Recurrent Teleconnection Patterns Linking Summertime Precipitation Variability over East Asia and North America

K.-M. LAU
Climate and Radiation Branch, NASA Goddard Space Flight Center, Greenbelt, MD, USA

and

Hengyi WENG
Center for Climate System Research, University of Tokyo, Tokyo, Japan

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Abstract

From analyses based on Singular Value Decomposition of rainfall and 500 hPa geopotential height anomalies, we have identified two atmospheric teleconnection patterns linking interannual variability of summertime precipitation over East Asia and the continental United States. The first pattern is associated with enhanced rainfall over the Yangtze River region to above-normal rainfall over the US northeastern Great Plains and the Midwest, and reduced rainfall over the Atlantic coast. It features zonally elongated 500 hPa height anomalies over the subtropical and extratropical western North Pacific coupled to a regional circulation pattern over North America that regulates moisture transport from the Gulf of Mexico to the Northern Great Plains. The second pattern shows enhanced rainfall anomalies over the Huaihe River, northeastern and southern China and deficient rainfall over the central US. It connects the East Asian and North American continents via a pan-Pacific wavetrain signal, possibly stemming from Rossby wave dispersion from fluctuations of large-scale heat sources, and sinks in the Indo-Pacific region. Examination of associated sea surface temperature variability in the North Pacific suggests that the first pattern may be influenced by El Niño in the preceding spring, but becomes increasingly decoupled from tropical SST during the summer and fall. However, the second pattern has no significant relationship with El Niño.

Analysis of extreme rainfall statistics between regions in East Asia and North America suggests that occurrence of the aforementioned teleconnection patterns is associated with increased probability for extreme rainfall events over the Yangtze River Valley, coupled to increased probability of anomalies of the same sign over the US Midwest, and of the opposite sign over the US Mid-Atlantic coast. Our results suggest that the summertime teleconnection patterns should be further explored for additional sources of potential predictability of summertime floods or droughts over regions of East Asia and North America.

1. Introduction

The Asian summer monsoon represents the most dominant source of energy that drives the atmospheric general circulation, affecting hydro-climate variability not only in the Asian sector, but also regions far away. A number of previous studies have shown that convective heating over the subtropical western Pacific near the Philippines can excite a wavetrain pattern that spans the northern Pacific Ocean and North American (Nitta 1987; Huang 1985). Lau and Peng (1992) showed that a similar wavetrain may stem from marginally unstable normal modes of the summertime large-scale monsoon circulation. Chen (1993) pointed out...
the importance of summertime extratropical stationary eddies and their linkages to tropical SST and variability of the Asian monsoon. A number of recent studies (e.g., Li and Zhang 1999; Lau et al. 2000; Wang et al. 2001, and others) noted strong teleconnection signals emanating from the subtropical northwestern Pacific, through the Aleutians to North America during periods of enhanced Asian monsoon activities. In a similar vein, many studies have identified the important role of remote forcing in causing warm season precipitation anomalies over the US continent over a wide range of time scales, (Trenberth and Guillemot 1995; Mo et al. 1997; Livezey and Smith 1998; Mo 2000; Higgins et al. 2000). Also noted during episodes of extreme rainfall anomalies over North America, such as the great flood of the US Midwest during 1993, were pronounced sea surface temperature signals in the extratropical North Pacific, besides those in the tropical eastern Pacific (Ting and Wang 1997; Wang et al. 1999).

Even though previous studies have mentioned possible influence of Asian monsoon on North America climate, few have attempted to link summertime precipitation anomalies over the US continent to variability of the Asian monsoon. Recently, Lau and Weng (2000 a, b) reported preliminary findings of the possible existence of such a linkage. Lau et al. (2002) demonstrated additional sources of summertime rainfall predictability over the US Midwest, and the northern Great Plains from sea surface temperature (SST) variability in the North Pacific. Because of the repeat occurrences and the long duration (more than a season or longer) of these linkages or teleconnections, it is plausible that they are manifestations of recurrent climate pattern of the boreal summer coupled ocean-atmosphere system. In this study, we expand on the aforementioned studies, and further investigate and identify the presence of recurring summertime climate patterns linking summertime precipitation variability over the US continent and East Asia. Since these climate patterns may have different spatial and temporal structures, they need to be examined separately. In this paper, we focus only on interannual variability. Decadal and longer-time scales, including trends will be reported elsewhere.

2. Data and analysis procedure

We use monthly rainfall of 102 divisions over the continental United States from the National Center for Environmental Predictions (NCEP), and monthly rainfall from China based on 160 gauge observations for the period 1955–1998 (Lau and Weng 2001). To define teleconnection patterns, we use monthly wind and geopotential height fields from the NCAR/NCEP reanalysis (Kalnay et al. 1996) and monthly SST from the Hadley Centre for Climate Prediction Research. All data used are seasonal deviations from the 44-year climatological mean, which is defined as the average over June-July-August (JJA) for all the fields, except for rainfall, where the 3-month total is used. We decompose the seasonal data into Fourier harmonics, with the interannual component defined by harmonics with periods from 2–8 years, and decadal-interdecadal components with periods longer than 8 years. Unless otherwise stated in the text, the results and the comparison with observations are for the interannual component only.

Using a combination of correlation, Singular Value Decomposition (SVD) and regression analyses, we begin the analysis in Section 3, by identifying the large-scale circulation and SST features associated with summertime precipitation anomalies over the US, including an evaluation of the year-to-year contribution of the principal patterns to regional precipitation anomalies. In Section 4, we carry out an analysis of the co-variability of geopotential height, wind, and combined summertime rainfall over the US and China to explore the physical basis of possible recurrent climate patterns linking summertime rainfall variability in North America, and in East Asia. In Section 4, the results are further discussed in the context of individual events of major floods and droughts, and occurrence of joint precipitation extremes between key regions over the two continents. The conclusions and implications of this work are presented in Section 5.

3. Teleconnection associated with North America summertime precipitation

3.1 One-point correlation

To illustrate possible summertime teleconnection patterns linking East Asia and North
America, we have computed the one-point correlation maps of US summertime rainfall over different regions of the US continent with 500 hPa height field and SST. We find various teleconnection patterns associated with US summertime precipitation variability that suggest global scale underpinnings. As an example, the one-point correlation map of the global 500 hPa geopotential height and SST fields with respect to the JJA mean rainfall anomalies averaged over the central US and Midwest region (35°–47°N, 100°–85°W) is shown in Fig. 1a. Here, the summertime rainfall anomaly over the US Midwest region is coupled to a regional circulation pattern that may be a part of a trans-Pacific wavetrain pattern, with linkage to the western Pacific and East Asian monsoon regions. The teleconnection pattern is associated with distinct SST expressions over the North Pacific as evident in the SST correlation map (Fig. 1b). The largest SST loadings are found in the extratropical North Pacific, with large negative anomalies near Japan and the central North Pacific, and positive anomalies along the west coast of North America. There is a lack of coherent signal over the tropical central and equatorial Pacific. The overall SST pattern is quite different from those associated with El Niño.

3.2 Rainfall and 500 hPa height covariability

In this section, SVD analysis is carried out to identify the dominant patterns of 500 hPa geopotential height and summertime precipitation...
anomalies over the US. Only the first two SVD modes, whose eigenvalues are well separated from the higher order modes, are discussed. The first SVD mode (SVD-1) explains 32% of the squared covariance between the two fields, and features a rainfall pattern with a dipole structure linking rainfall anomalies in the northern central states and the Midwest to anomalies of the opposite sign in the eastern and southeastern states (Fig. 2a). The SVD-1 rainfall pattern is associated with a 500 hPa cyclone-anticyclone couplet over the northwest and southeast North America (Fig. 2b), which is connected to an extensive zonally elongated geopotential height anomaly, spanning the North Pacific, Japan and northeastern East Asia. The zonally banded structure over the East Asian sector (110°–150°E) can be identified with the characteristic pattern arising from the fluctuations of the East Asian jetstream and convection over the subtropical western Pacific (Lau et al. 2000). The principal components (Fig. 2c) show that SVD-1 has the largest positive projection (>2σ) during the great flood in the US Midwest in 1993. Large projections (absolute value > 1σ) are also evident in other years, notably 1955, 1961, 1967, 1989 and 1994. The re-occurrence, and the well-defined rainfall pattern, coupled with the expansive structures of the geopotential height pattern suggest that SVD-1 may be the manifestation of a recurring intrinsic climate mode during the boreal summer.

The second SVD mode (SVD-2) in Fig. 3a depicts a continental scale rainfall pattern centered over the central US having anomalies of the opposite sign in the northeastern and southern regions. Associated with the rainfall pattern is a pronounced wavetrain spanning the North Pacific, which appears to emanate from the East Asia/Japan region (Fig. 3b), similar to the correlation map shown in Fig. 1a. In SVD-2, much of the continental North America is dominated by a pronounced high centered to the northwest of the Great Lakes, while the northwest and Alaska are under the influence of a prominent low. The principal components (Fig. 3c) show large amplitude swings, signaling severe rainfall deficits over the central US in 1983, 1988 and 1991, and rainfall excesses in 1982, 1992, and 1998. During 1993, the large negative contribution of SVD-2 together with the large positive contribution from SVD-1 are responsible for the rec-
ord excessive rainfall over the Midwest region. However during 1988, SVD-2, but not SVD-1, is the dominant contributor to the continental scale rainfall deficit. Thus, the causes of the observed rainfall anomalies for a particular year depend largely on the relative excitation of SVD-1 and SVD-2, and possibly other factors, such as land-atmosphere feedback, which is not considered here. The aforementioned rainfall patterns are similar to those obtained using EOF analysis of the US summertime seasonal rainfall (not shown), with the first two modes explaining 20% and 16% of the interannual rainfall variability respectively.

### 3.3 SST regressions

Figures 4a and 4b show the regressions of SST against the rainfall PCs of SVD-1 and SVD-2 respectively. For SVD-1, the most prominent feature is an extensive tongue of cold water in the North Pacific along 40°N, which underlies the zonally oriented 500 hPa low associated with SVD-1 (see Fig. 3b). The extratropical cold tongue over the western Pacific coupled with the warm water to the south over the East China Sea and oceanic regions surrounding the maritime continent, provide a region of increased meridional SST gradient off the coast of East Asia. This increased gradient is an important factor in governing the fluctuation of the summertime East Asian jet-stream and the west Pacific subtropical high (Lau et al. 2000). SVD-1 also shows a noticeable SST signal over the equatorial eastern Pacific, suggesting a possible connection with El Niño.

The SST regression for SVD-2 (Fig. 4b) shows a strong similarity to the SST correlation pattern associated with rainfall over the central US region (see Fig. 1b). The strongest signal is found in the extratropics with a warm anomaly in the subtropical central Pacific, cold anomalies in the North Pacific, south of the Kamchatka Peninsula, and in the Gulf of Alaska, off the west coast of North America. The warm and cold SST anomalies appear to bear a coherent spatial relationship with the wavetrain signal in the 500 hPa geopotential height field shown in Fig. 3b, with the positive height field offset to the east of warm SST in the North Pacific. Likewise, the center of the 500 hPa trough over the west coast of North America is situated to the east of the cold water over the eastern North Pacific. Possible dynamical implications of these spatial relationships will be further discussed in Section 4.
3.4 Year-to-year contributions

In this section, we discuss the contributions of various SVD modes and by inference their underlying physical mechanisms to occurrence of precipitation anomalies over the US. Specifically, we develop a procedure to estimate how much the observed rainfall anomalies can be reconstructed from the geopotential field on a yearly basis. This procedure is important because it will allow regional precipitation information to be downscaled from the geopotential height field that can be obtained either from dynamical model predictions, or from data assimilation systems. Here, we compute the cumulative anomaly correlation (CAC) and the cumulative anomaly variance (CAV) based on the observed rainfall, and that reconstructed from the heterogeneous SVD modes. If we define $R_{i,J}$ as the $i$th year’s re-constructed rainfall field based on the first $J$ eigenmodes as:

$$R_{i,J}(x, y) = \sum_{j=1}^{J} (PC_{i,j} \times SVD_{j}(x, y)), \quad (1)$$

then

$$CAC_{i,J} = \frac{1}{\sigma(O_i)\sigma(R_{i,J})} \sum_{x, y} (O_{i,j} - \bar{O}_i)(R_{i,J} - \bar{R}_{i,J}),$$

$$CAV_{i,J} = 1 - \frac{1}{\sigma^2(O_i)} \sum_{x, y} (O_{i,j} - R_{i,J})^2. \quad (2)$$

In Eqs (1) and (2), the PCs are based on the geopotential SVD modes, $O_i$ denotes the ob-
served rainfall in the \(i\)th year. Essentially, the CAC is the spatial pattern correlation between the observed and the reconstructed rainfall based on successive inclusion of SVD modes, beginning with the lowest order mode. Similarly, CAV is a measure of the mode-by-mode contribution to the cumulative fractional variance of the reconstructed rainfall field. When the reconstruction is perfect, CAV is equal to unity, and when the error variance is as large as the observed variance, CAV is zero. When the error variance is greater than the observed, CAV can be negative. In practice, a reconstruction giving a CAV of zero or negative values should be rejected as of no value. The CAC and CAV methodologies have been reported in Lau and Weng (2001) and Lau and Wu (2001). Here, we carry out computations in Eqs (1) and (2) only up to the 5th mode, beyond which the CAC tends to level off. Heuristically, the total CAC (up to the 5th mode) may be regarded as the potential predictability of US rainfall precipitation, associated with the large-scale circulation. The 95% and 99% confidence level of the CAC, computed based on the estimated number of degrees of freedom from EOF analysis of the rainfall field, is 0.50 and 0.61 respectively.

Figure 5 shows the year-to-year variability of CAC and CAV. It is obvious from Fig. 5a that the first two modes account for a large portion of the observed rainfall variability for most years. In particular, the dominant contribution (>99% confidence level) of SVD-1 to the observed rainfall anomaly in 1993 and 1994 is obvious. For these two years, the CAV (Fig. 5b) due to SVD-1 exceeds 40% of the total variance. SVD-1 also contributes significantly (>95% confidence level) in many other years, i.e., 1955, 1961, 1967, 1968, 1989 and 1996. By comparison, strong SVD-2 events (greater than or close to 95% confidence level) occur less frequently, but are notable in 1958, 1959, 1988 and 1991. The CAV for SVD-2 is generally smaller compared to SVD-1. In some years, higher order modes are needed to raise the CAC above the 95% confidence level and the CAV to more than 20%, presumably because these modes are required to account for the larger spatial variability of the anomalies during those years.

Figure 5 shows that there is a general reduction of total CAC and CAV during the decades of the 1970’s and earlier, followed by an increase in the 1990’s, suggesting a possible interdecadal variation in the contributions of SVD-1 and SVD-2 to rainfall anomalies over the US. In the 21 years since 1978, 10(15) years have total CAC above the 99% (95%) level, with an average CAV of 29.4%. Whereas, in the 23 years before 1977, 7(10) years exceed the 99% (95%) level, with an average CAV of 16.3%.

This shift in the CAC and CAV statistics may reflect an increase in frequency of occurrence of severe events in US summertime precipitation in the last two decades. As seen in Fig. 5, this increase is principally due to the contributions of the first two modes. The reason for the increase is uncertain, but as a speculation may be related to the global warming trend in surface temperature and/or the abrupt shift of the global scale circulation since 1977 (e.g., Trenberth and Hurrell 1994; Lau and Weng 1999; Kumar et al. 1999; Krishnamurthy and Goswami 2000).

4. Co-variability of East-Asia and US rainfall anomalies

To provide further evidence of the teleconnection between the East Asian monsoon and US summertime rainfall, we have carried out a SVD analysis using 500 hPa geopotential height, and combined seasonal rainfall anomalies over the US and China. To take into account the large difference in magnitudes, the rainfall fields are first normalized by their maximum deviation in each region. SVD analysis is then performed in the same manner as described in Section 3.

4.1 Combined SVD-1

Figure 6 shows the spatial and temporal distributions of the combined SVD-1 based on the combined analysis. To facilitate physical interpretation, the regression of the rainfall principal component against the 850 hPa winds is also included in Fig. 6a. The strong similarity between the corresponding rainfall and height patterns in the combined SVD-1 and those of SVD-1 (Fig. 2) is quite obvious. Henceforth, we shall refer to the combined SVD-1 also as

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1 Since \(N = 15\) EOF modes are needed to account for 90% of the total rainfall variance, the effective number of spatial degree of freedom in the US rainfall field is \(N-1 = 14\) (cf., Bretherton et al. 1999).
SVD-1. The following discussion will be focused on features not already described in Fig. 2. The mid-tropospheric high over the southeast US is accompanied by strong low-level anticyclone, with a poleward low level jet along the southern Great Plains, flowing from the Gulf of Mexico to the Midwest region. This low-level jet is likely to be responsible for the excessive

Fig. 5. a) CAC and b) CAV between reconstructed and observed rainfall anomalies using principal components from the first five SVD geopotential modes. Contributions from SVD-1, SVD-2 and SVD 3–5 (combined) are indicated by heavy, medium and light shaded bars, respectively. The shaded (dashed) horizontal lines in (a) indicates the 95% (99%) significance level.
rainfall in the Midwest region and the rainfall deficit over the US east coast (Fig. 6c). The zonally elongated 500 hPa geopotential height, and 850 hPa zonal wind anomalies over the North Pacific and East Asia, are very similar to the dominant mode of interannual variability of the East Asian summer monsoon, associated with multi-cellular meridional overturnings along 110°–130°E (Lau et al. 2000). SVD-1 is associated with enhanced low-level convergence, and excessive rainfall over the Yangtze River Valley (YRV) near 30°N, and regions in northeastern China near 45°N (Fig. 6b). This mode is most pronounced in 1993, 1994 (with
negative sign) and in 1998 (Fig. 6d). The rainfall anomaly shown in Fig. 6b is almost identical to that observed in 1998, when record flooding occurred over the YRV.

The regressed SST pattern for SVD-1 (not shown) is nearly identical to that shown in Fig. 4a, with a strong cold tongue underlying the cyclonic circulation over the North Pacific. Since the teleconnection signal has interannual time scales, it is likely that extratropical ocean-atmosphere coupling will play an important role in the maintenance of this mode. This, however, is not inconsistent with the notion that the extratropical SST anomalies may be forced, at least initially, by atmospheric circulation anomalies (Lau and Nath 1996, 2001). The correlation coefficients of the SVD-1 rainfall PC with SST in the tropical equatorial Pacific in all El Niño regions have been computed (see Table 1). Assuming data from each year are independent, the 95% and 99% significance level is 0.30 and 0.38 respectively. The simultaneous correlation of PC1 with Niño-3.4 SST is 0.30 and 0.38 respectively. The simultaneous correlation patterns are similar for Niño-3 (5°N–5°S, 150°W–90°W), and Niño 1+2 (0°–0°, 90°W–80°W) SST, except that the simultaneous correlation with Niño 1+2 SST is found to be significant at the 95% level. The correlation patterns suggest that SVD-1 may be subject to the influence of El Niño in the antecedent seasons, but has intrinsic variability that begins to de-couple from tropical eastern Pacific SST anomalies in the northern summer and the following seasons.

4.2 Combined SVD-2

The combined SVD-2 (Fig. 7) displays a teleconnection pattern that is very similar to that shown in Fig. 3 for SVD-2. In the following, the combined SVD-2 will be referred to as SVD-2. Compared to SVD-1, the SVD-2 anticyclone-cyclone couplet over North America is more strongly developed and located at higher latitudes. As a result, the easterly flow at the southern flank of the low level anticyclone comes in from the Atlantic and travels a long distance over land, before turning northward and southward. The easterly flow has the effect of shutting off the US continent from the transport of warm moist air from the Gulf of Mexico, thus giving rise to the widespread rainfall deficit over the central US (Fig. 7c). The teleconnection pattern suggests a Rossby wave excited by an apparent heat source/sink in the southeastern Asian monsoon region. This is also evident in the formation of the anomalous anticyclone over the subtropical western Pacific, and the large convergence into the maritime continent and eastern Indian Ocean. The aforementioned regional circulation features are similar to those associated with interannual variability of the South Asian monsoon, with enhanced rainfall over the Bay of Bengal, Indo-China and southern China (cf., Lau et al. 2000). Over China, the rainfall signal is not as well defined as for SVD-1, with enhanced rainfall over the northeastern, the Huaihe River and the southern regions (Fig. 7b). The enhanced rainfall is consistent with the excitation of the anomalous west Pacific anticyclone in conjunction with an eastward shift of the climatological western Pacific subtropical high (Lau and Wu 2001; Lau et al.

### Table 1. Linear correlation of principal components of the first two dominant combined East-Asian and North America rainfall modes with SST at different lags for: a) Niño 3.4 region (5°N–5°S, 160°E–150°W), b) Niño 3 region (5°N–5°S, 150°W–90°W), and c) Niño 1+2 region (0–10°S, 90°W–80°W). Correlation coefficients exceeding the 95% confidence level are in bold.

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<th>MAM</th>
<th>JJA</th>
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As shown previously, the SVD-2 wavetrain connecting the rainfall anomalies over East Asia and North America has a distinct SST expression in the North Pacific, which is independent of El Niño (see Fig. 4b). Comparing with Fig. 4b, the warm SST anomaly in the central North Pacific appears to be situated underneath the region of strong northward flow, and the cold SST along the North America coast in regions of strong southward flow. Hence it is speculated that warm and cold temperature advection may also play a role in producing the SST anomalies. As in SVD-1, it is likely that the SST anomalies so generated may in turn feedback to the atmosphere to reinforce and prolong the coupled anomalies. There is no sig-
Significant correlation between the SVD-2 PC and SST in all the El Niño sub-regions and at all time lags. Hence this mode is independent of El Niño, at least in the linear sense.

5. Extreme rainfall events

In this section, we examine possible simultaneous relationship between extreme rainfall events in East Asia and North America implied by the teleconnection patterns. Note that the recurrence of teleconnections linking regions in the two continents, while suggesting important underlying physical linkages, does not necessarily translate into significant linear correlation between rainfall anomalies over the regions. We have computed the serial correlation coefficients between time series of areal averages of seasonal rainfall over key regions in the rainfall teleconnection, i.e., the YRV, the US Midwest (MW) and the Mid-Atlantic Coast (MAC), and found that the correlations are, generally not statistically significant at the 95% level. However, a low linear correlation does not preclude the possibility that the teleconnection may have an effect on the distribution of extreme rainfall events over the two continents. As the following results suggest, analyses of individual cases and statistics of extreme events may be more revealing in detecting possible shifts in the rainfall distribution.

The most disastrous summertime flooding over North America occurred during 1993, with heavy rainfall over the Midwest and drought condition along the Atlantic coast (Fig. 8c). In the same year, severe flooding occurred over

Fig. 8. Observed anomalies during JJA 1993 for a) 500 hPa height and 850 hPa wind, b) rainfall over East Asia, and c) rainfall over North America. The contour interval is 1 gpm in a) and 40 mm in b) and c)
The anomalous 500 hPa height and 850 hPa wind patterns shown in Fig. 8a bear strong resemblance to SVD-1 (see Fig. 6). Similarly, during the summer of 1998, record flooding occurred over the YRV, with a rainfall anomaly pattern over East Asia that was very similar to that of 1993 (Fig. 9b). During that year, above-normal rainfall was found over the US Midwest, and drought conditions prevailed over the Mid-Atlantic Coast (Fig. 9c). Although the magnitude of the rainfall anomaly over North America was not extreme, the pattern was similar to 1993. The anomalous 500 hPa height and 850 hPa wind patterns observed in 1998 (Fig. 9a) suggest large contributions from both SVD-1 and SVD-2 (see also Figs. 6 and 7, and discussion in Section 3.4). These two cases illustrate the recurrence of the dominant teleconnections could have influenced major floods and droughts over the two continents.

As expected, extreme regional rainfall events may also arise from local sources, and occur independent of the excitation of teleconnection. That means the relationship between regional rainfall extremes and the excitation of teleconnection patterns are not one-to-one, and may be better described in terms of probability of occurrences. A full treatment of probability of rainfall extremes requires higher temporal resolution and longer data set, and is outside the scope of this work. In the following, we provide a preliminary glimpse into extreme rainfall statistics from a crude analysis of the seasonal anomaly data. To examine the joint probability of extreme events, we define a joint event over a region in East Asia, and in North America, as one in which the rainfall anomalies over either one of the regions exceeds 1.5 times the standard deviation, or both exceed one standard deviation. Table 2a and 2b show respectively,
the years of joint events over the YRV region (105–120°E, 27–33°N), with respect to the US Midwest (MW), (100–85°W, 40–45°N) and the Mid Atlantic Coast (MAC), (80–75°W, 33–42°N). A strong excitation of either SVD-1 and/or SVD-2, (defined by either the corresponding rainfall or the height PC’s in Figs. 6 and 7 exceeding 1-standard deviation) is identified by the mode number in the last row of Table 2. For the YRV-MW regions, 9 out of 13 joint rainfall events have the anomalies of the same sign. The probability of positive rainfall events over the MW, given positive rainfall anomaly over the YRV, is 6 out of 6. Among the 6 events, five correspond to extremes (1962, 1969, 1980, 1993, 1998) over the YRV, each having a strong excitation of SVD-1, and a large contribution also from SVD-2 in 1993 and 1998. To be sure, excessive rainfall over the MW occurred in 1968, 1972, 1990, even when the YRV rainfall was below normal, or extremely negative. However these events occurred only during years when the teleconnection patterns were not excited. For extreme negative events over the YRV, the relationship is unclear. The joint distribution in Table 2a suggests that excessive rainfall over the YRV region tends to be associated with above rainfall over the MW. However, excessive rainfall over MW can also be generated locally, without excitation of summertime teleconnections. We also note that all three cases of major joint positive rainfall extremes in both regions (1962, 1993, 1998) occurred under the strong excitation of SVD-1. There is no obvious relationship of the years of joint extreme events to years of El Niño.

For the YRV-MAC joint events, Table 2b shows that 8 out of a total of 10 events have opposite polarity, with the exception of 1969 and 1989. Among these events, 4 out of the 4 (1972, 1978, 1981, 1983) are negative YRV events, and 4 (1957, 1980, 1993, 1998) out of 6 are positive YRV events. Out of the 8 joint events that show opposite polarity in rainfall anomalies in both the YRV and MAC, 6 pertain to strong excitation of SVD-1 and/or SVD-2, except in 1981. Note that all three major drought events (1957, 1993, 1998) over the MAC occurred in conjunction with positive rainfall anomalies over the YRV. These extreme event statistics suggest a shift in rainfall distribution favoring opposite-sign anomalies.

### Table 2a. Years with precipitation extremes in either the Yangtze River Valley (YRV) and/or in the US Midwest (MW). Above and below normal rainfall are denoted by positive and negative signs. Extremes events (see text for definition) are shown as ++, and −−−− respectively. Years in which teleconnection modes are strongly excited are indicated by mode numbers in the last row. Lack of strong excitations is indicated by N/A.

<table>
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<tr>
<td>1990</td>
<td>--</td>
<td>++</td>
<td>1,2</td>
</tr>
<tr>
<td>1991</td>
<td>--</td>
<td>++</td>
<td>1,2</td>
</tr>
<tr>
<td>1993</td>
<td>--</td>
<td>++</td>
<td>1,2</td>
</tr>
<tr>
<td>1998</td>
<td>--</td>
<td>++</td>
<td>1,2</td>
</tr>
</tbody>
</table>

### Table 2b. Same as Table 2a, except for YRV and the US Mid Atlantic Coast (MAC).

<table>
<thead>
<tr>
<th>Year</th>
<th>YRV</th>
<th>MAC</th>
<th>Modes (&gt;1σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1957</td>
<td>+</td>
<td>--</td>
<td>1</td>
</tr>
<tr>
<td>1969</td>
<td>++</td>
<td>++</td>
<td>1</td>
</tr>
<tr>
<td>1972</td>
<td>--</td>
<td>++</td>
<td>1</td>
</tr>
<tr>
<td>1978</td>
<td>++</td>
<td>++</td>
<td>1</td>
</tr>
<tr>
<td>1980</td>
<td>--</td>
<td>++</td>
<td>1</td>
</tr>
<tr>
<td>1981</td>
<td>++</td>
<td>++</td>
<td>1</td>
</tr>
<tr>
<td>1983</td>
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<td>++</td>
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<td>1989</td>
<td>++</td>
<td>++</td>
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</tr>
<tr>
<td>1993</td>
<td>--</td>
<td>++</td>
<td>1</td>
</tr>
<tr>
<td>1998</td>
<td>--</td>
<td>++</td>
<td>1</td>
</tr>
</tbody>
</table>
over the YRV and the MAC. Again, the relationship with El Niño is not obvious in Table 2b.

6. Conclusions

We have presented evidence that summertime precipitation anomalies in the North American continent and in the Asian monsoon regions may be linked by teleconnection patterns which may be components of recurring global climate modes in boreal summer.

Two dominant climate patterns governing precipitation anomalies over the U.S. have been identified using EOF, SVD, combined SVD and regression analyses. SVD-1 consists of large-scale cyclonic-anticyclonic couplets over North America, connected to zonally elongated 500 hPa geopotential height anomalies over East Asia across the extratropical North Pacific. It links rainfall anomalies of the same sign over the US Midwest and the Yangtze River Valley and becomes very pronounced during the great flood of the US Midwest in 1993, and the record Yangtze river flood in 1998. While the associated circulation and SST patterns may be linked to El Niño in the antecedent seasons, SVD-1 appears to depict a distinct circulation system arising from fluctuation of the East Asian jetstream, coupled to SST variations in the North Pacific. SVD-2 portrays an Asian-North America wavetrain connecting the subtropical western Pacific, via the Aleutians to northern North America. It is consistent with Rossby wave dispersion generated from fluctuation of anomalous heat sources and sinks in the western Pacific and Indian Ocean. Under the influence of SVD-2, drought conditions over the central US occur in conjunction with enhanced rainfall over northeastern, Huaihe River, and southern China. SVD-2 appears to be independent of El Niño. It is hypothesized extratropical air-sea interaction may be important in amplifying and sustaining these teleconnection patterns. Results suggest there may be enhanced frequency of occurrence of extreme events due to stronger contributions of the teleconnection patterns to US summertime precipitation since the late 1970s. Analysis of extreme rainfall statistics also indicate that the teleconnection patterns are associated with a shift in rainfall distribution favoring extreme events over the Yangtze River Valley, with events of the same sign over the US Midwest, and of the opposite sign over the US Mid-Atlantic Coast.

Overall, we find that remotely separated regional circulation features, which controls summertime rainfall anomalies over North America and East Asia respectively, may be linked via recurring climate patterns, which are global in nature. The occurrence of extreme precipitation events simultaneously over the two continents in individual years may depend, in part, on the excitation of these patterns. Our results suggest that these global patterns may be associated with summertime North Pacific SST signals that have evolved from the previous spring from conditions that may or may not be influenced by El Niño, but persisted through the summer and fall. Occurrence of joint extreme events over regions in East Asia and North America appear to be associated with the summertime teleconnection patterns more so than with El Niño. The possibility that enhanced predictability of warm season precipitation on seasonal-to-interannual time scales, especially with regard to the occurrence of extreme events over the two continents, may be derived from summertime teleconnection patterns should be further explored.

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References


