Wave Sources, Energy Propagation and Conversion for Anomalous Rossby Wave Activities Along the West Asian Jet Stream*

YANG Lianmei1(杨莲梅) and Zhang Qingyun2(张庆云)
1 Institute of Desert Meteorology, China Meteorological Administration, Urumqi 830002
2 Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029
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ABSTRACT

Characteristics of the wave sources, energy propagation and conversion for anomalous Rossby wave activities (RWAs) along the West Asian jet stream (WAJS) in summer are examined based on the NCEP/NCAR (National Centers for Environmental Prediction/National Center for Atmospheric Research) reanalysis data from 1958 to 2003, using the vorticity source equation, the Eliassen-Palm (EP) flux, and the wave energy equation under diabatic heating. The study aims to find the dynamical causes for RWA anomalies along the WAJS and to improve the understanding of mid-high latitude circulation anomalies. The results show that the negative vorticity source and the strong EP flux divergence over the Mediterranean Sea and the North Atlantic – Scandinavian Peninsula area act as the wave sources for RWA anomalies along the WAJS. When the intensity and position of the wave sources are anomalous, the excited eastward-propagating RWA along the WAJS also behaves anomalously. In strong (weak) years of RWA, Rossby waves excited by the strong divergence of EP fluxes over the Iceland – Scandinavian Peninsula area (east to the Scandinavian Peninsula) propagate eastward and southeastward. The eastward propagating waves become strengthened (weakened) after turning southeastward near the Ural Mountains and then entering the Asian subtropical westerly jet stream (ASWJS) over the Caspian Sea–Aral Sea–Xinjiang. The southeastward propagating waves also strengthen (weaken) after directly entering the ASWJS over the eastern Mediterranean–the Black Sea. Furthermore, the divergence of EP fluxes over the Mediterranean also strengthens (weakens) in the strong (weak) years, so they jointly bring about the strong (weak) RWA along the WAJS. Finally, the perturbation available potential energy (PAPE) along the WAJS (15°–60°E) produced by diabatic heating, is far greater than the conversion from the kinetic energy of the basic flow into the perturbation kinetic energy and from the available potential energy of the basic flow into PAPE. The RWA along the WAJS looks stronger (weaker) than normal when the PAPEs produced by diabatic heating over the Iranian Plateau and West Asia significantly strengthen (weaken), and therefore they are also the energy sources of RWA anomalies.

Key words: Asian subtropical westerly jet stream (ASWJS), quasi-stationary wave propagation, energy conversion, diabatic heating

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1. Introduction

The Asian subtropical westerly jet stream (ASWJS), which is a significant planetary-scale circulation system in the upper troposphere, is one of the important systems that affect synoptic- and climatic-scale anomalies, and is also an important carrier of the wave-mean flow interactions. Ambrizzi et al. (1995) showed that the ASWJS acts as a waveguide in boreal summer. Terao (1998, 1999a, b) argued that the activity of Rossby waves along the ASWJS causes dominant intraseasonal modes in the midlatitudes during boreal summer. Tao and Wei (2006) pointed out that the Rossby wave activities (RWAs) along the ASWJS are related to the activities of the Meiyu front, the western Pacific subtropical high and the Qinghai-Tibetan high, so RWA along the ASWJS is a very important member of the East Asian summer monsoon (EASM).
system, of which the interannual variability is closely connected to the East Asian climate variability. Lu et al. (2002) investigated the interannual variability of the stationary waves along the ASWJS in July and indicated that RWA along the ASWJS might be the mechanism that connects the EASM with the Indian summer monsoon (ISM), and like ENSO, it is another independent factor that affects the East Asian climate. Enomoto et al. (2003) and Enomoto (2004) emphasized the importance of the propagation of RWA along the ASWJS for the late summer climate in northern Asia. Ding and Wang (2005) held that the circum-global teleconnection (CGT) along the westerly jet stream in boreal summer is a significant source of climate variability in the mid-latitude zone, while the "Tokyo-Chicago express", the ISM-EASM teleconnection and the teleconnection over western Asia-middle Asia-Japan are regional manifestations of the CGT pattern. Therefore, RWA along the ASWJS in summer is of great importance.

In 1939, Rossby firstly studied the nature of the atmospheric long wave (the Rossby wave called afterwards) and theoretically concluded that it was caused by the variance of the geostrophic parameter along latitudes, and was closely related to the large-scale weather process. Subsequently, meteorologists conducted a series of wide and intensive investigations on Rossby waves, which makes the Rossby-wave theory substantial and abundant. Yeh (1949) firstly put forward the Rossby wave dispersion theory, which nicely explained the so-called "upstream effect" in the evolution of the atmospheric circulation. Hoskins and Karoly (HK for short) (1981) studied the response of a spherical atmosphere to the thermodynamic forcing and to the topographic forcing, and discussed the energy dispersion issue of the spherical stationary Rossby wave by using the slowly varying wavetrain theory, and further proposed the "Big Circle" theory on stationary Rossby wave energy dispersion. Xu and Gao (2002) applied HK's "Big Circle" theory to the mathematical model of a realistic westerly profile and orographic forcing, and gained the transfigured "Big Circle Path" wave-ray. In recent years, Ran et al. (2005) investigated the energy propagation features of low-frequency Rossby waves by the wave-ray theory, and then indirectly discussed the influence of diabatic heating on low-frequency Rossby waves through taking into account the effect of horizontal disturbance divergence and divergent wind in the barotropic vorticity equation. Duan and Wu (2005) deduced the Eliassen–Palm (EP) flux with the diabatic effect under the quasi-geostrophic frame based on the conventional wave-mean flow interaction theory, proved the consistency between the wave energy relationship of EP fluxes and the atmospheric energy circulation obtained by Lorenz, and concluded that the energy propagation process of large-scale stationary waves is a substantial part of the atmospheric energy recycle course.

In summer, the ASWJS is located around 40°N. Previous studies mostly focus on the activities of the East Asian jet stream (EAJS) in 100°–150°E. For instance, Kuang and Zhang (2006) and Ren and Zhang (2007) discussed the seasonal variation and influencing mechanisms of the EAJS. The Xinjiang Region in Northwest China is under the control of the ASWJS in summer. The meridional displacement of the West Asian jet stream (WAJS) and RWA along the WAJS, upstream of Xinjiang, are closely related to the summer climatic abnormality of Xinjiang (Zhang et al., 1986; Yang, 2007; Yang and Zhang, 2008). It is known that anomalously positive (negative) summer rainfall in Xinjiang is associated with the West Asian westerly jet axis that stays further south (north) than normal. However, the dynamic mechanism for the meridional displacement and the RWA along the WAJS is still not clear, which confines our understanding of the summer climate abnormality of Xinjiang. The purpose of this paper is to study the wave sources and the energy propagation features of the anomalous RWA along the WAJS, and to further examine the energy conversion characteristics so as to deeply understand the internal dynamics of the WAJS.

2. Data and method

In this study, the monthly mean data of the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR)
reanalysis data is used. The data has a 2.5° × 2.5° horizontal resolution and extends from 1000 to 10 hPa with 17 pressure levels in the vertical for 1958–2003. Seasonal means are constructed from the monthly means by averaging the data of June, July, and August (JJJA). The climatological mean in this paper is the average of data over 1971–2000.

The westerly jet stream zone is located around 40°N at 200 hPa during summer in the Northern Hemisphere, and consists of the Asian jet stream (0–210°E) and the North American jet stream. As a planetary-scale system, the Asian jet stream can be divided into the WAJS (15°–60°E) and the EAJS (100°–140°E), which differ greatly. The range of the EAJS is different in various investigations (Liao et al., 2004; Li et al., 2004; Tao and Wei, 2006), but the jet stream east of 100°E is commonly taken as the EAJS. The EAJS variance is closely related to the East Asian circulation system. The WAJS is located upstream of Xinjiang, and is believed to be closely associated with the weather and climate in Xinjiang. To further investigate the atmospheric dynamic process of the circulation abnormality over western and eastern Asia, this paper is to discuss wave sources, wave energy propagation and conversion features of anomalous RWA along the WAJS.

According to Sardeshmukh and Hoskins (1988), the vorticity source engendered by the upper troposphere stationary divergence field could be defined as:

\[
S' = -\nabla_x \cdot \nabla \xi' - V'_x \cdot \nabla (\xi + f) - (\xi + f)D' - \xi'D, \tag{1}
\]

where \( \nabla_x \) and \( V'_x \) are the mean and abnormal divergence winds, respectively; \( \xi \) and \( \xi' \) are the mean and abnormal relative vorticities, respectively; \( D \) and \( D' \) are the mean and abnormal divergence, respectively. Here, we only discuss the forcing function induced by the stationary divergence on the stationary wave. Due to the fact that the atmospheric large-scale divergence wind field is mainly related to diabatic heating and large-scale topography, \( S' \) basically stands for the forcing from the exterior stationary forcing source on the atmospheric stationary planetary wave. Therefore, the analysis of \( S' \) can explain the source region and the formation mechanism for the atmospheric stationary planetary wave.

Based on the previous work of Plumb (1985) and others, Takaya and Nakamura (1997) presented the EP flux along varying climatological basic flows, expressed by Eq. (2). The EP flux is a measure of the wave activity propagation, and its horizontal components (horizontal wave activity flux) indicate the horizontal transmission direction and the intensity of the stationary wave activity, which is employed here to explain the horizontal propagation features of the stationary wave activity.

\[
W = \frac{p}{2|U|} \left( \frac{U(\psi'_x^2 - \psi'_x \psi'_x)}{U(\psi'_x \psi'_y - \psi'_x \psi'_x)} + \frac{V(\psi'_y^2 - \psi'_y \psi'_y) + (\psi'_y^2 - \psi'_y \psi'_y)}{f^2 g^2 [U(\psi'_x \psi'_p - \psi'_x \psi'_x) + V(\psi'_y \psi'_p - \psi'_y \psi'_y)]} \right). \tag{2}
\]

In summer, the wavenumber of a quasi-stationary Rossby wave along the ASWJS is taken as 3–7 (Yang, 2007). Referring to Enomoto et al. (2003), we filtered out waves with wavenumbers less than 3, by a Fourier harmonic analysis of the 200-hPa stream function. Variable \( \psi' \) in Eq. (2) denotes a perturbation stream function after those waves with wavenumbers less than 3 are filtered out; \( |U| \) is the horizontal basic flow velocity; \( p \) represents pressure; \( U \) and \( V \) are the zonal and meridional components of the basic flow; \( S^2 \) is the static stability parameter. Here, we discuss the energy propagation features of static stationary wave activities with and without filtering.

The basic flow can be represented by zonal wavenumbers \( K < 3 \). Zonal wavenumbers \( K \geq 3 \) are assumed to be a perturbation to the basic flow. With this separation between the zonally-varying basic field and the perturbation, the modulation of the basic flow itself is diminished. A fourier transform is conducted on the wind speed field at 200 hPa in summer, and wavenumber \( K < 3 \) is taken as the basic field \((u_{\text{basic}}, v_{\text{basic}})\), then the perturbation wind speed \((u', v') = (u, v) - (u_{\text{basic}}, v_{\text{basic}})\) and the perturbation kinetic energy \( E_k = (u' \cdot u' + v' \cdot v')/2 \). \( E_k \) is averaged zonally over 15°–60°E and meridionally over the range 5° south and north of the axis of the zonal wind.
maxima. It is then normalized as the RWA index along the WAJS (referred to as WAJRI). This index preferably expresses the intensity, location, and RWA of the WAJS (Yang, 2007). The positive (negative) index cases are selected if the absolute normalized values of WAJRI are larger (smaller) than 1 (−1). Based on this criterion, the positive index summers are in 1964, 1970, 1973, 1976, 1983, 1984, 1989, 1994; and the negative index summers are in 1974, 1981, 1985, 1988, 1993, and 1998. Composite analyses are then carried out accordingly. Note, positive (negative) index years are also called positive (negative) RWA years.

Adopting the wave-energy equations inclusive of the diabatic heating effect deduced by Duan and Wu (2005), we study the energy transformation features with the following expressions:

\[
\begin{align*}
S_A &= -\frac{\rho u'v'}{p^2} - \frac{\rho_f u'v'}{p^2} - \frac{\rho T'}{p^2} - \frac{R^2 Q'^T}{p^2}, \\
S_B &= -\frac{\rho u'v'}{p^2} - \frac{\rho_f u'v'}{p^2} - \frac{\rho T'}{p^2} - \frac{R^2 Q'^T}{p^2}, \\
S_C &= -\frac{\rho u'v'}{p^2} - \frac{\rho_f u'v'}{p^2} - \frac{\rho T'}{p^2} - \frac{R^2 Q'^T}{p^2},
\end{align*}
\]

where \( S_A > 0 \) represents the conversion from kinetic energy (KE) of the basic flow into perturbation kinetic energy (PKE); \( S_B > 0 \) is the conversion from available potential energy (APE) of the basic flow into perturbation APE (PAPE); and \( S_C > 0 \) is the PAPE induced by diabatic heating.

3. The vorticity sources and energy propagation of anomalous RWA along the WAJS

Figure 1 shows the vorticity sources \( S' \), the horizontal wave activity flux vectors and divergence, and the horizontal wave flux vector and divergence after filtering out waves with wavenumber \( K < 3 \) at 200 hPa in positive RWA years. As shown in Fig. 1a, positive \( S' \) is mainly situated in the eastern Mediterranean Sea–Black Sea, the northern Atlantic–central and northern Europe, as well as to the south of Lake Balkhash, while intensive negative \( S' \) is located in the Iceland and to its south, the western Mediterranean Sea and the Black Sea–Aral Sea. Divergence wind anomalies (figure omitted) show that convergence wind anomalies correspond to positive vorticity sources while divergence wind anomalies correspond to negative vorticity sources. Then according to Eq. (1), divergence wind anomalies are the cause of vorticity source anomalies in Fig. 1a. In the eastern Mediterranean Sea–Black Sea, where the divergence zone of the EP flux is (Fig. 1b), Rossby waves are induced and propagate eastward, then become gradually weak along the jet stream. Their anomalies (figure omitted) indicate that the wave flux divergence over the eastern Mediterranean Sea–Black Sea strengthens, so both convergence and divergence of the downstream EP flux become enhanced. Meanwhile, the EP flux divergence over the Scandinavian Peninsula and the eastward wave propagation at the ASWJS entrance strengthen. After filtering out waves with \( K < 3 \) (Fig. 1c), the intensive divergence region of EP flux is located over the Northern Atlantic–Scandinavian Peninsula, with a divergence center at 57.5°N, 15°E. Stationary waves are excited and propagate eastward and southeastward from the negative vorticity source area. The eastward-propagating waves turn southeastward near the Ural Mountains and enter the ASWJS over the Caspian Sea and the Aral Sea, and the southeastward-propagating wave directly enters the ASWJS over the eastern Mediterranean Sea–Black Sea. Flux vectors and divergence anomalies (figures omitted) indicate that the EP flux divergence strengthens over the Northern Atlantic–Scandinavian Peninsula, the eastern Mediterranean Sea–Black Sea, as well as the Caspian Sea and the Aral Sea, and so does the eastward-propagating wave along the WAJS. Therefore, strengthening RWA along the WAJS is related to the eastward-propagating wave over the North Atlantic–Scandinavia Peninsula. The above analysis shows that: the component with \( K < 3 \) is quite strong in the wave-flow interaction along the Asian jet stream, and the wave source is over the Mediterranean Sea. After filtering out waves with \( K < 3 \), another wave source can be clearly found over the northern Atlantic–Scandinavian Peninsula. Therefore, they jointly bring about strong (weak) RWA along the WAJS. The positive RWA is closely associated with the eastward and southeastward propagating wave flux from the North Atlantic–Scandinavian Peninsula as well as enhanced divergence at the jet entrance.

Figure 2 shows that in the negative RWA years the vorticity source distributions are basically opposite to those in the positive years. The convergence
(divergence) anomalies of the divergence wind correspond to the positive (negative) vorticity sources (Fig. 2a). The intensive divergence regions of the EP fluxes are over the Mediterranean–Black Sea, which force the Rossby waves to propagate eastward (Fig. 2b). The anomalous distributions (figures omitted) indicate that the divergence of the EP fluxes over the Mediterranean–Black Sea weakens, resulting in decreased divergence and convergence in the downstream regions, as well as the eastward-propagating wave along the WAJS. Meanwhile, both the divergence of the EP fluxes over the Scandinavian Peninsula and the wave propagation at the jet stream entrance weaken. After filtering out waves with $K < 3$, the horizontal wave activity flux excited from the strong negative vorticity source and the intensive divergence region of the EP flux over the Scandinavian Peninsula can propagate outward, with its divergence center at $57.5^\circ$N, $30^\circ$E, and the intensive divergence region obviously departs to the east of that in strong years. The eastward propagating waves, after turning southeastward near the Ural Mountains, and the southeastward-propagating horizontal waves upon entering the ASWJS over the Mediterranean, become quite weak. The horizontal wave activity flux anomaly (figures omitted) shows that the divergence of the EP flux over the North Atlantic–Scandinavian Peninsula is weaker than normal. The wave propagation entering ASWJS from the high latitudes is weaker than normal, and so does the RWA along the WAJS. In conclusion, besides being correlated with the weaker forced Rossby wave at the entrance of the jet stream, the weak RWA along the WAJS is jointly influenced by the waves propagating from the North Atlantic–Scandinavian Peninsula and from the jet stream entrance.

4. Energy conversion of anomalous RWA along the WAJS

4.1 The conversion from kinetic energy (KE) into perturbation kinetic energy (PKE) of the basic flow

Figure 3 shows the summer climatological $S_A$, in
Fig. 2. As in Fig. 1, but for the weak RWA years.

Fig. 3. Longitude-height cross-sections of the summer climatological $S_A \left(10^{-3} \text{m}^2 \text{s}^{-3}\right)$ along 35°N (a), 40°N (b), and 45°N (c). Shadings indicate topography.
longitude-height cross-sections along 35°N (to the south of the westerly jet stream axis) (Fig. 3a), 40°N (along the jet stream axis) (Fig. 3b), and 45°N (to the north of the jet stream axis) (Fig. 3c). The conversion between KE of the basic flow into PKE near the ASWJS mainly occurs above 400 hPa, with its maximum around 200 hPa. The entrance areas to the south of the ASWJS axis display a rather intensive wave sink ($S_{A} < 0$), where the conversion from PKE into the KE of basic flow exists, and in consequence the westerly jet stream there strengthens. Moreover, weak and strong wave sources are over the Iranian Plateau and to the east of the Qinghai-Tibetan Plateau, respectively. In summer, $\overline{u}_{y} > 0$ is found to the south of the jet stream axis, and the perturbation zonal and meridional wind speeds $u$ and $v$ are correlated with each other negatively in the $S_{A} > 0$ area. Therefore, the KE of the basic flow is converted into PKE correspondingly in the process of atmospheric energy cycle and vise versa in the $S_{A} < 0$ areas. Wave source and sink distributions along 40°N are basically the same as those along 35°N, with $S_{A}$ slightly smaller than the latter. The wave source regions are over the Canadian Sea along 45°N, to the north of the jet stream axis. In conclusion, PKE is converted to KE of the basic flow at the jet stream entrance areas along the Asian jet stream axis and to its south; whereas KE is converted to PKE over the Iranian Plateau and to the north of the jet stream axis. The Iranian Plateau and the eastern Qinghai-Tibetan Plateau are important wave source areas.

Figure 4 shows the $S_{A}$ anomaly distributions for the positive and negative perturbation years. $S_{A} < 0$ in the jet stream entrance areas indicates that the conversion from PKE into KE of the basic flow strengthens, resulting in an acceleration of the westerly basic flow, while wave sink and wave source areas over the western and eastern Qinghai-Tibetan Plateau slightly weaken, respectively. The situation along 40°N is consistent with that along 35°N, while the wave source...

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**Fig. 4.** Longitude-height cross-sections of summer anomalies $S_{A}$ ($10^{-3} m^2 s^{-3}$) for strong (a, b) and weak (c, d) years of RWA along 35°N (a, c) and 45°N (b, d). Shadings indicate topography.
over the Caspian Sea along 45°N becomes stronger. In weak years, the $S_A$ anomaly distributions are evenly opposite to those of strong years. All of the above show that for positive (negative) years of RWA, the conversion from PKE into KE of the basic flow strengthens (weakens) over the jet stream entrance areas along the jet stream axis and to its south, and the conversion from KE into PKE of the basic flow strengthens (weakens) over the jet stream entrance areas to the north of the jet stream axis.

4.2 The conversion from APE into PAPE of the basic flow

The summer climatological $S_B$ is shown in the longitude-height cross-sections along 35°N (to the south of the westerly jet stream axis) (Fig. 5a), 40°N (along the jet stream axis) (Fig. 5b), and 45°N (to the north of the jet stream axis) (Fig. 5c). The conversion between PAPE and APE of the basic flow mainly occurs below 200 hPa, with the maximum over 400–300 hPa. The wave source is located at the Asian jet stream entrance region along 35°N below 200 hPa, with its intensive part over the eastern Mediterranean-Caspian Sea, thus APE of the basic flow transforms into PAPE there. The wave sink regions ($S_B < 0$) are respectively over the Iranian Plateau and the eastern part of the Qinghai-Tibetan Plateau (to the east of 115°E). The distributions of $S_B$ along 40° and 35°N are consistent with those to the west of 80°E, and to the further west, $S_B$ further strengthens, indicating the strong conversion from APE into PAPE of the basic flow along the jet stream axis. The jet stream entrance along 45°N is still the wave source region, but the lower troposphere over Central Asia is the wave sink area, because the westerlies strengthen with height at this latitude ($\overline{u'} < 0$), and intense surface heating needs cold advection to balance ($\overline{\nu' T'} < 0$).

Figure 6 shows the $S_B$ anomalies for the positive/negative years of RWA. As is depicted in Fig. 6a, $S_B$ anomalies at the Asian jet stream entrance along 35°N below 200 hPa, and to the west of 60°E, display a strong positive anomaly over the East Black Sea...
Sea–Aral Sea, which indicates that the conversion from APE into PAPE is stronger than normal. For 60°–100°E, $S_B$ shows a negative anomaly, suggesting that the wave sink over the Iranian Plateau boosts up, and the conversion from PAPE into APE strengthens. While both the wave source and the wave sink regions over the west and east of the Qinghai-Tibetan Plateau weaken, the anomalies of $S_B$ along 40°/45°N are consistent with those along 35°N, but the wave source and sink regions are significantly stronger/weaker than those to the south of the jet stream. The above analysis suggests that for the positive years of RWA, the conversion from APE into PAPE of the basic flow strengthens along the jet stream axis and to both its south and its north (including over the Iranian Plateau and to its north). The anomalies of $S_B$ for the negative years are opposite to those for the positive years.

4.3 The PAPE induced by the diabatic heating

Figure 7 shows the summer climatological $S_C$ in longitude-height cross-sections along 35°, 40°, and 45°N. We can find that in the whole troposphere along 35°N (Fig. 7a) over the Iranian Plateau and the Qinghai-Tibetan Plateau, there exists intensive positive PAPE ($S_C > 0$) induced by diabatic heating, and the $S_C$ over the Iranian Plateau is larger than that over the Qinghai-Tibetan Plateau. The $S_C$ along 40°N still manifests strong PAPE, but in the mid-upper troposphere it is half as weak as that around 35°N. Meanwhile, the $S_C$ over the Mediterranean is similar to that over the two plateaus. The $S_C$ to the north of the two plateaus at lower levels is stronger than that at mid-upper levels, which is related to the summer land-surface intensive heating in this arid and semi-arid region. There are three equally intensive PAPE areas induced by the diabatic heating: the Mediterranean Sea, the Iranian Plateau and to its north, as well as the Qinghai-Tibetan Plateau and to its north. The $S_C$ at middle and high levels along 45°N further weakens, with weak PAPE east of the Black Sea–Aral Sea, and strong PAPE at lower levels over the mid Asia–northwestern China, which is correlated with the land-surface thermal heating in arid and semi-arid regions.

Figure 8 shows the $S_C$ anomalies for the positive and negative RWA years. The $S_C$ anomalies along the
Fig. 7. As in Fig. 3, but for $S_C (10^{-1} \text{ m}^2\text{s}^{-3})$.

Fig. 8. As in Fig. 4, but for $S_C (10^{-1} \text{ m}^2\text{s}^{-3})$. 
WAJS and western Qinghai-Tibetan Plateau are positive, indicating that PAPE over the eastern Mediterranean–western Qinghai-Tibetan Plateau are stronger than normal. The $S_C$ anomalies along $40^\circ$N are similar to those along $35^\circ$N, while the positive anomalies ($9 \times 10^{-1} \text{m}^2\text{s}^{-3}$) over the Iranian Plateau are stronger than those along $35^\circ$N. The $S_C$ anomalies between $40^\circ$ and $80^\circ$E along $45^\circ$N are still positive, indicating that for positive years, PAPE along the WASJ are stronger than the climatological mean, with the most significant along the jet stream axis. In contrast, for the weak years (Figs. 8c, 8d), the distribution of $S_C$ anomalies along the jet stream is basically opposite to that for the strong years. The above suggests that PAPE induced by diabatic heating over the Mediterranean Sea, the Iranian Plateau and to its north are the energy source of anomalous RWA.

The order of magnitude for $S_A$ and $S_B$ is $10^{-3} \text{m}^2\text{s}^{-3}$ and that of $S_C$ is $10^{-1} \text{m}^2\text{s}^{-3}$. The total energy $S_A + S_B + S_C$ (figure omitted) for the strong and weak years of RWA along the WASJ are similar to $S_C$, which indicates that PAPE engendered by diabatic heating near the WASJ in summer is much larger than the conversion from KE and APE of the basic flow into wave energy. This further validates the numerical simulation results drawn by Liu et al. (2003), that is, the main forcing factor of the summer subtropical planetary-scale stationary wave is the large-scale latent and sensible heating.

5. Conclusions

In the present study, we have investigated the wave sources, energy propagation and conversion for anomalous RWA along the WASJ. The main conclusions are summarized as follows:

1) The wave sources forced by stationary divergence are located over the Iceland–Scandinavian Peninsula and the western Mediterranean for the strong years of RWA, while they are over the Scandinavian Peninsula–central Europe and Eastern Mediterranean–Black Sea for the weak years.

2) In the strong (weak) years of RWA, strong divergence of the EP flux excites an eastward propagation of the Rossby wave. There are two horizontal wave activity propagating paths. 1) RWAs propagate eastward, turn southeastward near the Ural Mountains and then enter the ASWJS over the Caspian sea, the Aral Sea, and Xinjiang in China, and this propagation process strengthens (weakens) for strong (weak) years. 2) RWAs directly propagate southeastward and enter the ASWJS over the eastern Mediterranean–Black Sea, and this propagation process also strengthens (weakens) for strong (weak) years. Besides, the EP flux divergence over the Mediterranean Sea strengthens (weakens) as well, and they jointly strengthen (weaken) the RWA along the WASJ.

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