Rain-on-Snow Event and its Relationships to Air Temperature over Northern Eurasia

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ABSTRACT

This study reveals the climatology of rain-on-snow events and its relationships to air temperature during winter season to reveal potential changes in number of rain-on-snow days and rainfall days under a warming climate over northern Eurasia. We found that both rain-on-snow days and rainfall days increase as air temperature increases and the magnitude of increase is most significant (about one day per 1°C increase) over European Russia. This study also suggests that rain-on-snow events may have a significant influence on river discharge, especially extremely high or low discharge, in the high-latitude regions.

Keywords: rain-on-snow, Eurasia, rainfall, air temperature

INTRODUCTION

Studies on the accelerating Arctic hydrological cycle under a warming climate have focused heavily on increases in precipitation amount (Nicholls et al. 1996; Ye 2001a), high intensity rainfall days (Groisman et al. 1999), snow depth (Brown and Braaten 1998; Ye et al. 1998; Ye 2001b), and river discharge (Berezovskaya et al. 2005; Serreze et al. 2003b; Yang et al. 2002; Ye et al. 2004; Peterson et al. 2002; Manabe et al. 2004; Oelke et al. 2004; Zhang et al. 1999). In addition, the reduction in both snow cover and ice cover in recent decades has been in the public spotlight (Brown and Goodison 1996; Robinson et al. 1995; Serreze et al. 1995; Stroeve et al. 2005). These changes have significant impacts on the 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 as much. For instance, rain-on-snow events, although occurring much less frequently than rain or snow events have had adverse impacts on ungulate population dynamics (Miller et al., 1975; Putkonon and Roe, 2003; Reimer, 1982; Solberg et al., 2001). However, the impact of changes in the frequency of rain-on-snow events, have not yet been studied.

Rain-on-snow events outside of the Arctic region have been found to trigger flooding (McCabe et al., 2007; Singh, 1997; Sui and Koehler 2001), increases in stream acidity (Eimers et al., 2007), avalanches in mountainous regions (McCabe et al. 2007; Sui and Koehler 2001; Singh 1997). A recent study of rain-on-snow events over the western United States suggested that their frequency

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has been decreasing due to the disappearance of snow on the ground caused by warmer air temperatures (McCabe et al. 007).

The impact of increasing air temperature on rain-on-snow events over the Arctic may be different from those in the western United States. Studies over northern Eurasia suggested that snow depth (Ye et al. 1998; Ye 2001b) and snowfall season length have increased (Ye, 2001c), but little change occurred in continuous snow cover length (Ye and Ellison 2003). Rain-on-snow events may actually become more frequent even though there might be little shift from solid to liquid precipitation due to below freezing temperatures in the region.

This purpose of this study is to use historical synoptic observational records to evaluate the relationship of rain-on-snow events and frequency of rainfall with air temperature over northern Eurasia during the winter season. In addition, the potential impacts of rain-on-snow events on river discharge will be explored.

DATA AND METHODS

The synoptic weather data are from the Six- and Three-Hourly Meteorological Observations from 223 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 6- (1936-1965) and 3-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, and wind speed and 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) are adjusted based on station time zone.

The types of current weather coded 50-59 representing ten types of drizzle (slight, moderate, heavy, etc.), 60-67 representing eight types of rain (intermittent, continuous, slight, etc.) and coded 80-82 include three types of rain shower (slight, moderate, heavy and violent). All of these are considered to be rain events. Thunderstorms of liquid products occurring at the observation time or during the preceding hour are coded 91, 92, or 95 and 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.

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), 7 (ice, snow, or melting snow covering ground completely), 8 (loose dry snow, dust, or sand covering more than one-half of the ground), or 9 (loose dry snow, dust, or sand 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 the 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 is used to check if it falls outside of the snowfall season. If it does not, the day is considered as missing for the rain-on-snow event.

To be 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.

The number of days featuring rain with snow on the ground is totaled for the entire year, and three seasons of winter seasons (December to February), spring (March to June to include all snow-covered days), and fall (September to November). 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 regardless of ground condition is totaled for the winter seasons for comparisons with rain-on-snow days. Among these 223 stations, 80 stations are retained for analyses (the ones that have quality data starting around 1936-37, no later than 1940-41). The locations of these 80 stations are shown in Figure 1. The number of missing rain-on-snow days ranges from 2 to16 for annual totals, with less missing days for each season during the 53 years of the study period. For example, the number of missing winter rain-on-snow days ranges from 1 to 13 days. The number of missing rain days ranges from 2 to 17 days. The slightly higher number of missing winters for rainfall days is due to the fact the weather code is checked for missing for all 90 or 91 days of each winter instead of just during the snow on the ground days.

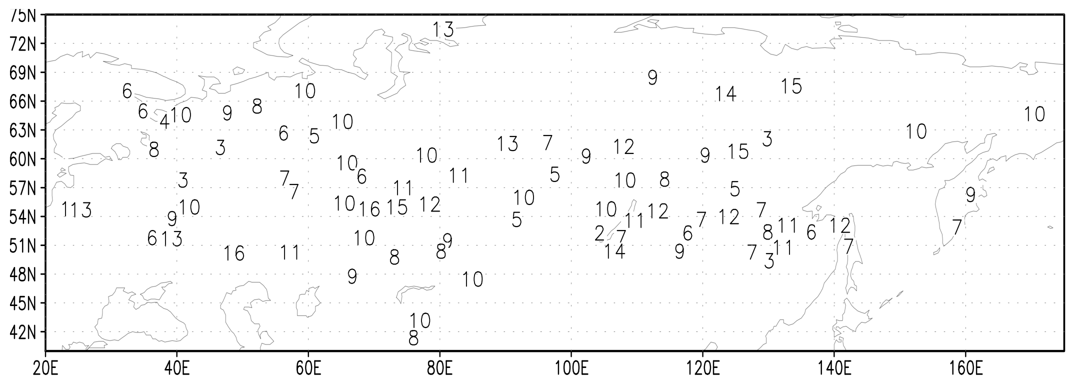

Figure 1. Location of the eighty stations and the number of missing rain-on-snow years during 1936/37-1989/90.

Daily air temperature (AIRT) which is measured at two meters above the ground, are 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.

To provide general information for the study region, the area-averaged values of rain-on-snow, rainfall days, and air temperature are calculated. To do this, station data are interpolated into grids of 5°latitude by 5°longitude using Willmott et al. (1985)'s Shepard's method of local-search interpolation on a spherical surface. Then the grids are adjusted for differences in surface area depending on the latitude by multiplying coefficients of square root of cosine latitude. Finally, the adjusted grid values are averaged to derive the area average values for each winter.

RESULTS

The numbers of rain-on-snow days range from 0 to 14 days each year and high number of days are mostly concentrated over European Russia, east of the Ural Mountain or 60°E (Figure 2). Rain-on-snow days increase in frequency towards the west where warm and moist air occasionally intrudes into the region.

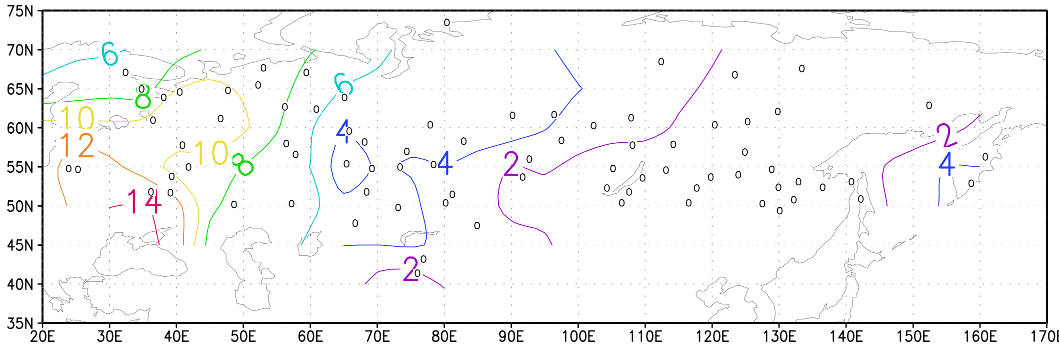

Figure 2. Mean total rain-on-snow days during 1936-1999

The mean rain-on-snow days during three seasons of fall, winter, and spring is shown in Figure 3. For the fall, the rain-on-snow mostly occurs over northern European Russia with 1-2 days over western Siberia and less than 1 day over eastern Siberia. For winter, the rain-on-snow occurs only over European Russia, almost no rain-on-snow events over Siberia. This pattern resembles that of total rain days during the winter season (not shown), except for the number of days that are less than the total rain days from east to west. This indicates that some of the rain days occur with no snow on the ground on the western side of European Russia during the winter season. For spring, the rain-on snow days spread out towards east into eastern Siberia although it is less than 1 day per spring (Figure 3).

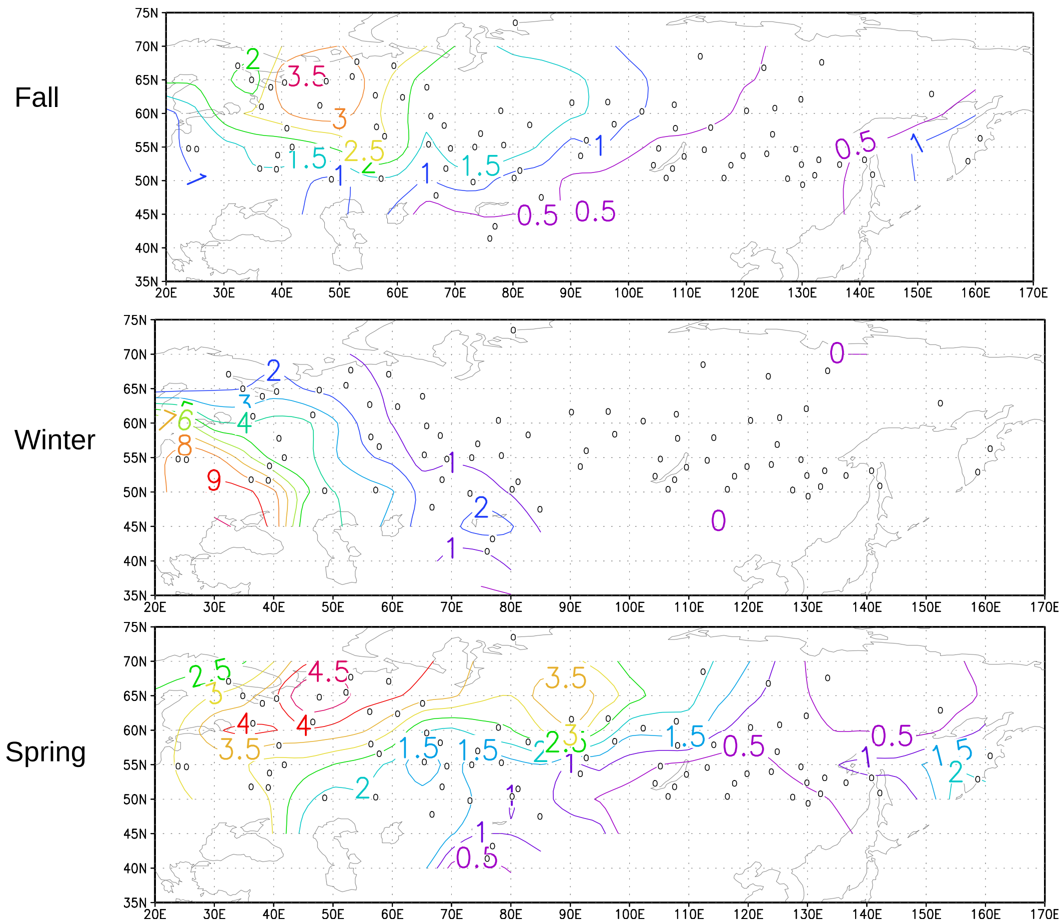

Figure 3. Mean rain-on-snow events for three seasons of fall, winter, and spring during 1936-1989.

The time series of area averaged winter rain-on-snow days does not show any significant trend during the study period of 1936-89. It increases in the early years, stays high during the 1950s and 60s, and decreases starting in the 1970s (Figure 4). When rain-on-snow days are plotted against mean air temperature, their frequency increases as air temperature increases (Figure 5), and the correlation coefficient is 0.3100 (significant at above a 0.05 level). This suggests that with an increase of air temperature by 7°C, the average rain-on-snow day increases about 2.5 days. In the same figure, the increases in total rain days are even more significant. The correlation coefficient is 0.3820, significant at a 0.01 level. Average rain days increase 3 days when air temperature increases about 7°C. No significant correlation between snow days and air temperature is found.

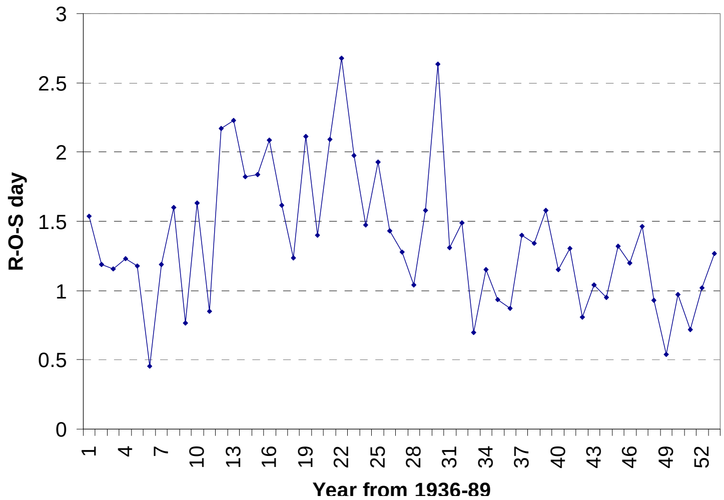

Figure 4. Time series of winter area-averaged rain-on-snow days from 1936-89 over northern Eurasia.

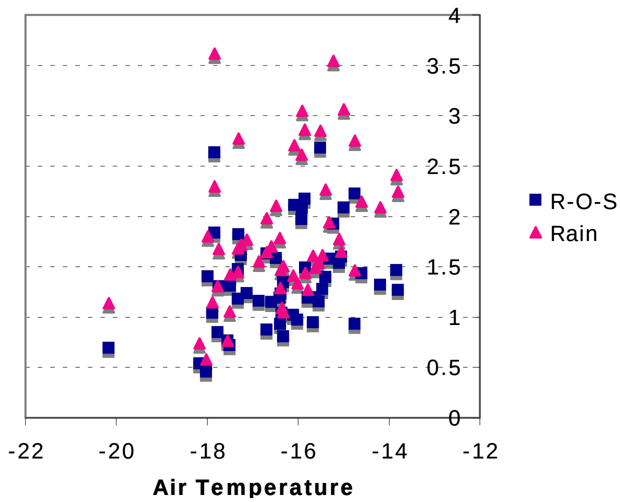

Figure 5. Scatter plot of the area-averaged rain-on-snow days and rainfall days against the area-averaged air temperature over northern Eurasia.

Since most rain-on-snow days are concentrated over the European Russia, west of 60°E (roughly the longitude of the Ural Mountains), the relationship is examined specifically for the European Russian region here. The grids of rain-on-snow values, air temperatures, rainfall days located east of 60°E (almost parallel to the Ural Mountains) are used to derive the area average values for this region. The hydrologic station (62.42°N, 52.28 ° E) at the mouth of the Pechora River is selected to reflect the large-scale discharge condition. Winter discharge values are used to correlate with rain-on-snow events, number of rain days, and air temperature.

The scatter plot of area-averaged (over west of 60°E) of both rain-on-snow and rainfall days against area averaged air temperature is shown in Figure 6. It is clear that both rain-on-snow days and rainfall days increase as air temperature increases during the winter season of the study region (Figure 6), with the magnitude of increase at about 6 days as the air temperature increases by about 6°C. This translates to about one rain-on-snow day/rain day increases per 1°C increase in air temperature. The correlation coefficient is 0.3986 (significant at a 0.01 level) for rain-on-snow days and is 0.3613 for rain days (significant at a 0.05 level).

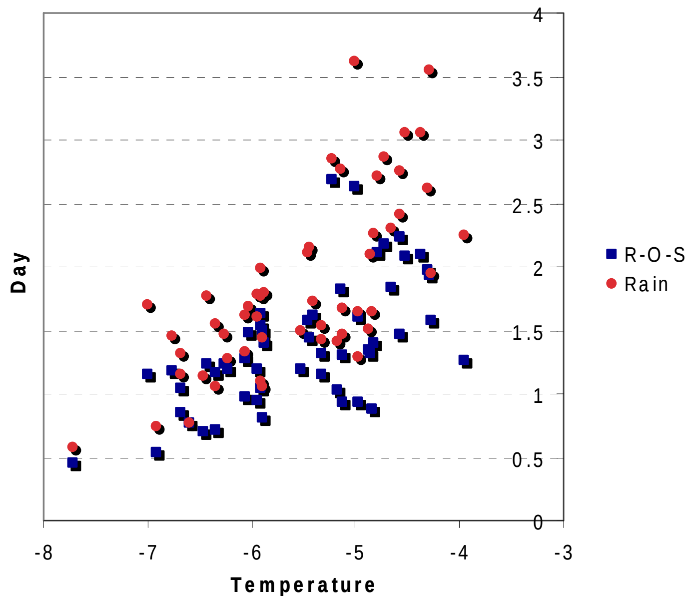

Figure 6. Scatter plot of area-averaged rain-on-snow days, rainfall days, and snowfall days against area-averaged air temperature for European Russian region (east of Ural Mountain).

The river discharge during winter season at the Pechora is most significantly correlated with rain-on-snow days with a correlation coefficient of 0.3878 (significant at a 0.01 level). The second significant correlation is with air temperature with a coefficient of 0.3564 (significant at a 0.02 level). River discharge is also correlated with rainfall days with a coefficient of 0.2758 at a 0.05 significance level. Figure 7 shows the discharge versus rain-on-snow days. Extremely low and high discharge winters are associated with extremely low and high averaged rain-on-snow days, suggesting the importance of the relationship during extreme winters.

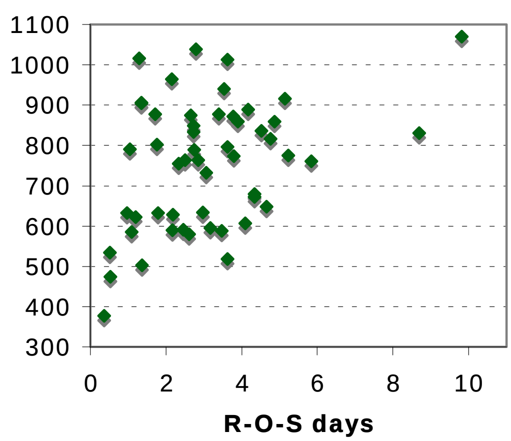

Figure 7. Scatter plot of winter mean discharge against area-averaged rain-on-snow day over the European Russia

SUMMARY

This study examined rain-on-snow days over northern Eurasia and their associations with air temperature and river discharge. We found that rain-on-snow day ranges from 0-14 and most concentrated on the area east of Ural Mountain, especially during winter season where no rain-on-snow events occur over Siberia. Both rain-on-snow days and rain days increase with the air temperature increases regardless of geographical regions of either averaged over the entire northern Eurasia or over western European Russia. The magnitude of increase in both rain-on-snow events and rainfall days is more significant over western Eurasia where climate is milder than over the rest of the region. There is, on average, about a one-day increase in rain-on-snow days per 1°C increase in air temperature over European Russia during winter season over the study time period. The frequency of rain-on-snow days is most significantly correlated with winter river discharge over the Pechora river basin, especially during extreme winters. Air temperature and rainfall days also significantly influence winter river discharge, but not as much as the frequency of rain-on-snow days does.

Rain-on-snow events have been studied very little although their influence on hydrological cycles, terrestrial and ecological system can be very significant. More studies are needed to investigate the impact of warming climate on such events especially over high-latitude regions where snow is present during at least half of the year. Future studies should examine the relationship at local scales and also include fall and spring seasons when the relationships may be different. Also the thresholds of atmospheric conditions in combination with the specific geographical information to identify transition from snow days to rain days needs to be identified. This will contribute to a better understanding of changes in precipitation characteristics and frequency in high-latitude regions under a warming climate.

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