Anomalous Modes of Moisture Transport by East Asian Summer Monsoon and Associated Rainfall Patterns in China

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1. Introduction

The Asian summer monsoon is one of most energetic components of global climate system (Yasunari 1990; Lau 1992; Ding 1994; Webster et al. 1998). Warm moist air is carried from the tropical Pacific and Indian oceans to the Asian continent by monsoonal circulation. Understanding the atmospheric moisture transport can advance our estimates of monsoon rainfall (Peixoto and Oort 1992). Limited by a dearth of reliable data, a completed depiction of the atmospheric branch of the hydrological cycle has not yet been obtained (Chen and Pfaendtner 1993; Webster 1994). The widespread availability of high-quality reanalysis datasets, such as NCEP-R1 reanalysis (Kalnay et al. 1996) and ERA-40 reanalysis (Uppala et al. 2005), has greatly helped us study the atmospheric hydrological branch, especially the association of moisture transport with monsoon rainfall (Huang et al. 1998; Simmonds et al. 1999; Zhang 2001; Fasullo and Webster 2002; Zhou and Yu 2005; Ding and Chan 2005; Chen and Huang 2007, 2008).

The climate of China is strongly influenced by the East Asian summer monsoon (EASM) (Tao and Chen 1987), which is a hybrid type of tropical and subtropical monsoon (Ding and Chan 2005; Huang et al. 2007), comprising the South China Sea (SCS) tropical monsoon, western North Pacific (WNP) tropical monsoon and East Asian subtropical monsoon. EASM-related rainfall anomalies exhibit significant regionality and complex variability (Lau 1992; Ding 1994), which frequently caused climatic disasters such as droughts and floods in China. As a result, numerous efforts have been devoted to investigating the physical mechanism responsible for EASM variability (e.g., Lau et al. 2000; Wang et al. 2001; Huang et al. 2004). As EASM is affected not only by the Indian summer monsoon flow, but also by the western Pacific subtropical high and the mid-latitude circulation, thus, the physical mechanisms of EASM variability are likely related to each of these components.

Previous studies on atmospheric moisture transport associated with the EASM circulation have focused mainly on either climatological conditions or specific cases. The complex variability of moisture transport by EASM and its impact on summer rainfall anomalies in China are not, however, well addressed. The main objective of this paper is therefore to examine the influence of EASM circulation on summer rainfall anomalies in China by evaluating the anomalous modes of moisture transport.

2. Data and methodology

The seasonal-mean atmospheric water balance equation (Peixoto and Oort 1992) can be simplified as:

$$\overline{P} \approx \overline{E} + \overline{C} \tag{1}$$

where the overbar denotes the average over 3-month summer (June-August) period. In Equation (1), P is the precipitation, E the evaporation from the surface, and C the convergence of vertically integrated moisture transport (VIMT). That is $C = -\nabla \cdot \vec{Q}$ and VIMT is defined as $\vec{Q} = 1/g\int_0^{p_s} q\vec{V}dp$. Here, g is the acceleration due to gravity, q the specific humidity, p_s the surface pressure, $\vec{V}$ the horizontal wind vector.

Since the NCEP-R1 reanalysis over-estimates interdecadal change around the late 1970s in the Asian region (Wu and Kinter 2002; Chen and Huang 2008), the ERA-40 reanalysis on a 2.5°×2.5° grid is chosen to estimate VIMT and its convergence for the period 1958-2002. Despite its potential shortcomings (Trenberth and Smith 2005), ERA-40 reanalysis can still provide us with a direct and trustworthy approach to the basic characteristics of moisture transport over the globe and specific regions of interest. Two sets of precipitation data are also used in this study. Monthly satellite-gauge-based precipitation estimates without numerical model outputs for the period of 1979-2002 (Xie and Arkin 1997) are obtained from CPC Merged Analysis of Precipitation (CMAP). Station precipitation for the period 1958-2002 is provided by China Meteorological Administration, which consists of the monthly averaged precipitation of 160 stations in China and has been widely used in the study of the East Asian monsoon climate.

To reveal the association between atmospheric moisture transport and summer rainfall anomalies in China, a multivariate empirical orthogonal function (EOF) analysis is applied to extract anomalous modes of VIMT, and time-frequency variations of different dominant modes can be well described by wavelet analysis (Torrence and Compo 1998). Regression analyses are also performed to examine anomalous circulation and rainfall patterns associated with these dominant modes.

3. Atmospheric hydrological branch in the EASM region

Due to concentration of voluminous water vapor in the lower troposphere over the tropical ocean, VIMT closely resembles low-level circulation over Asian monsoon region, and monsoon-related water vapor pathways had been described in previous analysis (Huang et. al 1998; Simmonds et al. 1999; Zhang 2001; Zhou and Yu 2005). Figure 1a shows the climatology of JJA-mean VIMT and CMAP rainfall for 1979-2002. According to recent studies (e.g., Huang et al. 2004; Ding and Chan 2005), we can choose the dashed frame in Fig. 1a as the core region of the EASM. For normal climatological conditions, EASM circulation is associated with China's rainfall through its role in transporting water vapor into China from the adjacent oceans, and strong convergence of warm water vapor extending from the tropics is a main factor to induce East Asian monsoon rainfall (Chen and Huang 2007).

The climatological result, however, cannot highlight the large year-to-year variations of summer rainfall in eastern China, an area (east of 100^{o}E) strongly affected by EASM as evidences from standard deviation of summer rainfall anomalies for the period 1958-2002 (Fig. 1b). Recently, some studies (e.g., Zhou and Yu 2005; Chen and Huang 2008) stressed moisture transport associated with typical anomalous rainfall patterns in China. Their results showed significant differences in the moisture source responsible for summer rainfall between climatological and anomalous conditions. In the following sections, we will examine anomalous modes of moisture transport by EASM and their impacts on summer rainfall anomalies in China.

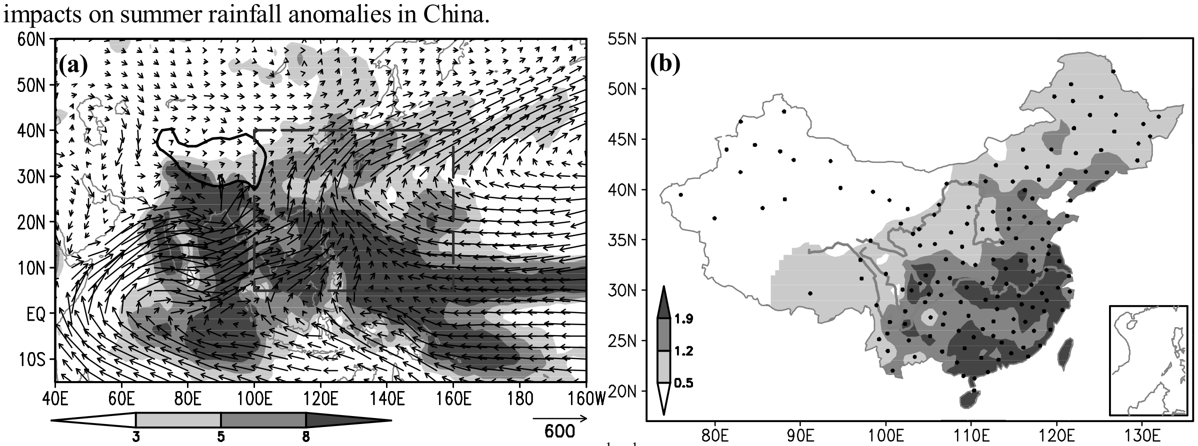

Fig. 1. (a) Climatology of JJA-mean ERA-40 VIMT (vector, kg·m^{-1}·s^{-1}) and CMAP rainfall (shading, mm/day) during 1979-2002. The thick contour encloses the Tibet Plateau higher than 3 km. The dashed frame denotes the core region of the EASM. (b) Standard deviation of JJA-mean rainfall (shading, mm/day) revealed by the station data for the period 1958-2002. Black dots indicate locations of 160 observational stations in China. The grey thick curves denote the Yangtze River and the Yellow River.

4. Dominant modes in anomalous moisture transport

A multivariate EOF analysis is applied to the zonal and meridional components of summer VIMT anomalies over the EASM region (dashed frame, see Fig. 1) for 1958-2002. The first two leading EOF modes account for 32.3% and

21.0% of the total variance, respectively. They are independent from the higher modes according to the criterion of North et al. (1982). Thus, anomalous VIMT associated with EASM are mainly from two dominant modes, referred to as EOF1 and EOF2. Fig. 2 shows self-regression patterns for these two modes, and significant tests have been performed on the linear regression equations by using an *F* test. The VIMT anomalies associated with these two modes therefore exhibit different wave-like features in magnitude and position. Corresponding to the EOF1 mode (Fig. 2a), an anomalous east-west elongated VIMT cyclone centred at (22.5°N, 130°E) dominates the EASM region, and an anomalous VIMT anticyclonic ridge is detected around 40°N extending from the central Pacific to Japan and North China. However, associated with the EOF2 mode (Fig. 2b), along with westward VIMT anomalies extending from the tropical western Pacific to Indian Peninsula, VIMT anomalies in the target region are jointly controlled by an anomalous VIMT anticyclone around northern SCS and an anomalous VIMT cyclone in the subtropical WNP, and an anomalous VIMT anticyclone centred at (40°N, 170°E) is also found northeast of the target region.

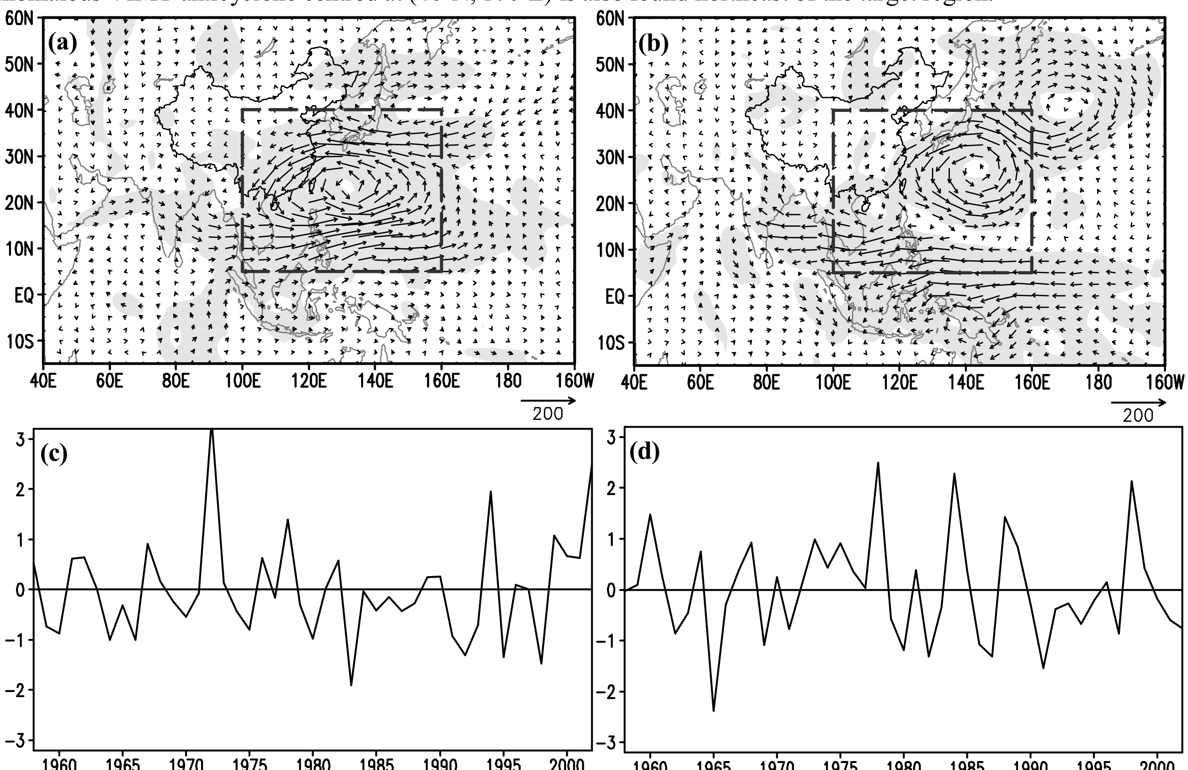

Fig. 2. Self-regression patterns for (a) EOF1 and (b) EOF2 modes of summer VIMT ($kg \cdot m^{-1} \cdot s^{-1}$) for the period 1958-2002. The dashed frame indicates the target region where a multivariate EOF analysis has been applied. Shading denotes significance at 95% confidence level. The standardized principal components for these two EOF modes: (c) PC1 and (d) PC2

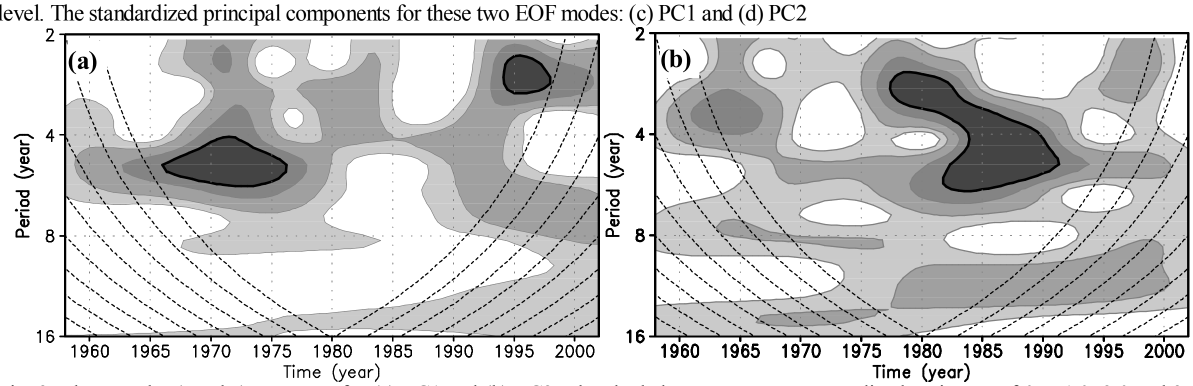

Fig. 3. The wavelet (Morlet) spectrum for (a) PC1 and (b) PC2. The shaded contours are at normalized variances of 0.5, 1.0, 2.0 and 3.0, while the thick contours are the 95% confidence level for white noise. The sloping-dashed region is the cone of influence.

The corresponding standardized principal components (PCs) show important differences in temporal evolution. The amplitude of PC1 decreases significantly around the late 1970s and increases around the early 1990s (Fig. 2c). The PC2, on the other hand, displays an increased variability around the late 1970s and a decreased variability around the early 1990s (Fig. 2d), which implies an out-of-phase tendency between the EOF1 and the EOF2 modes. A wavelet spectrum analysis shows differing time-frequency variation between PC1 and PC2. The PC1 (Fig. 3a) has two leading energy peaks at the 95% confidence level, with distinctive periodicities at 4-6 years between mid-1960s and mid-1970s, and 2-3 years around mid-1990s. The PC2 (Fig. 3b) has a prominent spectral peak at 3-7 years between the late 1970s and the early 1990s, significant at 95%. The wavelet analysis also suggests that the EASM variation does not show a regular quasi-biennial or quasi-quadrennial rhythm as presented in pervious study (Wang et al. 2001).

The moisture transport is closely linked to the atmospheric circulation. Linear regression maps for summer 850-hPa wind with respect to PC1 and PC2 (Fig. omitted) closely resemble Fig. 2, as expected. Thus, these two dominant modes are mainly controlled by EASM circulation in the lower troposphere. It should be pointed out that the wave-like pattern associated with the EOF1 mode, including an anomalous east-west elongated cyclone along 22.5^{o}N and an anomalous anticyclonic ridge along 40^{o}N, bears great similarity to the composite pattern with respect to the WNP monsoon index (WNPMI) shown by Wang et al. (2001, their Fig. 10c). This pattern has been hypothesized to be the result of Rossby wave dispersion due to anomalous heating near the Philippines (Nitta 1987; Huang and Sun 1992), and the PC1 positively correlates with the WNPMI with a correlation coefficient of 0.70 for the 45-yr period.

In contrast to the EOF1 mode, however, the wave-like pattern associated with the EOF2 mode has not been explored. Moreover, the decadal modulation between EOF1 and EOF2 modes also deserves further investigation. These are beyond the scope of the current paper.

5. Linkages between moisture transport and rainfall anomalies in China

According to equation (1), areas for which P-E < 0 are moisture source regions over which the atmospheric moisture fluxes diverge, and other areas are moisture sink regions where moisture fluxes converge. However, evaporation shows small difference between various summers in eastern China (Fan and Oglesby 1996; Simmonds et al. 1999), and EASM rainfall exhibits large year-to-year variations (see Fig.1b). Hence, The VIMT convergence plays a key role in physical linkages between moisture transport and summer monsoon rainfall anomalies in China.

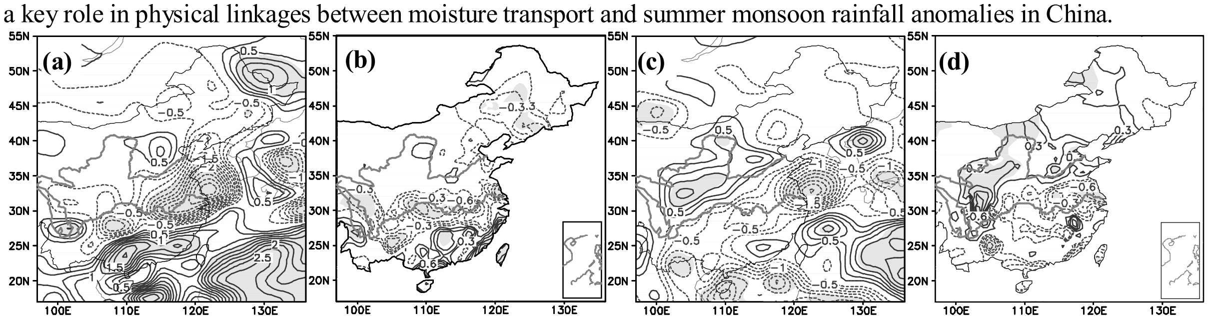

Fig. 4. Regression patterns for (a) VIMT convergence and (b) rainfall with respect to PC1; regression patterns for (c) VIMT convergence and (d) rainfall with respect to PC2. The contour interval is 0.25 mm/day for (a, c) and 0.15 mm/day for (b, d), and zero contours are not shown. Shading denotes significance at 95% confidence level. The grey thick curves denote the Yangtze River and the Yellow River.

The regression pattern for summer VIMT convergence with respect to PC1 (Fig. 4a) shows significantly negative VIMT convergence anomalies dominate the middle and lower reaches of the Yangtze River valley, while significantly positive VIMT convergence anomalies appear in South China. Such anomalies are likely responsible for the negative rainfall anomalies along the Yangtze River valley and positive rainfall anomalies in South China (Fig. 4b). In addition, negative rainfall anomalies closely responds to anomalous moisture source in Northeast China, but no significant variability is found along the Yellow River valley. The regression pattern for summer VIMT convergence with respect to PC2 (Fig. 4c) shows significantly negative VIMT convergence anomalies appear in the Yangtze-Huaihe River valley while significantly positive VIMT convergence anomalies dominate the Yellow River valley. Such anomalies result in negative rainfall anomalies in the Yangtze-Huaihe River valley and positive rainfall anomalies in the Yellow

River valley (Fig. 4d).

6. Summary

The summer vertically integrated moisture transport (VIMT) and its convergence have been estimated by using 45-yr ECMWF reanalysis (ERA-40) data. Physical linkages between moisture transport by East Asian summer monsoon (EASM) and summer rainfall anomalies in China have been also investigated.

On the whole, the above-mentioned results point out physical relationships between EASM-related VIMT, VIMT convergence and summer rainfall anomalies in a concise way, which are mainly regulated by two modes. However, the triggering mechanisms of different wave-like patterns associated with these two dominant modes are poorly understood. To improve forecast of summer rainfall anomaly in China requires further research..

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