Why Has the Land Memory Changed?

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ABSTRACT

The “land memory” refers to an interseasonal predictability of the summer monsoon rainfall in the southwestern United States, describing a relationship of the summer monsoon rainfall anomaly with anomalies in the antecedent winter season snow and land surface conditions in the western United States. This relationship has varied, however, showing a peculiar on-and-off feature in the last century. It is important to understand this variation so that the relationship can be used to assist making predictions of the monsoon rainfall for that region. This note offers the evidence and shows that the change of the land memory may have been a reflection of an irregular variation in the persistence of the sea surface temperature anomaly (SSTA) in the North Pacific Ocean; in epochs when the SSTA persisted from winter through summer, the SSTA and related anomalies in atmospheric circulation could have dominated the summer monsoon variation, whereas in epochs when the persistence collapsed the SSTA effect weakened and the effect of the land processes on the summer monsoon rainfall became prominent.

1. Introduction

The “land memory” refers to a predictability of the summer monsoon rainfall in the southwestern United States (31°–36°N, 104°–113°W) by the antecedent winter season precipitation anomaly in the western United States and associated land surface processes developed from the winter to the summer monsoon onset. In particular, an above-average (below average) winter precipitation in the northwestern (southwestern) United States preceded a below-average summer monsoon rainfall, and an above-average monsoon rainfall followed a reversed winter precipitation anomaly pattern in the western United States (Gutzler and Preston 1997; Higgins and Shi 2000). This interseasonal predictability could be an important utility for prediction of summer rainfall in the semiarid southwestern United States. However, this predictability has been varying in the last century: the predictive relationship was fairly robust in 1921–30 and in 1961–90, but was absent before 1920, between 1930 and 1960, and has weakened in recent decades since 1990 (Hu and Feng 2002). This irregular variation of the predictability must be understood so that we know when it could be used to assist making predictions of the summer monsoon rainfall and, additionally, what may be used to assist the predictions when the land memory fails. In this note, we provide evidence and postulate an explanation of the variation in the land memory and suggest a source affecting the summer monsoon rainfall variation when the land memory weakened.

When a variation is as irregular as the land memory, some processes external to the system of variation are affecting the system’s behavior. As we showed in a previous study (see Fig. 9 in Hu and Feng 2002), in the different epochs with active or absent land memory, the same winter season precipitation anomalies appeared in the western United States, although corresponding to very different summer monsoon rainfall anomalies in the southwestern United States. If there had been no other processes affecting the land memory, those same winter season precipitation and related land surface process anomalies would have led to a similar summer monsoon rainfall anomaly (either a wet or a dry monsoon). Thus, the observed very different “consequences” in the summer monsoon rainfall from similar antecedent winter season precipitation anomalies support the notion that similar land process effects may have always existed on the summer monsoon rainfall. Such an effect was not prominent in some of the epochs when external effects override that of the land processes on the summer monsoon rainfall. The irregular interference of land memory by those external effects may have resulted in the ob-
The results show the changes are significant at 99% confidence level. The significance in change of the correlations between different epochs. Z-transform test (Panofsky and Brier 1958) was applied to examine the significance in change of the correlations between different epochs. The results show the changes are significant at 99% confidence level.

The alternations of the land memory (Fig. 1a) coherent with changes in persistence of the SSTA in the North Pacific (Fig. 1b) suggest that the apparent weak memory in some epochs could be a result of a stronger effect on the summer monsoon rainfall from the SSTA because of its persistent anomaly and associated anomalies in the atmospheric circulation in the western United States (Namias et al. 1988). When the stronger effect from the SSTA dominated the monsoon rainfall variation, the land process effect on the summer monsoon rainfall, although it could well be present, was deemed to be secondary or trivial. To further elaborate this point, we refer the readers to the results in Fig. 2. Comparison and contrast of Figs. 2a and 2b reveal that the large summer monsoon rainfall difference between wet and dry monsoon summers in the epoch 1961–90 corresponded to a small but consistent difference in antecedent winter precipitation, and a wet summer followed by a drier winter (Fig. 2b). In the epoch 1931–60 (Fig. 2a), a rather different relationship existed; a small difference of the monsoon rainfall between the wet and dry monsoon years corresponded to a relatively large difference in the preceding winter precipitation. Additionally, a wet summer monsoon followed a wet winter, and the land memory effect was interrupted. Further contrasting Figs. 2b with 2a, we find that in the epoch 1931–60 (Fig. 2a) when the land memory was absent, the entire year (except for December) was wet or dry when the summer was wet or dry. In the epoch 1961–90 (Fig. 2b) when the land memory was active, the summer monsoon rainfall anomalies were opposite to the anomalies of the winter season precipitation. This difference in the annual precipitation variation between the two opposite epochs suggests that different processes may have dominated the variations in the southwestern United States. In the epoch of weak land memory, the entire year of wet or dry was likely an indication of a dominant role of the SSTA anomalies in the Pacific because, as summarized in Fig. 14 of Castro et al. (2001) on the relationship of the North American monsoon to

2. Data

Summer rainfall data for the southwestern United States used in this study were obtained from the monthly precipitation data of New et al. (2000) at 0.5° × 0.5° resolution from 1901 to 1998. The monthly SST data were obtained from the Global Sea Ice and Sea Surface Temperature (GISST) version 2.3 dataset at 1.0° × 1.0° resolution for the same period (Parker et al. 1995).

3. Results and discussion

In Fig. 1a, we show the variation of the relationship between the U.S. Southwest summer monsoon rainfall (total rainfall in monsoon months of July–September) and the antecedent winter (January–March) precipitation in the western United States (Hu and Feng 2002). A persistent relationship between the two is found in 1921–30 and in 1961–90. These two epochs coincided with two major periods when the SST anomaly (SSTA) in the North Pacific was least persistent (Fig. 1b). Here, persistence of the SSTA is defined as the lagged correlation of the SSTA in winter versus summer (July–September) and measures the continuation of the SSTA pattern from winter to summer. [This method has been applied in both atmospheric studies (Mo and Ghil 1987; van den Dool 1983) and oceanographic studies (Namias et al. 1988; Chao et al. 2000) to describe shifts of circulation regimes and climate variations.] A weak persistence would therefore indicate variations and large changes of the SSTA pattern in the North Pacific from winter to summer. On the other hand, a strong persistence would suggest a similar pattern of the SSTA in the North Pacific lasting from winter through summer and associated persistent atmospheric anomaly patterns in the North Pacific basin and North America (Namias et al. 1988). In Fig. 1b, the strong persistence of the SSTA is observed in the periods 1900–20 and 1931–60. In these epochs of strong SSTA persistence, the land memory effect on the summer monsoon rainfall was rather weak (Fig. 1a).

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tropical and North Pacific SST variations, a persistent SSTA pattern in the tropical and North Pacific could correspond to atmospheric flow and circulation patterns in the North Pacific and North America favoring a continuous wet or dry anomaly in the monsoon region. (Indeed, the pattern summarized in Fig. 14 of Castro et al. is for the onset month of the monsoon, but a persistent pattern of the SST could cause an atmospheric circulation pattern with similar features, contributing to a continuous wet or dry condition in the monsoon region during a year.) On the other hand, the reverse of the precipitation anomalies between the summer and preceding winter in the following epoch of active land memory indicates a weak SSTA effect and enhanced regional land process effects on the summer monsoon rainfall. The weak SST effect could result from a less persistent SSTA in the tropical and North Pacific and would allow regional land processes to play an important role in the monsoon variation.

This postulation on the interference of persistent tropical and North Pacific SSTA with the land memory can be examined from a different perspective using the relationship between the summer monsoon rainfall in the southwestern United States and the SSTA from winter to summer in the North Pacific. In Fig. 3, we show the correlation of the southwest U.S. summer monsoon rainfall versus the SSTA in the preceding winter and spring as well as in the summer for the epochs 1921–30 and 1961–90. The correlation is weak or absent, indicating a lack of a consistent influence of the SSTA on the summer monsoon rainfall. This result is consistent with the lack of a persistent SSTA in those epochs. In addition, the reversed correlation patterns for the monsoon rainfall versus the winter and summer SSTA in Figs. 3a and 3c further suggest different effects on the summer monsoon rainfall from a different SSTA in the antecedent winter and during the summer. Compared to Fig. 3, Fig. 4 shows a totally different effect of the SSTA on summer monsoon rainfall in the two epochs, 1901–20 and 1931–60, when land memory was weak and the SSTA persisted from winter through summer. Figures 4a–c show similar spatial correlation patterns of monsoon rainfall with the preceding winter to summer SSTA for the epoch 1901–20, and Figs. 4d–f show the same result for the epoch 1931–60. In the latter epoch, the SSTA in the north-central North Pacific and the eastern tropical Pacific were significantly correlated with the U.S. Southwest summer monsoon rainfall variations. This set of consistent SSTA correlation patterns indicates that the persistent SSTA from winter to summer in that epoch could have initiated and maintained circulation anomalies in the atmosphere, as articulated in Namias et al. (1988), and associated winter and summer precipitation variations in the land areas of the western United States. The same result is also shown in the earlier epoch of 1901–20, albeit its set of similar correlation patterns from winter through summer is a little different from the set of the epoch of 1931–60.

When the summer monsoon rainfall in the southwestern United States is significantly influenced by the antecedent winter and spring, as well as the summer, SSTA in the North Pacific in the epochs 1901–20 and 1931–60, it is unlikely that the local and regional effects from land surface process anomalies could dominate the monsoon rainfall variation. The land process effects may only become prominent when the SSTA effect weakens and the persistence of the SSTA in the tropical and North Pacific diminishes. Thus, the irregular change of the land memory could be a reflection of variation in the persistence of the SSTA in the North Pacific Ocean and the associated alternation of the SSTA effect on the summer monsoon rainfall.

The strong correlation of the summer monsoon rainfall and the preceding winter and spring SSTA in the tropical and North Pacific shown in Fig. 4 is, to some extent, similar to that found in Higgins and Shi (2000) but is quite different from the results in Castro et al. (2001), who showed a lack of correlation of the summer monsoon rainfall versus the preceding winter SSTA in three specific regions used in their analyses. Since the
Fig. 3. Correlations of the U.S. Southwest summer monsoon rainfall vs (a) the antecedent winter SSTA, (b) spring SSTA, and (c) summer SSTA in the North Pacific Ocean for the epoch 1921–30. Same correlations but for the epoch 1961–90 are shown in (d), (e), and (f) for winter, spring, and summer SSTA, respectively. The light shading indicates correlations significant at the 95% confidence level, and the dark shading indicates correlations significant at the 99% level. [(a)–(c) have higher spatial noise owing to a smaller number of sample years.]
Fig. 4. As in Fig. 3 but for the 1901–20 epoch. Same correlations but for the epoch 1931–60 are shown in (d), (e), and (f) for winter, spring, and summer SSTA, respectively. The shadings indicate significance of the correlation same as defined in Fig. 3.
Fig. 5. Partial correlations of (a) antecedent winter, (b) spring, and (c) summer SSTA and U.S. Southwest summer monsoon rainfall for the epoch 1931–60, after the land memory effect was suppressed. Panels (d)–(f) are as (a)–(c) but for the epoch 1961–90.
Castro et al. study was specifically on the relationship of the U.S. Southwest summer monsoon rainfall and the North Pacific SSTAs, it is necessary to explore this difference and its sources. One possible source, as Castro et al. suggested (p. 4464), is that “The weak lag correlation (in their results) using the NP (North Pacific) index is likely an artifact of the regions used to define it.” Indeed, a comparison of the regions used in defining their NP index showed that those regions are off from the ones showing significant correlations in Fig. 4. Another possibility is that the relationship examined in Castro et al. is for selected years in 1948–98, instead of the specific epochs that are the elements in this study. This difference in the focus of these studies, that is, interannual versus multidecadal-scale variations of the southwest U.S. summer monsoon rainfall could account for parts of the difference in the lag correlation results. This difference and associated results also disclose an additional feature of the SST relationship with the summer monsoon rainfall at multidecadal scales.

When persistent tropical and North Pacific SSTAs, strongly affect variations in the U.S. Southwest summer monsoon rainfall, the land processes constituting the land memory could also have interfered with the SST effect, weakening or enhancing it. To disclose the effect on the SSTAs from the influences of the land processes, we calculated the partial correlation of summer monsoon rainfall versus SSTAs by excluding the variance predictable of the land processes from the correlation (Panofsky and Brier 1958). The formula used in this calculation is

\[
    r_{TR,W} = \frac{r_{TR} - r_{TW}r_{RW}}{\sqrt{(1 - r_{TW})(1 - r_{RW})}},
\]

where \(r_{TR,W}\) is the partial correlation of the SSTAs (subscript \(T\)) and the monsoon rainfall (subscript \(R\)) without interference from the land memory (subscript \(W\)), which is described by the WP index defined in Hu and Feng (2002). The other symbols in (1) are regular correlations of the two variables indicated by the subscripts.

Results of (1) are shown in Fig. 5 for the two epochs, 1931–60 and 1961–90, both of which have a 30-yr length and are much longer than the two short epochs before 1930. Figures 5a–c show statistically significant correlations of the preceding winter and spring and summer SSTAs in the central North Pacific versus the monsoon rainfall after the land memory effect was partitioned out. Compared with the results in Figs. 4d–f, this result indicates that a persistent SSTAs in the central North Pacific has an independent effect on the summer monsoon rainfall. Another intriguing result from comparisons of Figs. 5a–c and 4d–f is that the partial correlations suggest an independent effect of the SSTAs in the tropical eastern Pacific on the monsoon rainfall, yet such an effect was not shown in Figs. 4d–f. This difference may indicate that through interference and interactions the land memory processes may have actually weakened the tropical SSTAs effect on the summer monsoon rainfall. In the meantime, the interactions may have also enhanced the SSTAs effect from the central North Pacific Ocean, contributing to the observed correlation pattern in Figs. 4d–f. Details of the interactions and how they modulated the SSTAs effect on the summer monsoon rainfall deserve further analysis.

The partial correlations for epoch 1961–90 in Figs. 5d–f show a lack of independent SSTAs effect on the monsoon rainfall, a feature similar to that in Figs. 3d–f, and further indicate a dominant role of the land processes on the monsoon rainfall when the SSTAs lacked persistence in the North Pacific.

To summarize, we have shown from various perspectives that the changes of land memory in the last century could have resulted from the irregular alternations of the persistence of the SSTAs in the North Pacific Ocean. As similar land processes developed after antecedent winter precipitation anomalies in the western United States, the “land memory” should always be present. However, the land memory effect dominated the U.S. Southwest summer monsoon variations when influence on the monsoon rainfall from the SSTAs in the North Pacific weakened. We found that the SSTAs effect could enhance and dominate on the summer monsoon rainfall in the epochs when the SSTAs was persistent from winter through summer in the North Pacific. In those epochs, the SSTAs effect dwarfed that of the regional land processes and configured a different annual rainfall variation in the southwestern United States. Although the land memory considerably weakened in those epochs, it interacted with the SSTAs effect, selectively enhancing the SSTAs effect of the central North Pacific Ocean.

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