# RAIN-ON-SNOW EVENTS IN THE WESTERN UNITED STATES

BY GREGORY J. McCABE, MARTYN P. CLARK, AND LAUREN E. HAY

Severity of rain on snow depends on a number of factors, and an overall decrease in these events appears to be driven, in part, by changes in El Niño–Southern Oscillation.

Rain-on-snow floods are a fascinating hydrometeorological phenomenon. Their severity depends not only on the magnitude of the precipitation, but also on the elevation of the freezing level and the water equivalent and areal extent of the antecedent snowpack. The necessary juxtaposition of these causative factors creates interesting challenges for both flood prediction and flood risk assessment.

Flood forecasting involves running a hydrologic model up to the start of the forecast period to estimate basin initial conditions (e.g., snowpack, soil moisture), and then running the model into the future with an ensemble of meteorological forecasts to produce probabilistic forecasts of streamflow (Day 1985; Clark and Hay 2004). The major uncertainties associated with predicting rain-on-snow events include the model estimates of the areal extent and water equivalent of the antecedent snowpack, the meteorological forecasts of precipitation and freezing level, and the model's representation of rain-on-snow processes. There is potential to improve flood forecasts by implementing snow data assimilation methods (McGuire et al. 2006; Andreadis and Lettenmaier 2006; Slater and Clark 2006; Clark et al. 2006), as well as innovative methods to use downscaled output from numerical weather prediction models (Clark and Hay 2004; Hamill et al. 2006). However, improving forecasts of rain-on-snow floods is limited by the lack of general knowledge about the character of rain-on-snow events in the western United States.

Assessment of flood risks involves fitting a statistical distribution to a sample of observed flood peaks, and calculating the water level for different probabilities (e.g., the 100-yr flood). This approach is limited by the small sample size used to construct the flood frequency curve, by the implicit assumption that the climate is stationary, and because the statistical distribution approach is unreliable when flood probabilities are extrapolated beyond the range of the data sample (e.g., Franks and Kuczera 2002; Merz and Bloschl 2003; Sankarasubramanian and Lall 2003; Sivapalan et al. 2005). Such limitations of the flood frequency approach seem unsuitable at a time when we are observing significant decreases in the

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seasonal snowpack and a shift to earlier timing of snowmelt in the western United States (Stewart et al. 2004; Regonda et al. 2005; Mote et al. 2005; McCabe and Clark 2005). Assessment of flood risks can be improved by better understanding the physical processes that cause floods of different types, as well as the frequency of occurrence of different flood types in different regions (Merz and Bloschl 2003). This information also is currently lacking in the western United States.

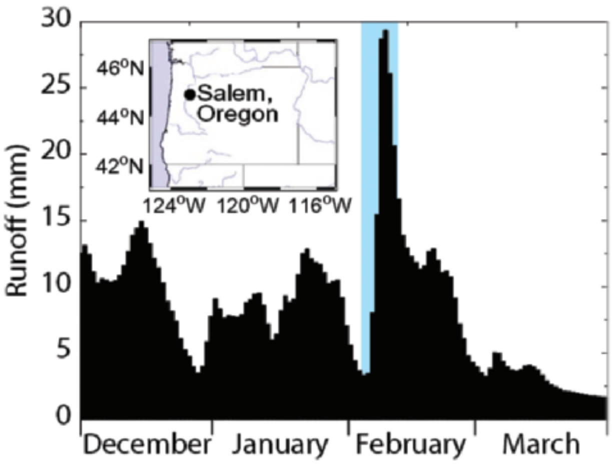


**Fig. 1. Daily runoff for the Willamette River basin measured at Salem during December 1995 through March 1996. The blue-shaded bar indicates the February 1996 rain-on-snow event.**

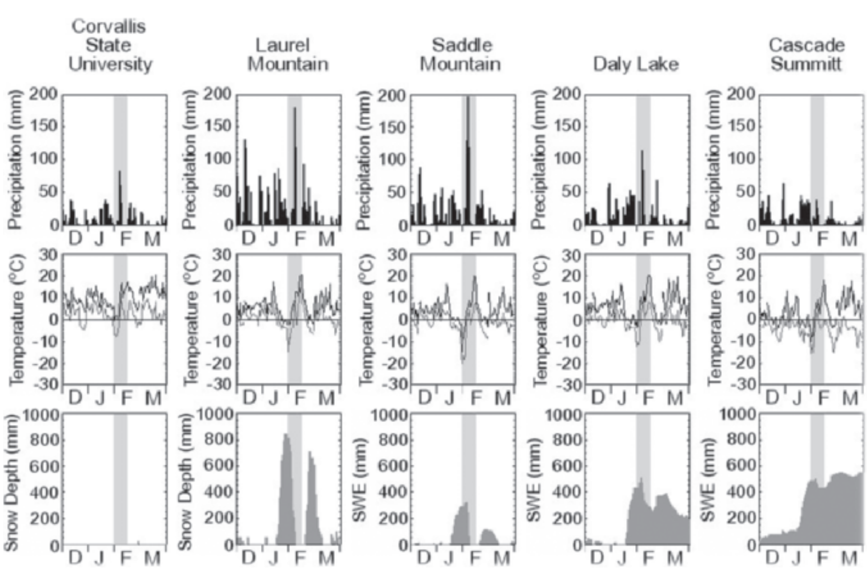


**Fig. 2. Precipitation (mm), minimum and maximum temperature (°C), and snow depth (mm) or SWE (mm) during December 1995 through March 1996 for sites in the Willamette watershed. The gray-shaded bars indicate the February 1996 rain-on-snow event. Snow depth data were available for cooperative weather stations and SWE data were available for snow telemetry stations.**

Given the potential significance of rain-on-snow floods, it is surprising that so little is known about them. Most knowledge of rain-on-snow events is based on anecdotal descriptions of different events, or on detailed case studies of the physical processes in individual events [see Marks et al. (1998, 2001) for a detailed description of the February 1996 event in the Pacific Northwest]. Very little is known about the relative importance of rain-on-snow events for the flood hydrology of the western United States.

As a starting point, we perform an analysis of the characteristics of rain-on-snow events in the western United States. The purpose of this study is to provide basic information on the spatial patterns, seasonality, interannual variability, and trends of rain-on-snow events in the western United States.

**THE FEBRUARY 1996 RAIN-ON-SNOW EVENT IN THE WILLAMETTE RIVER BASIN.** A case study of a significant and widespread rain-on-snow event illustrates the hydrologic effects of rain-on-snow events. During February 1996 a wet Pacific storm brought heavy precipitation into the Pacific Northwest that fell on existing snowpacks (Marks et al. 1998). The rain-on-snow events subsequently resulted in substantial flooding in several areas of the Pacific Northwest (Marks et al. 1998). Figure 1 shows daily runoff for the Willamette River measured at Salem, Oregon. The rain-on-snow event (indicated by the blue-shaded bar in Fig. 1) produced a rapid rise in runoff during and after the event, which resulted in the flooding that occurred in the Pacific Northwest during February 1996.

Figure 2 illustrates the temporal evolution of the 1996 rain-on-snow event for a selection of cooperative (COOP) and snow telemetry (SNOTEL) weather stations in and around the Willamette River basin in Oregon (Fig. 3). Temperature and precipitation data were available for both the COOP and SNOTEL sites, whereas snow depth data were available for COOP sites and snow-water equivalent

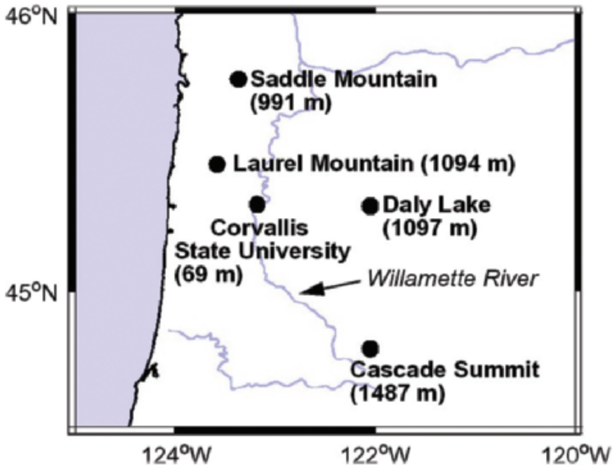


**Fig. 3. Climate stations used for the case study of the February 1996 rain-on-snow event in the Willamette River basin. [Site elevations (m) are indicated in parentheses.]**

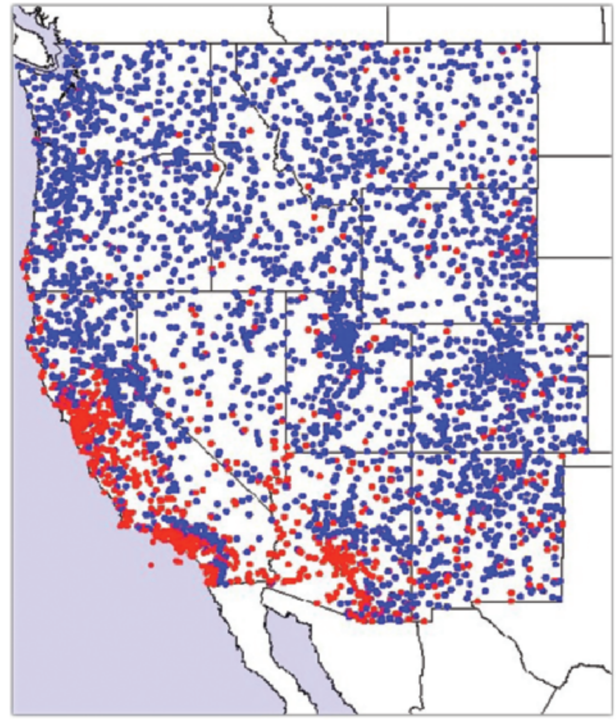

**Fig. 4. Sites analyzed in this study. Blue dots indicate sites with at least one rain-on-snow event, red dotes indicate sites with no rain-on-snow events during 1949 through 2003.**

(SWE) data were available for the SNOTEL sites. Snow depth and SWE are generally highly correlated; snow depth is a simple measure of the depth of snow on the ground, whereas SWE is a measure of the water content of the snow.

Steady precipitation and subzero temperatures in the second half of January formed a snowpack that reached 800 mm in depth at the Laurel Mountain COOP site (1094 m above sea level) and 300 mm in SWE at the Saddle Mountain SNOTEL site (991 m above sea level). The late-January SWE totals were even greater at high elevations. In the early part of February 1996, temperatures warmed such that both daily maximum and minimum temperatures were above freezing at all locations except the Cascade summit SNOTEL site. These warm temperatures were accompanied by extremely heavy rain, with daily precipitation totals ranging between approximately 30 and 200 mm (between about 1 and 8 in.). There was no snow at locations in the valley floor (e.g., at Corvallis, left column of Fig. 2), but the snow at the midelevations melted off completely (e.g., Laurel Mountain and Saddle Mountain), and there was significant melt at the high-elevation Daly Lake SNOTEL site. This torrential rain and extensive snowmelt produced the large runoff event that caused the flooding throughout the Willamette Valley.

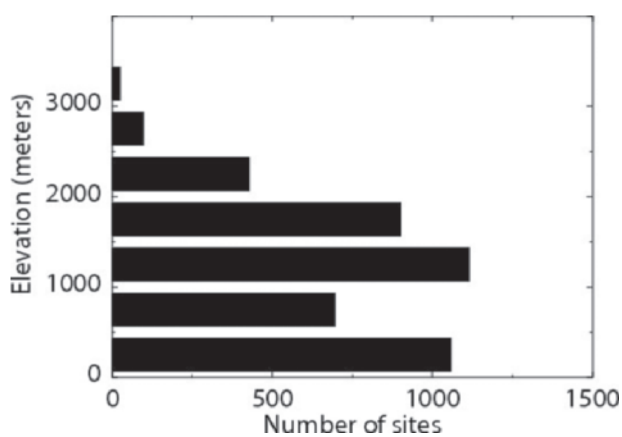


**Fig. 5. Number of sites for seven elevation bands (0–500, 501–1000, 1001–1500, 1501–2000, 2001–2500, 2501–3000, and greater than 3000 m).**

## SPATIAL PATTERNS AND SEASONALITY OF RAIN-ON-SNOW EVENTS.

Daily precipitation and snow depth of 4318 cooperative weather stations in the western United States were used to examine the spatial and temporal variability of rain-on-snow events for water years 1949 through 2003 [please see Clark and Slater (2006) for more details on the data and quality control procedures]. The 4318 sites have a nearly uniform spatial coverage across the western United States (Fig. 4); however, the number of sites decreases with increasing elevation, especially above 2000 m (Fig. 5). SNOTEL data were not used for this study because most SNOTEL measurements began in the early 1980s and do not provide a long record for analysis.

A rain-on-snow event for a site was defined as a day when precipitation occurred and snow depth decreased. Although a rain-on-snow event may not result in a decrease in snow depth, the interest of this study is the rain-on-snow events that could potentially have a hydrologic effect (e.g., resulting in a change in streamflow); thus, only rain-on-snow events that resulted in a decrease in snow depth were analyzed. For all days defined as rain-on-snow events, precipitation amount and snow depth reduction also were computed. Of the 4318 sites, 3364 experienced at least one rain-on-snow event during 1949–2003 (Fig. 4).

Figure 6 illustrates the total number of rain-on-snow events on a monthly basis that occurred during the period of study. Rain-on-snow events are most frequent in the Pacific Northwest (the red hues in Fig. 6). At 380 sites over 100 rain-on-snow events occurred over the 55-yr period of record. This translates to almost two events each year. There are 86 sites that experienced at least 200 rain-on-snow events, and two sites located in the Pacific Northwest experienced more than 400 rain-on-snow events.

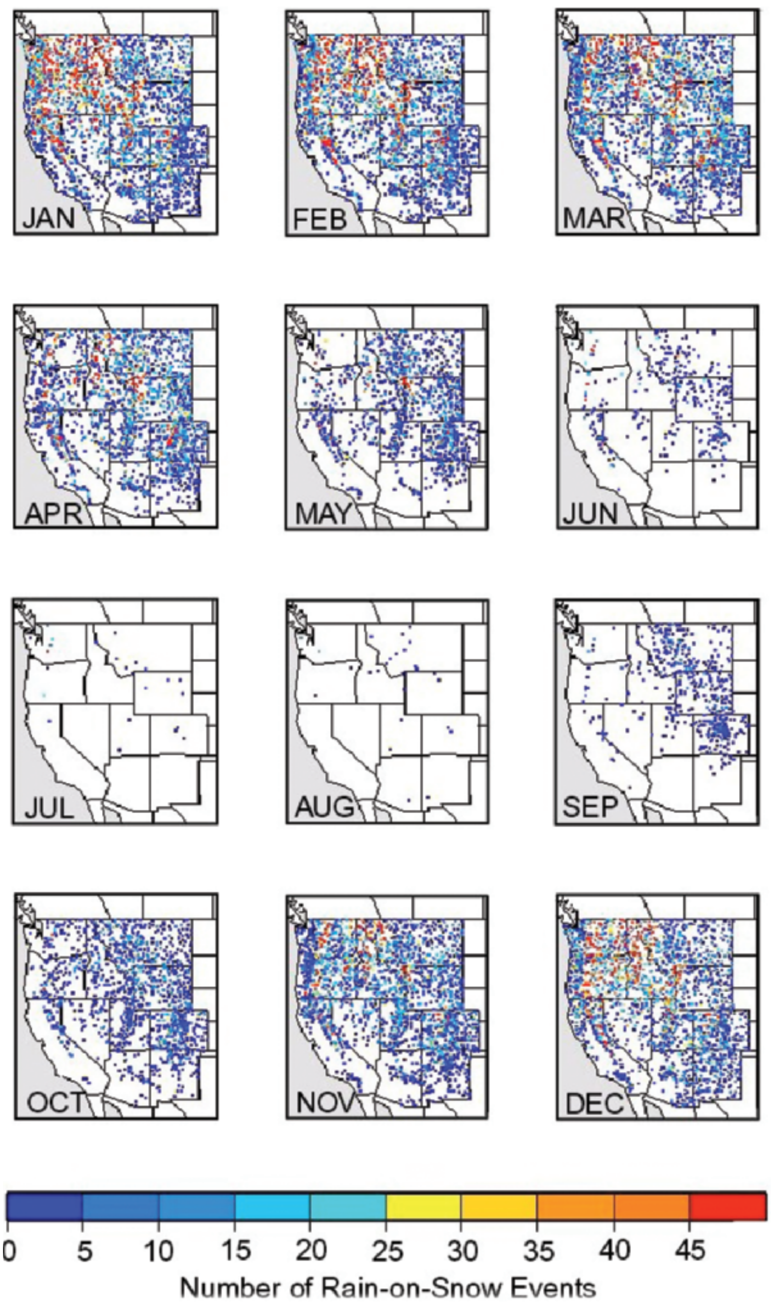


**Fig. 6. Total number of rain-on-snow events by month during 1949–2003.**

Rain-on-snow events are less frequent in the colder interior western United States, although rain-on-snow events in the interior West can occur as early as September and as late as June. The incidence of rain-on-snow events in the “shoulder” seasons in the interior West occurs because of the long snow season. The events in September result from early snowpacks that develop and are affected by subsequent rainfall; the events in May and June occur because snowpacks persist into the late spring/early summer when temperatures are warm enough for precipitation to fall as rain rather than as snow. Overall, the October through May period included the majority of rain-on-snow events for most sites.

In addition to the frequency of rain-on-snow events by month, the mean magnitude of snow depth loss during rain-on-snow events also was computed for each month (not shown). During January when rain-on-snow frequencies are the highest, snow depth losses are generally greatest in the northwestern United States. During April and May (and June) the largest snow depth losses per rain-on-snow event occurs in the interior western United States. This eastward shift in the magnitude of snow losses per rain-on-snow event occurs because during the spring/early summer months the magnitude of snow depth is largest in the interior western United States; thus, rain-on-snow events in these locations can still melt a significant amount of snow.

An analysis of rain-on-snow events subdivided by elevation and season (cool season, October through March; and warm season, April through September) reveals some interesting characteristics of rain-on-snow events (Fig. 7). The precipitation characteristics examined in this analysis include those that are necessary for rain-on-snow events to occur: 1) precipitation days, 2) precipitation days of rain, 3) precipitation days with snow on the ground, and 4) rainfall on snow that results in a loss of snowpack (i.e., rain-on-snow events).

During the cool season the lowest elevations experience the largest number of precipitation days (Fig. 7c), whereas for the warm season the elevational distribution of precipitation days is relatively uniform (Fig. 7d). The slight decrease in precipitation occurrence with elevation in the cool season initially seems somewhat counterintuitive given the importance of orographic precipitation in the western United States. However, most high-elevation sites are in the dry interior West, suggesting that the elevational dependence may reflect the proximity to moisture sources rather than orographic uplift. Nevertheless, the temperatures at low-elevation sites are warmer, which affects both the precipitation phase [rain versus snow (Fig. 7e)] as well as the number of days with snow on the ground (Fig. 7g).

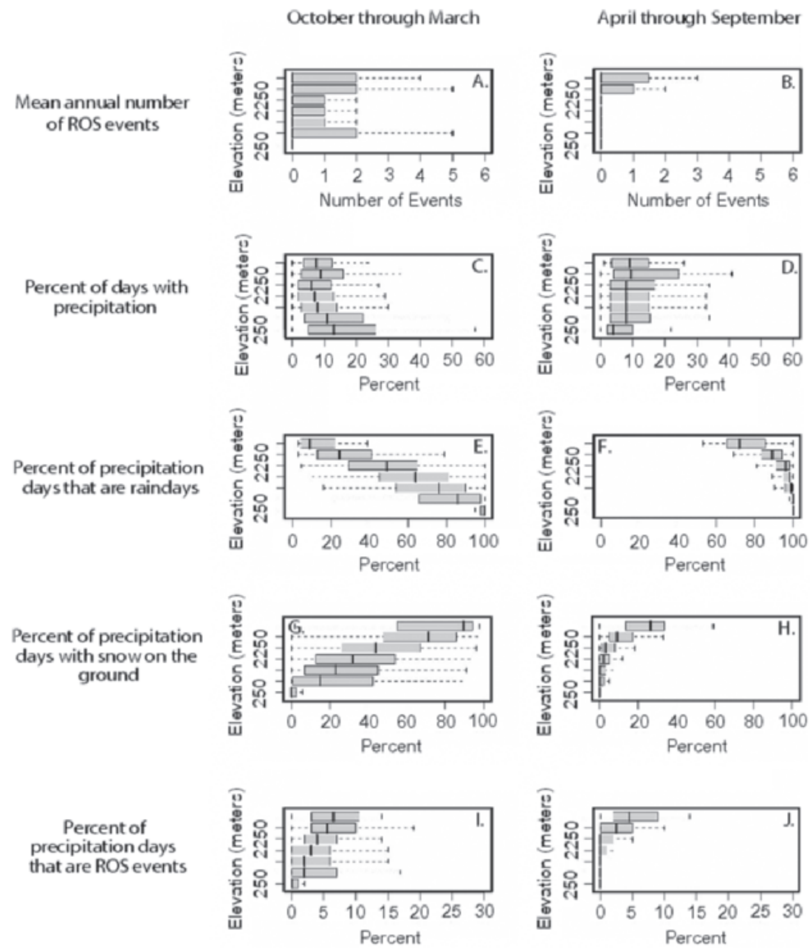


**Fig. 7. Box plots of the distributions of precipitation and rain-on-snow (ROS) statistics by elevation for cool (October through March) and warm (April through September) seasons. (The elevation bands used are 0–500, 501–1000, 1001–1500, 1501–2000, 2001–2500, 2501–3000, and greater than 3000 m. Elevation bands are indicated by the center elevation for each band. The gray-shaded boxes indicate the range of values between the 25th and 75th percentiles, the dark vertical line indicates the median, and the ends of the dashed lines indicate the 1st and 99th percentiles of the distributions.)**

The number of rain days at a site is an important precipitation characteristic related to the frequency of rain-on-snow events. For the cool season the percentage of precipitation days that are rain days is nearly 100% at the lowest elevations, and this percentage decreases rapidly with increased elevation (Fig. 7e). However, for the warm season the percentage of precipitation days that are rain days is above 90% up to approximately 3000 m (Fig. 7f). Even above 3000 m, for most sites, over 70% of the precipitation days are rain days during the warm season.

Another necessary condition for rain-on-snow events is an accumulation of snow on the ground. During the cool season the percentage of precipitation days with snow on the ground is close to zero for low elevations, but from 80% to 90% for most sites at the highest elevations (Fig. 7g). Even during the warm season the percentage of precipitation days with snow on the ground for the highest elevations is over 20% for most sites (Fig. 7h). Temperatures at low-elevation sites are warmer, which affects both the number of days with snow on the ground (Figs. 7g and 7h) as well as precipitation phase (rain versus snow; see Figs. 7e and 7f).

The combination of the percentage of precipitation days, the percentage days that are rain days, and the percentage of precipitation days with snow on the ground results in a distribution of cool-season rain-on-snow events (expressed as a percentage of precipitation days) that slightly increases with elevation (Fig. 7i). At the lowest elevations the percentage of cool-season precipitation days that are rain-on-snow events is close to zero for most sites (Fig. 7i). For the warm season the distribution of rain-on-snow events, as a percentage of precipitation events, increases from near zero at the lowest elevations to a median value of near 5% for the highest elevations (Fig. 7j). This elevation relation with rain-on-snow events during the warm season is primarily related to the number of days that snow is on the ground.

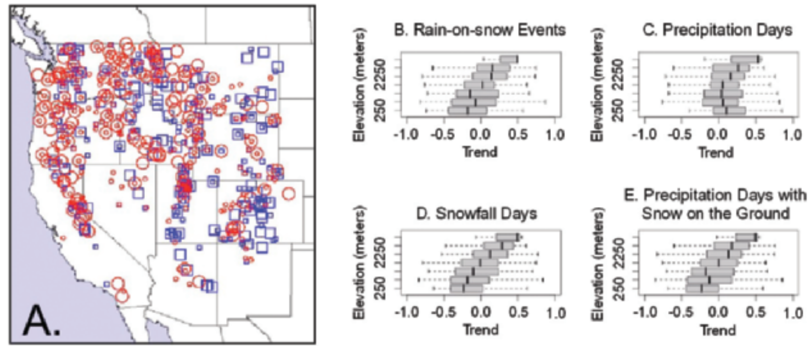


**Fig. 8. (a) Linear trends (expressed as correlations with time) of ranked October through May total rain-on-snow events, 1949–2003. Red circles (blue squares) indicate decreasing (increasing) trends. Large symbols indicate trends that are significant at a 95% confidence level. Box plots of trends in October through May: (b) number of rain-on-snow events by elevation, (c) number of precipitation days by elevation, (d) number of days with snowfall by elevation, and (e) number of precipitation days with snow on the ground by elevation. (The elevation bands used are 0–500, 501–1000, 1001–1500, 1501–2000, 2001–2500, 2501–3000, and greater than 3000 m. The elevation bands are indicated by the center elevation for each band. The gray-shaded boxes indicate the range of values between the 25th and 75th percentiles, the dark vertical line indicates the median, and the ends of the dashed lines indicate the 1st and 99th percentiles of the distributions.)**

## INTERANNUAL VARIABILITY AND TRENDS IN RAIN-ON-SNOW EVENTS.

An analysis of trends in rain-on-snow events provides information regarding the nonstationarity of hydrologic conditions in the western United States. This analysis is motivated by concerns regarding the hydrologic effects of global warming, and because previous research has indicated trends in the magnitudes of snowpacks and the timing of snowmelt runoff in the western United States (McCabe and Wolock 1999; Stewart et al. 2004; Mote et al. 2005; McCabe and Clark 2005).

The trend analysis is complicated by the rare occurrence of rain-on-snow events at many sites. Hence, in this analysis we restricted attention to sites with at least 35 (out of 55) yr with rain-on-snow events during the October through May period. This criterion resulted in 477 sites selected for analysis. Because these sites still included some zeros in the time series of rain-on-snow events, Spearman's rho was used to evaluate trends and monotonic relations between variables. Spearman's rho is based on ranked data and is more resistant to the effects of outliers than are traditional parametric correlation statistics, such as Pearson's *r* (Helsel and Hirsch 1992).

Linear trends of the ranked October–May rain-on-snow events indicate a noisy mixture of increasing and decreasing trends across the western United States (Fig. 8a). Of the 477 sites analyzed, 107 indicate significant (at a 95% confidence level) increasing trends and 136 sites indicate significant decreasing trends. These trends are presented with the caveat that COOP data are poorly suited to trend analysis, due to changes in observing practices (e.g., observation time) and changes in station locations (Regonda et al. 2005). These trends should therefore be interpreted as being more suggestive than conclusive. Any inferences drawn from these long-term changes should be done in tandem with the assessment of changes in other hydroclimate variables in the western United States (Cayan et al. 2001; Stewart et al. 2004; Mote et al. 2005; Hamlet et al. 2005; Regonda et al. 2005; McCabe and Clark 2005).

An examination of these trends by elevation indicates that the most significant increasing trends are for the highest elevations (Fig. 8b), and the most significant decreasing trends are for the lowest elevations. Trends in rain-on-snow events appear to be related to trends in the number of days with snowfall (Fig. 8d) and the number of precipitation days with snow on the ground (Fig. 8e). These patterns emphasize the importance of antecedent conditions for rain-on-snow events. The decrease in the number of days with snow on the ground at low elevations is consistent with previous research on declining mountain snowpack in the western United States (Hamlet et al. 2005; Mote et al. 2005; Regonda et al. 2005).

There also appears to be a tendency for decreasing trends in the northwestern United States, and a slight tendency for increasing trends in the southwestern United States (Fig. 8a). This pattern of trends appears to indicate some of the northwestern–southwest dipole of precipitation characteristics associated with El Niño–Southern Oscillation (ENSO) in the western United States (Cayan and Peterson 1989; Redmond and Koch 1991; Clark et al. 2001; McCabe and Dettinger 2002).

**CONNECTIONS WITH ENSO.** To determine whether there is an ENSO signal in the frequency of rain-on-snow events we correlated ranked mean October–May Niño-3.4 sea surface temperatures (SSTs) with ranked October–May rain-on-snow frequencies for each of the 477 sites selected for the trend analyses. The monthly Niño-3.4 SST data were obtained from the Royal Netherlands Meteorological Institute climate explorer Web site (online at http://climexp.knmi.nl). Correlations indicate the familiar dipole of precipitation response to ENSO in the western United States (Fig. 9a). For El Niño (La Niña) conditions rain-on-snow frequencies are lower (higher) than average in the northwestern United States and higher (lower) than average in the southwestern United States. These results indicate an ENSO signal in the rain-on-snow frequency data.

Examination of correlations between rain-on-snow frequencies and Niño-3.4 SSTs by elevation indicates a slight association with elevation, such that the correlations are negative for low elevations and positive for high elevations, but the relation is not statistically significant. The relation between elevation and rain-on-snow–ENSO correlations is likely driven by the relation between latitude and elevation of the 477 sites analyzed ($r = -0.70$, $p < 0.01$). Thus, the sites in the southwestern United States (low-latitude sites) are associated with high elevations and a positive correlation between rain-on-snow event frequencies and Niño-3.4 SSTs, whereas sites in the northwestern United States (high-latitude sites) are associated with lower elevations and negative rain-on-snow event correlations with Niño-3.4 SSTs.

Comparison of the pattern of trends in rain-on-snow events (Fig. 8a) and the pattern of correlations between rain-on-snow event frequencies and Niño-3.4 SSTs (Fig. 9a) produces a correlation of 0.53 ($p < 0.01$). This correlation suggests that there may be some relation between ENSO and trends in rain-on-snow events.

During the mid-1970s there was a shift in the tropical Pacific Ocean to more frequent El Niño conditions (Ebbesmeyer et al. 1991). This shift to more frequent El Niños resulted in drier and warmer conditions in the Pacific Northwest and wetter conditions in the southwestern United States. Decreases in rain-on-snow events are most easily found for low-elevation (less than 500 m in elevation) sites (Figs. 8a and 8b). There are 46 sites with elevations below 500 m and all but two are located in Washington

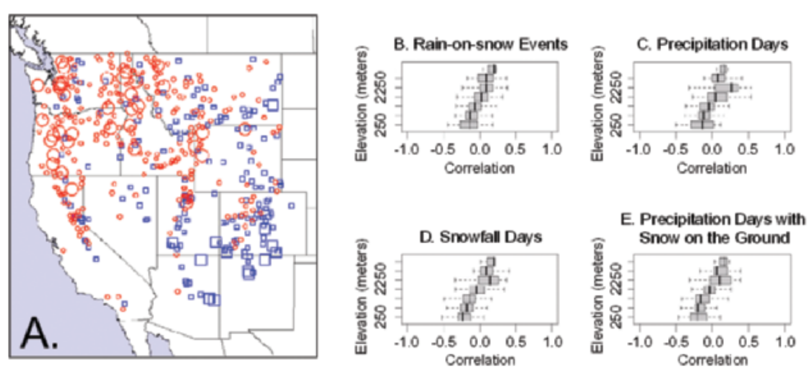


**Fig. 9. (a) Correlations between ranked October through May total rain-on-snow events and ranked mean October through May Niño-3.4 sea surface temperatures, 1949–2003. Red circles (blue squares) indicate negative (positive) correlations. Large symbols indicate correlations that are significant at a 95% confidence level. Box plots of correlations between ranked mean October through May Niño-3.4 sea surface temperatures and the (b) number of rain-on-snow events by elevation, (c) number of precipitation days by elevation, (d) number of days with snowfall by elevation, and (e) number of precipitation days with snow on the ground by elevation. (The elevation bands used are 0–500, 501–1000, 1001–1500, 1501–2000, 2001–2500, 2501–3000, and greater than 3000 m. The elevation bands are indicated by the center elevation for each band. The gray-shaded boxes indicate the range of values between the 25th and 75th percentiles, the dark vertical line indicates the median, and the ends of the dashed lines indicate the 1st and 99th percentiles of the distributions.)**

and Oregon (an additional site is located in northern California and another is located in central Idaho). The changes in temperatures and precipitation associated with the increased frequency of El Niño events are consistent with a decrease in rain-on-snow events in this region.

**CONNECTIONS WITH TEMPERATURE.** Recent studies indicated increasing temperatures in the western United States during the past several decades with subsequent effects on hydrologic conditions that include decreasing snowpacks and a shift to earlier snowmelt runoff (Stewart et al. 2004; Mote et al. 2005; McCabe and Clark 2005). Given that the occurrence of rain-on-snow events is dependent on the development of snowpacks, we performed an analysis of the relations between rain-on-snow events and regional air temperature. In this analysis, mean October through May air temperature for the western United States was computed using monthly temperature data for the climate divisions in the western United States for which there are rain-on-snow data. The climate division data were obtained from the National Climatic Data Center Web site (online at www.ncdc.noaa.gov/oa/climate/onlineprod/drought/ftppage.html). A regional temperature value was used for this analysis, rather than point values for each site, to perform an analysis at a spatial scale similar to the ENSO analysis.

Figure 10a illustrates correlations between ranked mean October–May temperature for the western United States and rain-on-snow events at each site. Correlations for a majority of the sites (366 sites) are negative, with 167 of the negative correlations being statistically significant at a 95% confidence level. There are only five positive correlations that are statistically significant. The large number of negative correlations between temperature and rain-on-snow event frequencies indicates that as temperature increases rain-on-snow events become less frequent. The negative correlations are most common for low-elevation sites (Fig. 10b). This relation is consistent with the relation observed between increasing temperatures in the western United States and decreasing snowpacks (Mote et al. 2005), and the large number of decreasing trends in rain-on-snow events, particularly for low-elevation sites (Figs. 8a and 8b).

The influence of temperature on rain-on-snow event frequency appears to be through the effects of temperature on the number of days with snowfall (Fig. 10d) and the number of precipitation days with snow on the ground (Fig. 10e). Increases in temperature in the western United States and associated decreases in snowpacks (Mote et al. 2005) have resulted in decreased opportunities for rain-on-snow events for many sites in the western United States. As elevation increases the influence of increases in temperature on rain-on-snow frequency appears to decrease (Figs. 10b–10e). This is likely because temperatures at high elevations are cold enough that increases in temperature have not greatly decreased the number of days with snowfall (Fig. 8d) or the number of days with snow on the ground (Fig. 8e). Similarly, Mote et al. (2005) found that increasing winter temperatures had little effect on snowpacks in the interior western United States, where winter temperatures are too cold for warming to affect snow accumulation.

A comparison of the pattern of trends in rain-on-snow events

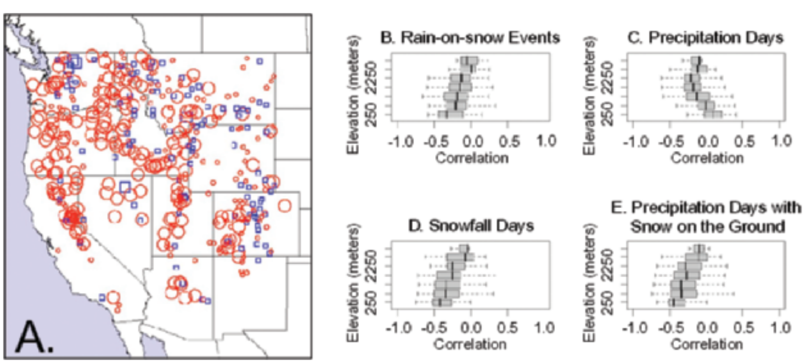


**FIG. 10. (a) Correlations between ranked October through May total rain-on-snow events and ranked mean October through May temperature averaged for the western United States, 1949–2003. Red circles (blue squares) indicate negative (positive) correlations. Large symbols indicate correlations that are significant at a 95% confidence level. Box plots of correlations between ranked mean October through May temperature and the (b) number of rain-on-snow events by elevation, (c) number of precipitation days by elevation, (d) number of days with snowfall by elevation, and (e) number of precipitation days with snow on the ground by elevation. (The elevation bands used are 0–500, 501–1000, 1001–1500, 1501–2000, 2001–2500, 2501–3000, and greater than 3000 m. The elevation bands are indicated by the center elevation for each band. The gray-shaded boxes indicate the range of values between the 25th and 75th percentiles, the dark vertical line indicates the median, and the ends of the dashed lines indicate the 1st and 99th percentiles of the distributions.)**

(Fig. 8a) with the patterns of correlation between temperature and rain-on-snow event frequencies (Fig. 10a) indicates a correlation of 0.75 ($p < 0.01$). This correlation indicates a strong association between sites with a decreasing (increasing) trend in rain-on-snow events and sites with a negative (positive) correlation between temperature and rain-on-snow event frequencies. This strong association suggests that warming temperatures in the western United States are possibly a contributor to the decreasing trends in rain-on-snow events observed for low-elevation sites (Figs. 8a and 8b). However, decreases in precipitation, particularly in the northwestern United States (where the sites with the lowest elevations are found), have undoubtedly contributed to decreases in rain-on-snow events. Mote et al. (2005) similarly report significant effects of increased temperature and decreased precipitation on decreasing snowpacks in the northwestern United States. Additional research is needed to determine the relative strengths of temperature and precipitation effects on trends in rain-on-snow events.

**CONCLUSIONS.** Monthly rain-on-snow events for 4318 sites in the western United States were examined for water years 1949 through 2003. Rain-on-snow events are most frequent during the months of October through May; however, at sites in the interior western United States rain-on-snow events occur frequently in early summer and early fall. The spatial patterns and seasonal variability of rain-on-snow events also varies by elevation.

The rain-on-snow event data also indicate temporal trends in rain-on-snow events. Trends in rain-on-snow event frequencies are generally positive for high-elevation sites and negative for low-elevation sites. In addition, the interannual variability of October–May rain-on-snow events is correlated with ENSO, and ENSO also appears to account for some of the spatial variability of trends in rain-on-snow events.

Rain-on-snow events for a majority of sites also are negatively correlated with mean October–May temperature for the western United States. Increases in temperature appear to be a contributing factor to the decline of rain-on-snow events for many sites in the western United States, particularly low-elevation sites, through effects on the occurrence of snow and the length of time that snow is on the ground.

Although the climate conditions associated with rain-on-snow events appear to follow logical climate relations, this study has provided one of the first inventories of the magnitude of these relations, as well as a description of elevation differences in the relations. This information is useful as a base for additional research into rain-on-snow events, which should improve both flood forecasts and assessments of flood risk.

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