

Climatic Role of the Southerly Flow from the Gulf of Mexico in Interannual Variations in Summer Rainfall in the Central United States*

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ABSTRACT

This study continues the investigation of causes of the interannual variations in summer rainfall in the central United States. A previous study by the authors showed that the ENSO teleconnection significantly affected the interannual variations in summer rainfall in the central United States in two epochs, 1871–1916 and 1949–78. The teleconnection effect weakened in the epochs 1917–48 and 1979–97. The current study partially answers the question: What affected the interannual summer rainfall variations in the two epochs when the ENSO teleconnection weakened? Its results showed that the low-level southerly flow from the Gulf of Mexico was another source of interannual summer rainfall variations. The southerly flow possessed significant interannual variations independent of the ENSO variation. In the epochs when the ENSO teleconnection broke down, the variations of the southerly flow amplified. In the meantime, the circulation anomalies in the lower troposphere in the central United States favored a convergence and an unstable thermal profile. They helped to engage the variations in the southerly flow and the summer rainfall variation in the central United States and to maintain the interannual summer rainfall variation. A coherent variation of this source and ENSO teleconnection in different epochs sustained the observed interannual variations of the summer rainfall in the central United States. The coherent variation of the role of these two different sources was in accord with the multidecadal variation in SST in the mid- and high-latitude North Pacific Ocean, supporting the notion that the multidecadal variation in the SST may have facilitated the coherent variation.

1. Introduction

Summer-season (June, July, and August) rainfall in the central United States, an area defined in this study as 37.5°–45.0°N and 90.0°–105.0°W, has statistically significant interannual variations of 3–6 yr (Hu and Feng 2001). These quasi-periodic variations are desirable in making regional climate predictions. They are a characteristic of the region's climate and can thus be used as a measure in evaluating the region's climate change.

In an effort to explain the causes of the interannual variations in the region, we (Hu and Feng 2001, hereinafter Part I) reexamined several sources that have been suggested as causes of the region's summer rainfall variations. These possible causes include tropical Pacific SST variations associated with El Niño–Southern Oscillation (ENSO); (e.g., Ropelewsky and Halpert 1986; Trenberth and Branstator 1992; Ting and Wang 1997)

and variations in the low-level southerly flow from the Gulf of Mexico (e.g., Mo et al. 1995; Paegle et al. 1996). We found that the relationship and teleconnection between variations of tropical Pacific SST during ENSO and the summer rainfall in the central United States varied fairly regularly over the period of 1870–1997. We found two epochs, 1870–1916 and 1949–78, that show a strong and statistically significant positive correlation between tropical Pacific SST anomalies (SSTAs) and anomalies in the summer rainfall. Warm (cool) SST in the central equatorial Pacific Ocean corresponded to above- (below)-normal summer rainfall in the central United States. In those epochs, interannual SST variations in the ENSO cycle could enforce similar timescale variations in summer rainfall in the central United States. This teleconnection did not persist, however. Rather, it languished in the epoch 1917–48 and in the recent decades beginning in the late 1970s. These results indicate a dynamic relationship of ENSO and interannual variations in tropical Pacific SSTA and summer rainfall variations in the central United States.

In Part I, we also identified a process regulating/facilitating the observed variation in the ENSO teleconnection: a quasi-periodic multidecadal SST variation in the midlatitude North Pacific Ocean. In the two high-teleconnection epochs, 1870–1916 and 1949–78, the

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boreal summer SST in the midlatitude North Pacific Ocean was warmer than the 1871–1997 average and was surrounded by cooler-than-average SSTs (see Part I). In the two low- or nonteleconnection epochs 1917–48 and 1979–97, the SSTA distribution reversed in the mid- and high-latitude North Pacific from that in 1870–1916 and 1949–78. In company with these changes, the lower-tropospheric circulation anomalies also reversed in the western Northern Hemisphere (NH).

The fairly regular variation in ENSO teleconnection with the summer rainfall in the central United States supports that the ENSO cycle can explain the interannual variation in the summer rainfall in those high-teleconnection epochs [epochs 1 (1870–1916) and 3 (1949–78)]. It will help to provide a complete explanation of the interannual variations in the summer rainfall if we can find an answer to the question: What maintained the similar-amplitude interannual variation in the summer rainfall in epochs 2 (1917–48) and 4 (1979–97) when the ENSO teleconnection broke down?

In the effort to answer this question, our attention was focused on the climatic role of the low-level southerly flows from the Gulf of Mexico. Previous studies have identified the southerly flow from the Gulf region as a major source affecting summer rainfall in the central United States. Some of the studies have attributed recent extreme cases of summer rainfall anomalies (floods and droughts) in the central United States to anomalies in the southerly flow from the Gulf region (Helfand and Schubert 1995; Mo et al. 1995, 1997; Paegle et al. 1996). They suggested that in different climatic conditions anomalies of circulation in the Gulf of Mexico and the low-level southerly flow affected differently the rainfall development in the central United States. Based on these previous studies, our hypothesis in this study is that the variations in low-level southerly flow from the Gulf of Mexico are the major source of the interannual variations in summer rainfall in the central United States in the epochs when the ENSO teleconnection with the summer rainfall variation broke down. To prove or disprove this hypothesis, we will need to answer the following three questions. 1) Does the low-level southerly flow from the Gulf of Mexico have significant interannual variations?¹ 2) How did the variations of the southerly flow affect interannual variations in summer rainfall in the central United States during the epochs when the ENSO effect languished? In answering this question, we also need to answer the question of 3) how the effect of the southerly flow varied between the epochs while

the mean flow remained southerly in the summer months over the years.

In the following sections, we will present the analyses and results to answer these questions. In section 2, we describe the data sources and analysis methods. The analysis procedure takes the steps first to present, in section 3, the interannual variations of the southerly flow from the Gulf of Mexico and to show the relationship of its variation and the summer rainfall variation in the central United States. We will show the differences in meridional wind structures in opposite epochs to demonstrate the role of the southerly flow in development of rainfall variations in the central United States. In section 4, we will describe a mechanism that engaged the southerly flow from the Gulf region with the circulation in the central United States and yielded the interannual summer rainfall variation. A summary of the study and a theory of the interannual variation in summer rainfall in the central United States are presented in section 5.

2. Data and methods

Data used in this study include monthly total precipitation, the global SST, the NH sea level pressure (SLP), geopotential height, and wind in the troposphere. All data, except for precipitation, were averaged over the three summer months (June, July, and August: JJA) to obtain summer mean values. Summer rainfall is given as the total rainfall of JJA.

The monthly precipitation data were obtained from Dai et al. (1997). They were in a grid format of a $2.5^\circ \times 2.5^\circ$ resolution over the globe for the time period of 1871–1995. Dai et al. (1997) discussed the procedure used to produce this (mostly land) dataset. We examined the summer rainfall data for the central United States (37.5° – 45.0° N, 90° – 105° W) extracted from this dataset against station data in the region and found similar variations. Because the station data were from the same stations with such long records, this consistency test showed that the sampling procedure used in Dai et al. (1997) did not create significant bias variations in the dataset.

Monthly SST data were from the Global Sea-Ice and SST dataset (GISST) version 2.3b from the Met Office (Parker et al. 1995a; Rayner et al. 1996). They covered the period of 1871–1998 with a $1.0^\circ \times 1.0^\circ$ resolution. As cautioned by Hurrell and Trenberth (1999), there were significant differences between the GISST and National Centers for Environmental Prediction (NCEP) 1961–90 SST data at some regional scales, for example, the Gulf of Mexico area and inter-sea-ice zones. The trend of GISST SST after 1981 also was different from that of the NCEP dataset. Hurrell and Trenberth recommended that a 3- or 5-month running mean be applied to the GISST monthly data after 1981 to minimize these differences. Accordingly, we used a 3-month running average of the SST data in our analyses.

¹ We notice that atmospheric circulations may possess slow-time-scale components, such as interannual variations resulting from oceanic effect or air–sea interactions. In this question, we are interested in whether the southerly flow from the Gulf of Mexico may have interannual variations regardless of possible causes of such variations. Identifying the causes of the variations is beyond the scope of this study.

Data for SLP were obtained from the National Center for Atmospheric Research (NCAR) Dataset ds010.1 (Trenberth and Paolino 1980). They had a $5.0^\circ \times 5.0^\circ$ resolution and covered the period of 1899–1998. We used the NCEP–NCAR reanalysis (Kalnay et al. 1996) of geopotential height and wind to evaluate atmospheric circulations and dynamic structure. The reanalysis data start in 1958.

Various statistical evaluation techniques, including composite, correlation, and moving correlation, were used along with significance test methods in the analyses.

3. Effect of low-level southerly flow on the summer rainfall variation

a. Interannual variation in the southerly flow from the Gulf of Mexico

If the low-level southerly flow from the Gulf of Mexico has significant interannual variations, its effect on rainfall development in the central United States will result in similar interannual variations in the rainfall. We thus examined the interannual variation in intensity of the low-level southerly flows. For several reasons discussed below we used the SWI index to examine this variation:

$$\text{SWI} = \bar{\phi}_e - \bar{\phi}_w, \quad (1)$$

where $\bar{\phi}_e$ and $\bar{\phi}_w$ are geopotential heights averaged between 925 and 850 hPa over the areas (25° – 35°N , 90° – 95°W) and (25° – 35°N , 100° – 105°W), respectively, and over the summer season. SWI measures the summer-season average low-level geostrophic southerly flows from the Gulf of Mexico into the central United States. Justifications for using the low-level pressure or geopotential height differences as a measure of low-level wind strength were discussed in several previous studies (e.g., Carleton et al. 1990; Shi and Zhu 1996). Carleton et al. (1990) used a similar index to measure the monsoon wind intensity in the southwestern United States.

We calculated SWI from the reanalysis data (1958–97) and compared it with the vertically integrated (1000–700 hPa) moisture flux in the entrance region of the southerly flow (\bar{q}_v , 25° – 35°N , 92.5° – 102.5°W). Figure 1a shows that SWI has varied consistently with \bar{q}_v . Their correlation was 0.86 and was even higher at 0.95 when we filtered decadal- and longer-scale variations in the two data series. Figure 1b shows the variation in SWI (dashed line) versus the normalized summer rainfall variation in the central United States (Pr, thick solid line), and Fig. 1c shows \bar{q}_v versus Pr. Both SWI and \bar{q}_v show a similar variation relationship with the Pr variation. We used SWI because \bar{q}_v is not available for before 1958 to meet our analysis need for southerly flow variations in epochs 1 and 2.

In Fig. 1, both SWI and \bar{q}_v showed a large increase in fluctuations of the southerly flow and associated

moisture flux since the late 1970s. More important, both their variations showed a more “in-phase” relationship with the summer rainfall in the central United States after 1980 than before. This is quantified by the contrasting correlation coefficients in Figs. 1b and 1c for the periods before and after 1980. The improved relationship after 1980 suggests an engagement of the southerly flow from the Gulf of Mexico with the circulation and rainfall development in the central United States. This in-phase relationship was established at the time when the ENSO teleconnection with the summer rainfall variation in the central United States weakened (starting in the late 1970s).

In Fig. 1, the SWI and \bar{q}_v clearly showed interannual-scale variations. Thus, the more-engaged variations between SWI (\bar{q}_v) and the summer rainfall in epoch 4 (1979–97) when the ENSO effect weakened suggest that the interannual variation in the southerly flow affected interannual variations in the summer rainfall.

It is possible that the interannual variations in the southerly flow may result from variations in SST in the tropical Pacific region. In such a case, the interannual variations in the southerly flow would merely be a different realization of the interannual variations in the tropical Pacific region. To verify that the interannual variation in the southerly flow is independent of interannual SST variations in the tropical Pacific region, we examined the interannual variations in the SWI and the SST in the Niño-1 to Niño-4 regions. After applying different sampling and testing schemes, including the Monte Carlo method, we found that the highest correlation among the tests was 0.06 and insignificant. These test results confirmed that the interannual variations in the low-level southerly flow from the Gulf of Mexico are an independent source affecting interannual variations in summer rainfall in the central United States.

b. Effect of southerly flow on rainfall variations in the central United States

To identify the role of the southerly flow from the Gulf region in the interannual summer rainfall variations as well as variations of such a role between the epochs, we examined the composites of the wet and dry years in the epochs. Because interannual variations in summer rainfall in an epoch are shown by alternations in wet and dry years, the composites of wet and dry years in the epoch describe circulation anomalies corresponding to the interannual variations in the summer rainfall. We used the difference in circulation anomalies between different epochs to illustrate the circulation characteristics of those epochs further. Figure 2 shows the composites of 850-hPa atmospheric circulation anomalies for the wet and dry years in the western NH for epochs 3 and 4. We developed the wet (dry) composite for 1958–78 from the five wettest (driest) summers in that 20-yr period. In epoch 4, we took off a short transition period from 1978 to 1980 from epochs 3 to 4 and chose

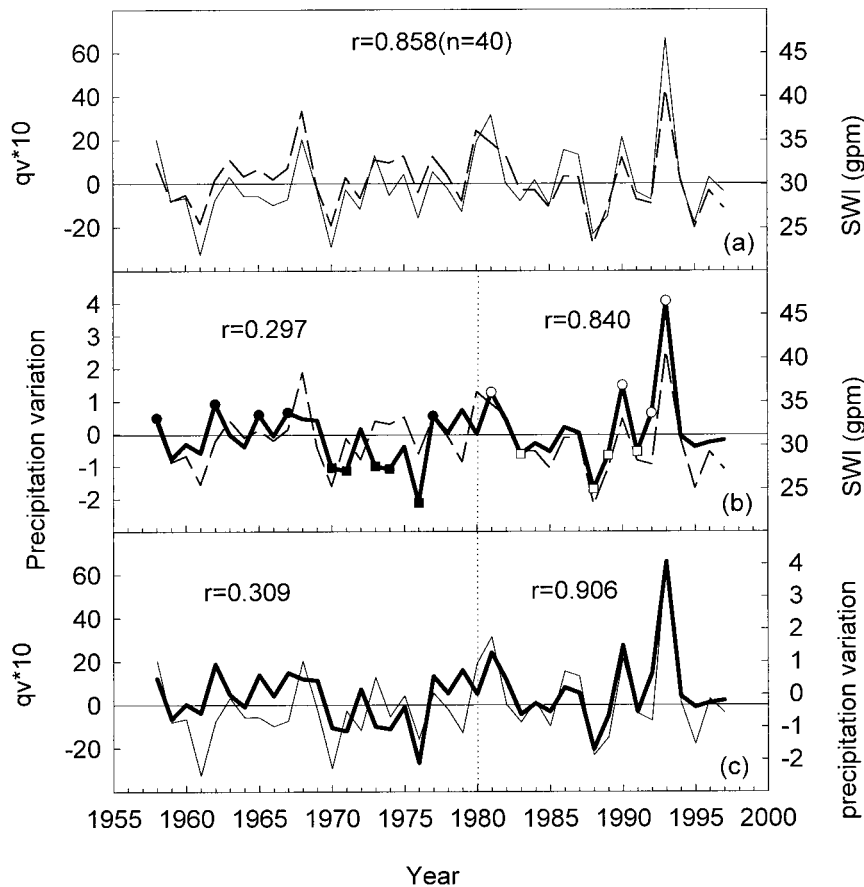


FIG. 1. (a) Variations of SWI (dashed line) and $\overline{q_v}$ (thin solid) in 1958–97 and their correlation coefficient (see text for details), (b) variations of SWI and Pr (thick solid), and (c) variations of $\overline{q_v}$ and Pr. The filled circles (squares) in (b) mark the years used in wet (dry) year composite for epoch 3, and the open circles (squares) mark the years used in wet (dry) year composite for epoch 4.

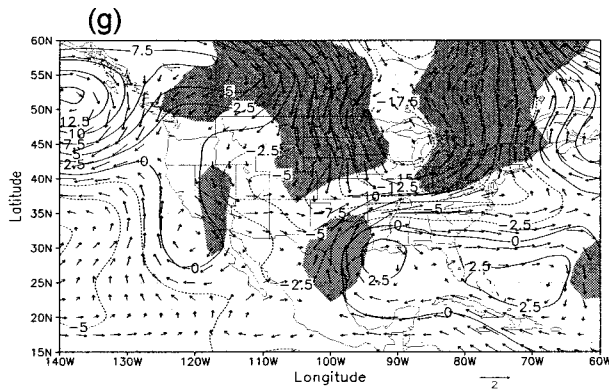
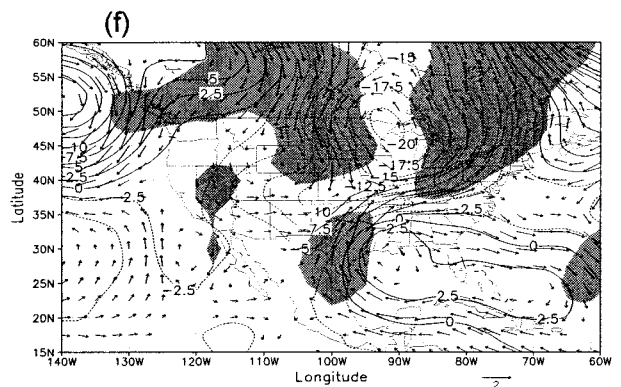
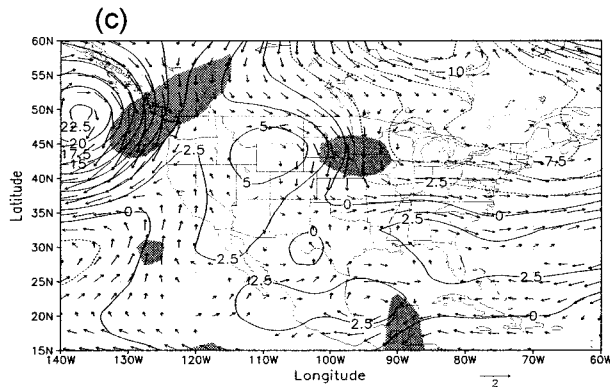
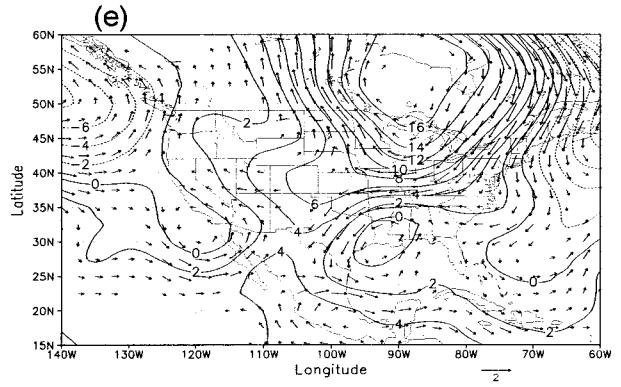
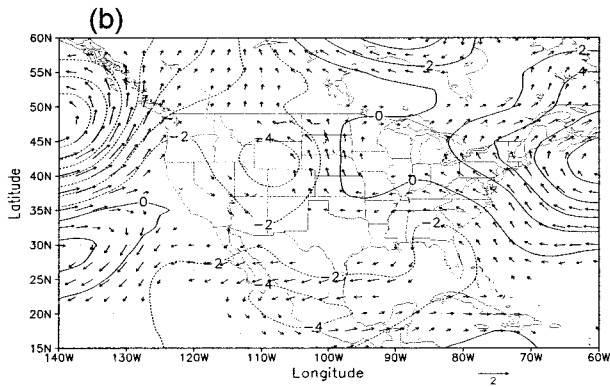
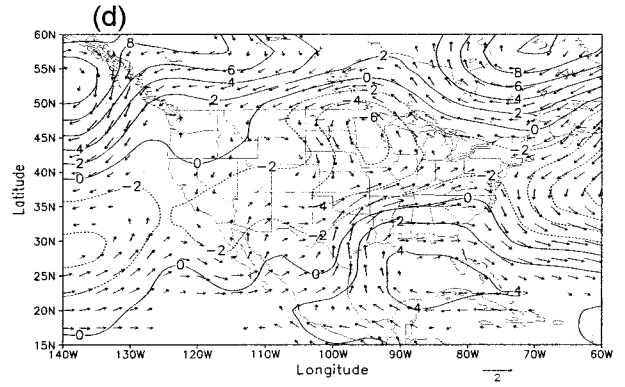
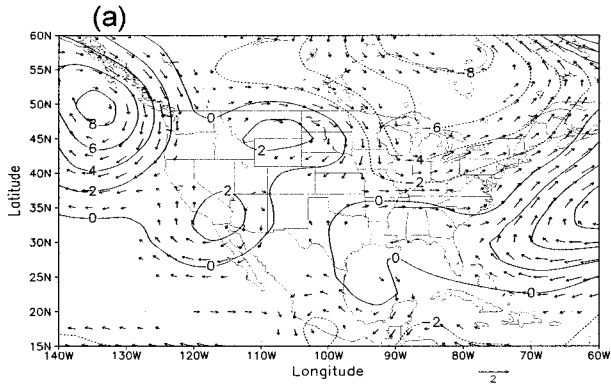
the four wettest (driest) summers for the composite in the 17-yr period 1981–97 (see Fig. 1b). The number of cases in each composite is adequate (10 out of a group of 21 and 8 out of 17, respectively) given the fact that a composite is a subset of a group with specified properties and that the composites are for interannual-scale variations.

Figure 2a shows an enhanced northerly anomaly along the eastern fringe of anticyclonic anomalies in the northwestern United States in the wet years of epoch 3. It helped to create a convergence anomaly in the central United States and to contribute to positive rainfall anomalies in the region. Figure 2b shows that in dry years of epoch 3, the northerly anomaly was replaced by a southerly anomaly that created a low-level divergence anomaly in the central United States. Correspondingly, the region's summer rainfall decreased. The effect of the northerly anomaly also was shown in Ting and Wang (1997) in midtroposphere circulations and was suggested as a major anomaly feature in the wet years for a similar period.

A comparison of the flow anomalies in the central

and southern United States between wet and dry years in epoch 3 shows few differences. Both Figs. 2a and 2b show a similar weak northerly anomaly in the entrance region of the southerly flow from the Gulf of Mexico. This fact indicates that the southerly flow from the Gulf played a minor role in the summer rainfall variations in epoch 3. This finding is further supported by the statistical test result in Fig. 2c indicating that in epoch 3 the alternation of northerly and southerly flow anomalies in the north-central and central United States was significant (>95% confidence level) and contributed to the region's rainfall variations. The test shows insignificant changes in southerly flow anomalies in the Gulf region.

In epoch 4, large anomalies of low-level southerly flow became the major feature in the central United States. Figure 2d shows a stronger-than-average southerly flow in wet summers from the Gulf of Mexico entering the central United States. The flow stretched farther northward into the northern Great Plains. A northerly flow anomaly also was present in the region, but it was much weaker than the southerly flow anom-



alies and also was weaker than the northerly anomalies in the early epoch. As suggested by the anomaly pattern in Fig. 2d, this flow was closely related to the southerly anomalies. In dry years of epoch 4, the anomalies of southerly flow from the Gulf region were replaced by strong anomalies of northerly flow to the Gulf (Fig. 2e). These results indicate that in epoch 4 the influences of the southerly flow from the Gulf became engaged with circulation anomalies in the central United States and dominated the rainfall variations. This observation also is supported by the statistically significant alternations in flow anomalies in the central United States and the Gulf of Mexico region (Fig. 2f). In Fig. 2f, the shading area in the entrance region of the low-level southerly flows from the Gulf indicates a significant enhancement of the southerly flows in wet years in epoch 4. The shading area in the northern Great Plains shows significant changes (reverse) of meridional flows in wet and dry years. A strong convergence (divergence) zone was created in the central United States as a result of the significant changes in flow anomalies in wet (dry) years.

The anomaly fields in Fig. 2 also indicate that the circulation anomalies are generally much stronger in epoch 4 than in epoch 3. There are large geopotential gradient differences between Figs. 2a and 2d and between 2b and 2e. They suggest different circulation regimes dominating in different epochs to facilitate the southerly flow effect on the interannual summer rainfall variations in the central United States.

In epoch 4, the summer of 1993 was very wet in the central United States. Because this summer was a sample element in the composite, it is a legitimate concern how this single event may have influenced the wet year composite for the epoch (Figs. 2d–f). We thus reevaluated the wet year composite without 1993 but found similar results. Figure 2g shows the difference between wet and dry years in the epoch (without 1993) and the test result for its significance. A comparison of Figs. 2g and 2f (with 1993) indicates a similar pattern of low (high) pressure anomalies in the central United States (Gulf of Mexico). The significance test result also is similar.

To illustrate further the change of the role of the southerly flow from the Gulf in circulation and rainfall variations in epochs 3 and 4, we show in Fig. 3 the composites of vertical profiles of meridional wind anomalies in wet and dry years in the two epochs. The wind anomaly at a latitude point was calculated as the average of anomalies in a longitude bin 92.5° – 102.5° W. These anomalies were relative to the southerly climatological summer mean meridional wind in the region.

We see from comparisons of Figs. 3a and 3c that the wind anomalies below 500 hPa are southerly from 20° to 38° N in the central United States and are northerly poleward of 40° N in wet years of both epochs. This distribution created a convergence of meridional wind in the central United States and favored rainfall development. In dry years, both the epochs (Figs. 3b and 3d) showed a reversed pattern of meridional wind anomalies and a divergence field in the central United States.

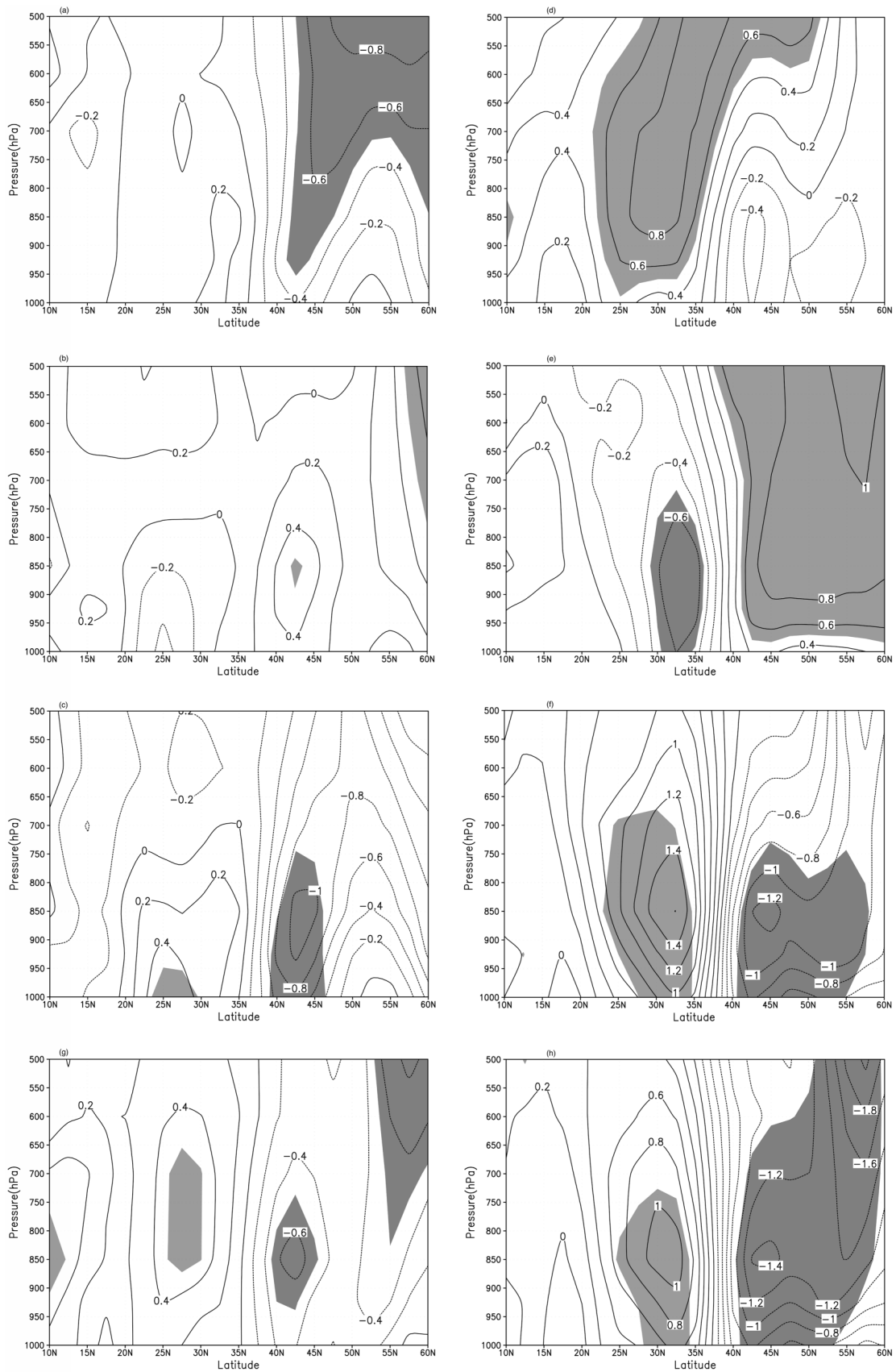
The striking difference between the two epochs is in the details of the anomalies. Figure 3a showed strong northerly wind anomalies from high latitudes dominating the wind field and convergence anomalies in the central United States. The southerly wind anomalies were very weak. A significance test of the wind anomalies in epoch 3 (Fig. 3c) showed changes in northerly wind played a significant role in creating the interannual convergence and rainfall anomalies in the central United States. The change in southerlies from the Gulf played little role in the rainfall variations. In contrast, Fig. 3d showed that in epoch 4 the wet years had a deep layer of strong anomalous southerly flows from the Gulf of Mexico. The northerly wind anomalies were very shallow and weak. The dry years (Fig. 3e) had a strong northerly wind anomaly from the central United States to the Gulf contributing to the divergence in the central United States. A similar significance test (Fig. 3f) confirmed that the southerly flow from the Gulf played a much more significant role in epoch 4 than in epoch 3. In epoch 4, the change of the role of the southerly and northerly wind anomalies showed an engagement of the southerly flow from the Gulf of Mexico with the circulation and summer rainfall variations in the central United States.

We also examined the effect of the wet year of 1993 on the composites of the meridional wind profiles in epoch 4. The results are shown in Figs. 3g and 3h. This very wet event was indeed associated with a strong southerly wind anomaly from the Gulf region. This is shown by differences between Figs. 3d and 3g. Its effect on the composite was, however, not significant. Figure 3h (without 1993) is similar to Fig. 3f (with 1993), showing (also comparing with Fig. 3c) the same significant enhancement of the role of the southerly flow in the epoch.

These results showed that even though a mean southerly flow was in the central United States during the summer months, anomalies in the southerly flow only became significant and directly affected interannual rainfall variations in epoch 4 when the ENSO teleconnection weakened. The variations in the southerly flow

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FIG. 2. Composite of 850-hPa geopotential (gpm) and wind (m s^{-1}) anomalies for (a) wet and (b) dry years in epoch 3. (c) Difference between (a) and (b). Shading shows the significant ($>95\%$ confidence level) meridional wind change between the wet and dry years. (d), (e), and (f) Corresponding results for epoch 4. (g) Similar to (f) but without 1993 in the composite. Wind arrows are omitted in all the panels when wind speed is weaker than 0.3 m s^{-1} .



became engaged with the circulation and rainfall variations in the central United States. When the ENSO teleconnection was active and strong in epoch 3, the southerly flow from the Gulf had weak variation and effect on the central U.S. rainfall variation. In this epoch, the teleconnection was dominant, and the associated northerly anomalies in the northern section of the central United States played a key role in the interannual summer rainfall variations.

The contrast of anomalies in the southerly flow from the Gulf of Mexico in the opposite epochs are also shown in the composite meridional wind profiles along a cross section at 30°N. Figure 4 shows that the low-level southerly flow from the Gulf of Mexico was present in both epochs. Its center was unchanged at 100°W. It is again the variations of the flow that were different in the two opposite epochs. In epoch 3, the thickness and intensity of the southerly flow changed little in both wet and dry years (Figs. 4a and 4b). Even though large interannual rainfall anomalies developed, there was little activity in the southerly flow. This is confirmed in Fig. 4c by the significance test result.

In epoch 4, the variations in the southerly flow enhanced significantly. Both thickness and intensity of the southerly flows increased in the wet years and weakened in dry years (Figs. 4d–g). The significant fluctuations in the southerly flow between the wet and dry years in epoch 4 demonstrate an elevated role of the southerly flow in interannual variations of summer rainfall in the central United States.

c. Extending the analysis to before 1958

In this subsection, we extend the above analysis to the two epochs before 1958, that is, epoch 1 in 1871–1916 and epoch 2 in 1917–48. Because of a lack of sufficient sounding data before 1958, we used the SLP data to calculate SWI from a definition similar to (1), and defined it as SWI_p . The variations in SWI and SWI_p were compared (Fig. 5) for the years after 1958 when both data existed. The thick lines in Figs. 5a, b show a 5-point binomial running mean of the annual variations in SWI and SWI_p . Except for a few years around 1970–75, they have been consistent (correlation coefficient = 0.69), indicating that SWI_p is a good proxy for variations of the low-level southerly flow from the Gulf region. Using SWI_p for the years before 1958, we examined variations in the southerly flow and relationships between the flow and the summer rainfall variations in the central United States. (This was another reason that

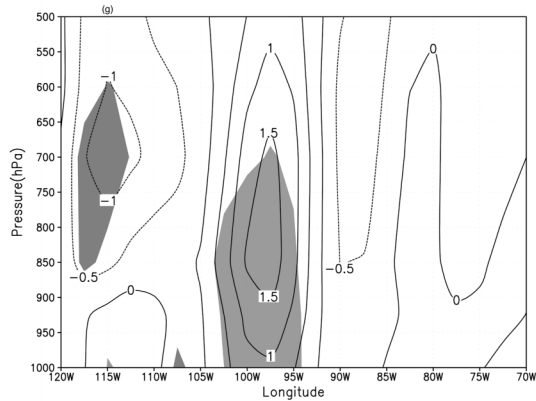
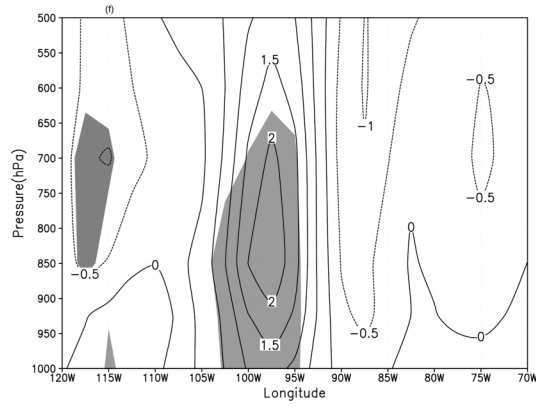
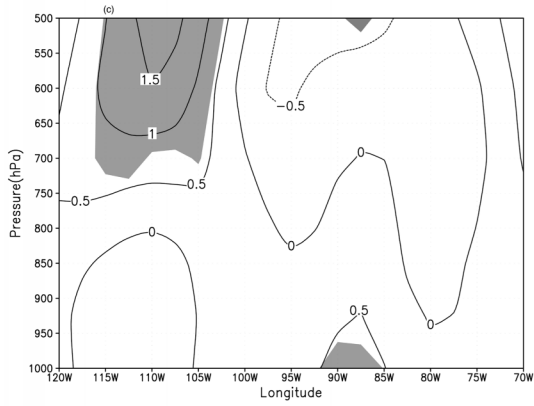
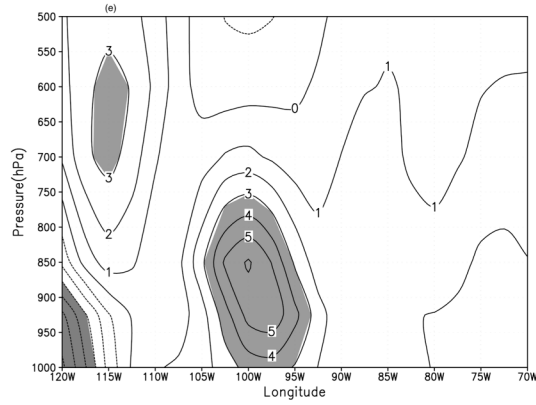
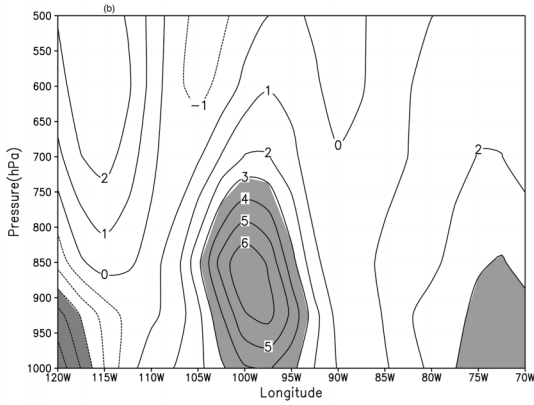
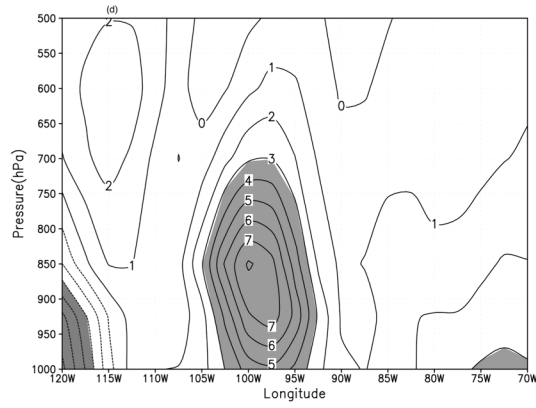
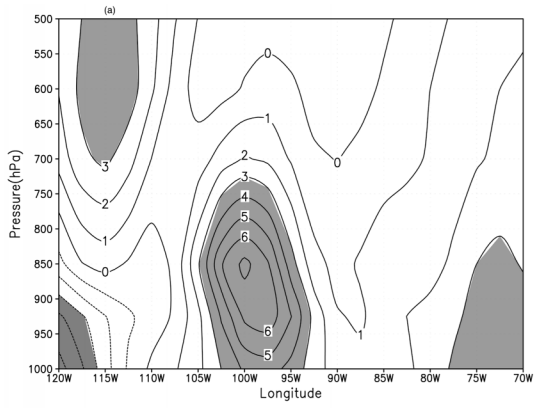
we used SWI instead of $\overline{q_v}$ in our analyses, though they have varied coherently.)

We analyzed variations in SWI_p and summer rainfall in the central United States in epochs 1 and 2 and found that the anomalies of the low-level southerly flow from the Gulf of Mexico were significantly correlated with the anomalies of the summer rainfall at most times in epoch 2. There was no correlation in the late years in epoch 1. (Note: the SLP data began in 1899.) Figure 6a shows a 21-yr moving correlation between summer rainfall in the central United States and SWI_p . Each value on the curve is the correlation coefficient of a 21-yr period centering at that year. The dashed line in Fig. 6a shows the 95% confidence level. The result shows that significant correlations between the two variations existed in 1925–37 (central portion of epoch 2) and after the 1970s (epoch 4). They showed insignificant and near-zero correlations before 1925 (late years of epoch 1 and some transition years between epochs 1 and 2) and in 1937–79 (epoch 3). The change in the correlation between epochs 3 and 4 in Fig. 6a supports the notion that in epoch 4 the southerly flow from the Gulf region significantly enhanced its role in interannual variations in the summer rainfall in the central United States. A similar enhancement also was observed in many years in epoch 2.

The correlation coefficients also show a multidecadal variation. More interesting, it has been nearly out of phase with the variation in the correlation coefficient between the tropical Pacific SST and the summer rainfall (Fig. 6b; Hu and Feng 2001). This out-of-phase relationship shows that when the equatorial Pacific SST variation significantly influenced the interannual variations in the summer rainfall in the central United States (ENSO teleconnection) the southerly flow played a weak role in the rainfall variations and vice versa. Sequential alternations of the two sources of the interannual oscillations could have sustained the interannual variations of summer rainfall in the central United States.

We presented in Fig. 6c the variation of the average NH surface temperature for the period of 1880–1997. It has been in phase with the sequential alternation of the two sources of interannual variations. To be specific, when an abrupt warming of the NH surface temperature occurred, the ENSO teleconnection broke down. At the same time, the influence of the southerly flow from the Gulf of Mexico was enhanced. When the NH surface temperature cools, the ENSO teleconnection resumed

FIG. 3. Profiles (1000–500 hPa) of meridional wind anomalies averaged in longitude bin 92.5°–102.5°W at latitudes from 10° to 60°N for (a) wet and (b) dry years in epoch 3. Dark (light) shading indicates northerly (southerly) wind anomalies greater 0.5 m s⁻¹. (c) Difference between (a) and (b). Shading shows significant (>95% confidence level) wind changes between wet and dry years. (d), (e), and (f) Corresponding results for epoch 4. (g) and (h) Similar to (d) and (f) but without 1993 in the composite.



its dominant role as the influence of the southerly flow weakened.

4. An interpretation of the enhanced effect of the southerly flow

In this section, we examine the details in changes of the effect of the southerly flow from epochs 3 to 4 and show the potential processes contributing to the changes. Figure 7 shows 850-hPa composites of anomalies in geopotential and wind for the two epochs. The anomalies are relative to the 40-yr (1958–97) average shown in Fig. 7c. Figure 7 shows that the flow anomalies in epoch 3 created an average divergence anomaly in the central United States (shown in Fig. 8), and in epoch 4 they configured a convergence anomaly (a reversal of Fig. 8).

We compared the circulation anomalies in wet and dry years in epoch 3 (see Figs. 2a and 2b) with the average anomaly field (Fig. 7a) and found that in wet years the anomalies in anticyclonic circulation in the eastern North Pacific shifted northwest and increased. They also spread east to the entire northwestern United States. The anticyclonic anomalies strengthened northerly flow into the central United States along the eastern fringe of the anticyclonic anomalies. In the meantime, the Gulf region showed little change in circulation anomalies. The strong northerly flow anomalies weakened the average divergence field (Fig. 8) and created a convergence field in the central United States (figure not shown) to favor an increase in summer rainfall.

The dry years in epoch 3 showed again major anomalies in the eastern North Pacific and the western United States. The anticyclonic circulation anomalies in the eastern North Pacific shifted southwest and weakened. Cyclonic anomalies developed in the northeastern North Pacific. The divergence anomaly enhanced in the central United States. Summer rainfall was suppressed. The southerly flow from the Gulf of Mexico showed minor changes. These results indicate that in epoch 3 the circulation variations in the North Pacific played a dominant role in causing circulation and rainfall anomalies in the central United States, whereas the southerly flow from the Gulf of Mexico played an inactive role.

In epoch 4, these outstanding changes in circulation anomalies in the northeastern North Pacific were not observed. We found, instead, distinct circulation anomalies in the southerly flows from the Gulf of Mexico between the wet and dry years. In wet years, an anticyclonic anomaly in the Gulf region strengthened and bulged northward into the central United States (Fig.

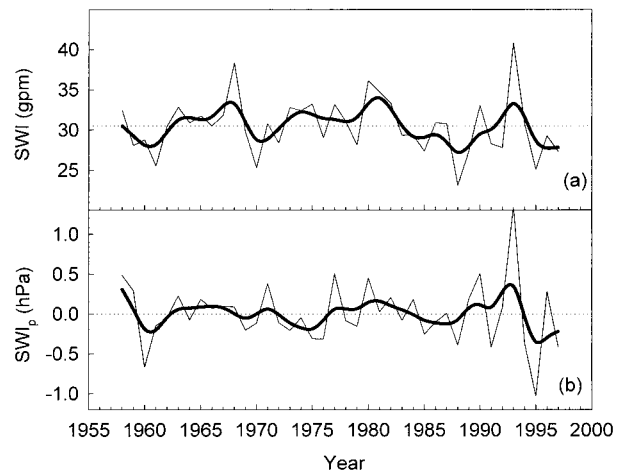


FIG. 5. (a) SWI (thin line) and 5-point binomial running mean of SWI (thick line); (b) SWI_p (thin line) and 5-point binomial running mean of SWI_p (thick line).

2d). As a consequence, the low-level southerly flow enhanced. A cyclonic circulation anomaly developed in the central United States, with enhanced convergence and summer rainfall. In this process, the southerly flow clearly showed an enhanced role.

The dry years in epoch 4 had a strengthened cyclonic circulation anomaly in the Gulf of Mexico. Northerly flows along the western flank of the anomaly center helped to form a low-level divergence in the central United States. In the northern section of the central United States, the anticyclonic anomalies (Fig. 7b) concentrated into one center and intensified, weakening the average convergence and suppressing summer rainfall development in the central United States.

What could be a reason for the southerly flow from the Gulf of Mexico to enhance its role in rainfall variations in some epochs but not in others? One factor could be the low-level atmospheric stability in the central United States. The low-level southerly flow usually transports moisture from the Gulf of Mexico into the central United States. Circulation anomalies in the Gulf region and fluctuations of the southerly flow can amplify when the moisture flow is channeled in convective storms in the central plains during summer. A strong tendency for such storms to develop resides in an environment with low-level convergence and weak thermodynamic stability. Because we have shown the presence of average low-level convergence anomalies in the central United States in epoch 4 when the southerly flow had a strong effect, we will show that in epoch 4 the

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FIG. 4. Profiles (1000–100 hPa) of meridional wind across 30°N latitude between 70° and 120°W for (a) wet and (b) dry years in epoch 3. Dark (light) shading indicates northerly (southerly) wind greater than 3.0 m s⁻¹. (c) Difference between (a) and (b). Shading shows significant (>95% confidence level) wind changes between wet and dry years. (d), (e), and (f) Corresponding results for epoch 4. (g) Similar to (f) but without 1993 in the composite.

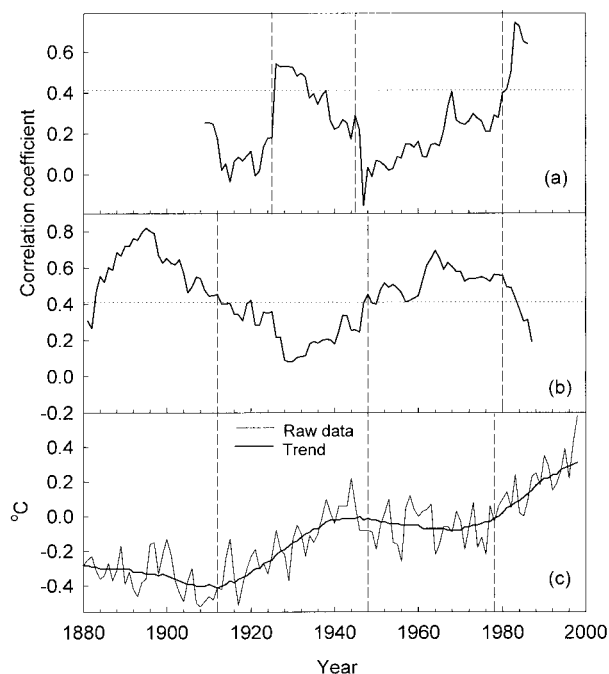


FIG. 6. (a) The 21-yr moving correlation of SWI/SWI_p and central U.S. summer rainfall. (b) The 21-yr moving correlation in boreal summer SST in Niño-3.4 and Niño-4 region and central U.S. summer rainfall. The dotted line in (a) and (b) is the 95% significance level, based on the Student's *t* distribution for the null hypothesis of no association. (c) Annual average NH temperature anomaly (thin line), based on 1950–79 mean [Data were from Jones et al. (1986) and Parker et al. (1995b)], and its long-term trend (thick line) reconstructed using singular spectral analysis method (Vautard et al. 1992).

atmosphere also had a weaker-than-average thermodynamic stability. We measure the low-level thermodynamic stability by the lapse rate of equivalent potential temperature for saturated air, that is, $\partial\theta_e^*/\partial z$, between 700 and 925 hPa. Figure 9 shows the 1958–97 variation of $\partial\theta_e^*/\partial z$ averaged for the summer season over the central United States. The average value of $\partial\theta_e^*/\partial z$ was about -3 K km^{-1} . It clearly shows two very different stability values for the two epochs; a large negative lapse rate was in epoch 4 and a small negative value in epoch 3. The average lapse rate was 1.5 K km^{-1} larger in epoch 3 than in epoch 4. Although the summer lapse rate in both epochs fell in the conditionally unstable category, the bigger negative value of the lapse rate indicates that the thermodynamic condition of the environment was much more conditionally unstable in epoch 4 than in epoch 3. The weak stability in lower troposphere and low-level convergence anomalies in epoch 4 favored active convective storms and created an environment for interactions of the southerly flow with the circulation and rainfall variations in the central United States. Effects of the southerly flow on summer rainfall variations in the central United States became elevated.

The similarity of the SLP pattern in epochs 3 and 1 and epochs 4 and 2 (Fig. 10) suggests that a similar

stability change existed between epochs 1 and 2 as between epochs 3 and 4. Average convergence in the low-level flow anomalies and weak stability in the lower troposphere in epoch 2 favored a similar environment as in epoch 4. Thus, in epochs 2 and 4, interannual variations of the southerly flow supported interannual variations in the summer rainfall.

5. Summary and concluding remarks

Continuing the investigation of the origin of the interannual variations in summer rainfall in the central United States (Hu and Feng 2001, Part I), we have found an answer to the question left in the Part I study: What are the sources affecting interannual variations in the summer rainfall in epochs 2 (1917–48) and 4 (1979–98) when the influence of the tropical Pacific SST anomalies on the summer rainfall languished? We found that a source maintaining the interannual summer rainfall variations in those epochs was the low-level southerly flow from the Gulf of Mexico.

We showed that the low-level southerly flow from the Gulf has significant interannual variations similar to that identified in the summer rainfall. The variations were independent of SST interannual variations in the tropical Pacific region. Therefore, they are independent sources of the interannual summer rainfall variations in the central United States. Our analysis further revealed that their effects on the summer rainfall variations varied over the years. The variation was coherent but in an opposite phase with the variation of the ENSO teleconnection and the summer rainfall in the central United States. The southerly flow variations amplified and significantly affected the summer rainfall variations in epoch 4 when the ENSO teleconnection effect on the variations weakened. The southerly flow variations damped and its effect weakened in epoch 3 when the ENSO teleconnection effect strengthened. A similar coherent and out-of-phase relationship also was found in the late years in epoch 1 and in epoch 2.

The following two circulation features in epochs 2 and 4 helped to engage the southerly flow variations with summer rainfall variation in the central United States: 1) a persistent convergence anomaly and 2) an enhanced unstable thermal structure in the lower troposphere in the central United States. The unstable environment with a tendency of convergence in those epochs favored development of convective storms in summer months in the central United States. This setting of circulation anomalies helped to create a potential for resonant variation between the rainfall in the central United States and the southerly flows from the Gulf of Mexico. Thus, the interannual variation in the southerly flow easily engaged with rainfall development in the central United States and resulted in a similar variation in the central United States summer rainfall. These two features weakened in epochs 1 and 3. A low-level divergence anomaly and a relatively stable thermal struc-

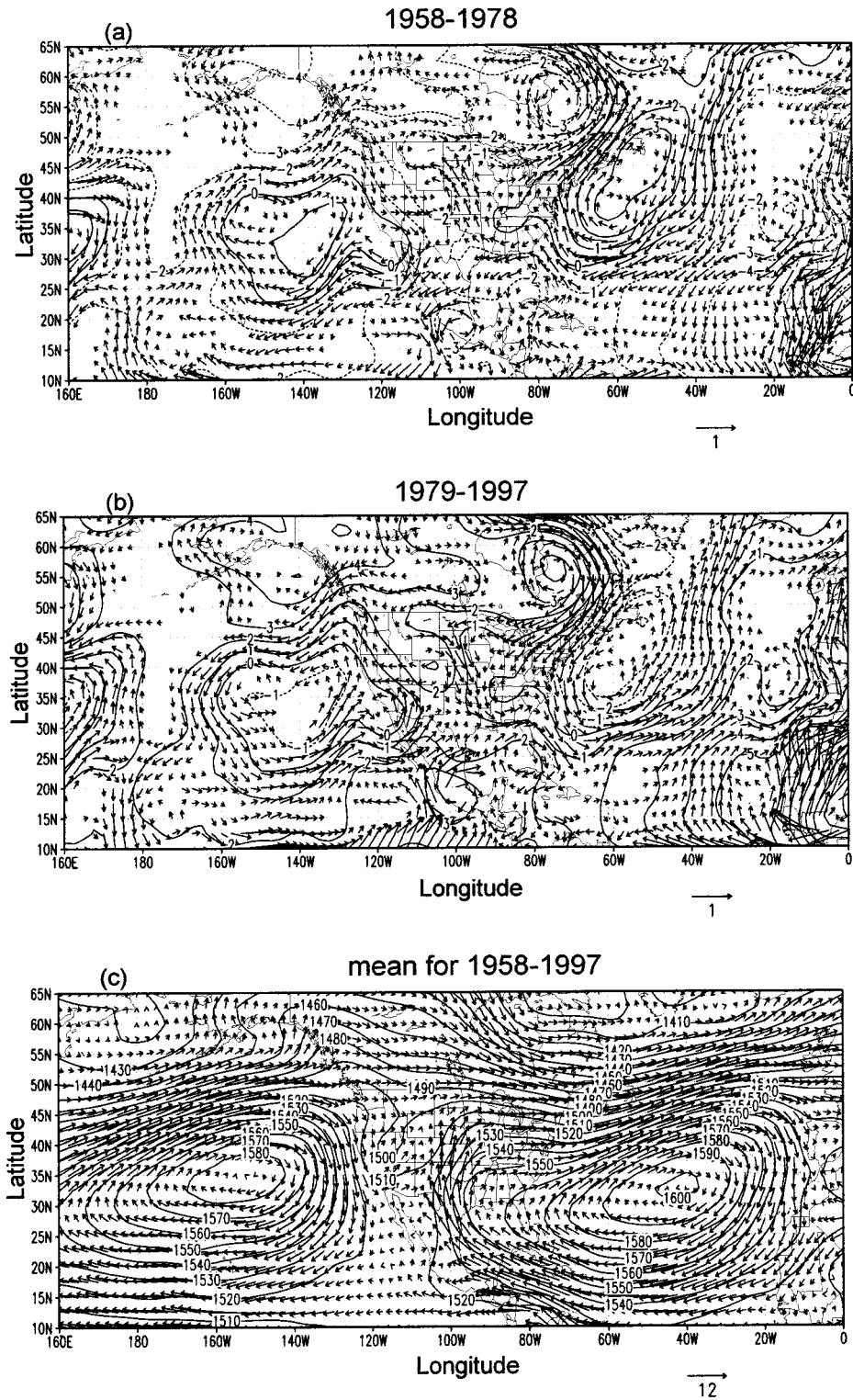


FIG. 7. Composite of 850-hPa geopotential (gpm) and wind ($m s^{-1}$) anomalies for (a) 1958–78 and (b) 1979–97. The wind arrows are omitted when wind speed is less than $0.3 m s^{-1}$. (c) The mean geopotential and wind for 1958–97.

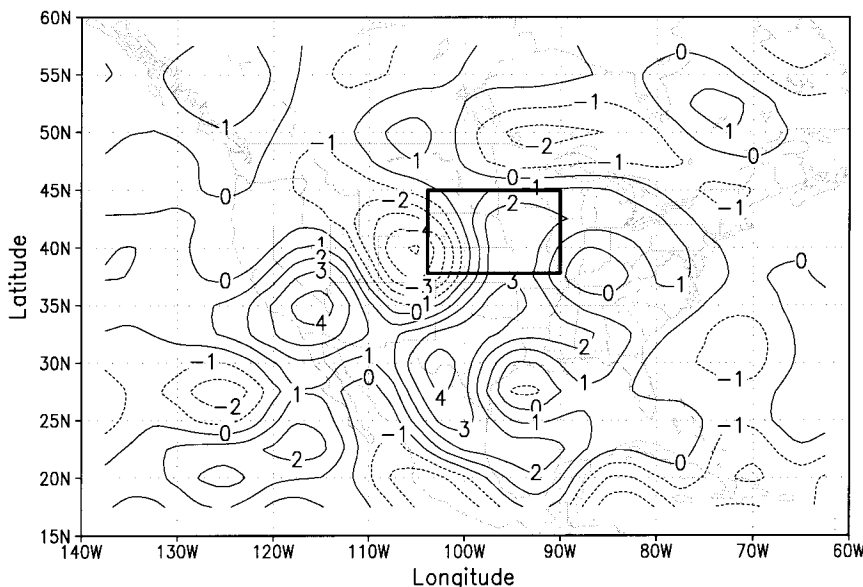


FIG. 8. Divergence anomalies (10^{-7} s^{-1}) for epoch 3. The central U.S. region is encompassed by the rectangle.

ture in the central United States discouraged interactions between the southerly flows and summer rainfall variations. Concurrent with these changes, the ENSO teleconnection enhanced and dominated the interannual rainfall variations in the central United States.

These coherent variations in the role of the southerly flow from the Gulf of Mexico and the ENSO teleconnection contributed to the observed persistent interannual variations in summer rainfall. The differences in the two sources may be attributable to the wide spectrum in the observed interannual summer rainfall variations (see Fig. 1 in Part I).

The coherent variations have evolved concurrently with an observed similar multidecadal variation in SST in the central North Pacific Ocean; a warmer SSTA in the central North Pacific coexisted with the unique circulation anomaly in the western NH and an enhanced ENSO teleconnection with the central U.S. summer rainfall, and a cooler SSTA coexisted with a different circulation anomaly and an enhanced southerly flow ef-

fect on the rainfall. Because of prominent roles of oceans in developing multidecadal variations, the multidecadal variations in SST in the North Pacific may have been a regulating force of the observed coherent variations.

It is worthy to indicate further that the coherent variations also have been in phase with the variation in the average NH surface temperature since the late nineteenth century (see Fig. 6). The “abrupt warming” of the NH temperature has corresponded with breakdown of the ENSO teleconnection and, in the meantime, an elevated effect of the southerly flow from the Gulf of Mexico on the interannual summer rainfall variation in the central United States. The increase of NH surface temperature in the abrupt-warming epochs may have resulted in the observed decrease of the conditional stability in the central United States, as also suggested in Trenberth (2000). Decrease of the NH surface temperature in the cooling epochs, on the other hand, may have contributed to the more stable profile and discouraged the effect of the southerly flow from the Gulf. It remains to investigate the relationship between the NH climate variation and alternation of the observed mechanism in the interannual summer rainfall variations in the central United States.

We point out that the results of this study showed two dominant sources affecting the interannual rainfall variations in the central United States. They may have coexisted with other possible mechanisms that could have interacted with the two identified mechanisms and altered from time to time their effects on the rainfall variations. Such interactions are beyond the scope of this study. We also caution the readers that limitations

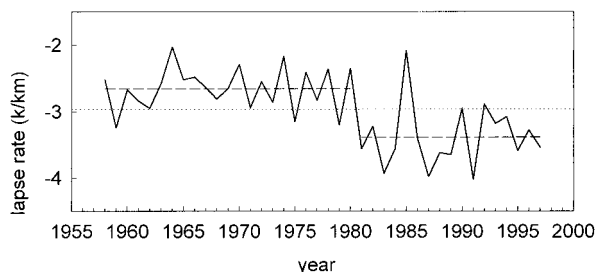


FIG. 9. Variation in vertical gradient of equivalent potential temperature for saturated air in the central United States. Dashed line shows the average for the two epochs.

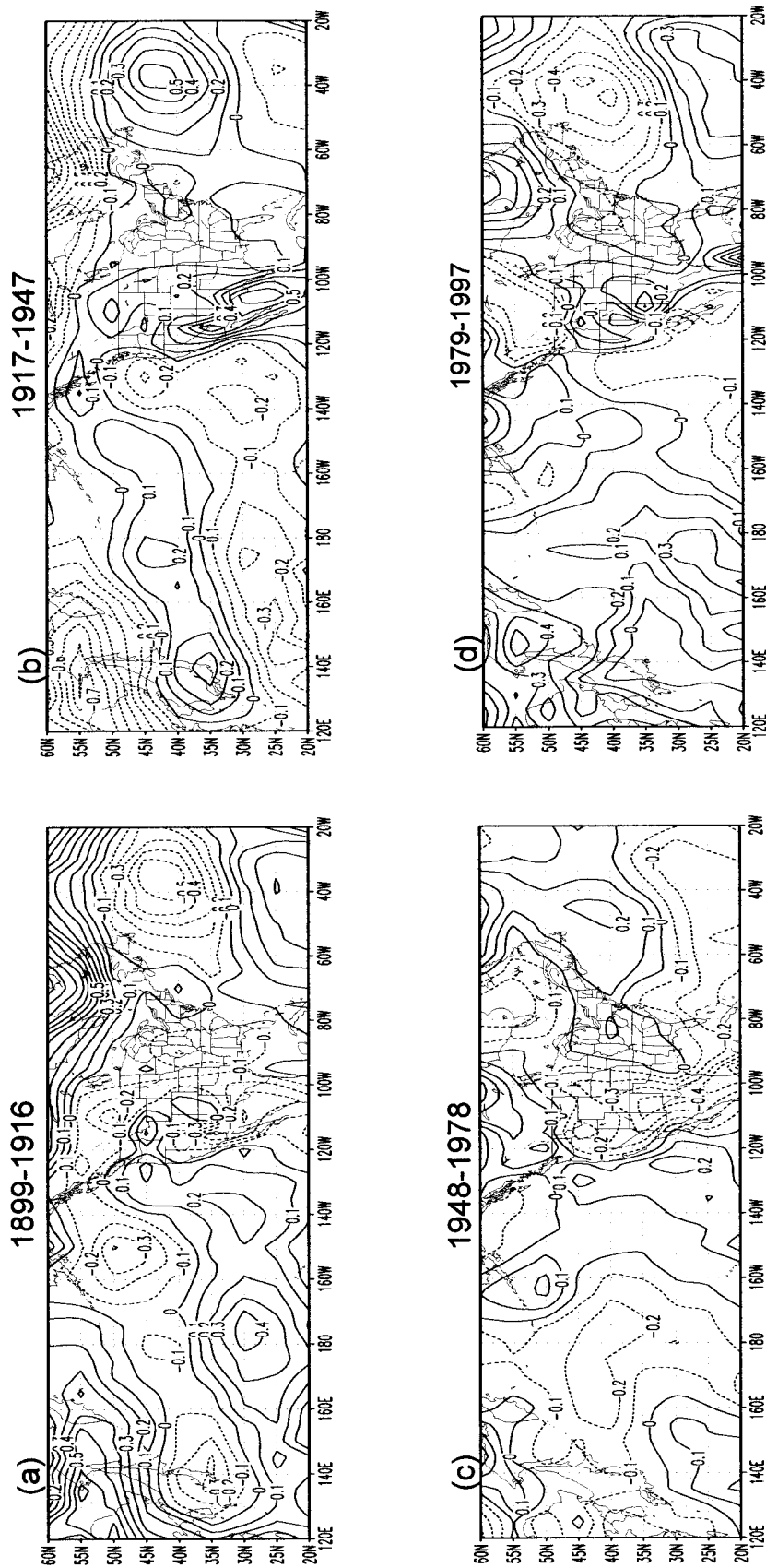


FIG. 10. Composite summer SLP anomaly of (a) 1899–1916, (b) 1917–47, (c) 1948–78, and (d) 1979–97. The linear trend of summer SLP was removed in making the composites. Note the similarity of the SLP anomaly distribution between (a) and (c) and between (b) and (d) in the central and eastern North Pacific and the contiguous United States and Mexico.

of the data length cast a reasonable doubt on the persistence of the identified multidecadal variation in the role of the southerly flow in the interannual summer rainfall variation. Further investigation will be necessary when longer data records become available.

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