

Influence of Snowfall Anomalies on Summer Precipitation in the Northern Great Plains of North America

STEVEN M. QUIRING¹, AND DARIA B. KLUVER²

ABSTRACT

Using observations from 1929 to 1999, we examine the relationship between winter/spring snowfall anomalies and summer precipitation over the northern Great Plains of North America. Both composite and correlation analysis indicate that anomalously dry (wet) summers are associated with negative (positive) snowfall anomalies during the preceding winter and spring. It is posited that below (above) normal snowfall is associated with decreases (increases) in spring/early summer soil moisture and associated decreases (increases) in local moisture recycling during summer. It appears that the snowfall anomalies must exceed some minimum threshold before they have a significant impact on atmospheric circulation and precipitation during the following summer. There is also significant temporal variability in the strength of the correlations between snowfall and summer moisture. Relationships between April–May snowfall and summer moisture were generally quite strong between 1929 and 1954 and 1970 to 1987, but were relatively weak during 1955 to 1969 and after 1987. This suggests that other factors may be modulating the importance of land surface processes.

Keywords: snowfall, precipitation, drought, Great Plains

INTRODUCTION

Land surface conditions (e.g., snow cover, soil moisture) are important sources of seasonal climate predictability (Koster and Suarez, 2001; Koster *et al.*, 2003; Koster *et al.*, 2004). Numerous studies have demonstrated that Eurasian/Tibetan snow cover influences Indian/Asian monsoonal circulation and precipitation (Kripalani *et al.*, 2002; Robock *et al.*, 2003; Wu and Qian, 2003; Fasullo, 2004; Zhang *et al.*, 2004). Snow cover and snow water equivalent have also been linked to variability in the North American Monsoon (Gutzler, 2000; Ellis and Hawkins, 2001; Hawkins *et al.*, 2002; Lo and Clark, 2002; Matsui *et al.*, 2003). Other studies have identified connections between Eurasian snow cover extent and summer air temperature in the United Kingdom (Qian and Saunders, 2003), and Canadian river discharge (Déry *et al.*, 2005). Although both the presence and amount of snow can have a significant impact on the climate of local and remote regions, our understanding of the relationship between snow cover and climate is still incomplete. This is especially the case in the northern Great Plains of North America where there are a paucity of studies examining the relationship between snowfall/snow cover and summer precipitation.

While Koster *et al.* (2004) found a strong coupling between soil moisture and precipitation in the Great Plains, to date no observational studies have examined the relationship between winter/spring snowfall (which contributes to soil moisture recharge) and summer drought

¹ Department of Geography, Texas A&M University, College Station, Texas, USA

² Department of Geography, University of Delaware, Newark, Delaware, USA

conditions. Therefore the utility of land surface conditions for making seasonal climate forecasts merits further attention in this region. This paper utilizes observational data (1929 to 1999) to examine the relationship between winter/spring snowfall anomalies and summer moisture (precipitation) anomalies in the northern Great Plains of North America.

DATA AND METHODS

The northern Great Plains of North America, as defined in this study, include portions of three Canadian provinces (Manitoba, Saskatchewan, and Alberta) and 12 US states (Colorado, Iowa, Idaho, Minnesota, Missouri, Montana, Nebraska, North Dakota, Nevada, South Dakota, Utah, and Wyoming). The analysis is based on monthly drought index and snowfall data (1929–1999) that have been interpolated to a one-degree grid spanning 40° to 54° N; 95° to 113° W (18 grid cells in the northeastern corner of the study region were omitted due to inhomogeneities in the data).

Drought (moisture) indices are commonly used to quantify moisture conditions within a region, to detect the onset, and to measure the severity and spatial extent of drought events (Alley, 1984). The Moisture Anomaly Index (subsequently referred to as the Z-index) was developed by Palmer (1965) and it is calculated using a soil moisture/water balance algorithm. The Z-index represents the departure from normal (or climatically appropriate) moisture conditions in a given month, when the Z-index is positive (negative) conditions are wetter (drier) than normal (Palmer, 1965). The Z-index was selected to represent summer moisture anomalies in the northern Great Plains since previous research has shown that this index is well-suited for monitoring moisture (drought) conditions in this region (Quiring and Papakyriakou, 2003). Drought data for the US were provided by the National Climatic Data Center at the climate division level (available at: <http://www.ncdc.noaa.gov>) and then interpolated to a one-degree grid. Details on how the Canadian Z-index data were generated can be found in Quiring and Papkyriakou (2003, 2005).

The snowfall data were developed by T. Mote and collaborators at the University of Georgia (T. Mote, 2004, *personal communication*). It is based on daily observations from the National Weather Service cooperative station network and the Canadian Daily surface observations. The data were interpolated to a one-degree latitude by one-degree longitude grid using Spheremap, a spatial interpolation program.

RESULTS

Only a weak linear relationship exists between snowfall and summer moisture when conditions are averaged over the study area (248 grid cells). Correlations are weakest between fall (SON) snowfall and summer moisture anomalies (0.05), they increase to 0.17 during winter (DJF) and spring (MAM). During the final two months of spring (April and May) the correlation improves to 0.22. Averaging over space and time (1929 to 1999) masks significant spatial and temporal variability present in the snowfall-summer moisture relationship.

Figure 1 shows the relationship between April–May snowfall and summer moisture anomalies in the northern Great Plains (1929–1999). It is clear that the nature of this relationship has varied over time. Linear correlations were calculated using a sliding 15 yr window (e.g., first correlation was calculated using 1929 to 1944, the second correlation was calculated using 1930 to 1945, and the last correlation was calculated using 1984 to 1999) (Figure 2). Correlations between April–May snowfall and summer moisture anomalies varied from 0.82 (1971–1985) to –0.01 (1955–1969). The relationship was quite strong in the 1930s/1940s and 1970s/1980s, but was relatively weak in the 1950s/1960s, and since the late 1980s. Correlations between winter snowfall and summer moisture anomalies varied from 0.58 (1954–1968) to –0.54 (1942–1956). During the early part of the record winter snowfall was negatively correlated with summer moisture. A significant shift in the relationship occurred during the 1950s and since the 1950s there has generally been a positive relationship between winter snowfall and summer moisture. The relationship between winter snowfall and summer moisture is different than the relationship between April–May snowfall and summer moisture. Typically when there are relatively strong

correlations between April–May snowfall and summer moisture, there are weak (or negative) correlations between winter snowfall and summer moisture.

A more detailed examination revealed that there is a stronger relationship between April–May snowfall and summer moisture during years that have large snowfall anomalies (snowfall anomalies that are more than one standard deviation above/below the mean). There are 11 yrs with April–May snowfall anomalies more than one standard deviation below the mean. Eight of these 11 yrs were followed by drier than normal summers in the northern Great Plains and the mean Z-index for the 11 yrs is -0.44 . There were also 11 yrs with April–May snowfall anomalies more than one standard deviation above the mean. Nine of these 11 yrs were followed by wetter than normal summers and the mean Z-index for the 11 yrs is 0.46 . Based on all 22 yrs, the linear correlation between April–May snowfall anomalies and summer moisture is 0.49 (statistically significant at the 95% confidence level).

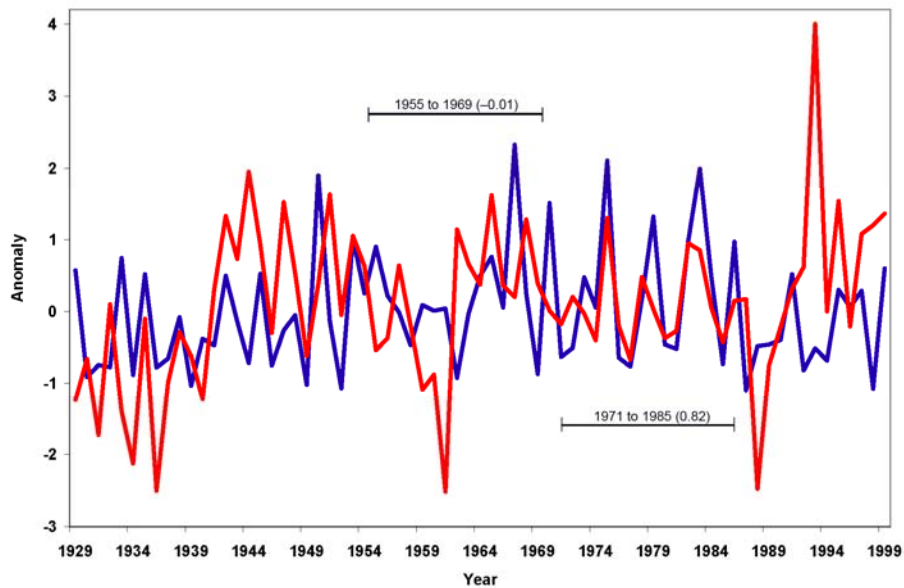


Figure 1. April–May snowfall anomalies (blue line) and summer moisture anomalies (Z-index) (red line) averaged over the northern Great Plains study region (1929–1999). The two 15 yr periods with the highest (0.82) and lowest (-0.01) linear correlations are indicated.

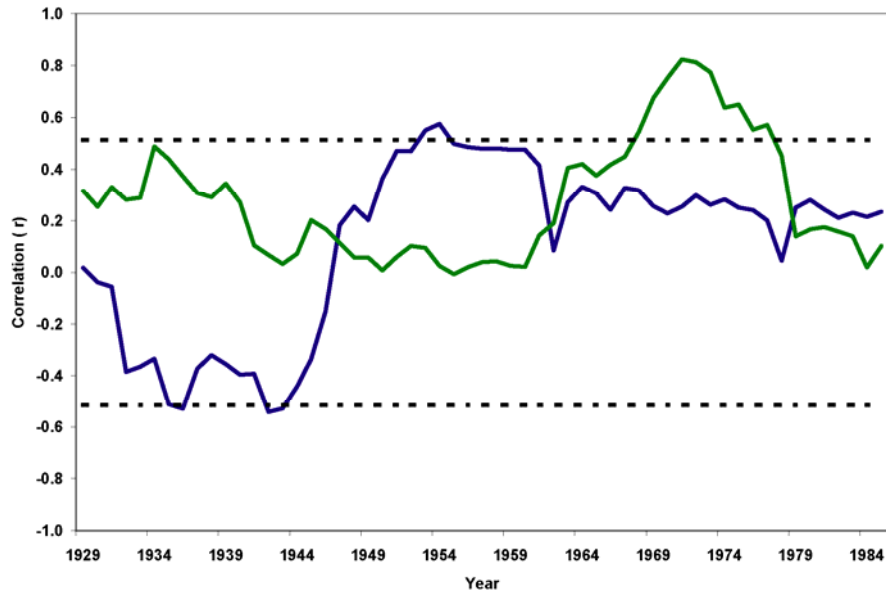


Figure 2. Linear correlations between winter (DJF) (green line) and April–May (blue line) snowfall anomalies and summer moisture anomalies (Z-index) calculated for all 15 yr time periods between 1929 and 1999. Dashed lines indicate the 95% significance level.

The relationship between April–May snowfall and summer moisture anomalies is further strengthened if the candidate years are restricted to those occurring during the two periods (1929–1954 and 1970–1987) when land surface conditions appear to be the dominant source of seasonal climate predictability. During these two periods there were 8 yrs with April–May snowfall anomalies that were more than one standard deviation below the mean. Seven of these 8 yrs were associated with drier than normal moisture conditions during the summer (mean Z-index = -0.73). There were also 8 yrs with April–May snowfall anomalies that were more than one standard deviation above the mean. Seven of the 8 yrs with large positive April–May snowfall anomalies were followed by wetter than normal moisture conditions during the summer (mean Z-index = 0.63). Based on these 16 yrs the linear correlation between April–May snowfall and summer moisture is 0.70 (statistically significant at the 95% confidence level).

Significant spatial variability is also evident in the relationship between April–May snowfall and summer moisture anomalies (Figure 3). Linear correlations across the study region are generally positive with the highest correlations (up to 0.63) in southern Manitoba and South Dakota. There is only one grid cell in Wyoming where there is a statistically significant negative correlation (-0.23). Statistically significant correlations between April–May snowfall and summer moisture anomalies are found in approximately 56% of the study area. These grid cells tend to be concentrated on the eastern side of the study region and are notably absent from most of Wyoming, the eastern part of Montana, and southern Saskatchewan.

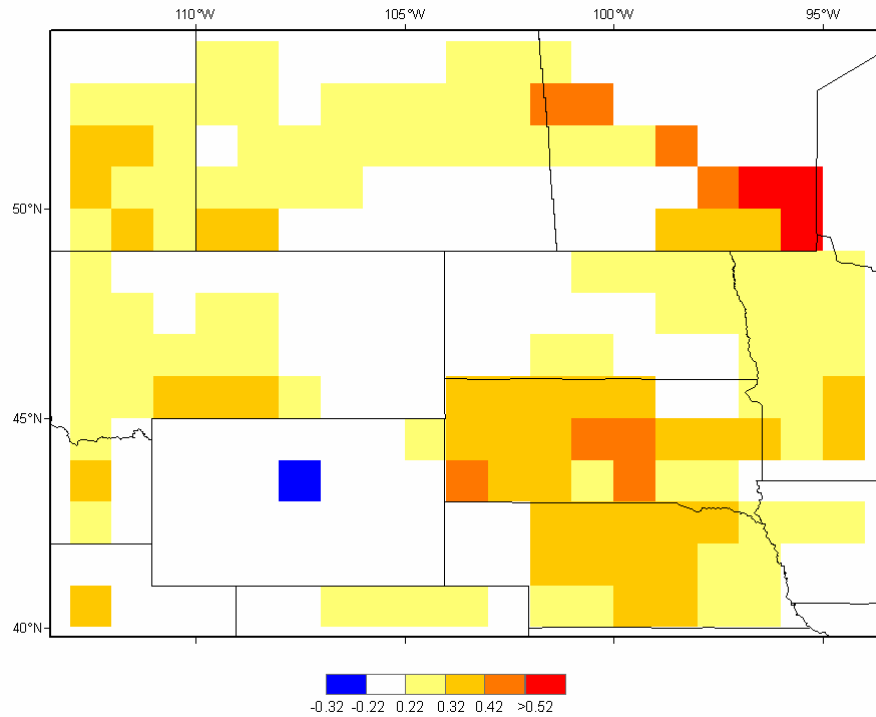


Figure 3. Linear correlations between April–May snowfall and summer moisture anomalies (Z-index). Colored grid cells are those with statistically significant correlations (95% significance level).

Based on a composite analysis, the five driest summers between 1929 and 1999 (Table 1) are associated with a mean winter (spring) snowfall anomaly of -66.7 mm (-62.4 mm) (Figure 4). Approximately 85% of the study region received below normal snowfall during the winter and spring seasons prior to the five driest summers. About 28% (25%) of the study region had winter (spring) snowfall anomalies that are more than 100 mm below average and only 2% (1%) received winter (spring) snowfall that was more than 100 mm above normal. The five wettest summers between 1929 and 1999 were associated with a mean winter (spring) snowfall anomaly of 6.2 mm (21.6 mm). Approximately 53% (46%) of the study region received above normal snowfall during the prior winter (spring). About 15% (12.1%) of the study region had winter (spring) snowfall that was greater than 100 mm above normal and only 7% (1%) received winter (spring) snowfall that was more than 100 mm below normal. Results of the composite analysis indicate that anomalously dry (wet) summers are associated with significant negative (positive) snowfall anomalies during the preceding winter and spring, which supports the results of the correlation analysis. However, the composite analysis demonstrated that the winter/spring snowfall anomalies associated with the driest summers are typically greater in magnitude and more spatially extensive than the snowfall anomalies associated with wettest summers.

Table 1. Ten driest and wettest summers (mean Z-index) between 1929 and 1999 (ranked by severity).

Driest Years		Wettest Years	
Year	Z-Index	Year	Z-Index
1961	-2.52	1993	4.00
1936	-2.51	1944	1.95
1988	-2.48	1951	1.63
1934	-2.13	1965	1.62
1931	-1.73	1995	1.54
1933	-1.40	1947	1.52
1929	-1.24	1999	1.36
1940	-1.23	1942	1.33
1959	-1.09	1975	1.30
1937	-0.99	1968	1.28

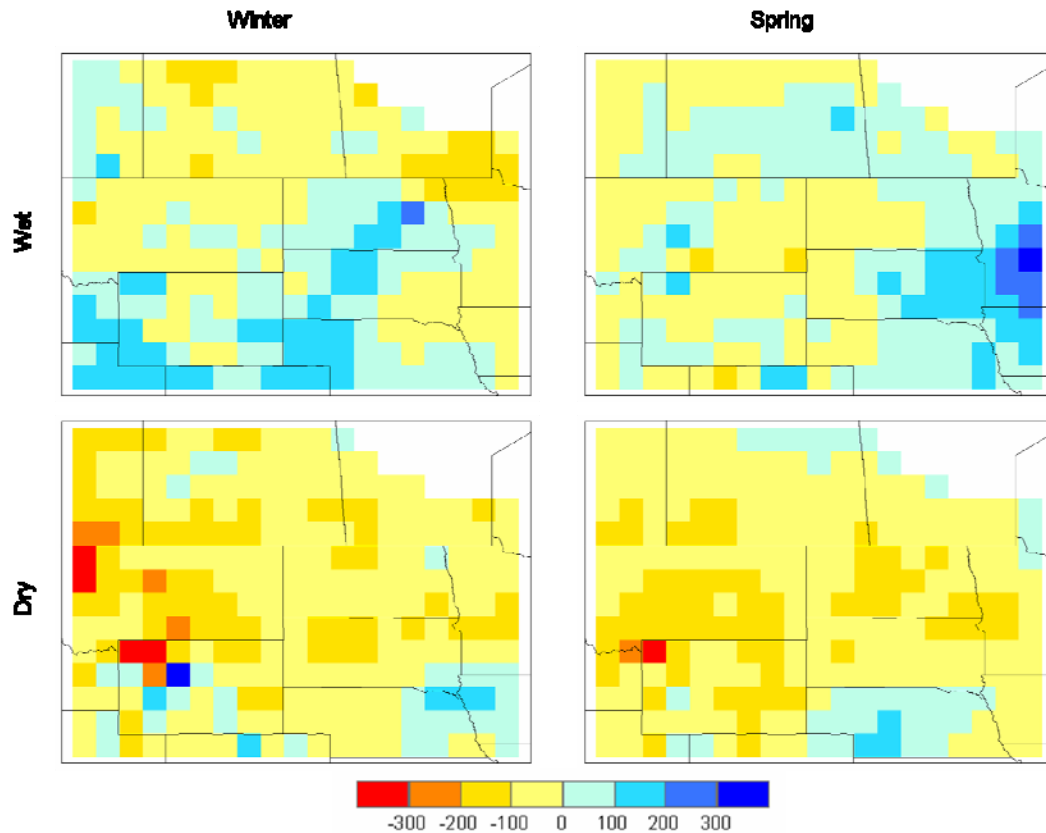


Figure 4. Composite snowfall anomalies (mm) in winter, and spring associated with the five wettest summers (1993, 1944, 1951, 1965, 1995) and the five driest summers (1961, 1936, 1988, 1934, 1931).

DISCUSSION

The observational data demonstrate that below (above) normal snowfall in winter/spring is generally associated with anomalously dry (wet) summers in the northern Great Plains. It is hypothesized that below normal snowfall is linked to summer drought via negative soil moisture anomalies in spring and early summer that reduce local moisture recycling. Our findings appear to support those of Namias (1991), who suggested that reduced soil moisture during the late

winter/early spring could contribute to a warm, dry summer in the region by reducing the amount of local moisture recycling and by modifying the large-scale atmospheric circulation.

The strength of the relationship between winter/spring snowfall and summer moisture anomalies has varied significantly over space and time. Linear correlations between April–May snowfall anomalies and summer moisture conditions ranged from approximately zero (1955–1969) to 0.82 (1971–1985). Other empirical studies have also found that the strength of the relationship between land surface conditions (e.g., snow cover and soil moisture) and precipitation has varied significantly during the 20th century (Gutzler, 2000; Hu and Feng, 2002; Zhu *et al.*, 2005). Hu and Feng (2004) suggest that the relationship between land surface conditions and precipitation patterns over the North American Monsoon region is modulated by sea surface temperature (SST) anomalies in the Pacific Ocean. They found that when SST anomalies were strong (weak), land surface conditions tend to have less (more) influence. Therefore it is hypothesized that atmospheric and/or oceanic forcings are modulating the relationship between snowfall and summer moisture conditions in the northern Great Plains. However, the reasons for the differential influence of winter versus spring (April–May) snowfall (Figure 2) are unknown and merit future study.

Relationships between April–May snowfall and summer moisture anomalies also varied spatially. The strongest relationships were found in southern Manitoba and South Dakota and statistically significant correlations were present across approximately 56% of the study region. Previous research has also demonstrated that the coupling between land surface conditions (e.g., soil moisture and snow) and precipitation can be highly spatially variable (Lo and Clark, 2002; Koster *et al.*, 2004; Dominguez *et al.*, 2006). Our results demonstrate that even within a relatively small area there can be substantial differences in the strength of the relationship between spring snowfall and summer moisture anomalies.

The relationship between spring snowfall and summer moisture may be non-linear since it appears that snowfall anomalies must exceed some minimum threshold before they have a significant (and consistent) influence on summer moisture conditions. The mean correlation between April–May snowfall and summer moisture anomalies increased from 0.22 (all years) to 0.49 when only the years with snowfall anomalies more than one standard deviation above/below the mean were considered.

The lack of spatial and temporal stability in the relationship between snowfall and summer moisture anomalies has significant implications for understanding and forecasting the occurrence of severe hydrologic events (e.g., floods and droughts). Additional study is needed to identify the factors that are responsible for modulating the strength of the snowfall-summer moisture relationship over space and time. Although spring snowfall conditions can, in some cases, explain more than half of the variance in summer moisture, the lack of spatial and temporal stability in this relationship limits its utility for producing accurate forecasts of summer droughts in the northern Great Plains.

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