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Atmospheric Water Vapor Transport Associated with Two Decadal Rainfall Shifts over East China

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Abstract

The atmospheric water vapor transport and moisture budget associated with two decadal summer rainfall shifts in 1978/79 and 1992/93 over East China were investigated using observational precipitation and the European Centre for Medium-Range Weather Forecasts (ECMWF) 40 Years Re-Analysis (ERA-40) dataset. After 1978/79, summer precipitation increased abruptly in the Yangtze-Huaihe River valley (YH) but decreased in South China (SC) and North China (NC). Associated with this rainfall shift, southerly water vapor transport over East China was weakened; an anticyclonic moisture circulation anomaly along with decreasing moisture convergence existed in SC; abnormal water vapor from western SC converged in YH with that from western NC, then turned eastward, instead of northward to NC. After 1992/93, rainfall over SC increased dramatically. This is closely related to two abnormal anticyclonic moisture circulations to the south and the north when their northwesterly and southwesterly outflows converged over SC. During these two regime shifts, it was the variation of meridional water vapor flux, located mainly in the lower troposphere, which played an important role in the rainfall anomalies over YH, SC, and NC. The water vapor transport anomalies were mainly controlled by the disturbance wind field instead of the disturbance moisture field.

1. Introduction

Water vapor transported by atmospheric circulation is one of the most important processes in the hydrologic cycle and plays a vital role in determining rainfall distribution. Heavy rainfall can be created only if water

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vapor is continuously transported into a sink region from outside (UNESCO 1978; Trenberth et al. 2003).

A great deal of effort has been devoted to the study of interdecadal variability in precipitation over East China. In the past few decades, summer rainfall over the southern part of northeast China and the Yellow River basin had decreased greatly (Qian and Qin 2008). It has been stated that North China probably entered a dry spell after 1977 (Zhou and Huang 2003; Sun and Chen 2003). On the other hand, enhanced summer rainfall was found over southeast China; summer rainfall over the Yangtze-Huaihe River valley transited from a drought period to a rainy period in the late 1970s (Wu and Chen 1998), causing frequent floods, tremendous loss of life, and property damage (Gong and Ho 2002). After 1992/93, the above-normal rain belt shifted southward to the south of the Yangtze River and South China (Sun and Chen 2003). Rainfall over southern China underwent an obvious increase, which was even stronger than that over the Yangtze-Huaihe River valley in the first regime shift (Wu et al. 2010). In summary, summer rainfall over East China has experienced two significant regime shifts during the past few decades. That is, the main rain belt anomaly existed in northeast China before 1978, shifted rapidly southward to the Yangtze-Huaihe River valley in the late 1970s, and extended farther into South China after 1993 (Ding et al. 2008, 2009; Qian and Qin 2008).

This interdecadal variability in summer rainfall over East China is not only a regional phenomenon but also the consequence of significant changes in the climate system over East Asia. Actually, summer rainfall over East China mainly results from the northward advance of the summer monsoon. The East Asian summer monsoon has experienced significant weakening since the mid-1970s (Wang 2001; Ding et al. 2010), which probably resulted in less southerly moisture transport over East Asia. The moisture supply to North China was deficient, while that to the Yangtze-Huaihe River valley was surplus. In the study of possible physical processes governing the second regime shift in 1992/93, Wu et al. (2010) stated that it was closely related to two abnormal anticyclones over the South China Sea (SCS)-subtropical western North Pacific (WNP) and North China-Mongolia. The outflows of these two abnormal anticyclones converged over South China, inducing abrupt enhancement of moisture convergence.

Water vapor transport plays an important role in the regional hydrologic cycle; it dictates the available water supply to regional rainfall to some extent. Moisture transport from the tropical oceans, such as the northern Indian Ocean, the South China Sea (SCS), and the western Pacific Ocean, is vital for determining the rainfall pattern in China (Simmonds et al. 1999; Ninomiya and Kobayashi 1999; Ding and Sun 2001). It is advected mainly by large-scale circulation, especially over East Asia, where most of the water vapor is transported by the summer monsoon flow. In contrast to the Indian monsoon region, meridional water vapor transport is greater than zonal water vapor transport in the East Asian monsoon region in summer (Huang et al. 1998). Huang et al. (2011) pointed out that the spatio-temporal variations in summer water vapor fluxes are closely associated with the interdecadal variation in precipitation over East Asia. Hence, the study of water vapor transport has long been the focus of research on rainfall variability over East China. Although the characteristics of the two rainfall regime shifts over East China have been intensively studied (Zhou et al. 2006), many aspects of water vapor transport associated with these regime shifts remain unknown. For example, what is the abnormal water vapor transport pattern associated with moisture supply during the two regime shifts? Is the water vapor transport anomaly located mainly near the surface, the lower troposphere, or the middle troposphere? Which boundary is crucial to the regional moisture budget? Does the crucial boundary vary within two regime shifts? What are the contrasting roles played by the wind field and moisture field? To address these questions, this study will investigate the horizontal and vertical patterns of water vapor transport anomaly, the moisture across each regional boundary, and the regional moisture budget associated with two rainfall transitions.

The remainder of this paper is organized as follows: Section 2 introduces the datasets and methodologies. The two decadal regime shifts in rainfall over East China will be studied briefly in Section 3. The spatial variation in water vapor transport associated with the two rainfall transitions will be described in Section 4. The horizontal and vertical distribution of the regional moisture budget and moisture across each lateral boundary will be investigated in Section 5. The constrasting roles played by wind and humidity field in the decadal changes of water vapor transport will be studied in Section 6. The discussion and summary follow in Section 7.

2. Data and analysis methods

Gauge-based daily precipitation data during 1958–2002 from 730 meteorological stations in China, collected and subjected to quality control procedures by the China Meteorological Administration (Bao 2007; Zong et al. 2008), were used in this study to reveal the

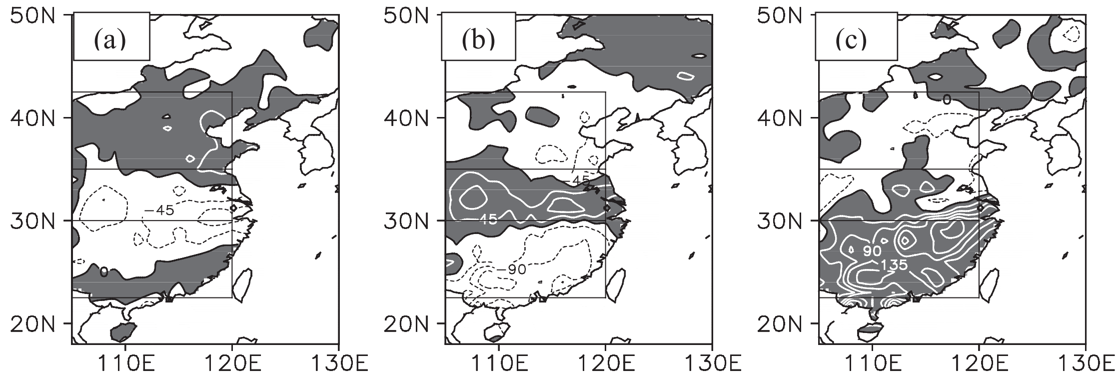

Fig. 1. Spatial distribution of summer rainfall (JJA, mm) anomalies over East China during (a) 1958–1978, (b) 1979–1992, and (c) 1993–2002, subjected to the 1958–2002 mean. The contour interval is 45 mm. Shading denotes values > 0 mm. The solid frames represent the three regions defined in this study, that is, North China (NC, 35°–42.5°N, 105°–120°E), the Yangtze-Huaihe River valley (YH, 30°–35°N, 105°–120°E), and South China (SC, 22.5°–30°N, 105°–120°E).

climatological characteristics of two decadal rainfall shifts over East China. This dataset, which includes the information from nearly all first- and second-class national climate stations, is the best daily dataset available for studying rainfall variation in China.

In this study, East China is defined as the region to the east of 105°E, where summer rainfall is influenced mainly by the East Asia summer monsoon. The rainfall to the west of 105°E is different from that of East Asia as it is greatly associated with topographic lifting and partly affected by the Indian summer monsoon, and thus will not be investigated in this study. To reveal the spatial pattern of two rainfall regime shifts, summer (June–August) rainfall anomalies over East China during the periods 1958–1978, 1979–1992, and 1993–2002 are displayed (Fig. 1). Before 1978/1979, compared to the below-normal rainfall over the Yangtze-Huaihe River valley, the rainfall over North China and the southern part of South China were above normal. After the first rainfall shift, rainfall over the Yangtze-Huaihe River valley increased significantly, while that over North China and South China decreased. In the second rainfall transition, rainfall over South China increased abruptly. These results are consistent with those of Ding et al. (2008). Based on the spatial pattern of these two regime shifts, East China was divided into three regions in this study: North China (NC, 35°–42.5°N, 105°–120°E), the Yangtze-Huaihe River valley (YH, 30°–35°N, 105°–120°E), and South China (SC, 22.5°–30°N, 105°–120°E).

Studies of atmospheric moisture transport are often challenged by the applicability of any particular data source (Mo and Higgins 1996). Considering the time span of interest (starting before the 1970s in order to investigate the variation of precipitation in the mid-1970s, which is referred to the "climate shift") and the quality concerns related to NCEP/NCAR I (Yang et al. 2002; Wu et al. 2005), we chose the four-time daily reanalysis dataset provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) 40 Years Re-Analysis (ERA-40) for the boreal summer (June–August; JJA) to estimate water vapor flux and the regional moisture budget. The 850-hPa and 200-hPa horizontal wind components are also used to describe the characteristics of atmospheric circulation. The horizontal resolution of this dataset is 2.5°×2.5° latitude-longitude (Uppala et al. 2005). The time range of this dataset is the period 1958–2002.

The vertically integrated water vapor flux ($\vec{Q}$) in the troposphere from the surface to 200 hPa (nearly all the water vapor gathered below 200 hPa) is calculated by:

$$\vec{Q} = \frac{1}{g}\int_{200}^{p_s} q\vec{V}dp, \tag{1}$$

where g, q, $\vec{V}$, and p_s are the acceleration of gravity, specific humidity, horizontal wind vector, and surface pressure, respectively (Trenberth 1991). The vertically integrated water vapor flux is first calculated by using the four-time daily data and then converted into the seasonal mean.

The moisture transport via each boundary (N) is calculated by:

$$N = \frac{1}{g}\int_L \vec{Q} \times \vec{n}\, dl, \tag{2}$$

where L is the length of the boundary and $\vec{n}$ is the inward-pointing normal vector of the boundaries of the target region (Schmitz and Mullen 1996). The regional moisture budget is calculated as the net effect of moisture transport via each boundary; the positive regional moisture budget represents atmospheric water vapor transported from outside and converged within the region.

Water vapor flux anomaly can be decomposed as:

$$\begin{aligned} \vec{Q}' &= \vec{Q} - \overline{\vec{Q}} \\ &= \frac{1}{g}\int_{200}^{p_s}\left(\left(\bar{q} + q'\right)\left(\overline{\vec{V}} + \vec{V}'\right) - \overline{\left(\bar{q} + q'\right)\left(\overline{\vec{V}} + \vec{V}'\right)} \right) dp \\ &= \frac{1}{g}\int_{200}^{p_s} \bar{q}\vec{V}'\, dp + \frac{1}{g}\int_{200}^{p_s} q'\overline{\vec{V}} dp \\ &\quad + \frac{1}{g}\int_{200}^{p_s}\left(q'\vec{V}' - \overline{q'\vec{V}'} \right) dp \end{aligned} \tag{3}$$

where overbar indicates time average, '′' indicates anomaly. On the right-hand side, the first term represents the mean moisture field transported by the disturbance wind field (Q'_{wind}); the second term represents the disturbance moisture field transported by the mean wind field ($Q'_{moisture}$); the third term represents the anomaly of the disturbance moisture field transported by the disturbance wind field.

3. Two decadal rainfall shifts over East China

In addition to the ascending motion and the microphysics inside cloud droplets, another ingredient determining whether rain falls or not is the moisture supply (Trenberth et al. 2003). Generally, regional moisture supply arises mainly from two sources: local evaporation and externally advective moisture. Benton et al. (1950) and Budyko (1974) pointed out that even on the most extensive continent where the relative role of local evaporation is maximized, the majority of precipitation is contributed by externally advected moisture. In light of this and the questionable quality of evaporation data which was mainly retrieved from model output, we focus exclusively on externally advected moisture as the source for rainfall over East China.

To reveal the relationship between water vapor supply, ascending motion, and rainfall over three regions of East China, standardized time series of the regional moisture budget, vertical p-velocity at 500 hPa (multiplied by –1, that is, $-\omega_{500}$), and summer rainfall anomalies over NC, YH, and SC are displayed in Fig. 2. The variations in summer rainfall over the three regions strongly coincide with the simultaneous $-\omega_{500}$ and moisture budget. The correlation coefficient of regional rainfall over SC is 0.68 with $-\omega_{500}$, 0.88 with moisture budget. The corresponding coefficients are 0.68 and 0.90 over YH, 0.73 and 0.69 over NC. All these coefficients are statistically significant at the 99% confidence level and remain nearly unaltered after removing the linear trend. Additionally, the continuous reduction in rainfall over NC, along with the abrupt increases in rainfall over YH in the late 1970s and over SC around the early 1990s are clearly shown together with the trends in regional moisture budget and vertical p-velocity at 500 hPa (Fig. 2). To further examine these regime shifts, the student t-test is applied (Table 1). The differences between pre- and post-transition regional rainfall, $-\omega_{500}$, and moisture budget in NC, YH, and SC are significant at the 98% confidence level, except for $-\omega_{500}$ in the first transition over YH. That is, associated with regional rainfall, the $-\omega_{500}$ and moisture budget of the three regions also showed remarkable decadal regime shifts during the past few decades. The rainfall variation over East China was influenced so markedly by the moisture budget at the interannual and decadal scales that it is reasonable for us to investigate the possible mechanisms governing regional rainfall shifts over East China from the angle of moisture circulation.

Table 1. Regional summer rainfall (R, mm), regional water vapor budget (NET, mm), and vertical p-velocity at 500 hPa ($-\omega_{500}$, –Pa s^{-1}), over NC, YH, and SC, averaged before and after two decadal regime shifts, and confidence level according to the student t-test for the difference in variables before and after rainfall regime changes. Rainfall regime changes take place in 1978/79 over NC and YH, and in 1992/93 over SC.

region	var	before	after	T-test
NC	R	301	267	98%
	NET	57	–8	99%
	$-\omega500$	–0.00053	–0.0071	99%
YH	R	408	469	98%
	NET	172	242	98%
	$-\omega500$	0.025	0.028	85%
SC	R	556	700	99%
	NET	236	396	99%
	$-\omega500$	0.035	0.044	99%

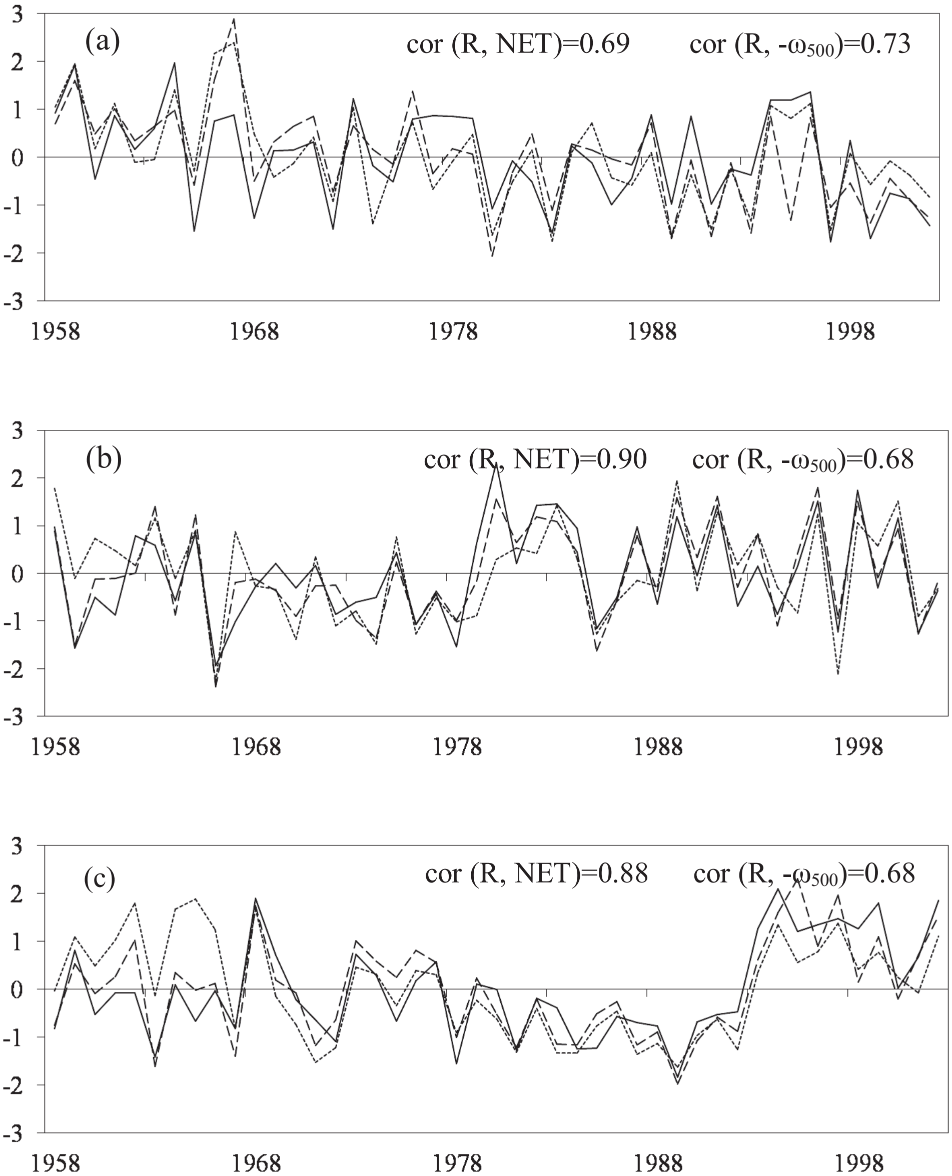

Fig. 2. Normalized time series of summer rainfall (R, solid), vertical p-velocity at 500 hPa ($-\omega_{500}$, short dashed), and regional moisture budget (NET, long dashed) anomalies averaged over (a) NC, (b) YH, and (c) SC. Correlation coefficients between regional summer (June–August averaged) rainfall and simultaneous vertical p-velocity at 500 hPa ($-\omega_{500}$), water vapor budget (NET) over NC, YH, and SC are shown in the top right corner, respectively.

4. Water vapor transport associated with two rainfall transitions

The climatological summer moisture transport over East China has been widely investigated in previous studies (e.g., Simmonds et al. 1999; Zhou et al. 1999). It is characterized by three branches: the cross-equator flow around 105°E, the southwesterly flow of the Indian summer monsoon, and the southeasterly flow of the WNP summer monsoon. Westerly water vapor transport is also important in the northern part of East China (Li et al. 2011). A vast area extending from the

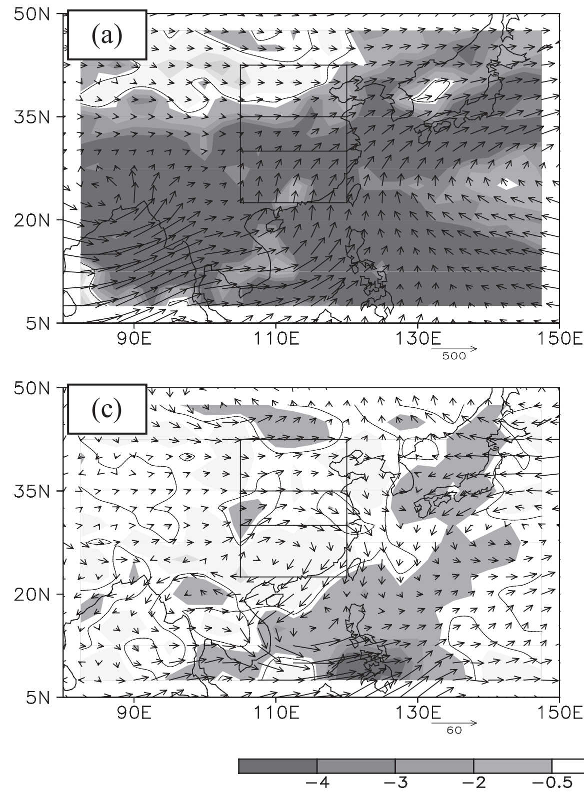

Fig. 3. Anomalous vertically integrated water vapor transport (vector, kg m^{-1} s^{-1}) and its divergence (shading, 10^{-5} kg m^{-2} s^{-1}) during (a) 1958–2002, and (b) 1958–1978, (c) 1979–1992, and (d) 1993–2002. The contours represent the zero isoline of divergence of water vapor flux. The rectangles denote the regions of NC, YH, and SC from north to south, respectively.

tropical Indian Ocean and South Asia to East Asia and the WNP is influenced by the southwesterly and southeasterly monsoon flows, acting as a water vapor sink in summer (Fig. 3a).

To investigate the moisture circulation associated with two decadal rainfall regime shifts, the abnormal vertically integrated water vapor transport and its divergence over East Asia during the periods 1958–1978, 1979–1992, and 1993–2002 are depicted in Fig. 3b–3d. During 1958–1978, accompanying an abnormal anticyclonic moisture circulation over northeast China, westerly water vapor transport over YH decreased; moisture gathered by the monsoon flow invaded northward to higher latitudes. The enhanced water vapor transport to NC resulted in stronger water vapor convergence, thus cultivated a favorable environment for the above-normal rainfall over NC. Over SC, abnormal water vapor input from the SCS joined the southwesterly water vapor transport from the northern Bay of Bengal and led to enhanced water vapor convergence, thus augmenting the above-normal precipitation over western SC.

After 1978/79, westerly water vapor transport from the northern Indian Ocean was enhanced. However, it traveled eastward to the WNP, instead of northward to East Asia, causing a diminished water vapor supply to East China but intensive convergence over the Philippines. This is consistent with Zhang's (2001) finding that the stronger the Indian summer monsoon water vapor transport, the less water vapor is transported to East Asia. An anomalous anticyclonic moisture circulation was located over SC associated with the weakened water vapor convergence, inducing a deficiency in moisture supply and thus contributing to the below-normal precipitation over SC. More water vapor was transported eastward and converged over YH instead of being advected northward to NC. This intensive moisture convergence created favorable conditions for the abruptly enhanced rainfall over YH. The weakened southerly water vapor transport to NC associated with the weakened summer monsoon may have resulted in decreased moisture input and thus the decline in rainfall over NC after 1978/79.

During 1993–2002, two anomalous water vapor flows converged over SC and YH. The one from lower latitudes was associated with a widespread anticyclonic moisture circulation over the SCS and the WNP. Abnormal moisture originates from the tropical western Pacific rather than the Bay of Bengal. The other flow from higher latitudes was related to the anticyclonic moisture circulation anomaly situated over NC and Mongolia. The convergence of these two anomalous flows played a key role in the southward shift of enhanced rainfall to SC after 1992/93.

Variation in water vapor transport and its convergence were consistent with the two rainfall regime shifts in the past few decades. Anomalious moisture supply plays a key role in the occurrence of above- or below-normal rainfall over East China.

5. Water vapor budgets

The spatial distribution of water vapor flux anomaly over East Asia is a fundamental process to the two rainfall regime shifts. It shows the direction of abnormal moisture transport via each boundary. However, all these results are qualitative, while a quantitative analysis of the regional moisture budget is desirable—for example, to investigate the comparative contribution of each boundary. To achieve this, the transport across each regional boundary and the regional water vapor budget are calculated based on the previously defined boundaries of SC, YH, and NC.

5.1 Spatial distribution

Climatically, SC, YH, and NC are sinks for water vapor. The moisture budgets of these regions are 31.4×10^{13}, 15.4×10^{13}, and 2.3×10^{13} kg s^{-1}, respectively, showing a strong north-to-south gradient (Fig. 4). The net moisture budget of SC is twice that of YH, and more than 10 times of that of NC. This seems physically plausible, as it is consistent with the meridional weakening of summer rainfall over East China. Comparison of the water vapor across each lateral boundary reveals that the western and southern boundaries are the main input boundaries, while the eastern boundary is the main output boundary, with the output being much stronger than that via the northern boundary. Nearly 75% of the water vapor transported into East China comes from the lower-latitude oceans via the southern boundary. It converges with the moisture input via the western boundary over SC and then exits via the eastern and northern boundaries of SC. The meridional transport via the southern and northern boundaries of the three regions shows an obvious north-to-south gradient. In contrast, the strength of the westerly transport input (defined as the zonal transport divided by the length of the boundaries, not shown in the figure) via the western boundaries displays a south-to-north gradient, being strongest over NC and weakest over SC. The strength of the transport via the eastern boundaries, however, shows a small gradient, with that over NC and YH slightly larger than that over SC.

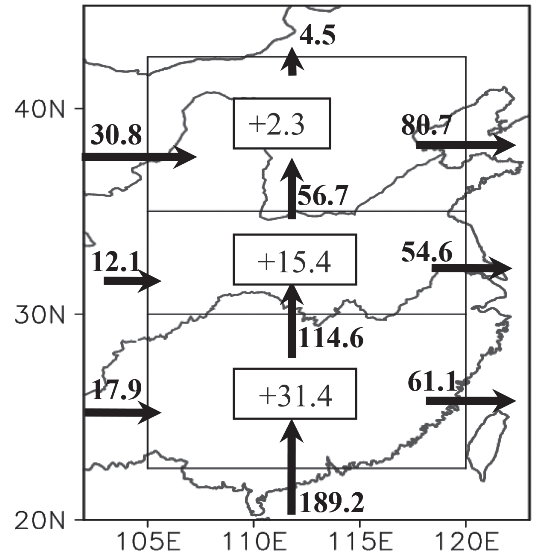

Fig. 4. Climatological mean of the summer regional water vapor balance and moisture budget via each regional boundary. Dark arrows indicate the direction of the net horizontal transport across each face of the volume. Magnitudes are presented as $1.0 \times 10^{+13}$ kg s^{-1}. Numbers in panes indicate the net flux convergence (positive numbers) and divergence (negative numbers) for the three regions.

The variations in regional water vapor budget and water vapor transport across each lateral boundary of SC, YH, and NC are shown in Fig. 5. During the first rainfall transition, the variations in the regional moisture budget correspond well with that of rainfall over the three regions, which confirms the important role played by the moisture budget in the decadal rainfall changes over East China. After 1978/79, the moisture input via the southern boundary of NC decreased by 30%, and the output via the northern boundary increased slightly. Both were responsible for the reduc-

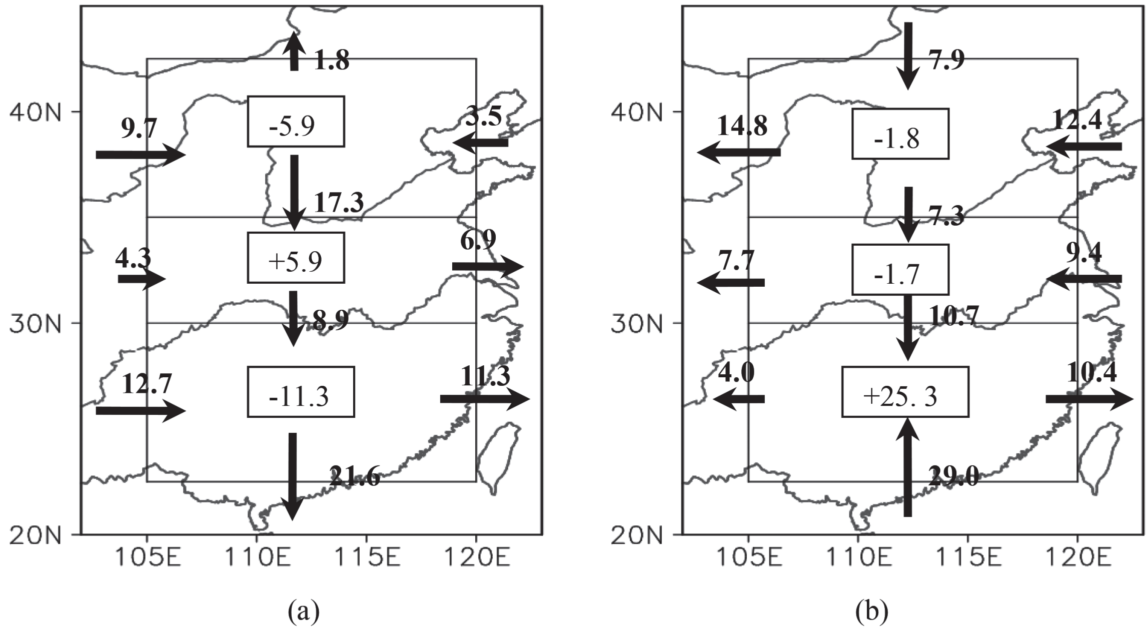

Fig. 5. Same as Fig. 4, but showing the differences associated with the two rainfall regime changes. (a) 1979–1992 minus 1958–1978, (b) 1993–2002 minus 1979–1992.

tion in regional moisture budget over NC. Over YH, although the strength of the meridional transport was weakened associated with the weakening of the East Asian summer monsoon, the decline of output via the northern boundary was much larger than that of input via the southern boundary. The convergence of meridional transport was much stronger than the divergence of zonal transport; thus, the net regional moisture budget of YH increased. Over SC, the stronger input via the western boundary was nearly offset by the enhanced output via the eastern boundary. However, the decrease of input via the southern boundary was much larger than that of the output via the northern boundary. Therefore, the net regional budget of SC decreased after 1978/79. It should be pointed out that the meridional water vapor fluxes played a key role in the three regions during the first rainfall shift.

After the second rainfall shift, the most outstanding variation in moisture budget took place over SC (Fig. 5b). This resulted from stronger input via the southern boundary (about 15% above the climatic mean) but weaker output via the northern boundary (about 9% below the climatic mean). Both were favorable for intensive above-normal incoming water vapor over SC, even though the effects of the abnormal transport via the western and eastern boundaries were opposing values. Over YH and NC, moisture transport via all four boundaries decreased after 1992/93, and the regional budget was slightly below normal.

5.2 Vertical distribution

In addition to the total integrated column, the vertical distribution of regional water vapor budget and water vapor transport via each lateral boundary of NC, YH, and SC were also investigated (Fig. 6). After the first rainfall transition, the deficit in the moisture supply over NC took place mainly in the lower troposphere from the surface to 700 hPa and was partially due to the weakened input via the southern boundary and the enhanced output via the northern boundary. Compared to the lower-level deficit, there was a surplus of moisture at the upper level, but it was much smaller in magnitude. Over YH, although there was a deficit due to below-normal input from the south near the surface, the regional moisture budget had a substantial surplus from 850 hPa to 400 hPa as a result of the weaker low-level meridional output to the north via the northern boundary under the influence of the weaker East Asian summer monsoon. After the second rainfall regime shift, the regional moisture budget over SC from the surface to the mid-troposphere (500 hPa) was obviously larger than it was, with the maximum in the layer of 850–775 hPa. This was mainly due to the enhanced input via the southern boundary and the

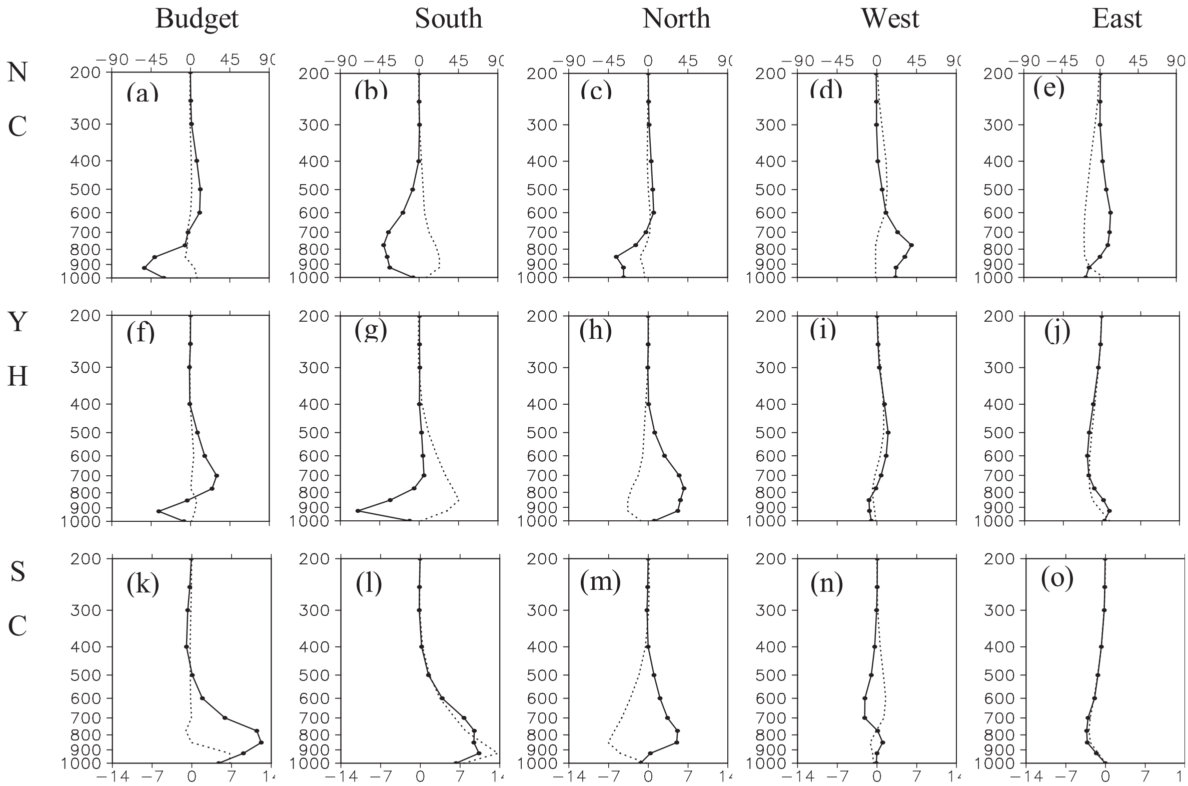

Fig. 6. Vertical distribution of the regional water vapor budget and water vapor transport via each lateral boundary from the aspect of climate mean (dashed, x-axis at the top) and differences associated with two regime shifts in rainfall (solid with dots, x-axis at the bottom, calculated by 1979–1992 minus 1958–1978 over NC and YH in the first shift, and by 1993–2002 minus 1978–1992 over SC in the second shift). Water vapor transport on the vertical level is calculated as $\vec{Q}_{level} = q \times \vec{V}\Big|_{level}$ (unit: $m^2\ s^{-1}$). The upper panel (a–e) represents North China, the middle panel (f–j) represents the Yangtze-Huaihe River valley, and the lower level represents South China (k–o). (a), (f), and (k) denote the regional water vapor budget; (b), (g), and (l) denote water vapor transport via the southern boundaries, (c), (h), and (m) for that via the northern boundaries, (d), (i), and (n) for that via the western boundaries, and (e), (j), and (o) for that via the eastern boundaries. Water vapor transport via the northern and eastern boundaries is multiplied by (–1) for easy comparison. Unit of the x-axis is $10^3\ m^2\ s^{-1}$.

weaker output via the northern boundary. It is interesting to note that over the three regions, compared to the abnormal meridional transport via the southern and northern boundaries, the abnormal zonal transport via the eastern and western boundaries took place mainly in the middle level and in a smaller magnitude.

5.3 *Comparison between the roles of moisture transport via different boundaries*

It was concluded that the variation in meridional moisture transport played a dominant role during the two rainfall regime shifts based on spatial distribution of water vapor transport via each boundary. To further examine this result, a correlative analysis was carried out. Figure 7 shows 19-year running correlations between regional moisture budget and water vapor transport via each lateral boundary and meridional zonal net water vapor transport over NC, YH, and SC. Over SC, the correlations of regional moisture budget with water vapor transport via the western and eastern boundaries were low and insignificant in most years. However, the correlation was significant with water vapor transport via the northern boundary before the mid-1970s, but with water vapor transport via the southern boundary after the mid-1980s, implying that the moisture circulation over SC varied during the past

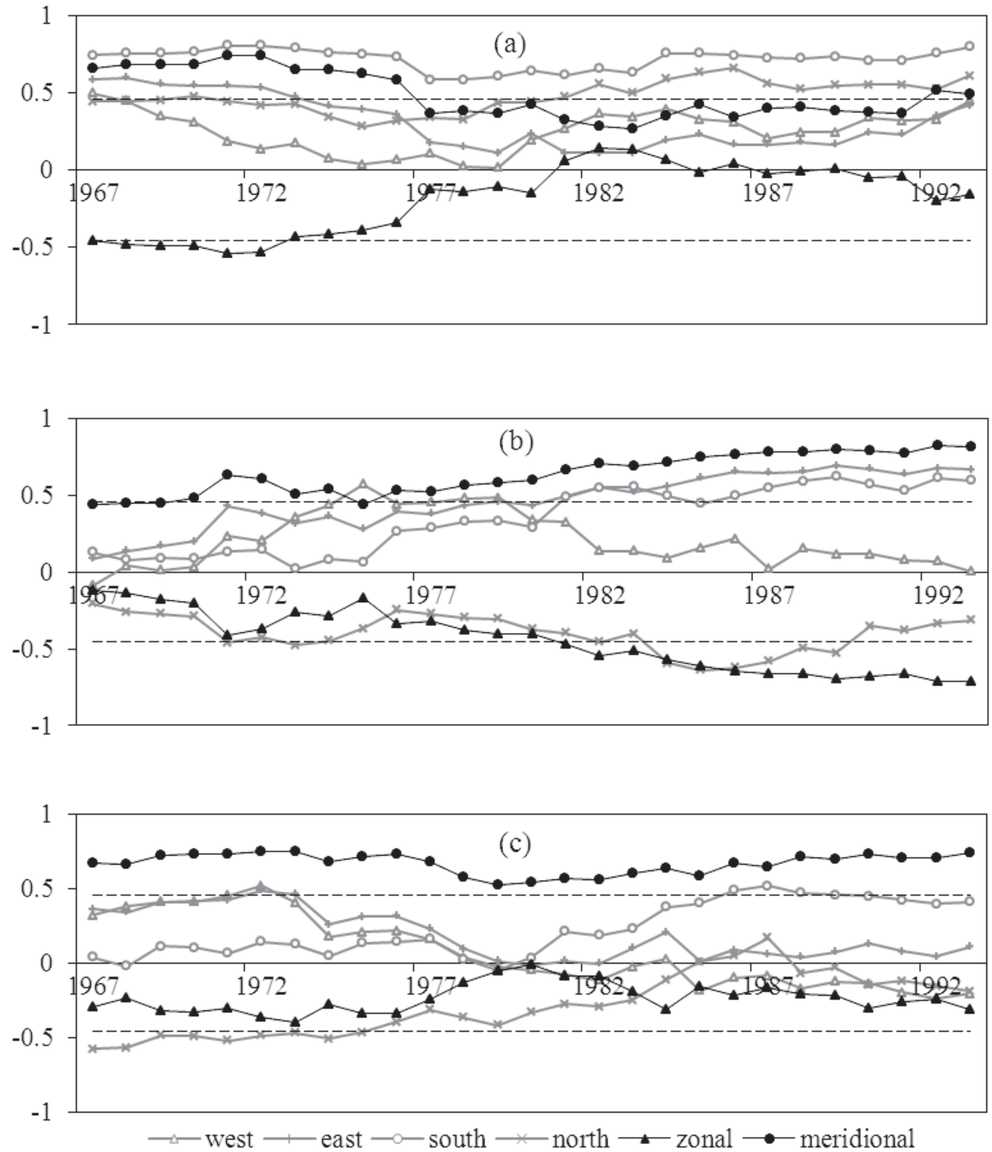

Fig. 7. Nineteen years of running correlations between the regional moisture budget and water vapor transport via each lateral boundary, including meridional and zonal net water vapor transport over (a) NC, (b) YH, and (c) SC. The meridional net water vapor transport is calculated by the net effect of the transport via the southern and northern boundaries, while the zonal net water vapor transport is calculated by the net effect of the transport via the western and eastern boundaries. The dashed lines represent the 95% confidence level according the student t-test.

few decades (Li et al. 2011). It is interesting to find that the regional moisture budget had a high correlation with meridional net moisture transport over SC, with the correlation coefficient above the 95% confidence level during the whole period. This close relationship was also found over YH. The running correlation coefficient of the regional moisture budget was largest and most significant with meridional net moisture transport. Hence, the regional moisture budget over YH was also dominated to some extent by moisture convergence in the meridional direction. However, in NC, the correlation with the regional moisture budget was highest with moisture transport via the southern boundary, instead of meridional net water vapor transport. This might be because NC was dominated mainly by the southeasterly transport rather than the southerly transport; the moisture input from the south was exported mainly via the eastern boundary rather than the northern boundary. In summary, both the deviation and correlation analysis demonstrated that the regional moisture budget over East Asia was influenced mainly by meridional moisture transport during the two rainfall shifts.

6. The impacts of wind and moisture disturbance on water vapor transport anomaly

Decadal variations in water vapor transport and regional moisture budget played an important role in the two regime rainfall shifts over East China. Recognition of possible factors that affect regional moisture supply will no doubt enrich our knowledge of drought and flood conditions over East China. Water vapor transport is the transport of moisture from source regions to sink regions by the wind field. Its variation is the combined effect of wind and humidity fields. Huang et al. (1998) pointed out that the water vapor convergence over the East Asian monsoon region is mainly due to the wet advection caused by the monsoon flow and the north-to-south humidity gradient. Jiang et al. (2009) and Li et al. (2011) stated that water vapor transport over East China is governed mostly by the general wind field, especially that on the lower level. To investigate the contrasting roles played by wind and humidity fields on the decadal changes of water vapor transport, the water vapor flux anomaly was decomposed according to Eq. (3). Q'_{wind}, $Q'_{moisture}$ respectively represent the effect of the disturbance wind field and disturbance moisture field on water vapor transport anomaly, which together capture most of the water vapor transport anomaly (Figure not shown). The spatial distributions of Q'_{wind}, $Q'_{moisture}$ during 1958-1978, 1979-1992 and 1993-2002 are shown in Figs. 8, 9, 10.

Before the first rainfall transition, the patterns of Q'_{wind} and its divergence (Fig. 8a) were similar to those of total moisture transport anomaly (Fig. 3b) in both the spatial distribution and the magnitude. Moisture advected by the disturbance wind field from the Bay of Bengal and South China Sea converged to the west of SC, while eastward moisture transport over northern SC and YH was weakened. Enhanced moisture transportation invaded northward to NC and converged. The wind field anomaly at 850 hPa showed a similar pattern as Q'_{wind} (Fig. 8c), which was reasonable because most of the moisture is concentrated in the lower level (Li et al. 2010). The above normal southwest summer monsoon flow from the Bay of Bengal to western SC via the south of Tibetan Plateau together with stronger southeast summer monsoon flow from tropical western Pacific Ocean to SC via SCS transported abundant moisture to East China. At the same time, the East Asian summer monsoon flow was stronger than normal, which invaded northward to NC instead of eastward over YH, bringing enhanced moisture to NC. Compared to Q'_{wind}, the role played by $Q'_{moisture}$ was negligible (Fig. 8b). The magnitudes of $Q'_{moisture}$ and its divergence were much smaller than those of Q'_{wind} over our target regions. It was reasonable as the percent change of moisture was much less than that of wind field (Figure not shown). The direction of $Q'_{moisture}$ over the ocean was opposite to the total moisture transport due to the weaker than normal moisture content over the ocean during this period (Fig. 8d). Hence, the disturbance wind field played a much more important role than the disturbance moisture field in the abnormal water vapor transport. The stronger southwest summer monsoon over the south of the Tibetan Plateau the stronger southeast summer monsoon over the western Pacific Ocean along with the enhanced East Asian summer monsoon were the main circulation systems which induced the abnormal moisture transport before 1979.

After the first rainfall transition, similar as that before 1979, the contrasting role played by disturbance wind field in the total water vapor transport anomaly was much larger than that of the disturbance moisture field (Figs. 9a, b). Associated with the weakened southerly wind over SCS and SC resulting from the weakened East Asian summer monsoon (Liu et al. 2004) (Fig. 9c), moisture transported into SC was less than normal, and instead invaded continually over southern SCS to the Philippines. Stronger-than-normal moisture output via the northern boundary of NC was mainly advected by the abnormal southerly wind over the high latitudes. During this period, $Q'_{moisture}$ from the ocean was in the same sign as the total water vapor transport because the variation of moisture content over the ocean was positive (Fig. 9d). However, as the moisture content over East Asia was drier than normal, strong convergence of $Q'_{moisture}$ could only be found near the coast of East Asia. Hence, Q'_{wind} played a dominated role in the abnormal water vapor transport during 1979–1992, while $Q'_{moisture}$ played a negligible role.

After the second rainfall shift, consistent with the previous two periods, the water vapor transport anom-

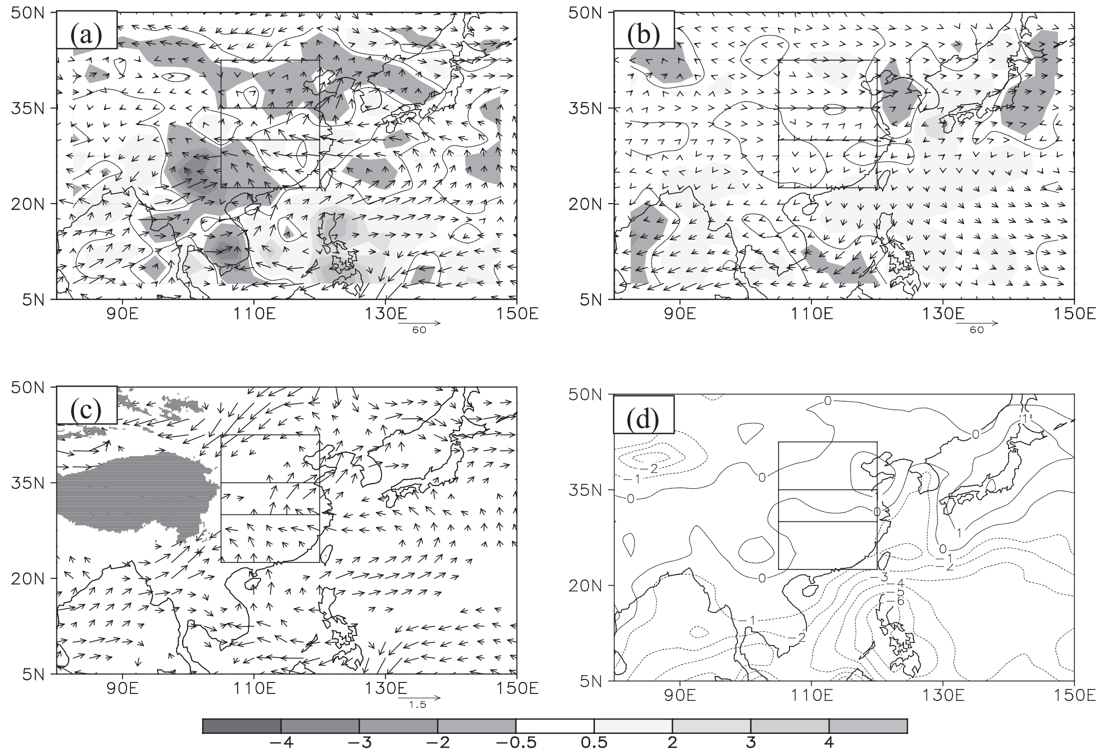

Fig. 8. (a) Mean moisture field transported by disturbance wind field (Q'_{wind} , vector, kg m^{-1} s^{-1}) and its divergence (shading, 10^{-5} kg m^{-2} s^{-1}), (b) disturbance moisture field transported by mean wind field ($Q'_{moisture}$, vector, kg m^{-1} s^{-1}) and its divergence(shading, 10^{-5} kg m^{-2} s^{-1}), (c) anomalous wind field (m s^{-1}) at 850 hPa, and (d) anomalous total precipitable water (mm) during 1958–1978. The contours in (a), (b) represent the zero isoline of divergence of water vapor flux. The rectangles denote the regions of NC, YH, and SC from north to south, respectively.

aly was dominated by Q'_{wind} instead of $Q'_{moisture}$ (Figs. 10a, b). The cyclonic circulation anomaly over SC and the abnormal southwesterly from the lower latitudes converged with the northeasterly from the middle and high latitudes at the lower level. The southwesterly anomaly was the outflow of a widespread anticyclone over the northern SCS and WNP, while the northeasterly was related to an abnormal anticyclone over NC and Mongolia (Fig. 10c). Wu et al. (2010) pointed out that the anticyclone to the south was a response to abnormal heating over the tropical Indian Ocean, while the one to the north was caused by abnormal cooling over the Tibetan Plateau during the previous winter and spring because of the greater snow cover. Associated with these wind field anomaly patterns, Q'_{wind} showed a similar pattern, with abnormal water vapor convergence over SC and part of YH.

Hence, the water vapor transport anomaly over East China during these two rainfall shifts was mainly controlled by the disturbance wind field instead of the disturbance moisture field. The wind field pattern at the lower troposphere represents the total water vapor flux to a great extent.

7. Discussion and summary

The water vapor transport associated with two decadal rainfall shifts in 1978/79 and 1992/93 over East China were studied in this paper. Questions regarding the abnormal water vapor transport pattern, moisture supply during the two regime shifts, main level where the anomalous water vapor transport was located, crucial boundary of the regional moisture budget and constrasting roles played by wind and humidity fields were all examined. The key results are summarized as follows:

After 1978/79, southerly water vapor transport over East China was weakened; an anticyclonic moisture circulation anomaly associated with decreasing moisture convergence lay over SC; abnormal water vapor from western SC converged with that from western NC

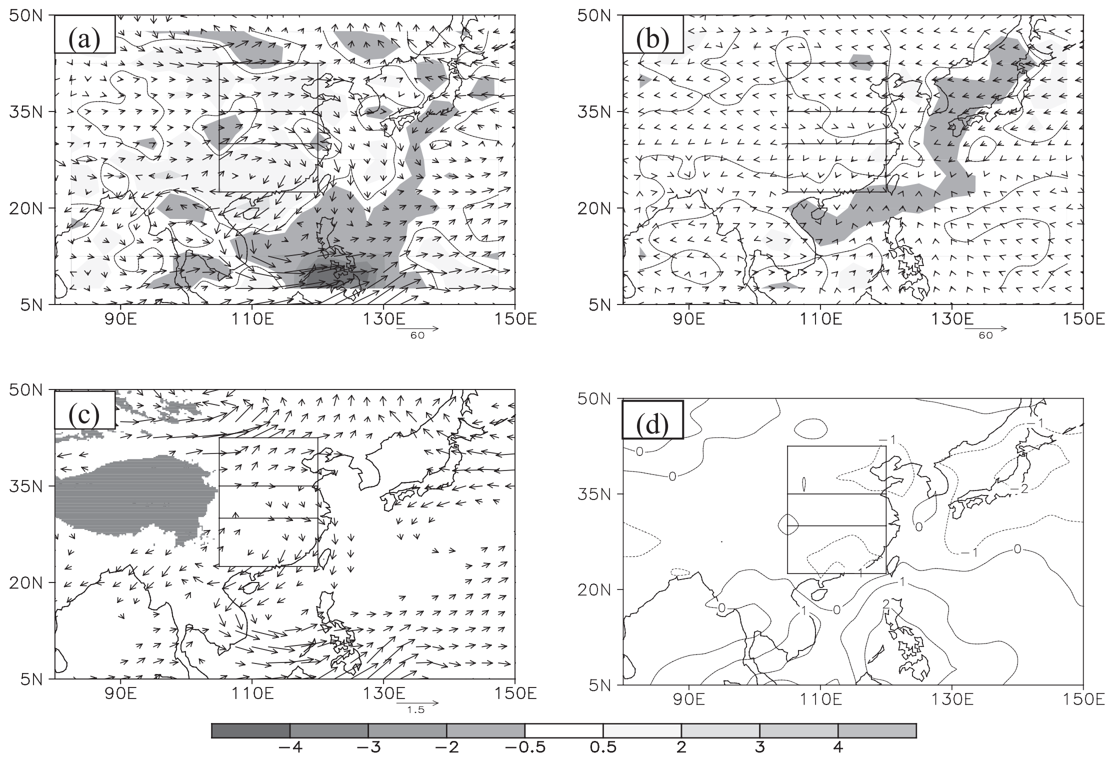

Fig. 9. Same as Fig. 8, but for 1979–1992.

over YH and turned eastward instead of northward to NC. Hence, summer precipitation increased abruptly over YH but decreased over SC and NC in the first regime shift. After 1992/93, convergence of anomalous water vapor transport from the lower and higher latitudes was found over SC and YH, resulting in intensive enhancement of rainfall over SC.

The comparative contribution of water vapor transport via each boundary on different vertical levels was studied. The magnitude of the water vapor transport variation in the meridional direction was much larger than that in the zonal direction; the regional moisture budget had high correlation with the meridional net moisture transport over SC and YH, as well as with the moisture input via the southern boundary over NC; it was the meridional water vapor fluxes that played key roles in the rainfall regime shifts over three regions. The vertical distribution of moisture transport via each boundary showed that the abnormal meridional transport via the southern and northern boundaries was located in the lower atmosphere, while the anomalous zonal transport via the eastern and western boundaries took place mainly in the middle level instead of the lower level.

The water vapor transport anomaly over East China during these two rainfall shifts was mainly controlled by the disturbance wind field instead of the disturbance moisture field. The wind field pattern in the lower troposphere represents the total water vapor flux to a great extent. The stronger southwest summer monsoon to the south of the Tibetan Plateau, stronger southeast summer monsoon over western Pacific Ocean and the enhanced East Asian summer monsoon were the main circulation systems that were associated with abnormal moisture transport before 1979. The less-than-normal moisture transport to East Asia was associated with weakened southerly wind over SCS and SC as a result of the weakened East Asian summer monsoon during 1979–1992. The convergence of an abnormal southwesterly from the lower latitudes and the northeasterly from the middle and high latitudes in the lower level was closely related to the abnormal pattern of water vapor flux after 1993.

In this study, the regional moisture budget, water vapor transport, and its divergence were all calculated based on the ECMWF ERA-40 reanalysis dataset. It provided us with a direct and reasonable approach to study water vapor circulation over a specific region.

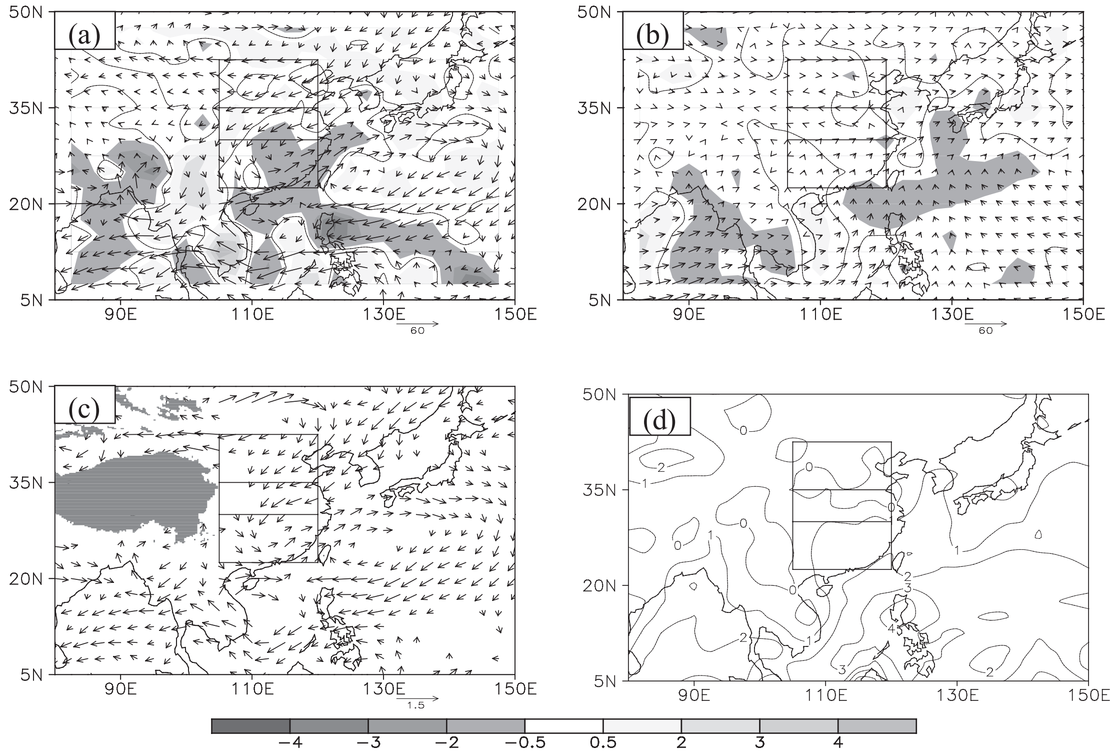

Fig. 10. Same as Fig. 8, but for 1993–2002.

However, many problems still remain in this dataset. Due to the introduction of satellite instruments, drifting ocean buoys, enhancements in observations from commercial aircraft, etc., there are a number of years in which certain characteristics of the dataset are improved stepwise, which may produce an inhomogeneity problem in a long-term study. However, the observed precipitation data used in this study are from the best daily dataset currently available for studying climate change in China which has been subjected to quality control procedures and has been examined in many studies (Zhai et al. 2005). Hence, the observed precipitation data are considered to be credible in this sense. The variations in water vapor circulation calculated by using the ERA-40 dataset were consistent with those in rainfall based on observed precipitation data; therefore, the discontinuity in quality of the ERA-40 appeared not to cause a fundamental problem in this study. However, we should remain cognizant of a number of potential shortcomings in using this reanalysis data, and the reliability of our results should be assessed through comparison with other observed datasets.

Moisture that condenses as rainfall may experience evaporation, condensation, and re-evaporation on its path before reaching the sink region. Therefore, based on water vapor flux, we showed only the moisture transport routine in the atmosphere, but not its actual source region. In the past few decades, a number of studies have tried to discover where the moisture ultimately originated. A direct way to detect the actual rainfall origin is to incorporate "tagged" water into general circulation models (GCMs) by tagging the moisture at its origins and following it through the atmospheric process until it has precipitated from the atmosphere (Koster et al. 1986; Bosilovich and Schubert 2002). However, this is limited by the accuracy of GCMs and the veracity of the numerically simulated hydrological cycle. Yoshimura et al. (2004) developed the Colored Moisture Analysis (CMA) technique, which provides a clearer, more integrated view of temporal and spatial changes in moisture transport fields and uses reanalysis data rather than GCM output. It may provide a useful tool in our search for the true sources of the moisture that is responsible for anomalous precipitation over East Asia, which we may study further in the future.

This paper revealed the variation in water vapor transport responsible for the two decadal rainfall regime shifts over East China. However, the physical mechanism of this variation in water vapor transport was not investigated in detail. Previous studies have indicated that moisture circulation is essentially controlled by a complex air-sea-land and tropical-extratropical interaction (Zhou and Chan 2007; Yuan et al. 2008; Tong et al. 2009). Furthermore, changes in atmospheric circulation are ultimately forced by surface variations (Li et al. 2006; Chan and Zhou 2005). Hence, to reveal the mechanisms that induced the two rainfall shifts, it is necessary to comprehensively consider external forces (Yang and Lau 1998), such as sea surface temperature over tropical and extratropical oceans, snow cover from the previous winter and spring, as well as temperature and soil moisture conditions over the land (Yoo et al. 2004; Huang et al. 2007; Wu and Qian 2003; Zuo and Zhang 2007). Wu et al. (2010) pointed out that the anticyclone over Mongolia responsible for the water vapor transport anomaly in the second rainfall variation was induced by upper-troposphere cooling, and the anticyclone over the northern SCS and WNP was associated with abnormal warming over the Indian Ocean. However, the reliability of these hypotheses is still being assessed and should be investigated further through climate modeling.

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References

Bao, M., 2007: The statistical analysis of the persistent heavy rain in the last 50 years over China and their backgrounds on the large scale circulation. *Chin. J. Atmos. Sci.*, **31**, 780–792 (in Chinese).

Benton, G. S., R. T. Blackburn, and V. O. Snead, 1950: The role of the atmosphere in the hydrologic cycle. Eos *Trans. AGU*, **31**, 61–73.

Bosilovich, M. G., and S. D. Schubert, 2002: Water vapor tracers as diagnostics of the regional hydrologic cycle. *J. Hydrometeor.*, **3**, 149–165.

Budyko, M. I., 1974: Climate and life. *Internal Geophysics Series*, vol. **18**, 508 pp., Academic, San Diego, CA.

Chan, J. C. L., and W. Zhou, 2005: PDO, ENSO and the early summer monsoon rainfall over south China. *Geophys. Res. Lett.*, **32**, L08810, doi: 10.1029/2004GL022015.

Ding, Y. H., Y. J. Liu, Y. Sun, and Y. F. Song, 2010: Weakening of the Asian summer monsoon and its impact on the precipitation pattern in China, *Int. J. Water Resour. Dev.*, **26**, 423–439.

Ding, Y. H., and Y. Sun, 2001: A study on anomalous activities of east Asian summer monsoon during 1999. *J. Meteor. Soc. Japan*, **79**, 1119–1137.

Ding, Y. H., Y. Sun, Z. Y. Wang, Y. X. Zhu, and Y. F. Song, 2009: Inter-decadal variation of the summer precipitation in China and its association with decreasing Asian summer monsoon. Part II: Possible causes. *Int. J. Climatol.*, **29**, 1926–1944.

Ding, Y. H., Z. Y. Wang, and Y. Sun, 2008: Inter-decadal variation of the summer precipitation in East China and its association with decreasing Asian summer monsoon. Part I: Observed evidences. *Int. J. Climatol.*, **228**, 1139–1161.

Gong, D. Y., and C. H. Ho, 2002: Shift in the summer rainfall over the Yangtze River valley in the late 1970s. *Geophys. Res. Lett.*, **29**, 1436, doi: 10.1029/2001GL014523.

Huang, A., Y. C. Zhang, and X. F. Gao, 2007: Impacts of coastal SST variability on the East Asian summer monsoon. *Adv. Atmos. Sci.*, **24**, 259–270.

Huang, R. H., J. L. Chen, and Y. Liu, 2011: Interdecadal variation of the leading modes of summertime precipitation anomalies over eastern China and its association with water vapor transport over East Asia, *Chin. J. Atmos. Sci.*, **35**, 589–606 (in Chinese).

Huang, R. H., Z. Zhang, and G. Huang, 1998: Characteristics of the water vapor transport in east Asian monsoon region and its difference from that in south Asian monsoon region in summer, *Sci. Atmos. Sinica*, **22**, 460–469 (in Chinese).

Jiang, X. W., Y. Q. Li, and X. Wang, 2009: Water vapor transport over China and its relationship with drought and flood in Yangtze River basin. *J. Geogr. Sci.*, **19**, 153–163, doi: 10.1007/s11442-009-0153-6.

Koster, R., J. Jouzel, R. Suozzo, G. Russell, W. Broecker, D. Rind, and P. Eagleson, 1986: Global sources of local precipitation as determined by the NASA/GISS GCM. *Geophys. Res. Lett.*, **13**, 121–124.

Li, C. Y., W. Zhou, X. L. Jia, and X. Wang, 2006: Decadal/interdecadal variations of the ocean temperature and its impacts on the climate. *Adv. Atmos. Sci.*, **23**, 964–981.

Li, X. Z., W. Liang, and Z. P. Wen, 2010: Characteristics of the atmospheric water vapor and its relationship with rainfall in south China in northern autumn, winter and spring. *J. Trop. Meteorol.*, **26**, 626–632 (in Chinese).

Li, X. Z., Z. P. Wen, and W. Zhou, 2011: Long-term change in summer water vapor transport over South China in recent decades. *J. Meteor. Soc. Japan*, **89A**, 271–282.

Liu, C. Z., H. J. Wang, and D. B. Jiang, 2004: The configurable relationships between summer monsoon and precipitation over East Asia. *Chin. J. Atmos. Sci.*, **28**, 700–712 (in Chinese).

Mo, K. C., and R. W. Higgins, 1996: Large-scale atmospheric moisture transport as evaluated in the NCEP/

NCAR and the NASA/DAO reanalyses. *J. Climate*, **9**, 1531–1545.

Ninomiya, K., and C. Kobayashi, 1999: Precipitation and moisture balance of the Asian summer monsoon in 1991 part II: Moisture transport and moisture balance. *J. Meteor. Soc. Japan*, **77**, 77–99.

Qian, W. H., and A. Qin, 2008: Precipitation division and climate shift in China from 1960 to 2000. *Theor. Appl. Climatol.*, **93**, 1–17, doi: 10.1007/s00704-007-0330-4.

Schmitz, J. T., and S. L. Mullen, 1996: Water vapor transport associated with the summertime North American monsoon as depicted by ECMWF analyses. *J. Climate*, **9**, 1621–1634.

Simmonds, I., D. H. Bi, and P. Hope, 1999: Atmospheric water vapor flux and its association with rainfall over China in summer. *J. Climate*, **12**, 1353–1367.

Sun, L. H., and X. F. Chen, 2003: Decadal climate characters and formation condition of flooding in south and drought in north in China. *J. Appl. Meteor.*, **14**, 641–647.

Tong, H. W., J. C. L. Chan, and W. Zhou, 2009: The Role of MJO and mid-latitude fronts in the South China Sea summer monsoon onset. *Climate Dyn.*, **33**, 827–841.

Trenberth, K. E., 1991: Climate diagnostics from global analyses: Conservation of mass in ECMWF analyses. *J. Climate*, **4**, 707–722.

Trenberth, K. E., A. Dai, R. M. Rasmussen, and D. B. Parsons, 2003: The changing character of precipitation. *Bull. Amer. Meteor. Soc.*, **84**, 1205–1217.

UNESCO, 1978: World water balance and water resources of the Earth. Paris, the UNESCO Press, **87**, 93–99, 587.

Uppala, S. M., P. W. Kållberg, A. J. Simmons, U. Andrae, V. D. C. Bechtold, M. Fiorino, J. K. Gibson, J. Haseler, A. Hernandez, G. A. Kelly, X. Li, K. Onogi, S. Saarinen, N. Sokka, R. P. Allan, E. Andersson, K. Arpe, M. A. Balmaseda, A. C. M. Beljaars, L.V. D. Berg, J. Bidlot, N. Bormann, S. Caires, F. Chevallier, A. Dethof, M. Dragosavac, M. Fisher, M. Fuentes, S. Hagemann, E. Hólm, B. J. Hoskins, L. Isaksen, P. A. E. M. Janssen, R. Jenne, A. P. McNally, J. F. Mahfouf, J. J. Morcrette, N. A. Rayner, R. W. Saunders, P. Simon, A. Sterl, K. E. Trenberth, A. Untch, D. Vasiljevic, P.Viterbo, and J. Woollen, 2005: The ERA-40 re-analysis. *Quart. J. Roy. Meteor. Soc.*, **131**, 2961–3012, doi: 10.1256/qj.04.176.

Wang, H. J., 2001: The weakening of the Asian monsoon circulation after the end of 1970's. *Adv. Atmos. Sci.*, **18**, 376–386.

Wu, R. G., and L. T. Chen, 1998: Decadal variation of summer rainfall in the Yangtze-Huaihe River valley and its relationship to atmospheric circulation anomalies over East Asia and western North Pacific. *Adv. Atmos. Sci.*, **15**, 510–522.

Wu, R. G., J. L. Kinter III, and B. P. Kirtman, 2005: Discrepancy of interdecadal changes in the Asian region among the NCEP–NCAR reanalysis, objective analyses, and observations. *J. Climate*, **18**, 3048–3067.

Wu, R. G., Z. P. Wen, S. Yang, and Y. Q. Li, 2010: An interdecadal change in southern China summer rainfall around 1992/93. *J. Climate*, **23**, 2389–2403.

Wu, T. W., and Z. A. Qian, 2003: The relation between the Tibetan winter snow and the Asian summer monsoon and rainfall: An observational investigation. *J. Climate*, **16**, 2038–2051.

Yang, S., and K. M. Lau, 1998: Influences of sea surface temperature and ground wetness on Asian summer monsoon. *J. Climate*, **11**, 3230–3246.

Yang, S., K. M. Lau, and K. M. Kim, 2002: Variations of the East Asian jet stream and Asian–Pacific–American winter climate anomalies. *J. Climate*, **15**, 306–325.

Yoo, S. H., C. H. Ho, S. Yang, H. J. Choi, and J. G. Jhun, 2004: Influences of tropical western and extratropical Pacific SST on East and Southeast Asian climate in the summers of 1993–94. *J. Climate*, **17**, 2673–2687.

Yoshimura, K., T. Oki, N. Ohte, and S. Kanae, 2004: Colored moisture analysis estimates of variations in 1998 Asian monsoon water sources. *J. Meteor. Soc. Japan*, **82**, 1315–1329.

Yuan, Y., W. Zhou, J. C. L. Chan, and C. Li, 2008: Impacts of the basin-wide Indian Ocean SSTA on the South China Sea summer monsoon onset. *Int. J. Climatol.*, **28**, 1579–1587.

Zhai, P. M., X. B. Zhang, H. Wan, and X. H. Pan, 2005: Trends in total precipitation and frequency of daily precipitation extremes over China. *J. Climate*, **18**, 1096–1108.

Zhang, R. H., 2001: Relations of water vapor transport from Indian monsoon with that over East Asia and the summer rainfall in China. *Adv. Atmos. Sci.*, **18**, 1005–1017.

Zhou, L. T., and R. H. Huang, 2003: Research on the characteristics of interdecadal variability of summer climate in China and its possible cause. *Climate and Environmental Research*, **8**, 274–290.

Zhou, T. J., X. H. Zhang, and S. W. Wang, 1999: The air-sea freshwater exchange derived from NCEP/NCAR reanalysis data. *Acta Meteorologica Sinica*, **57**, 264–282 (in Chinese).

Zhou, W., and J. C. L. Chan, 2007: ENSO and the South China Sea summer monsoon onset. *Int. J. Climatol.*, **27,** 157–167.

Zhou, W., C. Li, and J. C. L. Chan, 2006: The interdecadal variations of the summer monsoon rainfall over South China. *Meteorol. Atmos. Phys.*, **93**, 165–175, doi: 10.1007/s00703-006-018-9.

Zong, H. F., Q. Y. Zhang, and L. T. Chen, 2008: A study of the processes of East Asia-Pacific teleconnection pattern formation and the relationship to ENSO. *Chin. J. Atmos. Sci.*, **32**, 220–230 (in Chinese).

Zuo, Z. Y., and R. H. Zhang, 2007: The spring soil moisture and summer rainfall in eastern China. *Chin. Sci. Bull.*, **52**, 1722–1724.