Consistency of Interdecadal Variation in the Summer Monsoon over Eastern China and Heterogeneity in Springtime Surface Air Temperatures

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Abstract

This study investigates the consistency of interdecadal variations in the East Asian summer monsoon (EASM) and changes in the heterogeneous structure of sea/land springtime surface air temperature (SAT) over eastern China and the adjacent ocean (including the South China Sea and part of the Western Pacific Ocean). A profile of the summer mean meridional wind over eastern China for the past 40 years shows a coherent interdecadal weakening trend for the EASM. The decadal-scale (11-year running mean) summertime (June–August) wind and springtime (March–May) SAT fields are decomposed using the empirical orthogonal function (EOF) method. The results indicate that both the leading eigenvector of the decadal-scale meridional wind and that for the SAT over East Asia account for more than 70% of the total variance. Their time coefficients show a similar trend, with the transition from negative to positive values occurring around 1978; i.e., the EASM turned from a stronger phase to a weaker phase around 1978. The springtime sea/land SAT distribution before and after 1978 also showed a shift in interdecadal trends. Therefore, the south-low/north-high nature of the principal component of springtime SAT over eastern China is closely related to the progressive weakening of the EASM. Our results suggest that within the context of the regional impact of global climate change, heterogeneous changes in the regional springtime sea/land SAT in eastern Asia might in part have led to a weakening of the effect of sea/land thermal driving on the EASM.

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1. Introduction

The rapid change in global climate recorded over the past 50 years has increasingly attracted the attention of the global community. Global warming is often misunderstood as a homogeneous warming throughout the world, when in fact climatic warming associated with the greenhouse effect is heterogeneous (Houghton et al. 2001). Based on a review of extensive previous studies of global climate change and past, present, and future regional responses, Ye et al. (2000) noted that the consensus understanding is that it is difficult for the Earth system and its various components to return to their original states once change has occurred. Therefore, the equilibrium states that will eventually be attained by the global and regional systems are an important scientific issue that demands close attention (Ye et al. 2001).

With regard to the response of the Chinese climate to heterogeneous variations in global climate and the temporal evolution of the regional equilibrium state in China, Wang et al. (2000a) reported an enhanced warming trend over the past two decades, whereas Yu and Zhou (2004) concluded that in the past 50 years the surface air temperature (SAT) over the mid-latitude regions of eastern China (as measured in March of each year) has displayed a unique decreasing trend. This cooling shift on the lee side of the Tibetan Plateau is not a local phenomenon: it is associated with the eastward extension of a cooling signal originating from North Africa. This cooling signal is related to the North Atlantic Oscillation (NAO) of the previous winter, while the continental stratiform cloud–climate feedback also plays a significant role in the amplification of the cooling shift (Li et al. 2005). Gong (1999) and Gong et al. (2000) pointed out that summertime precipitation in eastern China is in good agreement with the trend of mean temperatures in the Northern Hemisphere; accordingly, the pluvial summers in the 1980s and 1990s might have been related to the acceleration of global warming. Using a global coupled ocean–atmosphere–land system model (IAP/LASG GOALS), Guo et al. (2001) investigated global warming associated with increasing CO_2 (with the emphasis on climate change in East Asia) and found that under the scenario of a doubling of carbon dioxide, temperature and precipitation in East Asia would increase by 2.1° and 5%, respectively; the maximum increases in temperature and precipitation would occur in the middle-latitude mainland areas and the area near 25°N, respectively. The most recent simulations also indicate that global warming will lead to a change in the circulation of the East Asian summer monsoon, thereby affecting the summertime East Asian rain band (Bueh et al. 2003; Kimoto 2005).

Yatagai et al. (1994) suggested that summer rainfall in China shows remarkable decadal-scale fluctuations. Wang et al. (2000b) also found that precipitation trends in China are basically in agreement with those of global land precipitation, except that precipitation in China shows a more pronounced interdecadal variability and the major periods of precipitation trends in China are 3.3 and 26.7 years. The former might be associated with the impact of ENSO, while the latter reflects interdecadal climatic variability. Accordingly, Wang et al. (2000b) suggested that the low-frequency variations in rainfall recorded in China over recent decades are associated mainly with interdecadal climatic variability rather than climate trends. Shi et al. (2002) pointed out that the climate in northwest China has been in a transition from warm/dry to warm/wet since 1987 and that the transition might have resulted from interdecadal oscillations or a centurial trend.

During the Chinese summer, dry and above-normal SAT or floods and below-normal SAT generally occur together (Nitta and Hu 1996). Based on observation data and simulation results from the Coupled Model Intercomparison Project Phase II (CMIP2), Hu et al. (2003) analyzed the long-term trend of climate in various seasons in China and found that summertime precipitation showed a reducing trend in North China and an increasing trend in central China, especially in the middle and lower reaches of the Yangtze River. Summer temperatures exhibited a general warming trend in most areas but a cooling trend in central China. The authors also confirmed that a cooling (warming) trend generally coexists with a wetting (drying) trend during the Chinese summer and hypothesized that the long-term variations in summertime climate in China might be related to the warming trend in the sea surface temperature of the Indian Ocean (Hu 1997; Hu et al. 2003). Other research suggests that El Niño–

Southern Oscillation (ENSO) have an important influence on summertime precipitation in China (Wu et al. 2003).

China lies within the East Asian Monsoon region, and its climatic variability is closely related to changes in the intensity of the monsoon. According to Tao and Chen (1985), the components of the East Asian summer monsoon (EASM) system include the South China Sea, the equatorial Western Pacific monsoon trough (or ITCZ), the Indian Ocean southwest monsoon flow, the cross-equatorial flow east of 100°E, the Western Pacific subtropical high, equatorial easterlies, mid-latitude disturbances, the Meiyu (China) or Baiu (Japan) fronts, and Australian cold anticyclones. Wang and Tao (1984) found that strong and weak EASM differ in their meridional circulations: when the EASM is strong, its meridional circulation is also strong, and vice versa. Tao et al. (1988) also proposed that a northward/southward shift in the EASM system from normal positions in East Asia might result in droughts/floods over the Yangtze–Huaihe River valley, the Korean Peninsula, and Japan. Lu (2003) found that the remarkable reduction in rainy-season precipitation (July–August, referred to as JA hereafter) recorded in North China at the end of the 1970s corresponded to a southward shift in the East Asian westerly jet within the upper troposphere as well as an anomalous northerly wind in the lower troposphere over eastern China; both of these events are features of a weak EASM. Both Ding (2004) and Huang et al. (2003) documented the effect of ENSO cycles, the Western Pacific warm pool, the Tibetan Plateau, and land-surface processes on intraseasonal, interannual, and interdecadal variations in the EASM. The above studies found that while the mechanism behind the changes in the EASM is complicated, the regional sea/land thermal contrast over East Asia and interannual and interdecadal variations in the monsoon system are key factors that should not be neglected.

In the context of the complexity of the variability in the EASM and its physical mechanisms, the present paper focuses on the characteristics of the relationship between sea/land SAT differences and interdecadal variations in the EASM, especially the influence of interdecadal variations in springtime SAT in eastern China on variations in the EASM. In this paper, we explore the effect of global-warming-induced changes in the heterogeneous nature of the low-level thermal regime on variability in the EASM. This will help us to understand the mechanisms that link changes in EASM circulation to interdecadal variations in the distribution of summertime precipitation.

2. Data

The data used in this study include monthly rainfall data recorded at 600 meteorological stations (Fig. 1a) in China (China Meteorological Administration) from January 1961 to December 2000 and NCEP/NCAR reanalysis monthly data for the same period, including SAT, zonal (u) and meridional (v) wind on isobaric surfaces, and vertical velocity (ω) at a horizontal grid of $2.5^\circ \times 2.5^\circ$ (Kalnay et al. 1996; downloaded from the NOAA-CIRES Climate Diagnose Center website: http://www.cdc.noaa.gov).

To assess the reliability of the NCEP/NCAR reanalysis data, we generated a scatter plot (Fig. 1b) of the long-term mean monthly station SAT from March to August over the 600 stations compared with the corresponding reanalysis SAT at the nearest grid point to each station. Figure 1b shows that the station SATs have a significant correlation with reanalysis SATs: the correlation coefficient are as high as 0.8428, which is statistically significant at the 1% level. The point-by-point correlation coefficients between the observed SAT at each station and the reanalysis SAT at the nearest grid points for the spring seasons from 1961 to 2000 also show a positive correlation between the two data sets. The correlations are statistically significant at the 5% level for the overwhelming majority of the 600 stations, especially for those over eastern China (not shown). This indicates that the station SAT and reanalysis SAT not only depict similar climate states at each location, but that they show significantly "correlated" interannual variations. Therefore, it is feasible to use the reanalysis SAT to investigate the characteristics of sea/land thermal contrast and its effect on the EASM; this approach also avoids analysis errors associated with the heterogeneity of station SAT data.

Running means are commonly used when

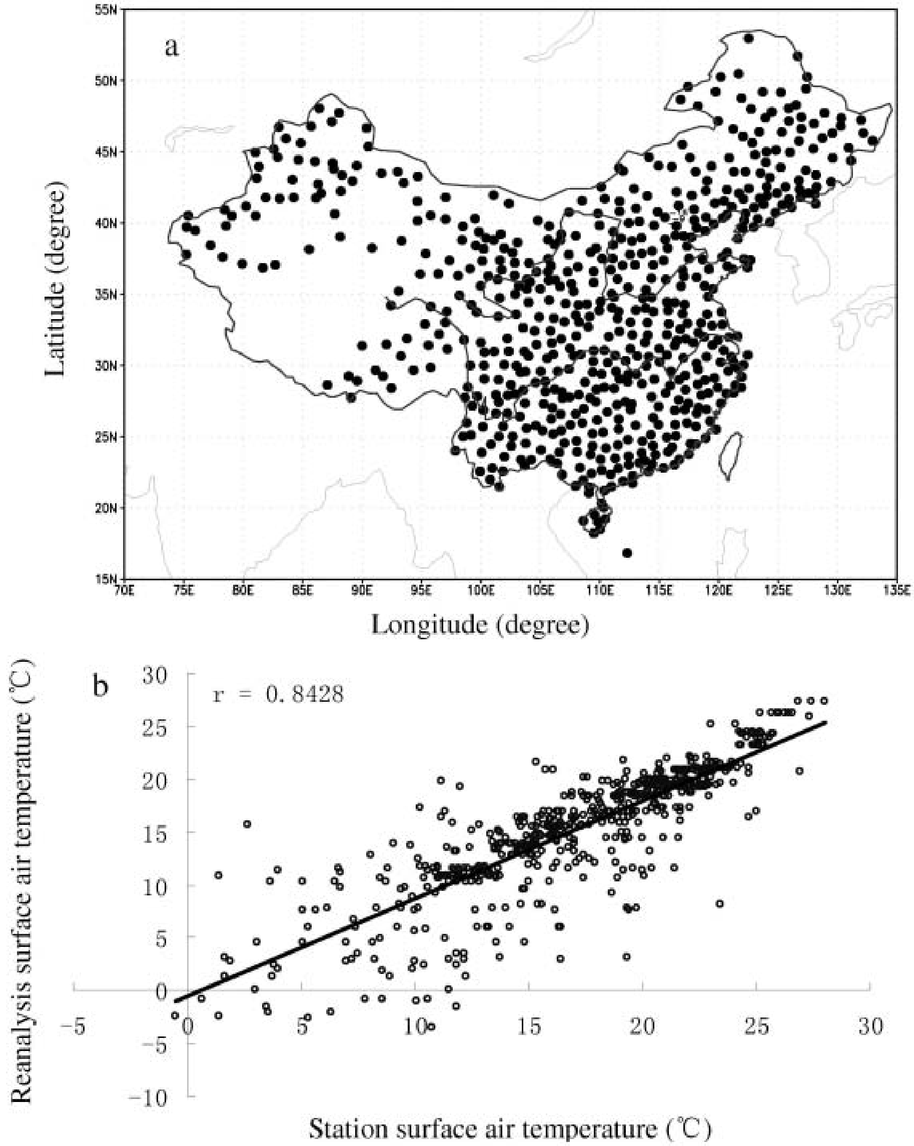

Fig. 1. (a) Locations of stations at which observed surface air temperatures (SAT) were measured. (b) Scatter plot of the mean station SAT versus reanalysis SAT from March to August for the period 1961–2000.

separating the annual- and decadal-scale components of meteorological variables. Liang et al. (2001) suggested that the 11-year running mean could be used to represent the decadal-scale component. As interdecadal variability is one of the focuses of the present paper, the 11-year running-mean fields are used as the time-filtered decadal component, following Liang et al. (2001).

3. Interdecadal variations in summertime precipitation and meridional wind over China

Precipitation in the Yangtze–Huaihe River valley has increased from 1951 to 1995, especially since the 1980s; this is consistent with the frequent occurrence of summer–autumn floods in the valley from the 1980s to the mid-

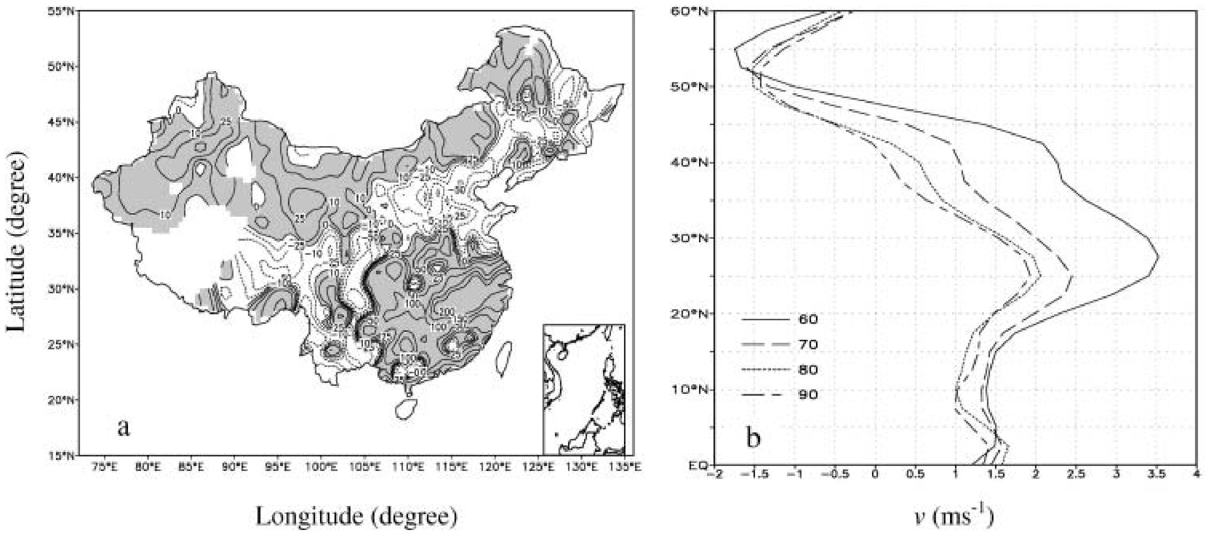

Fig. 2. Difference between the mean summertime precipitation over China in the 1960s and 1990s (a, mm; shaded areas are positive values) and the latitudinal profile of the 850 (hPa) meridional wind averaged over 100–120°E (b, m s^{-1}).

1990s. Over the same period, warming occurred mainly in those areas north of 35°N (Chen et al. 1998). Chen et al. (2004) analyzed climate change in China since the 1920s and found that warming in mainland China north of 35°N started in the early 1980s, whereas warming south of 35°N began in the late 1980s. Rainfall over China was below average in the 1960s and 1970s, but since the 1980s precipitation has increased in northwest China, northeast China, and the middle and lower reaches of the Yangtze River.

Figure 2a compares the summertime mean precipitation over China in the 1960s and 1990s. The summertime precipitation shows an increasing trend in the middle and lower reaches of the Yangtze River and South China, and a declining trend in North China. This is consistent with the trends in summertime precipitation over eastern China reported by previous studies (Chen et al. 1998; Huang et al. 1999; Chen et al. 2004). Recently, interdecadal variation in the EASM and its mechanism have drawn significant attention, with a number of studies (Shi et al. 1996; Guo et al. 2003) suggesting that since the middle of the 20th century many circulation indices and the EASM have undergone sudden changes characterized by a remarkable weakening that occurred in the mid-1960s and mid-1970s, remaining weak thereafter. The latitudinal profile of the summer 850 hPa meridional wind averaged over 100–120°E for the 1960s, 1970s, 1980s, and 1990s (Fig. 2b) reveals that the summer southerly shows an interdecadal weakening trend over eastern China (20–45°N), although the weakening trend is not obvious over the low-latitude ocean. Wang (2001) found that the EASM has clearly weakened since the late 1970s and that correspondingly, summertime precipitation has increased over the middle and lower reaches of the Yangtze River and decreased over the Yellow–Huaihe River valley. The finding of interdecadal weakening of the summertime 850 hPa southerly over eastern China during the past 40 years and interdecadal variation in the south-increase/north-decrease pattern for summertime precipitation further confirms the correlation between interdecadal variations in the EASM and summertime precipitation over eastern China.

Because of the high elevation of western China, which commonly exceeds 3000 m, we also plotted the longitudinal distribution of the summertime 500 hPa meridional wind averaged over 20–45°N for the period from the 1960s to the 1990s (Fig. 3). The interdecadal variations in summertime mean meridional wind over western and eastern China have an

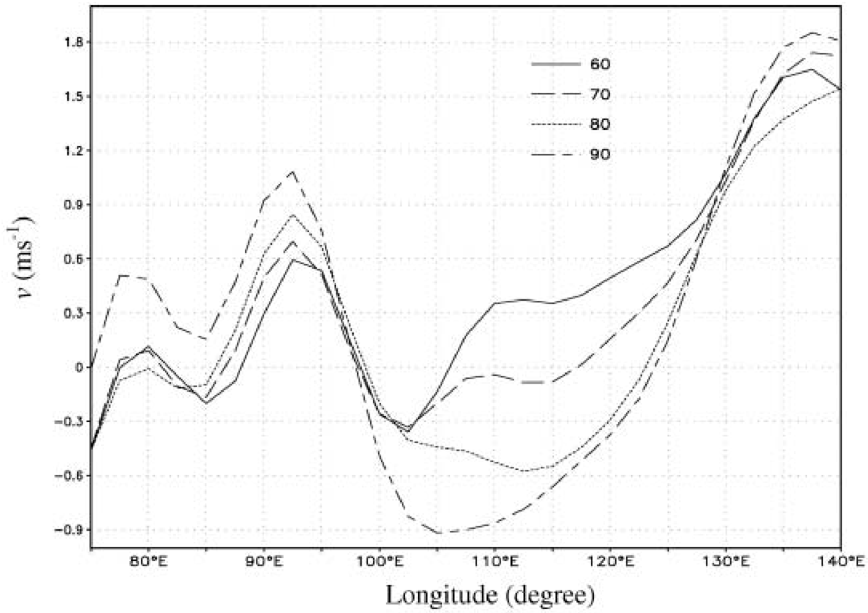

Fig. 3. Longitudinal distribution of the summer 500 hPa meridional wind averaged over 20–45°N for the period from the 1960s to the 1990s (m s^{-1}).

"anti-phase" character. That is, the summer southerly weakened and changed to a northerly at an interdecadal time-scale over eastern China (97.5–130°E), reflecting the gradually weakening trend of the EASM. In contrast, the summer southerly clearly strengthened over western China (west of 97.5°E), indicating a gradual strengthening of the southwest summer monsoon; this may be favorable for a transition in the climate in western China from warm dry to warm wet.

4. Interdecadal variation in the EASM from an EOF of East Asian summertime winds

On the basis of the analyses of interdecadal variations in summer meridional wind and summertime precipitation described in Section 3 and their relation over eastern China, the u and v components of the summer 850 hPa wind over the East Asian continent and Western Pacific Ocean area (0–60°N, 70–150°E) in 1961–2000 are smoothed with a 11-year running mean to obtain the decadal components; their anomalies are decomposed using the EOF method to obtain the spatial pattern of the principle component of interdecadal variations in wind.

Figure 4a is the vector field of the first eigenvector of the decadal components of the summertime 850 hPa u and v fields. The figure shows a remarkable northeasterly or northerly anomaly over the area east of the East Asian continent, the South China Sea, and the area east of the Bay of Bengal. A comparison of Fig. 4a and Fig. 4b reveals that the first eigenvector field of the decadal component of summertime 850 hPa winds over eastern China is similar to the difference between the means of summertime 850 hPa wind vectors for the periods 1979–2000 and 1961–1977 (i.e., a distribution that is characteristic of a weakening EASM).

The variations in the time coefficient (TC) of the first EOF eigenvector for the decadal component of summertime 850 hPa u and v fields (Fig. 5) show a consistent secular trend, i.e., the diminishing trend of negative values from the 1960s to the late 1970s, the transition from negative to positive around 1977–78, and the steady phase of the 1980s–1990s following the transition. The period of the "turning" of the first EOF eigenvector TC coincides with one of the periods of sudden climate change recorded during the late 1970s (Huang et al. 2003; Lu 1999). From the perspective of the spatial/temporal evolution of the leading EOF

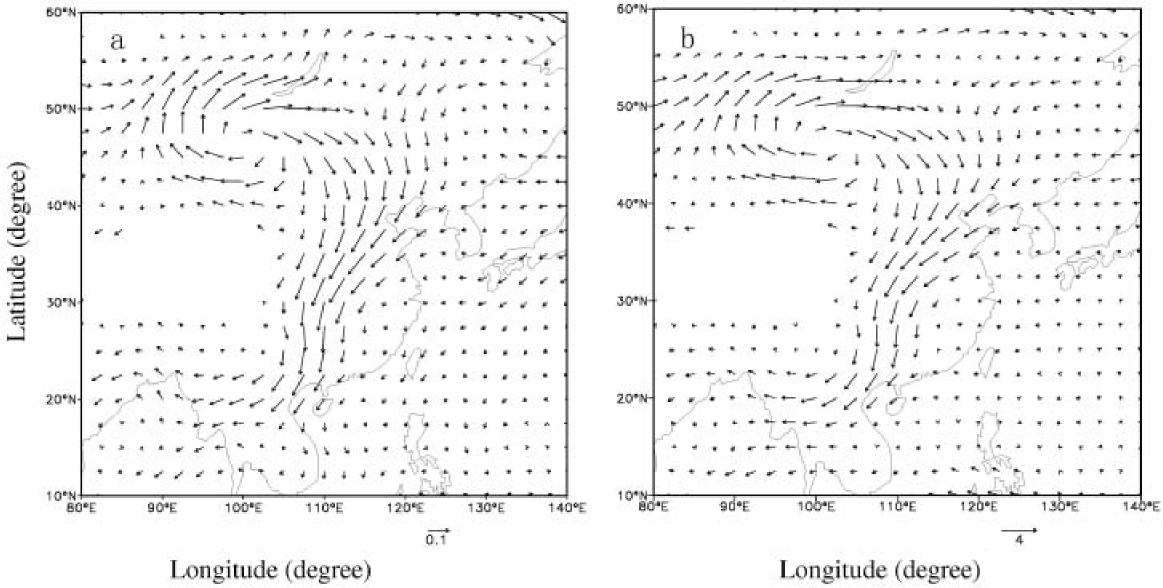

Fig. 4. Spatial patterns of the vector distribution of the first EOF eigenvectors of the decadal components of the summer 850 hPa wind fields (a). Difference between the mean summer 850 hPa wind vector fields for the periods 1961–1977 and 1979–2000 (b, m s^{-1}).

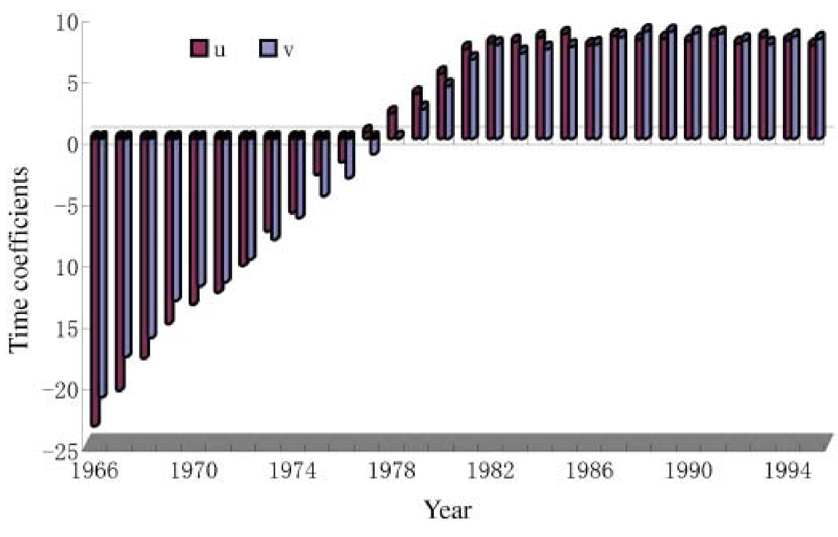

Fig. 5. Temporal evolution of the time coefficients of the first EOF eigenvectors of the decadal components for summer 850 (hPa) wind.

mode, the EASM prior to the end of the 1970s was in a stronger phase, followed by a gradual weakening and a relatively stable weaker phase. This EOF trend and the temporal evolution of its TC also reveal the presence of a "turning" point in EASM change from a strong to a weak phase and an interdecadal weakening trend over the past 40 years.

The spatial pattern of the first EOF eigenvector ($\sigma = 73\%$) of the summertime 850 hPa ω anomaly fields (not shown) also displays an area with a positive value of ω (descending mo-

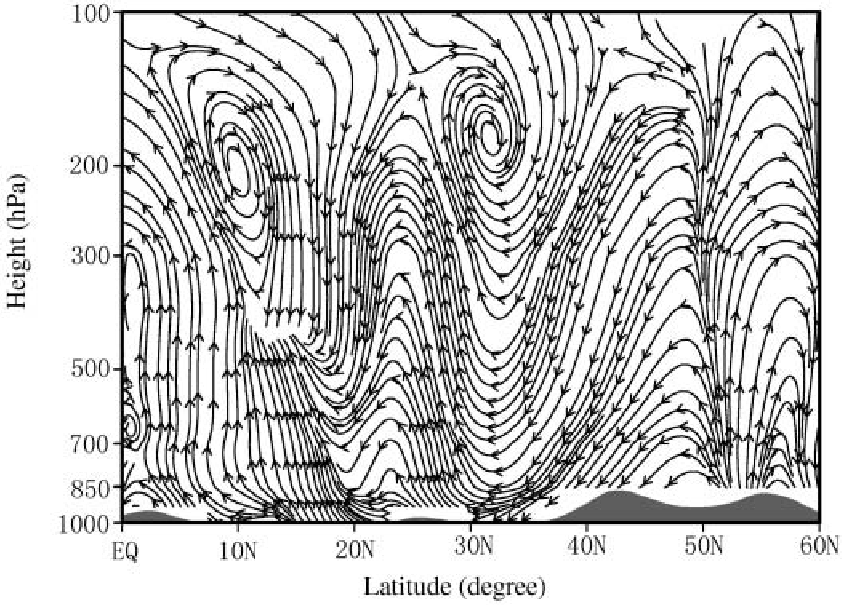

Fig. 6. Latitude–height cross-section of the difference in summer circulation (1979–2000 minus 1961–1977) along 115°E. The shaded areas at the base of the figure represent topography.

tion stronger than normal) in North China and an area with a negative value (ascending motion stronger than normal) in Southeast China. The corresponding TC shows a similar transition, i.e., the changes in vertical motion are opposite over southeast China and North China; this is in accordance with the interdecadal trend in summertime precipitation over eastern China (Fig. 2a).

Summertime horizontal and vertical winds over eastern China were characterized by a remarkable interdecadal variation during the period from the 1960s to the 1990s, with an abrupt change (from negative to positive TCs) recorded at the end of the 1970s. This trend is also evident in a latitude–height cross-section of the circulation difference (1979–2000 minus 1961–1977) along 115°E (Fig. 6). The cross-section shows a difference in the circulation, with an ascending branch over the southern part of 20–45°N, a descending branch over the northern part, and a northerly difference in circulation at lower levels. The difference in circulation is referred to as the trend of secondary meridional circulation before and after the transition, which is unfavorable to the northward advance of summertime low-level southerly flows and rain belts, thus reflecting the regional character of interdecadal weakening of the EASM. The above interdecadal variations in 850 hPa horizontal and vertical winds are in general agreement with the change in summertime precipitation over eastern China recorded over the past 40 years (Fig. 2a).

5. Interdecadal heterogeneous change in springtime SAT and links to the EASM

Zeng and Li (2002) stated that annual variations in the solar radiation that reaches the Earth result in the seasonal evolution of atmospheric circulation and cross-equatorial flows. Therefore, planetary thermal convection is the primary driving force of tropical monsoons. Comparatively, the quasi-stationary planetary wave induced by differences in surface conditions, e.g., differences in sea/land thermal properties and topographic height, is the secondary driving force. When the two driving forces are in phase, they result in the most remarkable tropical monsoons that occur in the Asia–Australia monsoon region. At the annual, decadal, and centurial scales, changes in sea/land thermal contrast are crucial for the rate of climate change of the Asian monsoons. Considering the lagged response of the atmosphere to the heating of the underlying surface, we ex-

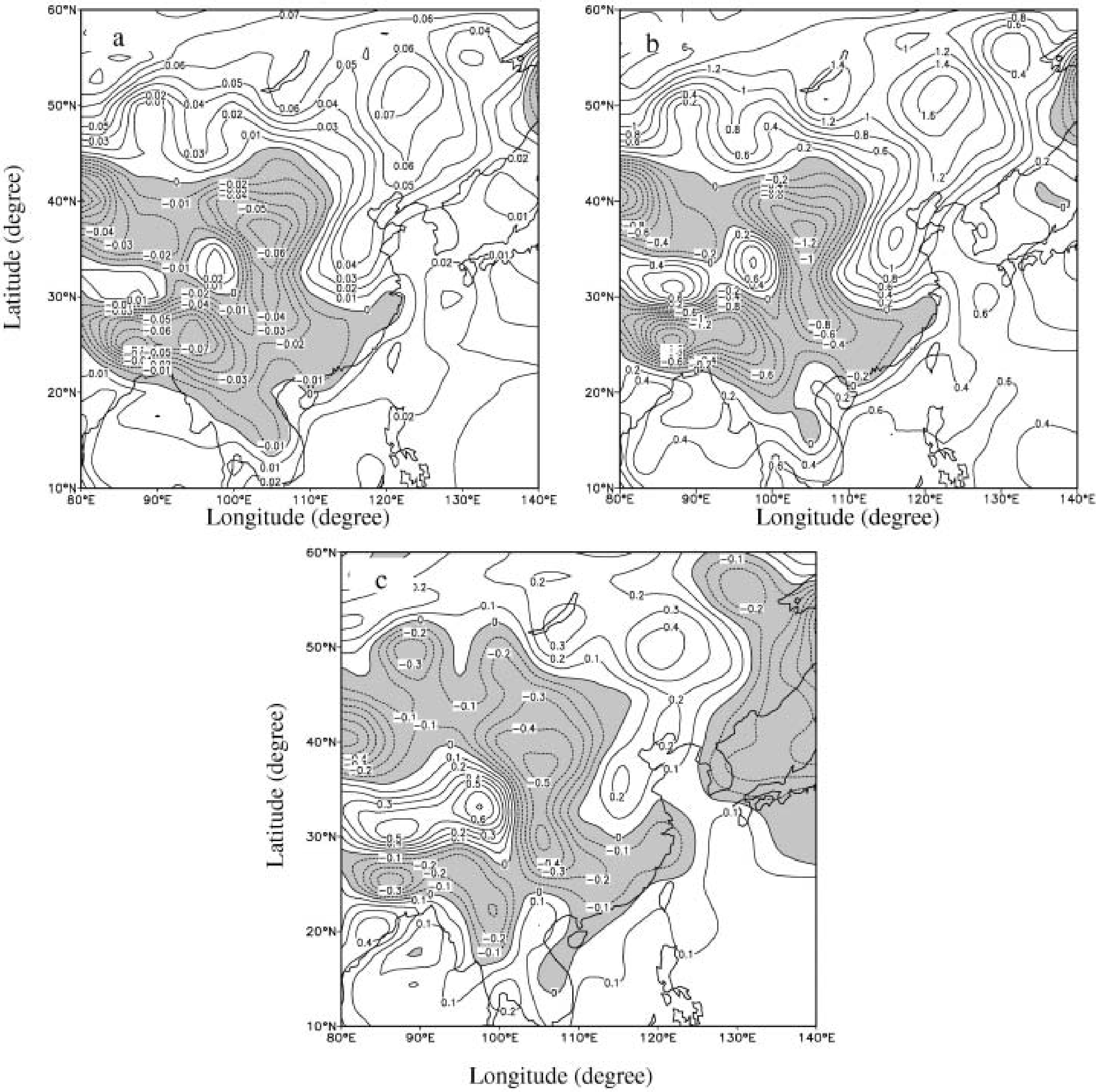

Fig. 7. Spatial pattern of the first EOF eigenvector of the decadal component of springtime SAT (a). Difference between the mean springtime SAT for the periods 1961–1977 and 1979–2000 (b, °C). Composite anomaly field of springtime SAT for years with weak summer monsoons (c, °C).

plore changes in the springtime sea/land SAT difference and its regional correlation with the EASM.

We used the EOF method to obtain the decadal-scale spatial/temporal characteristics of the anomaly in decadal component fields for the springtime SAT over the East Asia–Western Pacific area for 1961–2000. Figure 7a shows the spatial pattern of the first EOF eigenvector ($\sigma = 77\%$). The figure shows a principal component with a south-low/north-high pattern (i.e., negative/positive anomalies in eastern China south/north of 30°N) of springtime SAT over eastern China and positive anomalies in springtime SAT over the Western Pacific region, including the warm pool located near The Philippines. The difference between the means of springtime SAT for 1979–2000 and 1961–1977 (Fig. 7b) also shows a similar south-low/north-high pattern. Comparing the above results with the composite anomaly field of springtime SAT for years with a weak sum-

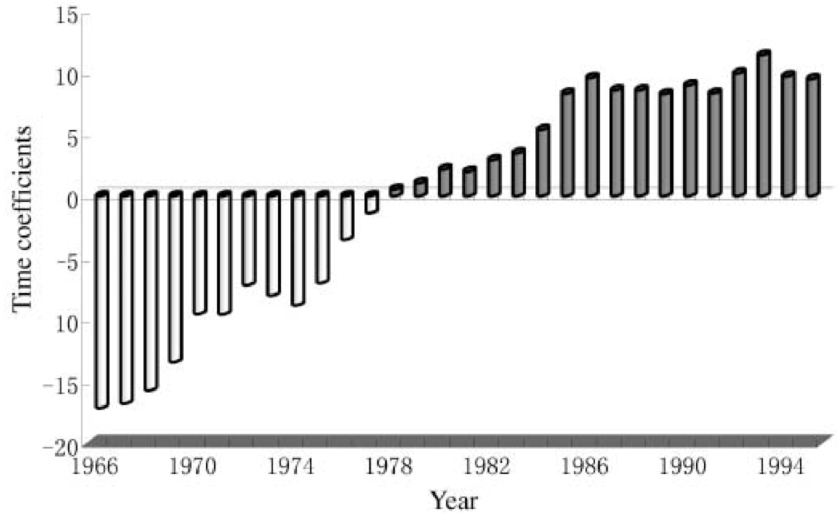

Fig. 8. Evolution of the time coefficient of the first EOF eigenvector of the decadal component for springtime SAT.

mer monsoon (years for which the TC of the first EOF eigenvector of the summer 850 hPa v anomaly field for 1961–2000 is above 10; Fig. 7c), it is evident that the spatial patterns of interdecadal variation in springtime SAT (Figs. 7a–b) are similar to the south-low/north-high distribution of the composite anomaly field of springtime SAT for years with a weak summer monsoon.

In comparing variations in the TCs of the first EOF eigenvector for the decadal components of summer u and v (Fig. 5) with those of the springtime SAT (Fig. 8), both show an overall diminishing secular trend of negative values from the 1960s to the early 1970s, a transition from negative to positive around 1978, and a relatively stable positive phase during the 1980s and 1990s; i.e., at a decadal scale, the heterogeneous character of springtime sea/land SAT over the East Asia–Western Pacific area is in agreement with the change in the principal components of the summer 850 hPa wind.

Based on the EOF analyses discussed above, it can be inferred that the springtime sea/land thermal contrast was stronger prior to 1978; correspondingly, the EASM was also stronger than normal during this period, i.e., springtime SAT anomalies showed a spatial pattern characterized by a positive anomaly over the southern part of the East Asian continent and a negative anomaly over the low-latitude ocean, although the difference was gradually decreasing. The sea/land SAT difference changed significantly around 1978: since 1978, the sea/land thermal contrast weakened, with a negative anomaly over the southern part of the East Asian continent and a positive anomaly over the low-latitude ocean, accompanied by a weaker EASM. The occurrence of the "turning" in sea/land thermal contrast also corresponds well with the transition of the summer 850 hPa wind from a stronger monsoon to a weaker monsoon.

To further confirm the correlation between heterogeneous variations in springtime sea/land SAT in the East Asian region and changes in the intensity of the EASM, we performed the following EOF-singular value decomposition (SVD) analysis. On the basis of the EOF mode analyses of the decadal components of summer 850 hPa meridional wind and springtime SAT in the East Asia region, the three leading EOF eigenvectors for meridional wind and the two leading EOF eigenvectors for springtime SAT (accumulated variance contributions of 94% and 91%, respectively) and their TCs were used to reconstruct meridional wind and SAT fields. The reconstructed meridional wind and SAT were then taken as the left and right variable-fields for SVD mode analysis. The variance contribution of the first pair of SVD singular vectors is 92%, and the spatial patterns and temporal evolution of the first singular vectors are similar to those of the first EOF eigenvectors of meridional wind and SAT, respectively (not shown). The analysis of the first pair of SVD heterogeneous correlation coefficient (HCC) fields of the EOF-reconstructed meridional wind and SAT (not shown) reveals that the eastern part of the East Asian continent and its offshore area shows a negative correlation for the HCC of 850 hPa meridional wind. The low-latitude ocean, the sea east of China, and the north of the continent are positive correlation areas for the HCC of SAT, while the central and southern areas of the continent are areas with significant negative correlations. These findings support the link between the summer 850 hPa meridional wind and SAT, thereby revealing the important connection between the heterogeneous nature of variations in springtime sea/land SAT and the weakening trend of summer 850 hPa meridional wind. This result further supports the proposal that the heterogeneous warming character of springtime sea/land SATs over the East Asian region is possibly one of the factors that acts to weaken the sea–land thermal-driving effect on the EASM.

6. Conclusions and discussion

Based on an EOF–SVD analysis of NCEP/NCAR reanalysis data and the monthly mean data of station precipitation and SAT in China over the period 1961–2000, we studied decadal-scale changes in summertime precipitation, the EASM, and springtime sea/land SAT differences over East Asia for the past 40 years. The main conclusions of the study are summarized in the following points.

(1) The summer mean southerly wind over eastern China in the period from the 1960s to the 1990s showed a clear interdecadal weakening trend; this is in agreement with the interdecadal trend of summertime precipitation in eastern China.

(2) Spatial/temporal variations in the first EOF eigenvectors for the decadal-scale summer 850 hPa wind and springtime SAT show that the temporal evolution of the EASM involved two periods of contrasting intensities, with the transition of the EASM from a stronger phase to a weaker phase occurring around 1978. The temporal evolution of the springtime sea/land SAT difference over the southern part of the East Asian continent and the Western Pacific region also shows two periods of contrasting intensities. In other words, the springtime sea/land SAT difference also recorded an interdecadal “turning” around 1978. The interdecadal variation in the EASM over the period from the 1960s to the 1990s is associated with the early-stage (springtime) sea/land SAT difference.

Various factors have been proposed to explain the observed interdecadal variation in the EASM, including global warming (Gong and Wang 2000; Bueh et al. 2003; Kimoto 2005), warming of the Indian Ocean (Hu 1997; Hu et al. 2003), ENSO (Huang et al. 2003; Wu et al. 2003) and even aerosol activity (Xu 1999; Menon et al. 2002). Yu et al. (2004) raised the possibility that interdecadal weakening of the EASM is linked to a distinctive upper-tropospheric and lower-stratospheric cooling change over East Asia. This mechanism of upper-tropospheric and lower-stratospheric cooling also appears to dominate the recent late-spring drought to the south of the Yangtze River in China (Xin et al. 2006). Our research results reveal the consistency of interdecadal variations in sea/land SAT differences during spring (early stage) and the EASM (late stage). This change in springtime SAT might be one of the causes of interdecadal weakening of the EASM observed in recent decades.

Understanding of the fundamental reason behind interdecadal variations in sea/land SAT remains a challenge in climate change research. In particular, within the context of global warming it is important to determine whether the genesis of heterogeneity in interdecadal variations of sea/land SAT over areas such as the southern East Asian continent, southern and northern areas of eastern China, and the low-latitude ocean is dominantly affected by natural factors, by human activities, or by both. We must determine the mechanism that dominates the genesis of the heterogeneity and the degree to which its effects can be accounted for by natural changes and human activities. Those problems remain to be addressed in future studies.

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