EXAMINING THE EFFECT OF FALL/SPRING SOIL MOISTURE ON SUMMER PRECIPITATION IN THE NORTHERN GREAT PLAINS

J.P. 2.7

Lei Meng[*] and Steven M. Quiring
Department of Geography, Texas A&M University, College Station, TX 77843

1. Introduction

Land surface processes are considered to be important predictors of seasonal precipitation along with global sea surface temperatures [*Hu and Feng*, 2004] and upper-troposphere circulation [*Quiring and Papakyriakou*, 2005; *Zhu, et al.*, 2005]. Snow cover and soil moisture are two of the most important indicators of land surface conditions. The persistence of snow cover and surface soil moisture anomalies is often called land memory, and it can last up to several months [*Pielke, et al.*, 1999; *Vinnikov, et al.*, 1996]. Previous studies have suggested that snow cover anomalies can influence precipitation in India [*Wu and Qian*, 2003], North America [*Ellis and Hawkins*, 2001], Korea [*Kripalani, et al.*, 2002], and China [*Qian, et al.*, 2003]. Other studies have shown that there is a link between Eurasian snow cover extent and summer air temperature in the United States [*Qian and Saunders*, 2003]. Like snow cover, soil moisture can also have a strong impact on the climate [*Koster, et al.*, 2003]. Researchers have demonstrated that soil moisture can play an important role in summer climate predictions in the mid-latitudes where the influence of sea surface temperatures (SST) are typically weaker [*Conil, et al.*, 2007]. However, the linkages between land surface processes and climate are strongly affected by the persistence of strong external atmospheric forcings, such as SST anomalies [*Hu and Feng*, 2004]. For instance, *Hu and Feng* [2004] demonstrated that winter precipitation can affect summer rainfall in southwestern United States when the persistence of SST anomalies is weakened.

Soil moisture anomalies modify the local climate by modifying surface energy and water fluxes [*Eltahir*, 1998]. Anomalously wet soils lead to increased evaporation, decreased surface temperature, and enhanced convective precipitation. However, the relationship between antecedent spring soil moisture and summer precipitation is not uniform (it varies spatially and temporarily) [*Meehl*, 1994; *Zhu, et al.*, 2005]. *Zhu et al.* [2005] examined the role of antecedent land surface conditons (e.g., soil moisture, snow water equivalent, and precipitation) on North American Monsoon rainfall variability and found a statistically significant inverse relationship between monsoon precipitation in Arizona and western New Mexico and antecedent winter precipitation in the southwestern United States. Recently, *Chow et al.* [2007] used a regional climate model (RCM) to examine the effect of the initial spring soil moisture on summer precipitation over the Tibetan Plateau (TP) and the Yangtze River region of eastern China. They found that TP spring soil moisture has a positive relationship with summer precipitation over the TP and the Yangze River region and a negative relationship with summer precipitation in the southern China.

Over the northern Great Plains of North America (NGP), the main sources of atmospheric moisture for summer precipitation are the transport of warm,

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**Corresponding author address*: Lei Meng, Department of Geography, Texas A&M University; email: leimeng@tamu.edu

moist airmasses from the Gulf of Mexico and local land surface feedback [*Laird, et al.*, 1996]. This agrees with *Koster et al.* [2004] who identified the Great Plains as one of the regions (hot spots) where soil moisture and precipitation are strongly coupled. *Schubert et al.* [2004] investigated the causes of droughts in the Great Plains using ensembles of long-term general circulation model forced with observed SSTs and found that approximately two-thirds of the total low-frequency rainfall variance can be explained by the land-atmospheric interaction (e.g., soil moisture) and only the small remaining part of the variance attributed to SST anomalies. Recently, *Quiring and Kluver* [2007] examined the effect of winter snow cover on summer precipitation in the NGP and indicated that there is a stronger linkage between spring snow cover anomalies and summer precipitation than fall/winter snow cover anomalies. However, there are very few studies that examine the relationship between spring/winter soil moisture and summer precipitation in the NGP due to the lack of soil moisture observations. In this research, Variable Infiltration Capacity (VIC) [*Liang, et al.*, 1996] simulated soil moisture was used to investigate the relationship between spring/winter soil moisture anomalies and summer precipitation. Research has shown that VIC simulated soil moisture is strongly correlated with measured soil moisture over large areas of the continental United States [*Abdulla, et al.*, 1996]. The Moisture Anomaly Index (Z-index), developed by *Palmer* [1965], represents the monthly averaged departure from normal moisture conditions with positive (negative) z-index indicating wetter (drier) than normal soil moisture. The Z-index was selected to represent summer precipitation anomalies in the NGP since previous studies have shown that this index is appropriate for indicating summer precipitation status (such as drought conditions) [*Quiring and Papakryiakou*, 2003].

2. Data and methodology

The NGP, as defined in this study, includes only the US portions of the Great Plains (Montana, North Dakota, Wyoming, South Dakota, Minnesota, Nebraska, and Iowa). The VIC soil moisture data (1915 to 2004) were aggregated to a one-degree grid with the total of 105 grids to match with the spatial resolution of Z-index. The summer season was defined as June, July, and August (JJA). Studies have shown that changes in deep soil moisture are more likely affected by long-term atmospheric conditions than the surface soil moisture, thus the deep soil moisture has a longer "memory" than surface soil moisture [*Schubert, et al.*, 2004; *Wu and Dickinson*, 2004]. Therefore, in this study, only soil moisture data below 10 cm were used to examine the effect of land surface conditions on summer precipitation anomalies. The soil moisture on Oct 31st and May 1st each year were used to represent the fall and spring soil moisture. The Z-index was calculated using a soil moisture/water balance algorithm. Drought data were obtained from 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 (total of 105 grid cells). The average of JJA monthly Z-index was used to represent summer precipitation conditions. The NCEP-NCAR reanalysis geopotential height data (1948-2004) [*Kalnay, et al.*, 1996] were used to evaluate mid-troposphere circulations.

3. Results

3.1 Spatial linkage between soil moisture and precipitation

There is a strong positive correlation between soil moisture anomalies and summer precipitation (Z-index) in the NGP. The correlations between fall (spring) soil moisture anomalies and summer precipitation (1915–2004) are statistically significant (at 95% significant level) over approximately 58% (72%) of the study region (Fig. 1). It is clear that the strength of the correlations vary greatly in the NGP. For fall soil moisture, the strongest linkage (dark red) occurred in the center of the study region which includes the southwestern part of North Dakota and northwestern South Dakota (Fig.1a). During spring, the strongest linkage moved toward southeast and occurred in most part of South Dakota (Fig.1b). Comparison of Fig.1a and 1b indicates that spring soil moisture has an even stronger correlation with summer Z-index than fall soil moisture in the study region. This indicates that soil moisture signal is stronger when correlating summer precipitation with spring soil moisture compared with fall soil moisture.

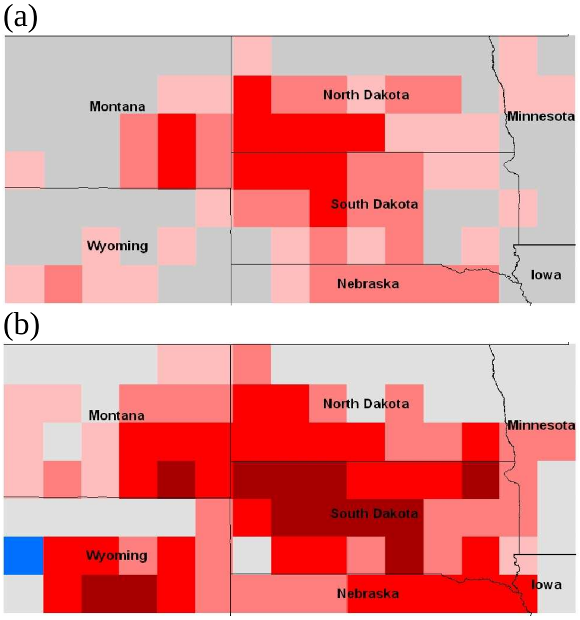

Figure 1. Correlation between fall (a) /spring (b) soil moisture and summer precipitation over the northern Great Plains during 1915-2004. (colored grids have significant correlations at 95% level, the darker red indicates stronger correlation and blue color means significant negative correlation).

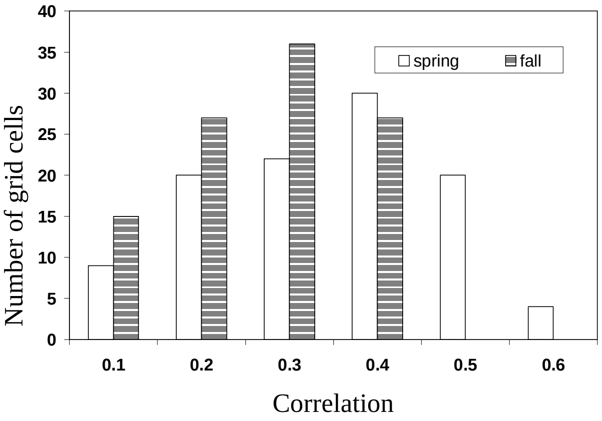

Figure 2. Histogram of the correlations between spring (solid)/fall (shaded) soil moisture and summer precipitation at each grid in the NGP during the period 1915–2004.

Fig. 2 shows the histogram of the correlations between spring/fall soil moisture and summer precipitation during 1915 to 2004. The mean correlation with summer precipitation is 0.21 for fall soil moisture and 0.29 for spring soil moisture (both are statistically significant at 95%). Therefore, both fall and spring soil moisture anomalies have significant correlations with summer precipitation, but the strength of these correlations varies greatly over the NGP. Such variation is possibly linked to external influences such as vapor transport from the Gulf of Mexico and SST variation and this merits further study [*Hu and Feng*, 2001a; b].

3.2 Temporal linkage between soil moisture and precipitation

Fig. 3 shows the 15-year moving correlation of soil moisture anomalies versus summer precipitation (Z-index) averaged over the entire NGP. It is obvious that the strength and sign of the correlation varies over time. The correlations between spring soil moisture and summer precipitation anomalies are only statistically significant during 1922–1937, 1946–1951, and 1971–1978.

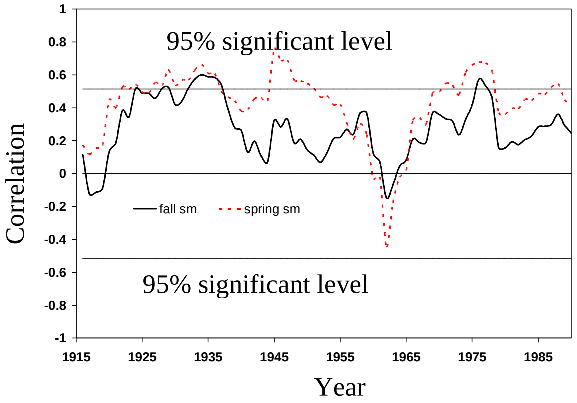

Figure 3. 15-yr sliding correlation of JJA precipitation versus spring (red dashed line)/fall (black solid line) soil moisture anomalies in the NGP.

The linkage between soil moisture and summer precipitation is weakest during the period 1955–1965 and there is a negative relationship (-0.52) between spring soil moisture and summer precipitation at the beginning of 1960s. This dynamic relationship between soil moisture and summer precipitation has also been found in other studies [*Hu and Feng*, 2004; *Zhu, et al.*, 2005]. The results suggest that spring soil moisture anomalies are more strongly correlated with summer precipitation than fall soil moisture anomalies (Fig. 3). The correlation between fall soil moisture anomalies and summer precipitation (Z-index) is only statistically significant during the period 1923–1937. This indicates that, on average, spring soil moisture is a better predictor of summer precipitation in the NGP.

3.3 Relationship during abnormal soil moisture anomalies

A further examination of the relationship reveals that there is even a stronger correlation between summer precipitation versus soil moisture anomalies during abnormally wet (>1 std dev) and dry (<-1 std dev) seasons. There were 16 wet falls and 12 dry falls and 13 of the 16 wet falls were followed by wetter than normal summers and 9 of the 13 dry falls by drier than normal summers. There were 11 wet springs and 12 dry springs during this period and all wet (dry) springs followed by wetter (drier) than normal summers. This also included 3 of 10 wettest years and 4 of 10 driest years between 1915 and 2004. The correlation between the abnormal falls and summer precipitation is 0.53 (statistically significant at 95% significant level) and it increases to 0.83 between the abnormal springs and summer precipitation. This suggests that abnormal spring soil moisture conditions can have a stronger effect on summer precipitation than abnormal fall soil moisture conditions. This conclusion is consistent with other studies [*Koster and Suarez*, 2001; *Pielke, et al.*, 1999].

We further investigated the ten driest and wettest summers in the study period (not shown). Based on composite analysis, the ten driest summers between 1915 and 2004 were associated with a mean daily fall (spring) soil moisture anomaly of -26.1 mm (-36.6 mm) (assuming the soil depth is 1 meter). Over 98% of the study region had drier than normal fall soil moisture and spring soil moisture prior to the ten driest summers. The ten wettest summers were associated with a mean daily fall (spring) soil moisture anomaly of +10.8 mm (+15.7 mm). Approximately 82% of the study region had wetter than normal fall and spring soil moisture prior to the ten wettest summers. The results reveal that the persistence of soil moisture for drier conditions might be longer and stronger than that for wetter conditions. This is consistent with the findings of *Wu and Dickinson* [2004].

3.4 Role of upper troposphere circulation

Fig.4 displays the composite difference (dry years minus wet years) maps for the 500mb geopotential height anomalies in May (left) and JJA (right) between the years that have abnormally dry and wet springs. Abnormally dry (wet) spring soil moisture conditions are associated with lower (higher) heights along the west coast of the US and over central and eastern Canada, and higher (lower) heights over the central and eastern United States (including the NGP) in May. Abnormally dry (wet) spring soil moisture conditions are associated with higher (lower) heights over the western half of North America (centered off the coast of Oregon) in summer (JJA). This demonstrates that atmospheric circulation anomalies are present not only during May (coincident with the abnormal soil moisture conditions), but also during the summer season that follows. However, the magnitude of the 500mb geopotential height anomalies are much larger in May than they are during JJA. It is not clear whether the spring soil moisture conditions are responsible for the observed atmospheric circulation anomalies.

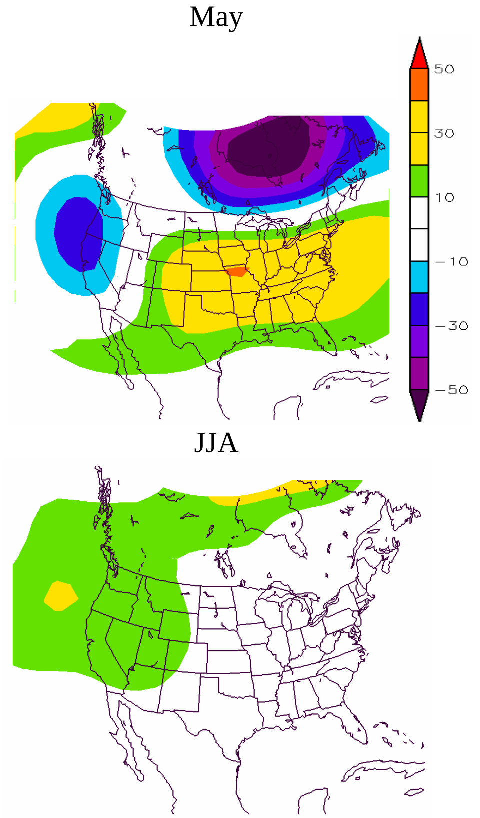

Figure 4. May (top) and summer (JJA) (bottom) 500-mb geopotential height anomaly (dry spring years (1956, 1959, 1961, 1980, 1988, 2002, 2004) minus wet spring years (1972, 1978, 1983, 1986, 1995, 1997, 1999)) during the period 1915-2004.

4. Summary and Discussion

Overall, our results indicate that there are statistically significant correlations between spring/fall soil moisture and summer precipitation in the NGP. However, the correlations vary significantly over space and time. In general, the correlation between spring soil moisture and summer precipitation is much stronger than the correlation between fall soil moisture and summer precipitation. The sliding-window correlations demonstrated that soil moisture only played a significant role in modulating summer precipitation during the three periods, 1922–1937, 1946–1951, and 1971–1978. The relationship between soil moisture and summer precipitation was not evident during 1952 to 1970. The period 1952–1970 is in good agreement with the period identified by *Hu and Feng* [2001a, 2004]. *Hu and Feng* [2004] found that teleconnections associated with North Pacific SST anomalies were dominant during the period 1949–1978 when there was strong persistence of SST anomalies. They also suggested that the influence of land surface processes on the summer rainfall became prominent only when the persistence of SST anomalies decreased. The results of this study are also consistent with other studies that have shown that the relationship between land surface conditions and summer precipitation is not stable during the 20th century [*Zhu, et al.*, 2005]. For instance, *Zhu et al.* [2005] examined the effect of precipitation, soil moisture and snow water equivalent anomalies on the southwestern US monsoon rainfall and identified that the correlation between precedent winter precipitation and monsoon rainfall was only statistically significant during 1965–1990.

It was also demonstrated that the strength of the correlations between soil moisture and summer precipitation increased when only the abnormally wet (>1 std dev) and dry (<-1 std dev) seasons were considered. The correlation between abnormal fall (spring) soil moisture and summer precipitation is 0.53 (0.83). Examination of the atmospheric circulation patterns demonstrates that these abnormally wet and dry spring seasons are associated with circulation anomalies in May and JJA. Our findings, which are in agreement with those of *Koster et al.* [2003], indicate that local land conditions play a role in modulating summer precipitation in the NGP.

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