (a) rainfall day (b) snowfall day. Red: positive correlation; Blue: negative correlation. Large shaded circle: significant at 99% confidence level and above; small shaded circle: significant at 95% confidence level and above

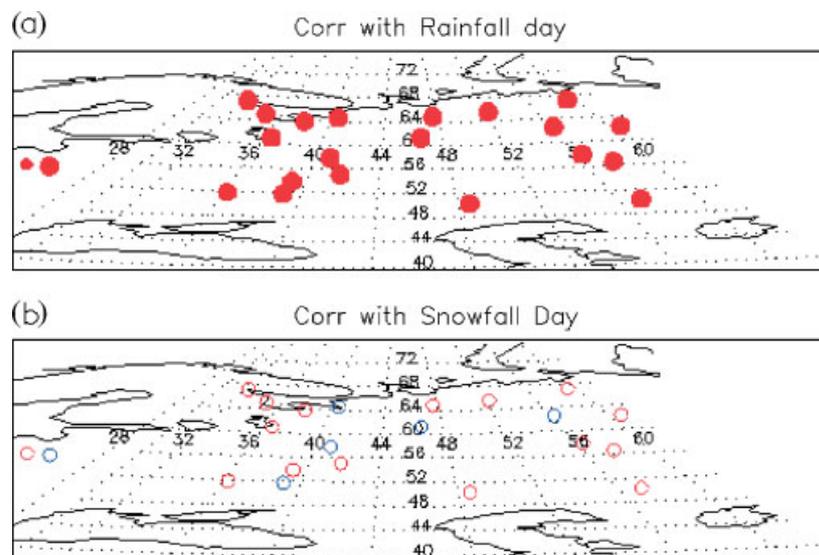


Figure 8. Correlation coefficients between rain-on-snow days with (a) rainfall days (b) snowfall days. Red: positive correlation; Blue: negative correlation. Large shaded circle: significant at 99% confidence level and above; small shaded circle: significant at 95% confidence level and above

The correlation between rain-on-snow days and air temperature at an inter-annual time scale during winter reveals that all 22 stations have positive correlations with 18 stations statistically significant at 99% and above, and two stations statistically significant at 95% and above (Figure 5). Only two stations, one located at the westernmost and one at the eastern side of the study region do not show statistical significance.

To visualize the temporal variations, the time series of rain-on-snow days and air temperature averaged from all the 22 stations and the winter NAO index are displayed in Figure 6. No statistically significant trends are found in any one of the time series during the study period of 1936/1937 to 1989/1990, but they show consistent inter-annual variations. In addition, the rain-on-snow days exhibit decadal variability increasing in the early years, staying high during the 1950s and 1960s, and decreasing starting in the 1970s. This is probably due to the decadal variability of the winter precipitation that is teleconnected to sea surface temperatures over the Pacific and Atlantic Oceans (Ye, 2001b).

To reveal changes in rainfall and snowfall days associated with air temperature, the correlation between rainfall days/snowfall days with air temperature is shown in Figure 7. Rainfall days show positive correlation with air temperatures at all 22 stations. Among them, 19 stations are statistically significant at 99% and above, one is statistically significant at 95% and above, and only two stations located on the eastern side of the study region are not statistically significant (Figure 7(a)). The correlation between snowfall days and air temperature shows 15 positive correlation stations located in the northern and 7 negative correlation stations located in the southern and western parts of the study region. The five positive correlation stations over the northeast and the two negative correlation stations over the westernmost locations are statistically significant. The negative correlation is likely

due to the relatively high air temperature conditions that change solid into liquid precipitation as air temperature increases to a certain threshold (Ye, 2008).

To determine whether the changes in rainfall days or snowfall days is affecting rain-on-snow days, the correlation maps between rain-on-snow and snowfall/rainfall days are shown in Figure 8. The rain-on-snow days are positively correlated with rainfall days at all 22 stations. Among these, 21 stations are statistically significant at 99% level and above, and one station is significant at 95% level and above (Figure 8(a)). This suggests that an increase in rain on snow is closely related to increases in rainfall days at these stations. The correlation of rain-on-snow days with total snowfall days shows mixed positive and negative correlations but none is statistically significant, suggesting that snowfall day changes have little effect on the frequency changes in rain-on-snow days over the study region (Figure 8(b)). This implies that owing to very low air temperature (mean winter air temperature ranges from -19 to -4°C), changes in rain-on-snow days are more directly controlled by the rainfall days over the region.

The correlation between the ratio of rain-on-snow *versus* rainfall and air temperature is predominantly positive except for four stations located over the southern and western edges of the study region (Figure 9). Eight eastern and northern positive correlation stations are statistically significant at 95% or 99% confidence level and above. This suggests that a larger proportion of rainfall days fall as rain-on-snow days at these stations. In other words, a larger magnitude of increase in rain-on-snow days than rainfall days over the northern study region occurs as air temperature increases.

The scatter plot of the rates of change in rain-on-snow days and rainfall days (per degree Celsius) and the corresponding station's mean air temperatures that have statistically significant correlations further confirms this

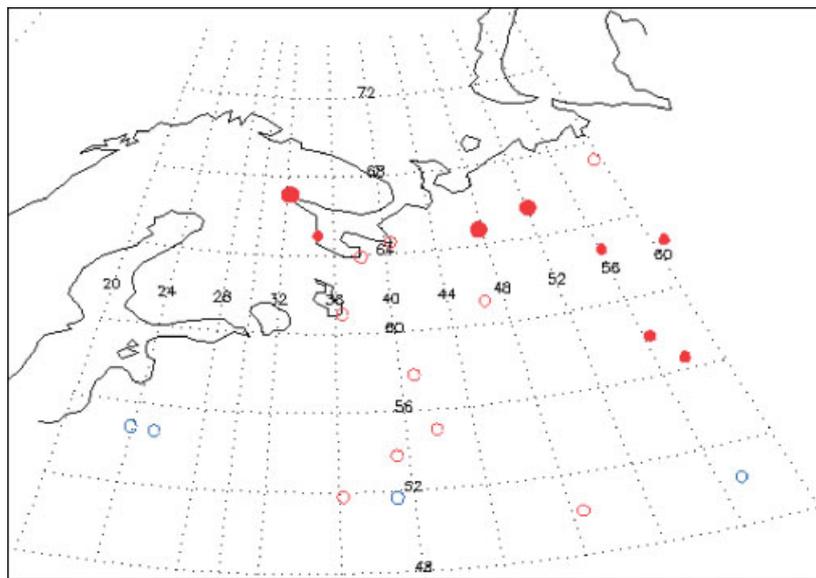


Figure 9. Correlation between temperature and ratio of rain-on-snow *versus* rainfall days. Red: positive correlation; Blue: negative correlation. Large shaded circle: significant at 99% confidence level and above; small shaded circle: significant at 95% confidence level and above

(Figure 10). It shows that the rate of rain-on-snow days change decreases from about 2.5 to 0.2 days per degree Celsius as stations' mean winter air temperatures increase from about -19 to -5 °C, while the rate of rainfall days increases from 0.1 to about 2.5 days per degree Celsius as air temperature increases at the same range among these stations. And the rates of rain-on-snow increase are higher than that of rainfall day increase when the stations' mean air temperatures are below about -8 °C. The opposite is true when the temperature is higher. This suggests that rain-on-snow days increase more rapidly at colder temperatures but that rainfall days increase more rapidly at higher temperatures. The opposite trend in changing rate per degree of temperature increase is possibly attributable to decreases in snowfall days and therefore fewer snow cover days at stations that have higher air temperatures. This threshold of -8 °C seems to match that at which the correlation between snowfall days and air temperature shifts from positive to negative over northern Eurasia (Ye, 2008).

The correlation of NAO with rain-on-snow, rainfall, and snowfall days is shown in Figure 11. Seventeen stations have positive correlation between rain-on-snow days and NAO index, with three that are statistically significant at 99% confidence level and above, and eight that are significant at 95% and above. Among five southern stations with negative correlations only one shows a statistically significant correlation (Figure 11(a)). A similar correlation pattern is found in rainfall days (Figure 11(b)) except for the two westernmost stations; they are significantly positively correlated with the NAO index. The NAO index is negatively correlated with snowfall days at stations located over the western side of the study region and is positively correlated with snowfall days at stations on the eastern side of the study region (Figure 11(c)). Only three negative correlation stations and one positive correlation station are statistically significant. The results

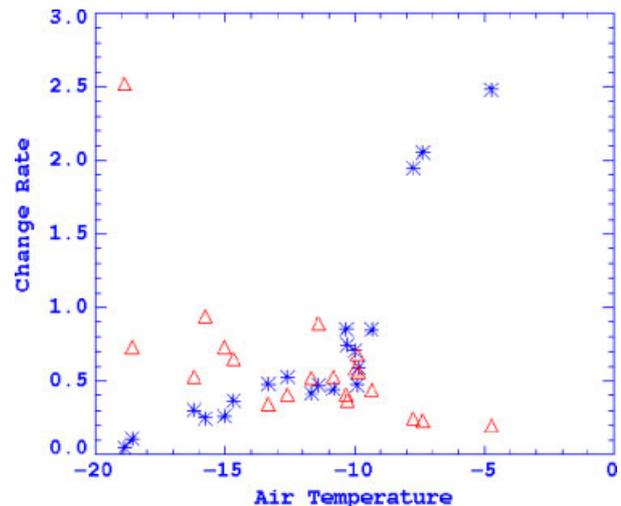


Figure 10. Scatter plot of rate of change in rain-on-snow days (triangles) and rainfall days (stars) versus stations' mean air temperature during winter

suggest that NAO influences rainfall days and therefore rain-on-snow days mostly over northern European Russia and has less influence on snowfall days over the study region. This is consistent with other research, which finds that under positive phases of NAO, warm and moist air moves further north (into the northern study region) bringing in higher air temperatures and more precipitation (while the southern region may suffer from less precipitation and colder temperatures) (Hurrell, 1995; Serreze *et al.*, 1997). The results also suggest that the relationship between rain-on-snow days and NAO is not as strong as that of surface air temperature for the study region.

SUMMARY

This study examines the climatology of rain-on-snow days over northern Eurasia and its relationships to air

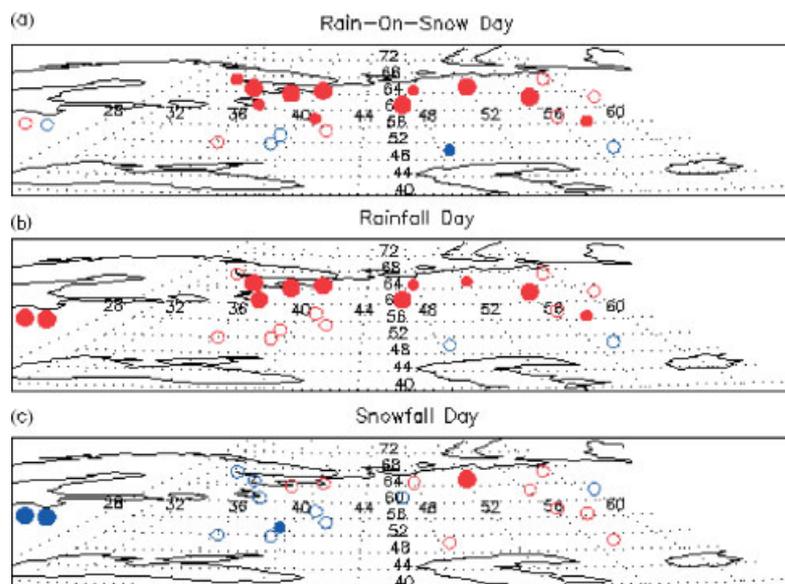


Figure 11. Correlation between NAO Index and (a) rain-on-snow days (b) rainfall days (c) snowfall days. Red, positive correlation; Blue, negative correlation. Large shaded circle: significant at 99% confidence level and above; small shaded circle: significant at 95% confidence level and above

temperatures, rainfall days, snowfall days, and atmospheric circulation over European Russia using synoptic observations for the time period of 1936/1937–1989/1990. We find that most rain-on-snow days occur west of the Ural Mountains (west of about 61 °E) during the winter season. Rain-on-snow days increase with air temperature and rainfall days but have no significant relationship to snowfall day changes. This suggests that changes in rain-on-snow days are predominantly related to changes in rainfall days accompanied by air temperature changes during the European Russian winter. Yet, snowfall days might be the limiting factor to the rate of increase in rain-on-snow days in areas where the mean air temperature is -8°C or higher. This is reflected in the higher rates of rain-on-snow day change when the mean air temperature is lower, opposite to that of rainfall days.

The NAO has a positive correlation with rain-on-snow days and rainfall days over the northern portion of the study region. Its influence on snowfall days is not as evident, although there is a clear regional pattern of separation between positive and negative correlation. The overall influence of atmospheric circulation on rain on snow is weaker than the influence of air temperature changes.

The results suggest that rain-on-snow days will increase at a rate of 0.5 day to 2.5 days per degree Celsius increase in air temperature. The most rapid increases will be at locations at which air temperature is low, and the rate of increase will slow down as air temperature rises above a certain threshold, somewhere around -8°C . This critical temperature of -8°C coincides with the critical temperature above which snowfall day switches from increases to decreases with air temperatures (Ye, 2008), thereby limiting the rain-on-snow day increases. The results also suggest that rain-on-snow days will invade central Eurasia, where it was a rare event before evident warming appears during the 1990s.

The apparent opposite relationships between rain-on-snow events and air temperature between European Russia and the western United States is likely due to the difference in climate regimes. In the western United States, the decrease in rain-on-snow events is mostly associated with decreases in snowfall days (McCabe *et al.*, 2007) due to its warmer climate. McCabe *et al.* also point out that air temperature has less impact on rain-on-snow days at high elevation stations where air temperature has little effect on the number of snowfall days due to their low temperature. The increases in rain-on-snow events over European Russia are due to increases in rainfall days, whereas snow cover does not have much impact because air temperature are frequently below freezing point. This study also suggests that snowfall day changes will become a limiting factor and rain-on-snow days will decrease eventually if air temperature continues to rise. However, given the current range of station temperature differences during the study period, only the magnitude of change is affected but not significantly enough to affect the direction of change in rain-on-snow days.

Rain-on-snow events over high-latitude regions have been studied very little, although their influences on hydrological cycles as well as terrestrial and ecological systems can be very significant. More studies are needed to investigate the potential impact of warming climate on this region where snow is present during at least half of the year. Future study should include data of more recent decades, during which warming is evident to confirm that the findings here still hold true. Also, the thresholds of atmospheric conditions in combination with the specific geographical information to identify transition from snow days to rain days need to be identified for this region. This will contribute to a better understanding of changes in precipitation characteristics in high-latitude regions under a warming climate.

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