JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 112, D15109, doi:10.1029/2007JD008397, 2007

Changes in winter snowfall/precipitation ratio in the contiguous United States

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Received 4 January 2007; revised 28 March 2007; accepted 27 April 2007; published 11 August 2007.

[1] The precipitation falling as rain or snow has different impact on regional water resources and their annual distribution. Shift from solid to liquid form of precipitation following the increase of the surface air temperatures could be quite important because such change could influence the timing of spring runoff and cause water shortage in summer. In this study, the ratio of snowfall to precipitation (S/P) for November–March in the contiguous United States is analyzed and temperature effects on the changes of S/P are examined for 1949–2005. Major results show that the S/P ratio has been decreasing strongly in the Pacific Northwest and the central United States. The S/P decreased slightly in the eastern United States. In the Pacific Northwest, the changes of S/P are attributed to decrease of both snowfall and precipitation with snowfall decreasing at a greater rate. In the central United States, decrease of the S/P ratio resulted primarily from the decrease of snowfall and increase of the winter precipitation. Averaged over the contiguous United States, the changes of S/P are mainly related to the changes of the snowfall and with little effect from changes of winter precipitation. Decreases of the S/P ratio are largest in March and least in January. The significant decreases of the S/P ratio are associated with large increase in mean winter wet-day temperatures in the western and central United States. Weak warming in the eastern United States concurred with weak and no change of S/P.

Citation: Feng, S., and Q. Hu (2007), Changes in winter snowfall/precipitation ratio in the contiguous United States, *J. Geophys. Res.*, *112*, D15109, doi:10.1029/2007JD008397.

1. Introduction

[2] Snowfall and snowpack are essential sources for irrigation and drinking water in many regions of the world. On global average, more than one third of irrigation water in the world is from snowmelt [*Steppuhn*, 1981]. Changes in snowfall and snowpack can influence regional water supply [e.g., *Dettinger and Cayan*, 1995]. In addition, the timing and rate of snowmelt runoff is often critical to spring flood development [e.g., *McCabe and Clark*, 2005; *Regonda et al.*, 2005; *Stewart et al.*, 2005]. From climate perspective, snow cover and snowpack significantly affect energy budget and water exchange at the surface and influence regional and global weather and climate [e.g., *Groisman et al.*, 1994; *Hu and Feng*, 2002].

[3] In the recent decades, snow and snow-driven hydrology over the North America has changed considerably accompanied with warming of the surface temperatures. The strong warming in the 1980s corresponded to large decline of snow cover in the North America [*Karl et al.*, 1993; *Frei et al.*, 1999; *Mote*, 2003; *Mote et al.*, 2005]. From analysis of the snow cover in the North America in 1900–1994, *Frei et al.* [1999] found that the snow cover in March has been decreasing since the 1950s. The decline of snow cover is particularly noticeable in the western United States (U.S.). This change has been attributed to increase of winter and spring temperatures, as elaborated by *Mote et al.* [2005] and *Stewart et al.* [2005]. They showed that, in the past 50 years, dates of peak snow accumulation and peak snowmelt runoff have occurred 10–40 days earlier than in the years before. In accordance, spring snowpack has decreased by about 11%. *Groisman et al.* [2001, 2004] also found from station observations substantial decrease of snow cover in March and earlier ending dates of the last snowfall since 1950 in the western and northern U.S.

[4] In addition to influencing snowpack and snowmelt, temperature increase, particularly in the cold season, may also have affected the precipitation that falls as snow, or the winter snowfall/precipitation (S/P) ratio. Changes from solid to liquid form of precipitation could be critical because such changes could influence the snowpack and snow cover, which affect the available snow for spring melt. Lack of adequate spring melt would yield shortage and interruption of stream flows and lead to hydrological droughts in late spring and summer. Some evidence of changes of S/P ratio in the recent decades has been shown by *Huntington et al.* [2004] and *Knowles et al.* [2006]. *Huntington et al.* [2004] found that in the New England area the S/P ratio decreased in 1949–2000. *Knowles et al.* [2006] showed a pronounced decrease of snowfall and S/P ratio in the western U.S. A study of snowfall in Illinois by *Heim and Angel* [1999] also showed decreased snowfall and fewer

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snow days in the 1980s and 1990s, compared to the 1950–1970. In addition, the central U.S. have suffered frequent “snow droughts” in the past years, providing an evidence of decreasing snowfall in the central U.S.

[5] The relationship between changes of the S/P ratio and temperature is complex and varies in regions. For example, *Huntington et al.* [2004] found the S/P ratio was weakly correlated with the surface air temperature, while *Knowles et al.* [2006] showed a strong nonlinear relationship between S/P and the surface air temperature. According to this relationship, the decrease of S/P was associated with a moderate increase of winter wet-day minimum temperatures (0–3°C) during 1949–2004. In addition, the strong decrease in snowfall occurred when winter wet-day minimum temperatures, averaged over their study period, were warmer than -5°C.

[6] The change of the surface air temperature in the U.S. is not uniform. During the second half of the 20th century, a strong warming trend was observed in the western and the northern U.S. Warming in the eastern U.S. was weak, however, and changed to cooling in the southeast U.S. [*Easterling*, 2002; *Feng and Hu*, 2004; *Groisman et al.*, 2004]. These varying trends of surface air temperatures could have different impacts on the snowfall and S/P ratio across the U.S. As an example, *Huntington et al.* [2004] showed strong heterogeneous change of S/P in the New England area. Because the previous studies [*Huntington et al.*, 2004; *Knowles et al.*, 2006] analyzed the changes of snowfall and S/P ratio and the impacts of temperature for a few parts of the U.S. it remains important from both hydrological and climatic perspectives that we examine and understand the snowfall and S/P changes for the contiguous U.S.

[7] The focus of this study is to provide a detailed description of spatial variations of snowfall and the S/P ratio in the contiguous U.S. Details of the data sources and methods used in the analyses are in section 2. Trends in winter snowfall and S/P ratio are analyzed and presented in section 3. Impacts of temperature on monthly and seasonal changes of the S/P ratio also are examined in section 3. The possible effects of decreasing S/P on water resources and surface moisture fluxes are discussed in section 4. Section 5 contains conclusions.

2. Data and Methods

[8] Daily maximum and minimum surface air temperatures, precipitation, and snowfall were obtained for this study from the U.S. Historical Climatology Network (USHCN [*Easterling et al.*, 1999]). The data set contains 1221 cooperative stations that have high-quality long-term observations. These observation data have been subjected to quality control which includes homogeneity testing and adjustments to assure their reliability.

[9] In this study, the liquid water equivalent of daily snowfall was determined following that described by *Huntington et al.* [2004] and *Knowles et al.* [2006]. When nonzero snowfall was recorded at a station on a given day, the total liquid of precipitation was used as snowfall water equivalent, S, for that day. Possible biases resulting from using this method to measure the snowfall water equivalent are discussed by *Huntington et al.* [2004] and *Knowles et al.* [2006]. For example, under mixed snow-rain conditions, use of total liquid of precipitation as S could result in a (positive) bias toward more “recorded snowfall” than the actual snowfall. However, as elaborated by *Knowles et al.* [2006] and *Yang et al.* [2005], the catch efficiency of precipitation gauges is typically lower for snowfall than for rainfall, especially in windy conditions. The undercatch of snowfall by the precipitation gauge will underestimate S. This negative bias, to some extent, may counter the previous positive bias and yield a small net bias. A more rigorous treatment of these effects was not possible at this time because of the absence of snowfall catch efficiency data and data flags for precipitation types at individual stations. These data limitations should be reminded in interpretations of the analysis results.

[10] This study focuses on the winter season, defined as November–March. To screen out the USHCN stations that have a large amount of missing values or little snowfall, the following four criteria were applied to each station. (1) If a winter month has missing precipitation (or snowfall) observations for more than 5 days that month was removed from the analysis. (2) If a winter has missing precipitation or snowfall observations for more than 10 days either clustered in one month or scattered in different months, that winter is considered having inadequate observations and was removed from the analysis. (3) Stations that contain more than 50% of winters of inadequate data in any 10-year period during 1949–2005 were excluded from this study. (4) Stations south of 37°N were excluded because most of them, except a few in mountainous areas of Arizona and New Mexico, have very little snowfall. (Inclusion of the stations in Arizona and New Mexico has little impact on the results of this study.) A similar set of criteria was used to screen the daily maximum and minimum surface air temperatures. These screenings ensure that the data used are sufficient to describe snowfall variations in the study period. There are 374 stations whose data met these sets of criteria for snowfall and temperature. These stations are fairly evenly distributed across the contiguous U.S., except in Montana and Wyoming (see Figure 1). Observations of precipitation, snowfall, maximum and minimum temperatures at those stations were used in our analyses.

[11] Data of 1949–2005 at each station were complied for snowfall water equivalent (S), total precipitation (P), S/P ratio, and the maximum and minimum surface air temperatures for wet (rainfall or snowfall) days, for each month and each winter. Daily (as well as monthly and winter) average air temperature was calculated as the arithmetic mean of the maximum and minimum air temperatures.

[12] Kendall’s tau slope estimator [*Sen*, 1968; *Gilbert*, 1987] was used to evaluate the trends of the variables at each station. This slope estimator is a nonparametric method assuming no a priori distribution of variations in the data, and has been used frequently for trend analysis in environmental and climate studies [e.g., *Hu et al.*, 2005; *Huntington et al.*, 2004]. Correlation analysis and regression also were used to analyze variations of the S/P ratio and its relationship with temperatures.

3. Results

3.1. Seasonal and Monthly Variations

[13] Figure 1 shows the trend of the S/P ratio in 1949–2005. While the spatial features of the trend in the New

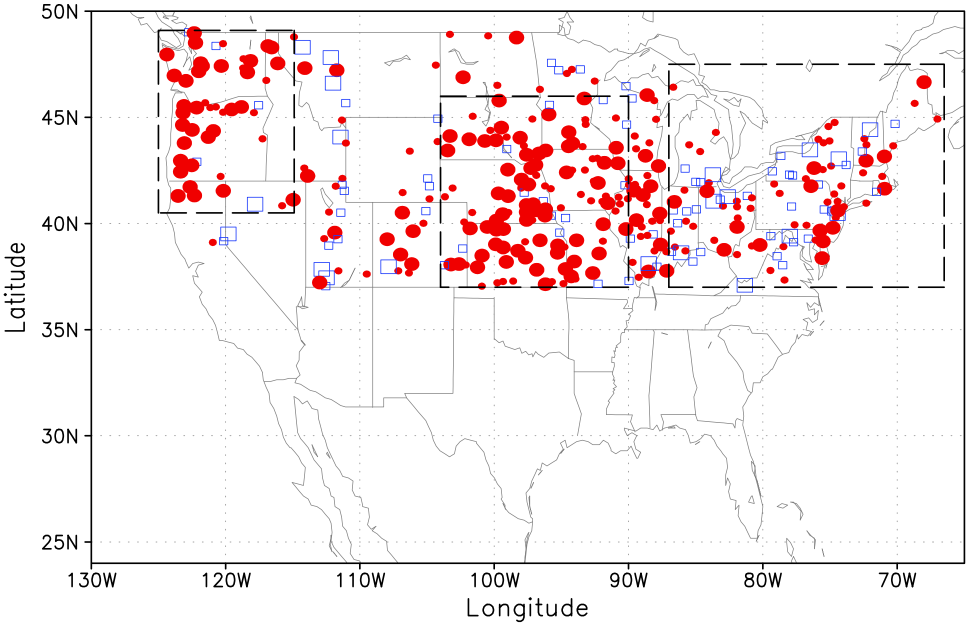

Figure 1. Trends of the winter S/P ratio in 1949–2005. Dots indicate decreasing trend and squares indicate increasing trend. Big dots (squares) indicate trends are significant at 95% confidence level. The regions confined by thick dashed lines are, respectively, the Pacific Northwest, the central and the eastern U.S. discussed in the text.

England area and the western U.S. are similar to that shown by *Huntington et al.* [2004] and *Knowles et al.* [2006], the areas showing coherent decrease of the S/P ratio are in the Pacific Northwest and the north-central U.S. In areas outside of these two boxes the trends are mixed with some stations showing increased S/P and others showing decreased S/P ratio. Among the 374 stations, 287 have decreased S/P. Among the 287, 135 stations show strong decreasing trend (significant at 95% confidence level). Meanwhile, the S/P ratio showed increase at 87 stations, of which 20 show strong increase (significant at 95% confidence level). On average, the contiguous U.S. has been experiencing strong decreases in the S/P ratio, a result suggesting that the precipitation has been falling as rain more often than snow in the last 5 decades.

[14] Changes of either or both types of precipitation (snowfall and rainfall) influence the S/P ratio. Thus, to better understand how the changes of S or P, or both, have influenced the S/P trend, we show in Figure 2 the long-term trends of S and P during 1949–2005. Compared to Figure 1, most of the stations show decreasing S in regions of negative S/P trend, a result suggesting that the decreased S/P ratio is primarily related to decreased amount of snowfall. The relationship between S/P and P is not as coherent as for S/P and S, however, and it is less geographically consistent. For example, over the Pacific Northwest, the S has been decreasing and P also decreasing at most of the stations. Because the averaged S in that region over the winter months has been decreasing at a large rate of −8.62% per decade, significant at 99% confidence level, the large decrease of S has caused the significant decreasing of S/P in the Pacific Northwest (Table 1). In the central U.S., the S has been decreasing but P increasing at most of the stations. The regional averaged S has been decreasing at −3.41% per decade but P increasing at 3.72% per decade (Table 1). These decreasing S and increasing P explain the strong decrease of the S/P ratio in the central U.S. In the eastern U.S., both S and P show weak decrease at a rate that has caused no net change of the S/P ratio (Table 1). These changes of S, P, and the S/P ratio shown in Figures 1 and 2 and Table 1 indicate different causes for the observed decreasing trend of the S/P ratio across the contiguous U.S.

[15] While there are on average many more stations with decreasing S/P than the number of stations with increasing S/P ratio (Table 2) for each winter month (November–March) in the contiguous U.S., the number of stations with decreasing S/P varies in different months (Table 2). Inspecting Table 2 we find that the month of March has the most stations showing decreasing S/P and the month of January has the fewest stations with decreasing S/P. The S/P decreased at 319 (85%) stations in March, of which 150 show significant decreasing trend. In contrast, S/P decreased at only 213 (57%) stations in January and increased at 161 stations. Moreover, the number of stations with significant decreasing S/P in January is about one half of the number of stations in March, albeit that number is still the second highest among all the winter months. On the other hand, the stations with significant increasing trend in January are 13 times (26 versus 2) as many as the stations in March (Table 2). The averaged S/P ratio over the contiguous U.S. also shows strongest decrease in March and weakest in January (Table 1). The overall strong decrease of the S/P ratio in March and weak decrease of S/P in January are consistent with the observed decreasing snowpack and snow cover in March and April and weak or no change in January in North America since 1950 [*Frei et al.*, 1999].

[16] The trends of the S/P ratio at each station across the contiguous U.S. for January and March are shown in

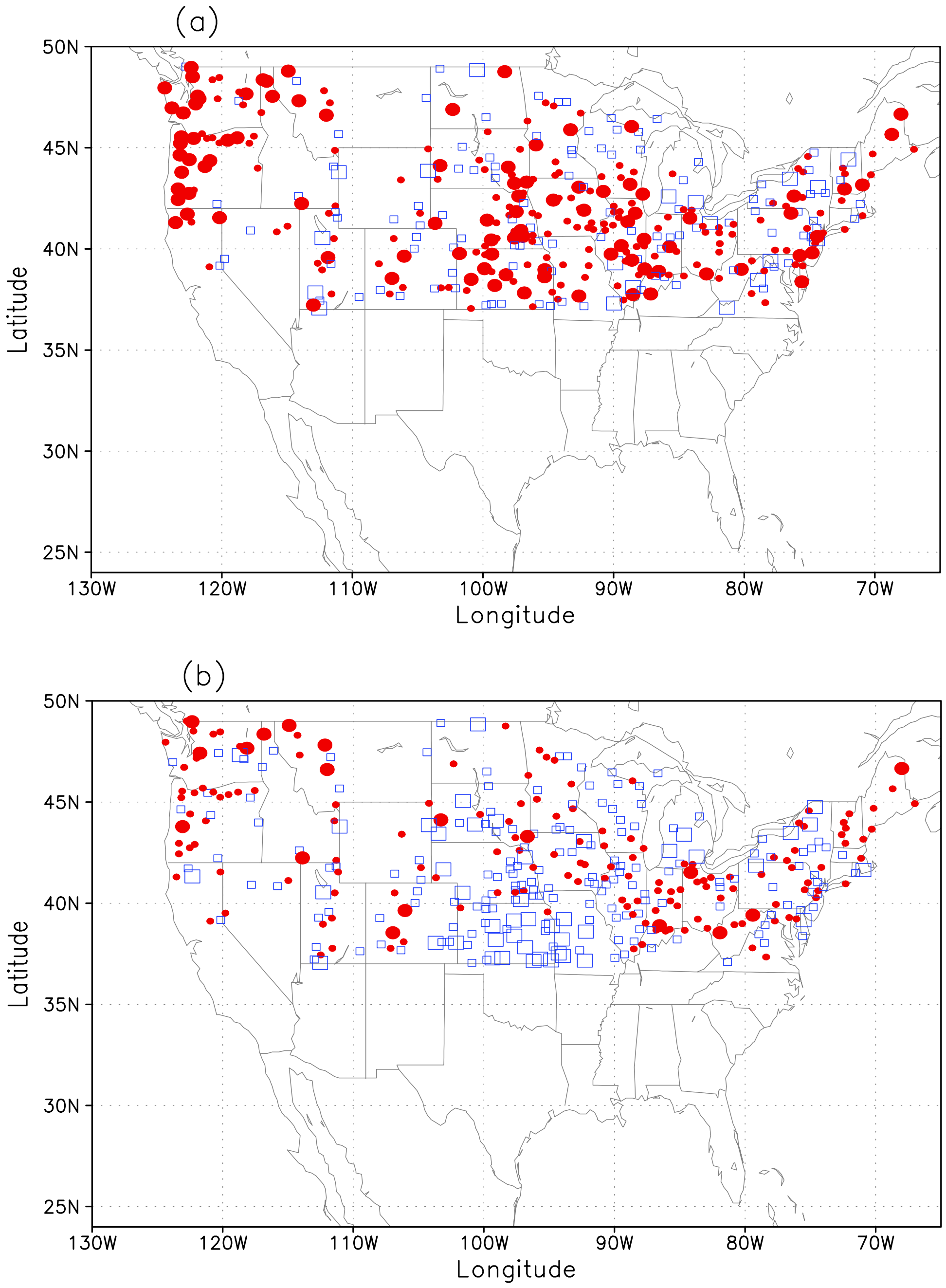

Figure 2. Trend in winter (a) snowfall and (b) precipitation in 1949–2005. Dots indicate decreasing trend and squares indicate increasing trend. Big dots (squares) indicate trends are significant at 95% confidence level.

Figure 3. In the Pacific Northwest the S/P ratio has been decreasing substantially in both months. In the central and eastern U.S., the S/P trends are quite different between January and March, however. In the central U.S. and in January (Figure 3a), stations with increasing S/P trend are blended with stations of decreasing trend. Together they give a weak decrease of S/P for the region. In the eastern U.S., especially in the Ohio Valley, the S/P ratio has been increasing at a majority of the stations. The averaged January S/P is a positive 1.46% per decade (Table 1). In contrast, much stronger decreasing trends of S/P are shown in March in the central U.S. (Figure 3b). The averaged S/P is −4.5% per decade, significant at 99% confidence level. In the eastern U.S., decreasing S/P in March replaced weak increase of S/P in January at majority of the stations, yielding an average decrease S/P for the region.

3.2. Roles of Temperature in Changes of S/P Ratio

[17] The possible roles of the surface air temperature in observed changes of the S/P ratio may be described qualitatively by the significant negative correlation shown in Figure 4a. Among the 374 stations, 359 (96%) have their S/P significantly correlated with the wet-day air temperatures. Only 3 (less than 1%) stations show weak positive

Table 1. Trends in S, P, S/P, and Wet-Day Temperature for the Pacific Northwest, Central, Eastern, and the Contiguous U.S. in 1949–2005[a]

Variables, Units	Nov	Dec	Jan	Feb	Mar	Winter (Nov–Mar)
			Pacific Northwest			
S, %/10yr	0.28	−5.91	−12.21[b]	−6.30	−16.83[b]	−8.62[b]
P, %/10yr	1.39	−0.76	−3.11	−3.23	−1.16	−1.32
S/P, %/10yr	−0.24	−0.77	−3.63[b]	−0.85	−2.89[b]	−1.55[b]
Wet-day temperature, °C/10yr	−0.08	−0.09	0.62[c]	0.28	0.66[b]	0.30[c]
			Central U.S.			
S, %/10yr	2.39	−4.19	0.43	−4.22	−9.70[b]	−3.41
P, %/10yr	10.34[c]	0.48	3.54	−0.81	1.00	3.72
S/P, %/10yr	−1.66[c]	−2.98	−0.68	−1.20	−4.50[b]	−2.69[b]
Wet-day temperature, °C/10yr	0.08	0.35	0.97[c]	0.10	0.97[c]	0.52[b]
			Eastern U.S.			
S, %/10yr	−4.87	−0.05	1.89	−4.16	−2.78	−0.62
P, %/10yr	0.20	−0.55	−1.22	−3.76	−0.01	−0.48
S/P, %/10yr	−1.02	−0.78	1.46	0.39	−0.99	0.01
Wet-day temperature, °C/10yr	0.35	0.09	−0.23	−0.11	0.28	0.09
			Contiguous U.S.			
S, %/10yr	−0.70	−2.92	−2.82	−4.06[c]	−6.57[b]	−2.82[c]
P, %/10yr	3.19[c]	−1.34	−1.49	−1.90	−0.16	0.18
S/P, %/10yr	−0.80[c]	−1.13	−0.33	−0.43	−2.14[b]	−1.02[b]
Wet-day temperature, °C/10yr	0.09	0.25	0.43	0.16	0.63[c]	0.36[c]

[a] The domains of the Pacific Northwest, central and eastern U.S. are shown in Figure 1.
[b] Significant at 99% confidence level.
[c] Significant at 95% confidence level.

correlations. These results indicate that increase in temperatures may have resulted in the decrease of the S/P ratio. This notion is further supported by the long-term change of the winter wet-day air temperatures in the past 56 years (Figure 4b). These temperatures have been steadily increasing, except for the regions in the Ohio Valley and some along the east coast. Inspections of the results in Figures 4b and 1 suggest a causal relationship of the warming temperature with the decreasing S/P in the contiguous U.S. The areas with decreasing S/P (the Pacific Northwest and the central U.S.) are associated with increasing surface air temperatures (Table 1). These results indicate that the increasing temperature could have resulted in more fraction of precipitation fell as rain than snow in those two regions. Meanwhile, the weak changes of wet-day temperatures in the eastern United States corresponded to weak or no changes of the S/P ratio.

[18] Changes of temperatures are not uniform across the winter months, however. As shown in Table 1, the warming in the contiguous U.S. is strong in March and weak in the other winter months. To examine the impacts of monthly wet-day temperature change on monthly S/P, we compare in Figure 5 the wet-day temperature change between January and March. In January, strong warming is found in the western and central U.S. and weak cooling in the eastern U.S. These changes are consistent with decrease of S/P in the Pacific Northwest and central U.S. and increase of S/P in the eastern U.S. (Figures 3a and 5a). In March, the temperature change in the western and central U.S. is similar to that in January but with larger amplitudes. In the eastern U.S. some stations show weak increase of March temperature and some show decrease. At stations with rising temperature their S/P ratio decreased and at stations with cooling temperatures their S/P ratio increased (Figures 3b and 5b). The averaged wet-day temperature in eastern U.S. in March shows slight increase, consistent with the slight decrease in S/P. The strong warming of the temperatures and decrease of the S/P in March in the Pacific Northwest and the central U.S. also are consistent with the early start of local growing season [*Feng and Hu*, 2004], decrease of spring snowpack and earlier start of peak spring snowmelt streamflow [*McCabe and Clark*, 2005; *Mote et al.*, 2005; *Regonda et al.*, 2005; *Stewart et al.*, 2005], and earlier blossoming of some plants [*Cayan et al.*, 2001; *Hu et al.*, 2005].

[19] To describe temperature change effect on snowfall and S/P ratio at individual stations, Figure 6a shows correlations between changes of the wet-day temperatures and S/P at the 374 stations. The overall aggregate correla-

Table 2. Number of Stations With Negative or Positive S/P Trend During the Last 56 Years in the Contiguous U.S.[a]

Month	Nov	Dec	Jan	Feb	Mar	Winter (Nov–Mar)
Negative trend	247 (70)	246 (54)	213 (72)	218 (43)	319 (150)	287 (135)
Positive trend	127 (16)	128 (19)	161 (26)	156 (11)	55 (2)	87 (20)

[a] The numbers in parenthesis are the stations with significant trend (at 95% confidence level).

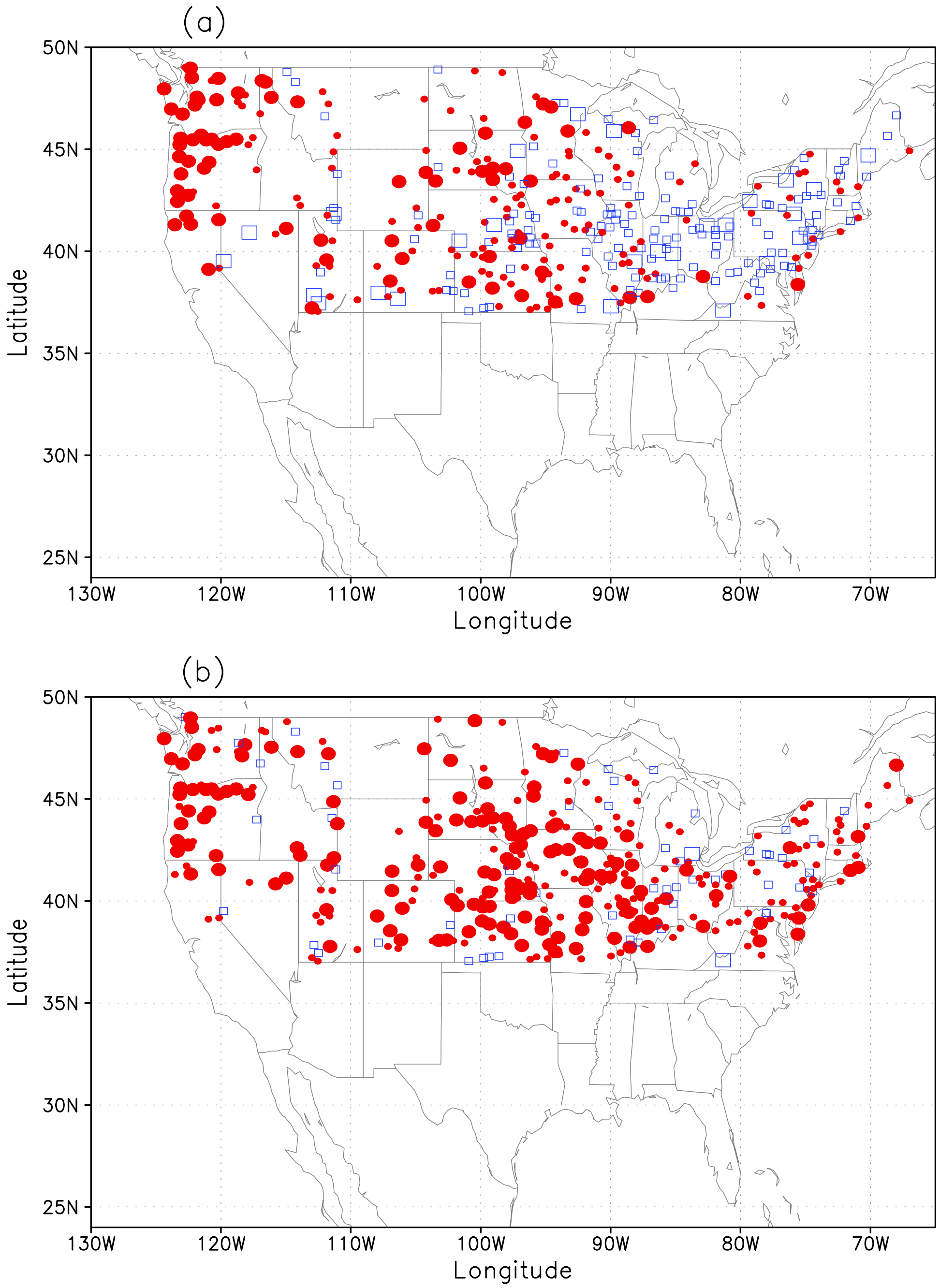

Figure 3. Trends in (a) January and (b) March S/P in 1949–2005. Dots indicate decreasing trend and squares indicate increasing trend. Big dots (squares) indicate trends are significant at 95% confidence level.

tion is −0.421, significant at 99% confidence level, again suggesting a strong effect of the wet-day temperature change on the S/P ratio. The correlation between changes of winter temperatures and S is much weak (−0.185, though significant at 95% confidence level). The weaker relationship between S and the temperature is attributed to increase of S at some stations (e.g., stations in Colorado and the Dakotas) whose temperatures also increased. The increase of both S and the temperature at those stations weakened the overall negative relationship between S and the temperature. Meanwhile, the total precipitation at those stations also increased at a larger rate than the increase of S so that their S/P decreased. The weaker increase of S than P, and decrease of S/P, in response to the same increase of temperature may have caused the weak correlation between S and the wet-day temperature compared to the correlation between S/P and the temperature.

[20] *Knowles et al.* [2006] suggest that changes from snow to rain were affected by daily minimum temperatures and strong snowfall decreased when wet-day minimum temperature was warmer than −5°C. However, *Dai* [2001] shows that winter nonshowery precipitations in the U.S.

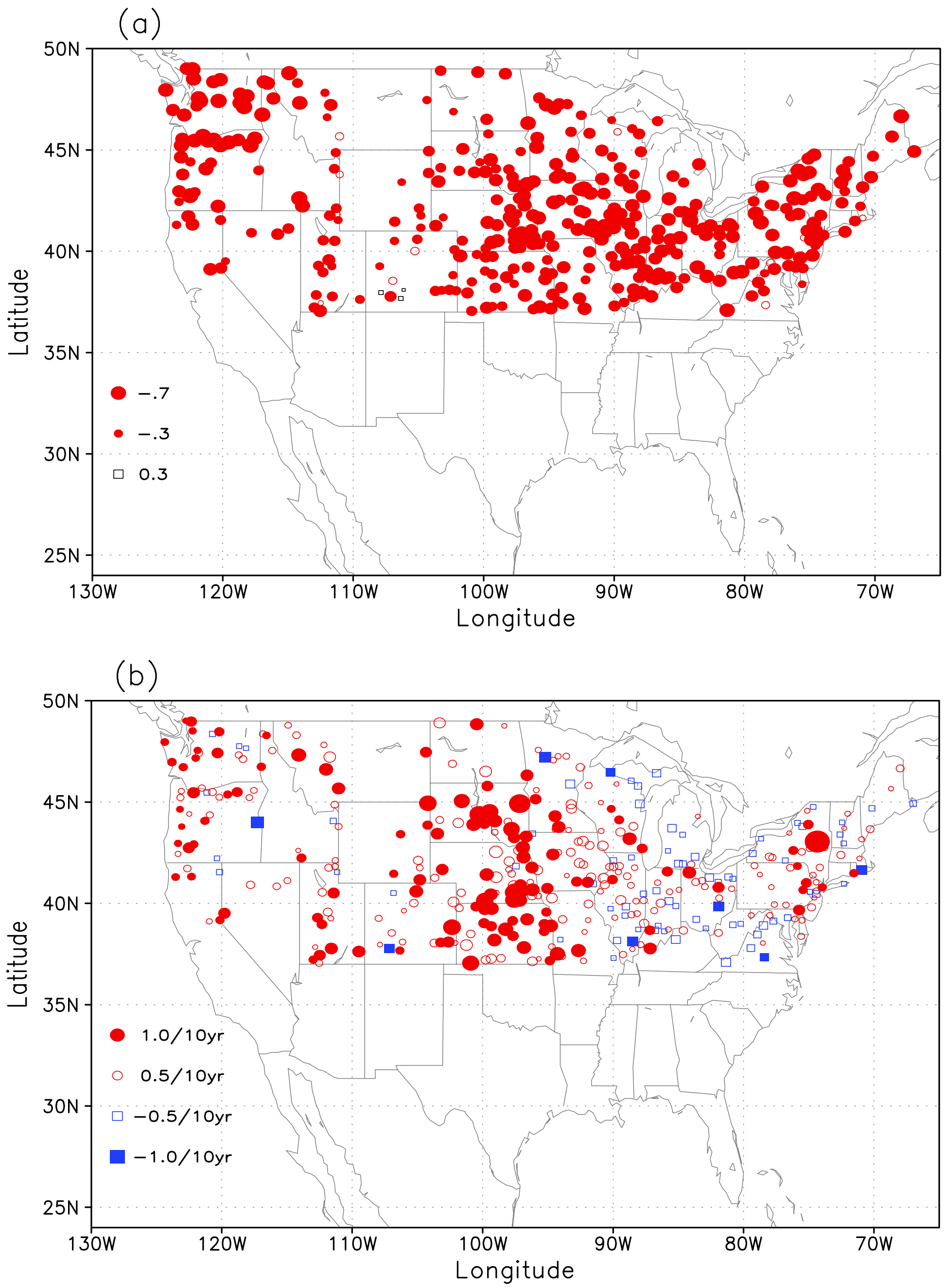

Figure 4. (a) Correlations between S/P and winter wet-day temperatures in 1949–2005. Dots indicate negative correlation and squares indicate positive correlation. Solid dots indicate the correlations are significant at 95% confidence level. (b) Trends in winter wet-day temperature in 1949–2005. Dots indicate increasing trend and squares indicate decreasing trend. The solid dots and squares indicate the trends are significant at 95% confidence level.

mainly occurred in early morning hours (4–8am local solar time) and showery precipitations occurred primarily in the afternoon and early evening hours (2–8pm local solar time). His results suggest that changes of winter precipitation form may be more affected by the daily mean temperature. *Nolin and Daly* [2006] have shown that changes of precipitation form are most significant at sites with daily mean temperatures close to 0°C. The notion that the change from snow to rain is affected by daily mean temperature is further supported by Figure 6b showing the changes of S and the mean wet-day air temperatures at the 374 stations. In Figure 6b large changes of S occur at stations with mean winter wet-day temperatures at or warmer than 0°C. When stations' mean wet-day temperature is cooler than 0°C, the changes of snowfall at those stations are very small, usually less than 1% per year. This is because at those stations the averaged winter temperature has been increasing but the actual temperature remains cold, below freezing. Winter

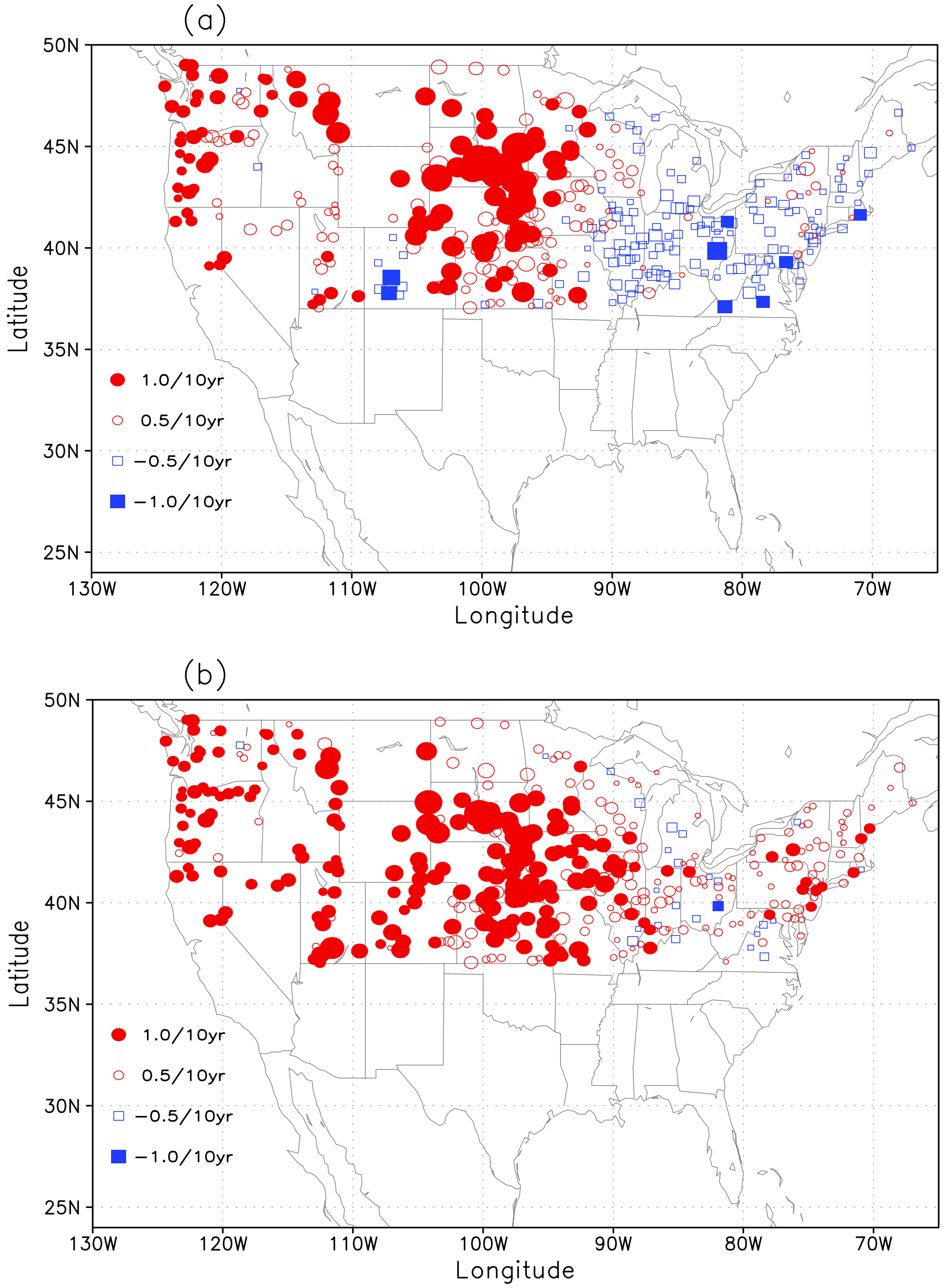

Figure 5. Trend in the wet-day temperature for (a) January, and (b) March in 1949–2005. Dots indicate increasing trend and squares indicate decreasing trend. The solid dots and squares indicate the trends are significant at 95% confidence level.

precipitation falls as snow in most of the time. This can explain the weak trend of S/P but significant warming of temperatures in the central Rocky Mountains during the last 56 years (Figures 1 and 4b). The central Rocky Mountains are also a region with little change of spring snowmelting runoff [*McCabe and Clark*, 2005]. Because the temperature in January is much colder than March, the mean wet-day temperature in January is less likely warmer than the freezing temperature, and the decreases of snowfall and S/P are much weaker than that for March (Figures 3 and 5 and Tables 1 and 2).

[21] So far, only average trends of S/P and their relationships with temperature change during 1949–2005 have been examined. The temperature increase in the contiguous U.S. was not monotonic in the last 5 decades, however: the temperature decreased from the late 1940s to the middle 1970s and then increased strongly since the 1970s [*Intergovernmental Panel on Climate Change*, 2001]. These opposite trends in temperature change during the third and fourth quarters of the twentieth century warrant further examinations of the S/P variation and effects of the temperature and precipitation. Figure 7 shows the trend of the

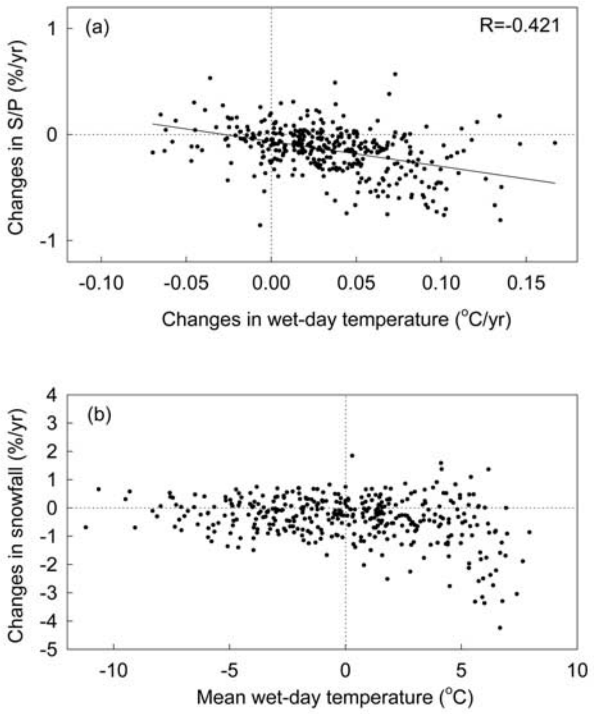

Figure 6. (a) Changes in S/P ratio versus changes in winter wet-day temperature in 1949–2005. (b) Changes in winter S versus the mean winter wet-day temperature in 1949–2005.

S/P ratio and the winter wet-day temperature during 1949–1975 and 1976–2005. Comparisons and contrasts of the S/P and wet-day temperature changes between the two periods confirm that the changes of the S/P echo the changes of the wet-day temperatures. The S/P in the Pacific Northwest and the central U.S. decreased in both periods, in accordance with the increase in wet-day temperatures. Different S/P and temperature changes are found, however, in the eastern U.S. where the S/P increased in the earlier period in association with a cooling trend in wet-day temperatures. The S/P considerably decreased in 1976–2005 when strong warming took place. The similar trend of the S/P ratio and the wet-day temperatures in both periods in the Pacific Northwest and the central U.S. and the opposite trends between the two periods in the eastern U.S. may explain why there is large decrease of S/P in Pacific Northwest and the central U.S. but no change of S/P in the eastern U.S. for the entire period of 1949–2005. The relationship between the temperature and S/P changes shown in Figure 7 also suggests that the temperature in those two periods has been the primary influence for the S/P variations.

4. Discussions

[22] Several studies have suggested that the winter temperature, precipitation, and snowfall are well related to large-scale climate forcing, such as ENSO, Pacific decadal Oscillation (PDO), and the Arctic Oscillation (AO) or North Atlantic Oscillation [*Kunkel and Angel*, 1999; *Knowles et al.*, 2006; *Higgins et al.*, 2000]. Below (above) average snowfall was found in the northern (southern) half of the contiguous U.S. during El Nino years. The impacts of La Nina on snowfall are much weaker than El Nino [*Kunkel and Angel*, 1999]. In addition, *Higgins et al.* [2000] found that the combined impact of ENSO and AO on winter temperature and precipitation is most significant in the south and southeast U.S., and insignificant or marginally significant in the other regions. This suggests that, although AO and the tropical Pacific sea surface temperature (a surrogate of ENSO) changed from negative to positive phase in the late 1970s and have favored below-average precipitation [*Higgins et al.*, 2000] and snowfall [*Kunkel and Angel*, 1999] in the northern half of the contiguous U.S., it may only partially explain the changes of snowfall and the S/P ratio. The PDO can also only partially explain the changes of snowfall and the S/P ratio in the western U.S. [*Knowles et al.*, 2006]. Other portions of the variability in snowfall and S/P may be attributed to the rising temperatures. With projected continuous warming, snowfall and the S/P ratio in the contiguous U.S., especially in regions with winter mean temperature around or slightly above the freezing point, is likely to further decrease, snowpack to melt earlier, and the storage of freshwater in snowpack to decline. Because a major portion of annual precipitation in the western U.S. comes from snowfall in the winter months, the annual precipitation is sensitive to the rising temperatures. More rainfall than snowfall in winter and early snowmelt in spring would elevate the risks of the winter and spring flooding. In fact, increases in cold season streamflow and flood risks in recent decades have been documented in the U.S. [e.g., *Groisman et al.*, 2004; *Lettenmaier et al.*, 1994]. Moreover, because most of the summer streamflow in the western U.S. is from snowmelt, decrease of S and S/P can substantially reduce summer water supply even if the annual precipitation remains unchanged or even increases slightly. As a consequence of decrease in S/P, summer months in the western U.S. become more vulnerable to droughts. Further understanding of possible changes of flood risks in winter and spring and drought risks in summer under projected future temperatures change is of great importance in developing water management strategies.

[23] The Pacific Northwest is a region with steady decrease of S and S/P in the last 5 decades. Both S and P have been significantly decreasing, with S decreasing at a greater rate (Figure 1 and Table 1). The region also faces the largest decline of spring snow cover [*Mote*, 2003; *Mote et al.*, 2005]. Because the winter snowfall and snow cover in the Pacific Northwest also is recognized as an important factor influencing the summer monsoon onset and rainfall in the southwest U.S. [*Higgins and Shi*, 2000; *Hu and Feng*, 2002], decreasing snowfall and snow cover could influence the monsoon onset and rainfall as well. According to *Hu and Feng* [2004] and *Robock et al.* [2003], anomalies of the

Figure 7. (a) Trends in S/P in 1949–1975. Dots indicate decreasing trend and squares indicate increasing trend. Big dots (squares) indicate trends are significant at 95% confidence level. (b) Trend in winter wet-day temperature in 1949–1975. Dots indicate increasing trend and squares indicate decreasing trend. Solid dots and squares indicate the trends are significant at 95% confidence level. (c) Same as Figure 7a but for 1976–2005. (d) Same as Figure 7b but for 1976–2005.

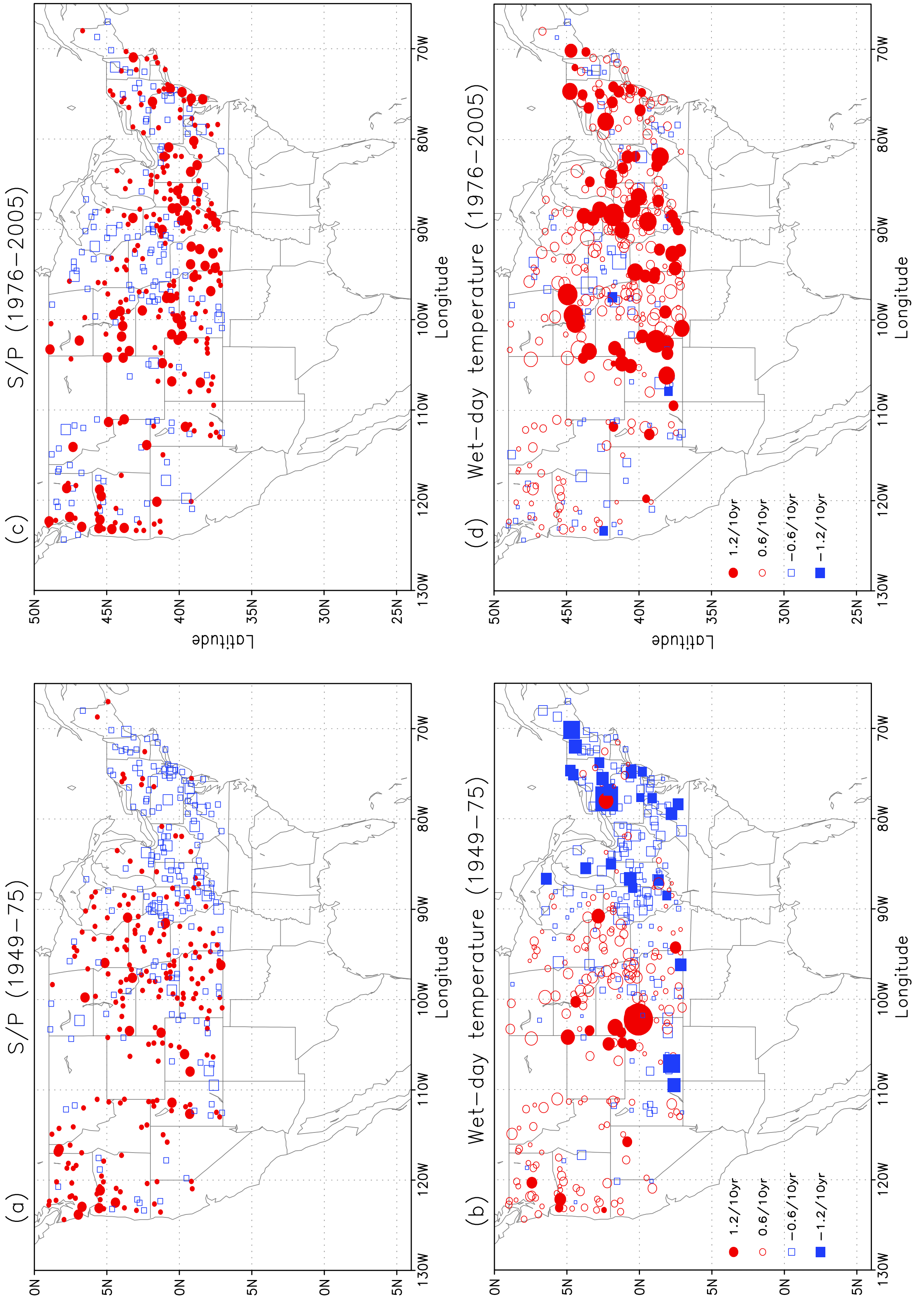
(a) S/P (1949–75)
(b) Wet–day temperature (1949–75)
(c) S/P (1976–2005)
(d) Wet–day temperature (1976–2005)
Latitude
Longitude
50N
45N
40N
35N
30N
25N
130W
120W
110W
100W
90W
80W
70W
1.2/10yr
0.6/10yr
−0.6/10yr
−1.2/10yr

Figure 7

soil temperature and soil moisture resulted from snow cover and snowmelt anomalies can persist for up to 3 months and influence the surface energy fluxes. When snowmelt occurs faster or ends earlier because of lack of snow cover and snowpack (decrease of S and S/P) the effect of snowmelt on soil temperature and moisture will fade early not to influence the summer season circulation and the monsoon onset and rainfall in the southwest U.S. From analyzing the variations of S and S/P during 1949–2005 we have found that while dramatic decrease of both S and S/P occurred in the U.S. Pacific Northwest since the late 1970s, in accordance with sharp increase of the surface air temperatures, the continuous decrease of S and S/P in the region has reduced the snowfall in the recent years after 1990 to only 76% of the average for 1949–2005. It is thus possible that the substantial decrease of the snowpack in the recent decade may have partially contributed to the weakening, since 1990, of the land memory effect of the northwestern U.S. on the following summer monsoon onset and rainfall in the southwest U.S. [*Hu and Feng*, 2002].

5. Conclusions

[24] The fraction of winter precipitation that fell as snow has decreased across most of the contiguous U.S. during 1949–2005. Significant decreasing trend of the S/P ratio is found in the U.S. Pacific Northwest (−1.55% per decade) and in the central U.S. (−2.69% per decade). A much weaker decreasing trend of the S/P is found in the eastern U.S. Decrease of S/P in the Pacific Northwest is accompanied by decrease of snowfall and winter precipitation, with the snowfall decreasing at a greater rate. In the central U.S., the snowfall has decreased but the total precipitation increased, however. In the eastern U.S., both S and P have decreased slightly and yielded weak changes of the S/P ratio. On average over the contiguous U.S., decrease of S/P is related to decrease of S and has little direct effect from changes of total winter precipitation. The decrease of the S/P ratio is largest in March when 85% of the stations in this study show decreasing trends of S/P.

[25] The changes of the S/P ratio are strongly correlated with the mean wet-day temperatures in winter. This temperature has been increasing in winter months in the western and the central U.S. so to cause decrease of S/P. The weak increase of the temperatures in the eastern U.S. is associated with weak changes of S/P. Because the temperature increase has been stronger in March than in January and other winter months, decrease of S/P is much larger in March. The geographical patterns of the increasing mean wet-day temperature and decreasing S/P in March coincide with the patterns showing earlier start of spring snowmelting flooding, earlier start of growing season, and earlier blossoming of some plants in the western and northern U.S. The variations of the S/P ratio in 1949–1975 and 1976–2005 also echo the inhomogeneous change of the wet-day temperatures in those different periods. Particularly strong decrease of S/P occurred in the Pacific Northwest and the central U.S. in both periods, in accordance with increase of the mean wet-day temperatures.

[26] Large changes of snowfall and the S/P ratio have mainly occurred at stations whose mean winter temperatures are at or slightly above the freezing point. Because temperature affects both precipitation forms (snowfall or rainfall) and the rate of snowpack ablation, moderate warming at those stations will likely lead to more of the precipitation falling as rain. The observed temperature increase at stations in the central Rocky Mountains did not cause shift of their S/P ratio, however, because despite the warming the mean temperatures at those high-elevation stations have so far remained below freezing.

[27] **Acknowledgments.** We thank Steve Ghan, the editor, and two anonymous reviewers for their suggestions and comments that have led to improvement of this manuscript. We also thank X. Lin of the U.S. High Plains Regional Climate Center for feedbacks and suggestions concerning the U.S. Coop stations observations and decisions on the stations used in this study. This work has been supported by USAD Cooperative Research Project NEB-40-040.

References

Cayan, D. R., S. Kammerdiener, M. D. Dettinger, J. M. Caprio, and D. H. Peterson (2001), Changes in the onset of spring in the western United States, *Bull. Am. Meteorol. Soc.*, *82*, 399–415.

Dai, A. (2001), Global precipitation and thunderstorm frequencies, part II: Diurnal variations, *J. Clim.*, *14*, 1112–1128.

Dettinger, M. D., and D. R. Cayan (1995), Large-scale atmospheric forcing of recent trends toward early snowmelt in California, *J. Clim.*, *8*, 606–623.

Easterling, D. R. (2002), Recent changes in frost days and the frostfree season in the United States, *Bull. Am. Meteorol. Soc.*, *83*, 1327–1332.

Easterling, D. R., T. R. Karl, J. H. Lawrimore, and S. A. Del Greco (1999), United States historical climatology network daily temperature, precipitation, and snow data for 1871–1997, *ORNL/CDIAC-118, NDP-070*, 84 pp., Carbon Dioxide Inf. Anal. Cent., Oak Ridge Natl. Lab., Oak Ridge, Tenn.

Feng, S., and Q. Hu (2004), Changes in the agro-meteorological indicators in the contiguous United States: 1951–2000, *Theor. Appl. Climatol.*, *78*, 247–264.

Frei, A., D. A. Robinson, and M. G. Hughes (1999), North American snow extent: 1900–1994, *Int. J. Climatol.*, *19*, 1517–1534.

Gilbert, R. O. (1987), *Statistical Methods for Environmental Pollution Monitoring*, 320 pp., Van Nostrand Reinhold, New York.

Groisman, P. Y., T. R. Karl, and R. W. Knight (1994), Observed impact of snow cover on the heat balance and the rise of continental spring temperatures, *Science*, *263*, 198–200.

Groisman, P. Y., R. W. Knight, and T. R. Karl (2001), Heavy precipitation and high streamflow in the contiguous United States: Trends in the 20th century, *Bull. Am. Meteorol. Soc.*, *82*, 219–246.

Groisman, P. Y., R. W. Knight, T. R. Karl, D. R. Easterling, B. Sun, and J. H. Lawrimore (2004), Contemporary changes of hydrological cycle over the contiguous United States: Trends derived from in situ observations, *J. Hydrometeorol.*, *5*, 64–85.

Heim, R. R., Jr., and J. R. Angel (1999), Urbana, Illinois: A case study of 20th century snowfall, paper presented at 11th Conference on Applied Climatology, Am. Meteorol. Soc., Dallas, Tex., 10–15 Jan.

Higgins, R. W., and W. Shi (2000), Intercomparison of principal modes of interannual and intraseasonal variability of the North American monsoon system, *J. Clim.*, *14*, 403–417.

Higgins, R. W., A. Leetmaa, Y. Xue, and A. Barnston (2000), Dominant factors influencing the seasonal predictability of U.S. precipitation and surface air temperature, *J. Clim.*, *13*, 3994–4017.

Hu, Q., and S. Feng (2002), Interannual rainfall variations in the North American summer monsoon region: 1900–98, *J. Clim.*, *15*, 1189–1202.

Hu, Q., and S. Feng (2004), A role of the soil enthalpy in land memory, *J. Clim.*, *17*, 3632–3642.

Hu, Q., A. Weiss, S. Feng, and S. Baenziger (2005), Earlier winter wheat heading dates and warmer spring in the Great Plains of the United States, *Agric. For. Meteorol.*, *135*, 284–290.

Huntington, T. G., G. A. Hodgkins, B. D. Keim, and R. W. Dudley (2004), Changes in the proportion of precipitation occurring as snow in New England (1949–2000), *J. Clim.*, *17*, 2626–2636.

Intergovernmental Panel on Climate Change (2001), *Climate Change 2001: The Scientific Basis*, edited by J. T. Houghton et al., 881 pp., Cambridge Univ. Press, Cambridge, U. K.

Karl, T. R., P. Y. Groisman, R. W. Knight, and R. R. Heim (1993), Recent variations of snow cover and snowfall in North America and their relation to precipitation and temperature variations, *J. Clim.*, *6*, 1327–1344.

Knowles, N., M. D. Dettinger, and D. R. Cayan (2006), Trends in snowfall versus rainfall in the western United States, *J. Clim.*, *19*, 4545–4559.

Kunkel, K. E., and J. R. Angel (1999), Relationship of ENSO to snowfall and related cyclone activity in the contiguous United States, *J. Geophys. Res.*, *104*(D16), 19,425–19,434.

Lettenmaier, D. P., E. F. Wood, and J. R. Wallis (1994), Hydroclimatological trends in the continental United States, 1948–88, *J. Clim.*, *7*, 586–607.

McCabe, G. J., and M. P. Clark (2005), Trends and variability in snowmelt runoff in the western United States, *J. Hydrometeorol.*, *6*, 476–482.

Mote, P. W. (2003), Trends in snow water equivalent in the Pacific Northwest and their climatic causes, *Geophys. Res. Lett.*, *30*(12), 1601, doi:10.1029/2003GL017258.

Mote, P. W., A. F. Hamlet, M. P. Clark, and D. P. Lettenmaier (2005), Declining mountain snowpack in western North America, *Bull. Am. Meteorol. Soc.*, *86*, 1–39.

Nolin, A. W., and C. Daly (2006), Mapping "at risk" snow in the Pacific Northwest, *J. Hydrometeorol.*, *7*, 1164–1171.

Regonda, S. K., B. J. Rajagopalan, M. Clark, and J. Pitlick (2005), Seasonal cycle shift in hydroclimatology over the western United States, *J. Clim.*, *18*, 372–384.

Robock, A., M. Mu, K. Vinnikov, and D. Robinson (2003), Land surface conditions over Eurasia and Indian summer monsoon rainfall, *J. Geophys. Res.*, *108*(D4), 4131, doi:10.1029/2002JD002286.

Sen, P. K. (1968), Estimates of the regression coefficient based on Kendall's tau, *J. Am. Stat. Assoc.*, *63*, 1379–1389.

Steppuhn, H. (1981), Snow and agriculture, in *Handbook of Snow: Principles, Processes, Management and Use*, edited by D. M. Gray and D. H. Male, pp. 60–126, Elsevier, New York.

Stewart, I., D. R. Cayan, and M. Dettinger (2005), Changes toward earlier streamflow timing across western North America, *J. Clim.*, *18*, 1136–1155.

Yang, D., D. Kane, Z. Zhang, D. Legates, and B. Goodison (2005), Bias corrections of long-term (1973–2004) daily precipitation data over the northern regions, *Geophys. Res. Lett.*, *32*, L19501, doi:10.1029/2005GL024057.

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