Impact of East Asian winter monsoon on rainfall over southeastern China and its dynamical process

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ABSTRACT: The present study investigates the impact of the East Asian winter monsoon (EAWM) on winter (January, February, and March, or JFM in short) rainfall over southeastern China (including South China and central eastern China) and its dynamical process by using station observations for the period 1951–2003 and the ERA-40 reanalysis for the period 1958–2002. It is found that there is a significant correlation between interannual variations of the EAWM and JFM rainfall over southeastern China. Analyses show that in weak EAWM years southwesterly anomalies at 700 hPa dominate over South China Sea, which transports more moisture into southeastern China, favouring rainfall increase. At the same time, the East Asian westerly jet weakens and displaces southward, contributing to the increase in ascending motion over southeastern China. The air temperature over southeastern China shows an obvious decrease at 300 hPa and increase near the surface. This enhances the convective instability and weakens the potential vorticity (PV), which explains the strengthening of ascending motion and the increase in JFM rainfall over southeastern China. In addition, the EAWM has impacts independent of El Niño Southern Oscillation (ENSO) on JFM rainfall over southeastern China. Moreover, the rainfall anomalies over central eastern China are more closely related to the EAWM than that in South China. Copyright © 2010 Royal Meteorological Society

KEY WORDS EAWM; rainfall; convective instability; potential vorticity

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1. Introduction

The East Asian winter monsoon (EAWM) is an important subsystem of the global climate system. And the EAWM is influenced by some factors, such as El Niño Southern Oscillation (ENSO), North Atlantic Oscillation (NAO), North Pacific Oscillation (NPO), and so on (Li, et al., 1994; Wu and Chan, 1995; Compo, 2001; Boyle and Chen, 1987; Lau and Chang, 1987). The most prominent feature of the EAWM is strong surface northeasterlies along the east flank of the Siberian high and the coast of East Asia. A broad trough at 500 hPa located over the longitude of Japan. At 200 hPa, the dominant feature is that the East Asian jet with its maximum located at just southeast of Japan, which is related to intense baroclinicity, large vertical wind shear and strong advection of cold air (Boyle and Chen, 1987; Lau and Chang, 1987; Ding, 1994; Wu and Chan, 1995; Compo et al., 1999; Chen et al., 2000; Wang et al., 2010). In the tropics, the strong convection is over the maritime continent during winter (Ramage, 1975; Chang et al., 2006). Extensive deep cumulus convection supplies a large amount of latent heat to the atmosphere. It is believed to be one of the most energetic heat sources of the global atmosphere and plays a substantial role in the atmospheric circulation during the Northern winter (Chang et al., 2006). The tropical convection over the maritime continent was intensified by cold surges that are characterized by strong northeast-erly winds penetrating deep into the equatorial region by observations (Chang et al., 1979; Lau and Chang, 1987). The cold surges are suggested to be an important link in mid-latitude and tropical interactions. The winter monsoon spreads its influence to planetary and global scales by way of the tropical–extratropical interaction (Yang et al., 2002).

The rainfall variability over southeastern China had been studied extensively (Chang et al., 2000; Wu et al., 2003; Zhou and Huang, 2003; Chan et al., 2004; Chan and Zhou, 2005; Xin et al., 2006; Wan et al., 2009; Zhou and Wu, 2010; Zhou et al., 2010). Most of these studies have focused on the relationship between rainfall and sea surface temperature (SST) in the cold season. The anomalous EAWM can induce circulation changes over East Asia (Ji et al., 1997; Chen and Sun, 1999; Chen et al., 2000; Huang et al., 2003; Chan and Li, 2004; Wang et al., 2010). Moreover, the rainfall anomalies are closely related to EAWM in China (Sun and Sun, 1994; Chen et al., 2000), whose results indicated that the variations of the EAWM influence the following summer rainfall in China. However, the impact of the EAWM on winter rainfall over southeastern China is studied rarely. Zhou and Wu (2010) pointed out that there are close relationships between EAWM and rainfall in China, whose results indicated that a weak EAWM corresponds to anomalous southwesterly winds over the
Section 2 describes the datasets used in this study. The present study uses monthly station rainfall data at 160 stations in China (the 160 stations distributions are presented in Figure 1(a)) during 1951–2003, which are provided by the National Meteorological Information Centre. These station observations are operated by the China Meteorological Administration consistently through the observation period. In the present study, the 50 stations distributions of southeastern China are also shown in Figure 1(a).

The study period covers several decades during which the NCEP-NCAR reanalysis and the ERA-40 reanalysis provide options for circulation data. Unfortunately, the NCEP-NCAR reanalysis has been found to have larger spurious changes during the study period (Yang et al., 2002; Inoue and Matsumoto, 2004; Wu et al., 2005; Zhou and Huang, 2010a). Thus, the present study uses monthly mean wind, temperature and PV from the ERA-40 reanalysis on a 2.5° × 2.5° grid of the European Centre for Medium-Range Weather Forecasts (ECMWF) (Gibson et al., 1997; Uppala, 2002), which covers the period 1958–2002.

The Niño-3.4 SST is derived from the monthly mean SST data of the MET Office Hadley Center on 1° × 1° grid, which covers the period 1900–2008 (Rayner et al., 2003).

The present study uses an EAWMI defined by Chen et al. (2000). This index is calculated by averaging meridional winds at 10 m over the East China Sea (25–40°N, 120–140°E) and the South China Sea (10–25°N, 110–130°E). The EAWMI is shown in Figure 2(a). Note that the positive values of the EAWMI indicate the weakening of the EAWM, whereas the negative values indicate the strengthening of the EAWM. From Figure 2(a), in addition to interannual fluctuations, the EAWMI shows an interdecadal change around the mid-1980’s. Positive and negative EAWM anomaly cases were identified according to Figure 2(a) and by the criterion that the standard deviation exceeds ±0.5. So, the selected positive EAWM anomaly cases are: 1958, 1960, 1966, 1969, 1973, 1979, 1983, 1987, 1991, 1992, 1997, and 1998 (a total of 12 cases). Negative cases are: 1963, 1965, 1968, 1970, 1971, 1972, 1974, 1976, 1977, 1984, 1989, and 1996 (a total of 12 cases). The positive and negative anomalies are corresponding to a weaker and stronger EAWM case. The composition of JFM 700 hPa wind anomalies based on positive and negative EAWMI is shown in Figure 3. Climatologically, the EAWM displays a clear northwesterly wind component at lower troposphere over eastern China (Figure 3(a)). In weak EAWM years, a prominent feature is that anomalous anti-cyclonic circulation dominated over western North Pacific, with significant southerly anomalies over South China Sea, which induces anomalous moisture convergence and upward motion and thus enhanced rainfall over southeastern China. Therefore, the objective of this study is to analyse the impact of the EAWM on JFM rainfall over southeastern China and its dynamical processes according to the potential vorticity (PV) theory by using station observations and the ERA-40 reanalysis.
China Sea (Figure 3(b)). These anomalous winds substantially enhance the moisture supply to southeastern China. These contribute to the increase in JFM rainfall over southeastern China. However, in strong EAWM years, the significant northeasterly anomalies dominated over South China Sea, which do not contribute to the increase in JFM rainfall in this region (Figure 3(c)). To further examine the EAWM related to rainfall over southeastern China, the composition of vertical velocity and water vapour convergence based on strong and weak EAWM is shown in Figure 4. A strong EAWM corresponds to anomalous moisture divergence (corresponding to positive values) and downward motion (corresponding to positive values) and thus decrease rainfall over southeastern China (Figure 4(a) and (b)). However, a weak EAWM corresponds to anomalous moisture convergence (corresponding to negative values) and upward motion (corresponding to negative values) and thus enhanced rainfall over southeastern China (Figure 4(c) and (d)). Thus, the EAWM has an impact on rainfall over southeastern China.

The impact of the EAWM on the rainfall over southeastern China is depicted by the regression and correlation analysis between the EAWMI and JFM rainfall in China. To exclude the effects of interdecadal change, the linear trend line of regression has been removed from raw EAWMI anomalies before calculating the correlation and regression for the period of 1958–2002. Figure 5 shows the regression and correlation between the EAWMI and JFM rainfall in China. There are significant positive correlation regions located over southeastern China (including South China and central eastern China), and the dark shaded region denotes correlation significant above the 99% confidence level. Furthermore, the regression results show that the most rainfall amount occurred over South China. This indicates that when the EAWM weakens, the JFM rainfall increases over South China and central eastern China, and vice versa. Moreover, the correlation coefficient between the EAWMI (Figure 2(a)) and JFM rainfall averaged over southeastern China (Figure 2(b)) reaches 0.6 for the period 1958–2002, which is above the 99% confidence level.

4. Impact of EAWM on variability of circulation over East Asia

The rainfall variability is closely related to atmospheric circulation changes. To understand the variability of JFM rainfall over southeastern China, the impact of the EAWM on the atmospheric circulation over East Asia is depicted by a regression analysis with respect to the EAWMI for the period 1958–2002. Figure 6 shows 700 hPa wind, 700 hPa vertical velocity, and 200 hPa wind anomalies, respectively. The described anomalies in the following correspond to positive EAWMI or weak EAWM.
Figure 3. Climatological mean of wind at 700 hPa (a) and composition of JFM wind at 700 hPa based on weak EAWM years (b), and strong EAWM years (c) (unit: m s\(^{-1}\)). The climatological monthly mean is based on the period 1961–1990.

Figure 6(a) shows that a prominent feature is an anomalous anti-cyclone over the western North Pacific. To the northwest flank of this anomalous anti-cyclone are anomalous southwesterly winds along the southeast coast of China. These anomalous winds substantially enhance the moisture supply to southeastern China. These contribute to the increase in JFM rainfall over southeastern China. Li et al. (2005) pointed out that the strong (weak) EAWM can lead to not only the occurrence of anomalous westerly (easterly) wind over the equatorial western Pacific but also anomalous cyclonic (anti-cyclonic) circulation over the east of the Philippines. The present results are consistent with Li et al. (2005). The ascending anomalies (corresponding to negative values) occur over southeastern China due to weakening of the EAWM, which favour the increase in rainfall in this region. In contrast, descending anomalies are seen over the western North Pacific (Figure 6(b)). In 200 hPa (Figure 6(c)), a prominent feature is the cyclonic wind anomalies over southeastern China, with significant anomalous easterlies and westerlies over northern and southern flank of this anomalous cyclone, respectively. These indicate that in weak EAWM years the East Asian westerly jet weakens and displaces southward, which contribute to increase in rainfall over southeastern China (Lin and Lu, 2009).

In order to assess the impact of EAWM on rainfall over southeastern China, the composition of anomalous circulation based on rainfall anomalies are analysed. Positive and negative rainfall anomaly cases were identified according to Figure 2(b) and by the criterion that the standard deviation exceeds ±0.5. So, the selected positive rainfall anomaly cases are: 1959, 1969, 1975, 1980, 1983, 1985, 1989, 1990, 1991, 1992, 1996, 1997, and 1998 (a total of 13 cases). Negative cases are: 1962, 1963, 1965, 1971, 1974, 1976, 1977, 1984, 1986, 1999, and 2002 (a total of 11 cases). The positive and negative anomalies are corresponding to an increase and decrease in rainfall over southeastern China. Figure 7 shows composition of JFM 700 hPa wind, 700 hPa vertical velocity, and 200 hPa wind anomalies based on difference between increase and decrease in rainfall anomalies, respectively. A prominent feature is that anomalous southwesterly winds occurred along the southeast coast of China, which is similar to that of Figure 6(a) (Figure 7(a)). The ascending anomalies (corresponding to negative values) also occur over southeastern China due to increase in rainfall in this region (Figure 7(b)). In 200 hPa, a prominent feature is that the cyclonic wind anomalies occurred over southeastern China (Figure 7(c)), which is similar to that of Figure 6(c).

Above results indicated that the anomalous circulation related to rainfall over southeastern China is almost in agreement with that related to EAWM. Therefore, there is a close relationship between the EAWM and JFM rainfall over southeastern China.

5. Impact of EAWM on variability of temperature over East Asia

The temperature anomalies at different levels obtained by regression with respect to the EAWMI are shown in Figure 8. From Figure 8(a), there are significant positive temperature anomalies at surface over southeastern China. Similar temperature anomalies are observed at 700 hPa (Figure 8(b)) except that positive anomalies in the tropics are more widespread and negative anomalies over the western North Pacific are replaced by positive anomalies. The positive temperature anomalies over southeastern China are induced by weakening of the EAWM. This is confirmed by the regressed temperature advection at 700 hPa with respect to the EAWMI shown in Figure 9. From Figure 9, the positive temperature advection anomalies occur over southeastern China and southeast coast of China. This indicates that the positive temperature anomalies at lower-level may be induced...
The above results indicate that the surface temperature increases obviously over southeastern China, while the temperature at 300 hPa decreases. The difference in temperature changes between upper and lower-levels may cause changes in the convective instability that, in turn, may result in variability of JFM rainfall over southeastern China.

6. The dynamical process of impact of thermal variability on rainfall

The results in previous sections show that the variability of JFM rainfall over southeastern China is associated with circulation and temperature anomalies. However, the dynamical process for changes of JFM rainfall over southeastern China is not clear. The upper-level temperature decreases, whereas the surface temperature increases over southeastern China. This thermal variability may result in dynamical variability. Therefore, the PV will be analysed because it is a synthetically physical term of dynamic and thermal state. Ertel (1942) pointed out that three-dimensional air-mass motion has conservative property when the motion is adiabatic and non-frictional. Hoskins et al. (1985) made systematic investigations on Ertel PV application to atmospheric motion diagnosis. The vertical component of PV is as follows (Zhou and Huang, 2010b):

$$ PV = g(\xi + f) \left( -\frac{\partial \theta_{se}}{\partial p} \right) $$

Figure 4. Composition of water vapor convergence (integration 1000–100hPa) (unit: $10^2$ g m$^{-2}$ s$^{-1}$) (a) and 700hPa vertical velocity (unit: $10^2$ Pa s$^{-1}$) (b) based on strong EAWM. (c) and (d) are the same as (a) and (b) except for weak EAWM. The climatological monthly mean is based on the period 1961–1990.

Figure 5. Regression of JFM rainfall in China with respect to normalized the EAWMI for the period of 1958–2002 (units: mm). The climatological monthly mean is based on the period 1961–1990. The dark and light shaded regions indicate correlation significant above the 99 and 95% confidence level, respectively. This figure is available in colour online at www.interscience.wiley.com/ijoc.
where \( g = 9.8 \text{ m s}^{-2} \) is the acceleration of gravity, \( \zeta \) is the relative vorticity, \( f \) is the Coriolis parameter, and \( \theta_{se} \) is the equivalent potential temperature.

Development of systematic PV depends on atmospheric stratification stability, baroclinicity, and vertical shear of wind. Generally speaking, the barotropic component is one order of magnitude larger than the baroclinic component (Wu and Liu, 2000), so variability of PV mainly depends on its barotropic component and convective instability \((-\partial \theta_{se}/\partial p)\). Thus, variability of JFM PV anomalies is calculated by using Equation (1).

Figure 10(a) shows regression of PV at 700 hPa with respect to the EAWMI. From Figure 10(a), negative PV anomalies cover southeastern China. These negative PV anomalies are related to the convective instability associated with different temperature changes at upper and lower levels. Figure 10(b) shows regression of convective instability at 700 hPa with respect to the EAWMI. From Figure 10(b), there are negative anomalies over southeastern China and southeast coast of China. This indicates a strengthening of convective instability over southeastern China, which favours the enhancing of ascending motion and the increase in rainfall in this region.

The relationship among anomalies of PV, \( \zeta \) and \(-\partial \theta_{se}/\partial p\) may be inferred according to Equation (1). The preceding results indicate that, over southeastern China, the \( \Delta \text{PV} = 0, -\partial \theta_{se}/\partial p < 0 \). Thus, it may be inferred that \( \Delta \zeta > 0 \) according to Equation 1. This is
confirmed by the regression of vorticity with respect with EAWMI (Figure 10(c)). Figure 10(c) shows significant positive vorticity anomalies over southeastern China. This suggests the development of cyclonic circulation anomalies over southeastern China, which is helpful for enhancing local ascending flow and increasing rainfall in this region.

7. Removal of ENSO impacts

Previous studies indicates that tropical Pacific SST anomalies in relation to ENSO can affect winter rainfall over South China (Zhang et al., 1999; Wang et al., 2000; Zhang and Suni, 2002; Wu et al., 2003; Zhou et al., 2010). Above-normal (below-normal) rainfall is observed during El Niño (La Niña) years. The El Niño influences the South China rainfall through an anomalous anti-cyclone over the western North Pacific (Wang et al., 2000; Wu et al., 2003). In fact, the wind anomalies seen in Figure 6 resemble closely to those corresponding to El Niño events. This raises the question whether the positive correlation of rainfall in southeastern China seen in Figure 5 is due to the impacts of tropical heating anomalies in association with SST anomalies.

In order to reveal whether the EAWM has impacts independent of ENSO, a partial correlation and regression analysis is performed with the ENSO impacts removed. The Niño-3.4 SST anomaly averaged over the region of 5S–5N, 170–120W is taken as an index to represent ENSO. The obtained EAWMI_res is that the coherent variability of simultaneous Niño-3.4 SST index is removed by means of a linear regression from the time series of the EAWMI as follows:

$$\text{EAWMI}_{\text{res}} = \text{EAWMI} - r \times \text{Niño-3.4 SST}$$

where $r$ is the regression coefficient of Niño-3.4 SST with respect to the EAWMI. After the ENSO signal is removed, the regression of rainfall, wind, and vertical velocity at 700 hPa with respect to the EAWMI_res is shown in Figure 11. From Figure 11(a), the significant positive correlation regions still occurred over South China and central eastern China, but the significant area and the magnitude of rainfall anomalies over South China are smaller compared with those seen in Figure 5. Differences consistent with the rainfall anomalies are seen in the vertical velocity. The ascent is limited to southeast coast of China (Figure 11(b)). These results indicate that the EAWM has a larger independent influence on winter rainfall in central eastern China. After removed ENSO impact, the impact of the EAWM on JFM rainfall is weakened over South China. For 700 hPa circulation
Figure 10. Regression of JFM PV (unit: \(10^6 \text{K}\cdot\text{m}^2\cdot\text{Kg}^{-1}\cdot\text{s}^{-1}\)) (a), convective instability (unit: \(10^5 \text{K}\cdot\text{Pa}^{-1}\)) (b), and vorticity (unit: \(10^5 \text{s}^{-1}\)) (c) at 700 hPa with respect to normalized the EAWMI for the period of 1958–2002. The climatological monthly mean is based on the period 1961–1990. The dark and light shaded regions indicate correlation significant above the 99 and 95% confidence level, respectively. This figure is available in colour online at www.interscience.wiley.com/ijoc

8. Summary

The present analysis identifies an obvious increase in JFM rainfall over southeastern China (central eastern China and South China) due to weakening of EAWM. The impact of EAWM on JFM circulation, temperature and PV anomalies are analysed to understand the cause for the increase in JFM rainfall over southeastern China and its dynamical process.

The results show that the anomalous southwesterly winds occur along the southeast coast of China in weak EAWM years. These anomalous winds substantially enhance the moisture supply to southeastern China and contribute to increase in JFM rainfall in this region. The results also show that negative temperature anomalies occur over southeastern China at upper levels and positive temperature anomalies occur at low levels. Furthermore, the positive temperature anomalies at lower-level may be induced by enhanced warm advection because of weakening of the EAWM. Therefore, the different thermal variability enhances the convective instability over southeastern China, which contributes to the strengthening of descending motion and increase in JFM rainfall in this region. The negative PV anomalies occur over southeastern China. It may be inferred according to the PV equation that vorticity anomalies are positive over southeastern China, which contributes to development of cyclonic circulation anomalies and increase in local JFM rainfall.

The partial regression analysis results show the EAWM has impacts independent of ENSO on JFM rainfall over southeastern China. Moreover, the rainfall anomalies over central eastern China are more closely related to the EAWM than that in South China.

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Figure 11. Regression of JFM rainfall (unit: mm) (a), vertical velocity at 700 hPa (unit: $10^2$ Pa/s) (b), winds at 700 hPa (Unit: m/s) (c), and temperature at 2 m (unit: °C) (d) with respect to normalized the EAWMI for the period of 1958–2002. The climatological monthly mean is based on the period 1961–1990. The dark and light shaded regions indicate correlation significant above the 99 and 95% confidence level, respectively. This figure is available in colour online at www.interscience.wiley.com/ijoc

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