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Seasonal Variation of the East Asian Subtropical Westerly Jet and Its Association with the Heating Field over East Asia

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ABSTRACT

The structure and seasonal variation of the East Asian Subtropical Westerly Jet (EAWJ) and associations with heating fields over East Asia are examined by using NCEP/NCAR reanalysis data. Obvious differences exist in the westerly jet intensity and location in different regions and seasons due to the ocean-land distribution and seasonal thermal contrast, as well as the dynamic and thermodynamic impacts of the Tibetan Plateau. In winter, the EAWJ center is situated over the western Pacific Ocean and the intensity is reduced gradually from east to west over the East Asian region. In summer, the EAWJ center is located over the north of the Tibetan Plateau and the jet intensity is reduced evidently compared with that in winter. The EAWJ seasonal evolution is characterized by the obvious longitudinal inconsistency of the northward migration and in-phase southward retreat of the EAWJ axis. A good correspondence between the seasonal variations of EAWJ and the meridional differences of air temperature (MDT) in the mid-upper troposphere demonstrates that the MDT is the basic reason for the seasonal variation of EAWJ. Correlation analyses indicate that the Kuroshio Current region to the south of Japan and the Tibetan Plateau are the key areas for the variations of the EAWJ intensities in winter and in summer, respectively. The strong sensible and latent heating in the Kuroshio Current region is closely related to the intensification of EAWJ in winter. In summer, strong sensible heating in the Tibetan Plateau corresponds to the EAWJ strengthening and southward shift, while the weak sensible heating in the Tibetan Plateau is consistent with the EAWJ weakening and northward migration.

Key words: East Asian subtropical westerly jet, seasonal variation, meridional difference of temperature, heating fields over East Asia

1. Introduction

The East Asian Subtropical Westerly Jet (EAWJ) is a narrow and strong westerly wind belt with large horizontal and vertical wind shears over the East Asian subtropical region. The axis of maximum wind speed is located at 200 hPa and reaches its southernmost position in March and its northernmost position in August. There are two northward jumps during the seasonal evolution of the jet axis from winter to summer. The mean wind speed at the jet center is about 60 m s^{-1} in winter and is reduced to half of this in summer. Yin (1949) pointed out that the start of the season is related to the northward shift of the upper-level westerly jet over the south of the Himalayas. Ye et al. (1958) further revealed that the abrupt change of the seasonal circulation in June (October) is characterized by a sudden northward (southward) shift of westerlies and easterlies. The seasonal variation of EAWJ is usually used as a criterion to divide the natural weather seasons in East Asia (Sheng, 1986). Tao et al. (1958) found that the beginning and ending of the Mei-yu in East Asia is closely related to the two northward jumps of the south branch of the westerly jet over Asia in June and July. Dong et al. (1987) analyzed the interannual variation of the zonal westerlies at 500 hPa in the Northern Hemisphere and indicated that the westerly index over East Asia in summer is associated with the interannual variation of the Mei-yu in China in early summer. Liang and Wang (1998) employed observation data and NCAR Community Climate Atmosphere Model (CCM3) simulation results to examine the relationship between the East Asian monsoon precipitation and the tropospheric jet and found that the EAWJ is closely associated with the Mei-yu and polar fronts as well as jet-transverse circulations. Moreover, the interannual variation of the spring monsoon rainfall in South China is related to the anomalous circulation over the North Pacific, which is linked with the

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westerly jet over North Asia and with the polar vortex (Wang et al., 2002). Yang et al. (2002) demonstrated that the EAWJ seems to be linked to the climate signals of Asia and the Pacific more strongly compared with ENSO. Much research on the other climate signals accompanied by the variation of the EAWJ has also been done (Ding, 1992; Lau et al., 2000; Lu et al., 2002; Kim et al., 2002; Lu, 2004; Li et al., 2004).

Due to the significant impact of EAWJ on the East Asian climate, much research has been carried out on the formation mechanism of EAWJ. It was assumed from earlier research that the formation of EAWJ is related to the orography and the thermal contrast between land and sea (Bolin, 1950; Smagorinsky, 1953). The orographic forcing experiment in a Northern Hemisphere barotropic model showed that the maximum zonal wind centers always occur in the downstream of major mountains in the Northern Hemisphere (Held, 1983). However, seasonal and interannual variations of the westerly jet intensity and location cannot be explained by only considering orographic effects. Thus it was proposed that inhomogeneous heating causes the disturbance of mean flow and results in the formation of the jet stream. Krishnamurti (1979) found that there is an obvious association between tropical heating centers and westerly jet centers in the Northern Hemisphere in winter. Further study (Yang and Webster, 1990) has shown that convective heating in the tropical region in summer can influence the variations of jet location and intensity in the other hemisphere in winter. Furthermore, the seasonal variation of the westerly jet center is closely associated with the heating fields in the tropical region (Dong et al., 1999, 2001).

Based on the research mentioned above, it is clear that orography and diabatic heating play important roles in determining the EAWJ location and intensity. However, less attention has been paid to the impact of the increase of meridional temperature gradient to the north of 35°N, which results from the increase of air temperature in the troposphere over the Tibetan Plateau, on triggering the northward jumps and westward migrations of EAWJ. Therefore, it is meaningful work to differentiate the relative contributions of sensible heating, latent heating, radiation and convective heating over East Asia to the EAWJ seasonal variations. But so far most studies have merely analyzed the formation and variation of EAWJ at 500 hPa in the middle troposphere, and further investigations on EAWJ are inhibited due to the lack of long-term upper-air data. Research on the EAWJ in the upper troposphere near 200 hPa has relatively little. In this paper, the seasonal variations of EAWJ structure, intensity and location are investigated by using National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis data and the relationships between EAWJ seasonal variations and heating fields over East Asia are also examined.

2. Data

The NCEP/ NCAR monthly mean reanalysis data (Kalnay et al., 1996) are used in this paper. The selected meteorological variables include zonal wind, air temperature, surface sensible heat flux, and latent heat flux, spanning from 1948 to 2000. The horizontal resolution of the wind field and air temperature is 2.5° × 2.5° (the number of grid points is 144(lon)×73(lat), with 17 layers in the vertical direction. The horizontal resolution of the surface flux data is 1.875° × 1.875°, corresponding to the Gaussian grid points in the T62 spectral model.

3. The structure of the EAWJ

3.1 *Vertical structure*

Due to the orographic distribution in the East Asian continent, particularly the impact of the Tibetan Plateau on the atmospheric general circulation, there exist obvious differences in the vertical structures of westerlies over the different orography. Figure 1 shows the latitude-altitude section of the zonal winds along 140°E, 115°E, and 90°E, where the underlying surface is ocean, flat orography, and the Tibetan Plateau, respectively. In winter, as shown in Fig. 1a, b, c, the weak easterly is dominant in the low latitudes (south of 20°N), while the westerly prevails in mid-high latitudes and the wind speed gradually increases from the low to high level in the troposphere, with a maximum wind speed center located at 200 hPa. The vertical axis of the westerly is located near 40°N between 900 hPa and 800 hPa in the low troposphere. With the increase of altitude, the jet axis is almost vertical near 30°N between 700 hPa and 400 hPa in the middle troposphere, and the wind speed increases significantly. The jet axis migrates a little northward between 300 hPa and 100 hPa in the upper troposphere, and the wind speed reaches a maximum at 200 hPa. Nevertheless, obvious differences can be found in the three sections over different topography. The westerly along 140°E is the strongest among the three meridional sections with a maximum wind speed center at 200 hPa exceeding 70 m s^{-1}; that along 115°E is relatively weaker with an intensity of approximately 60 m s^{-1}, and that along 90°E is the weakest with an intensity of 40 m s^{-1}. Moreover, the westerly jet axis along

140°E is 2–3° of latitude more northward than the two other sections. In particular, it can be seen from the section along 90°E that the blocking and bifurcating actions of the Tibetan Plateau on the westerly wind are salient in winter. The westerlies are obviously divided into two branches from 700 hPa to 500 hPa because of the existence of the Tibetan Plateau, and the impact gradually reduces with the increase of altitude and almost disappears above 400 hPa. The centers of the westerly wind merge into one that attains a maximum value at 200 hPa between 25°N and 30°N to the south of the Tibetan Plateau.

In summer (Figs. 1d, e, f), the most significant feature of zonal wind is that tropical easterlies in the upper troposphere are strengthened and extend northward while the westerly intensity is reduced significantly and the westerly jet axis migrates northward compared with that in winter, although the maximum westerly wind speed center is still located at 200 hPa. Opposite to the case in winter, the wind speed near the westerly center at 200 hPa along 90°E is the strongest among the three sections with a magnitude of 30 m s^{-1}, and the wind speed along 140°E is the weakest with an intensity of about 25 m s^{-1}. Along 90°E (Fig. 1d), the easterly wind system in the upper level over

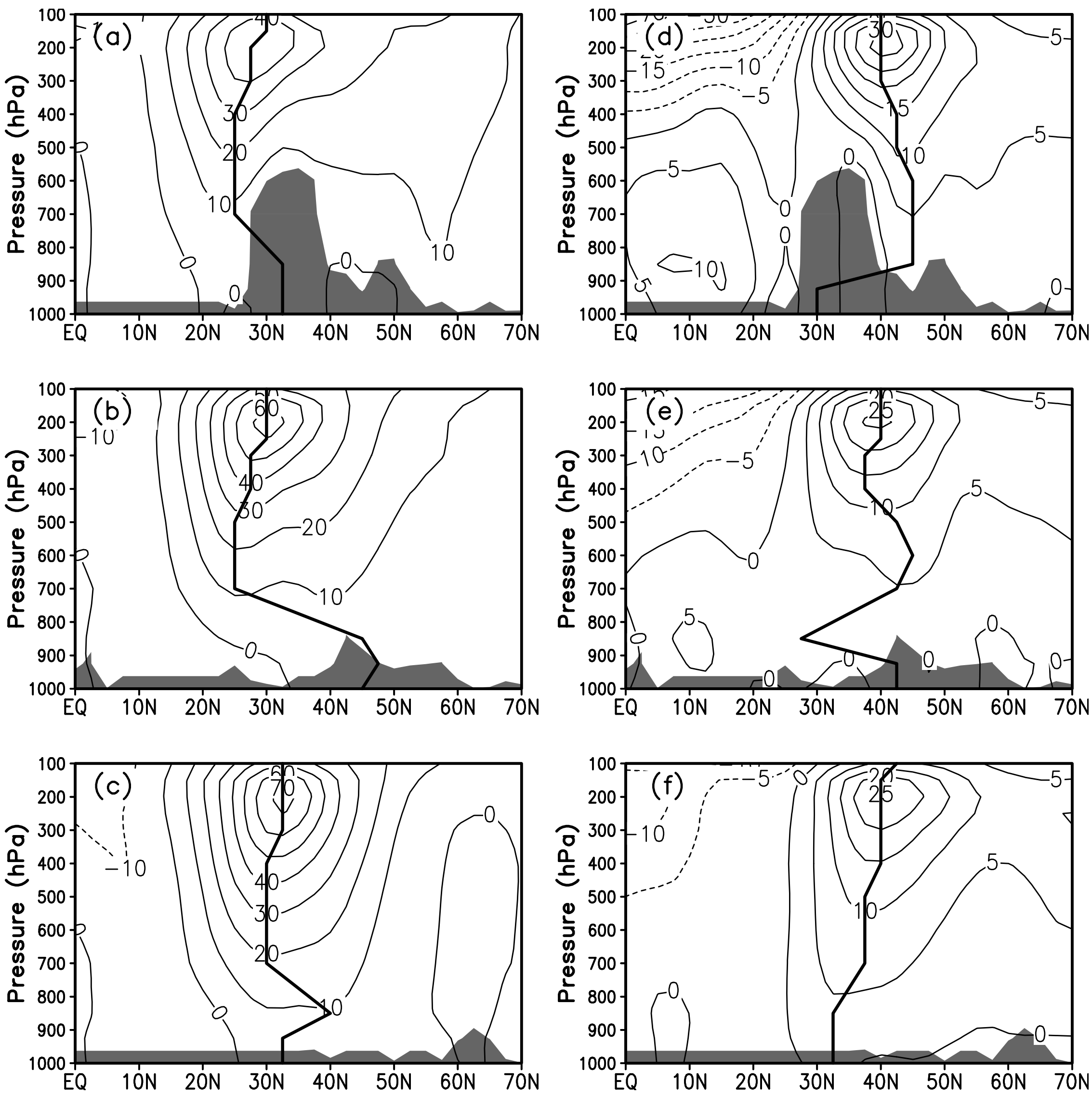

Fig. 1. The latitude-altitude sections of zonal wind speed along (a) 90°E, (b) 115°E, and (c) 140°E in winter (from December to February) and along (d) 90°E, (e) 115°E, and (f) 140°E in summer (from June to August). The bold solid line represents the vertical westerly axis. The shaded areas represent topography. (Units: m s^{-1})

the low latitudes is relatively strong and its intensity attains a value of 25 m s^{-1} near 100 hPa while the westerly center is located over the north of the Tibetan Plateau, and the westerly jet axis gradually tilts somewhat southward from the low to upper level. However, the vertical westerly axis along 140°E is situated near 30°N in the low level and is located near 40°N at 200 hPa, namely, the westerly axis gradually tilts to the north from the low to upper level in summer (Fig. 1f).

Figure 2 shows the longitude-altitude sections of zonal wind speed along 30°N in winter and along 42°N in summer, respectively. The westerly over the sea is markedly stronger than that over the land during wintertime, and the westerly center at 200 hPa is situated over the ocean. The axis gradually tilts to the west from 155°E to 140°E. In summer, two westerly centers at 200 hPa can be found, the stronger one located over the Tibetan Plateau, and the other one situated over the western Pacific.

3.2 *Horizontal structure*

Because the East Asian subtropical westerly is strongest at 200 hPa, this section focuses on the horizontal structure of the East Asian subtropical westerly jet at 200 hPa. The distributions of the zonal wind speeds at 200 hPa in winter and summer are given in Fig. 3. The easterly wind prevails over the regions to the south of 10°N at 200 hPa, and the maximum easterly center is located near the Indonesian Islands with an intensity of 10 m s^{-1}. The westerly is dominant to the north of 10°N, and the intensity of the westerly wind is relatively strong between 20°N and 40°N, mostly exceeding 30 m s^{-1}. The EAWJ axis is situated near 30°N, and the EAWJ center is located over the ocean to the south of Japan, nearly at 140°E and 32°N, with an intensity of more than 70 m s^{-1}. In summer, the tropical easterly wind intensifies and expands northwards to the north of 20°N. The EAWJ axis migrates to the area near 42°N, about 10° more north than the location in winter. The EAWJ center appears at 90°E and 40°N over the Tibetan Plateau, and its intensity is merely 30 m s^{-1}, significantly weaker compared with that in winter.

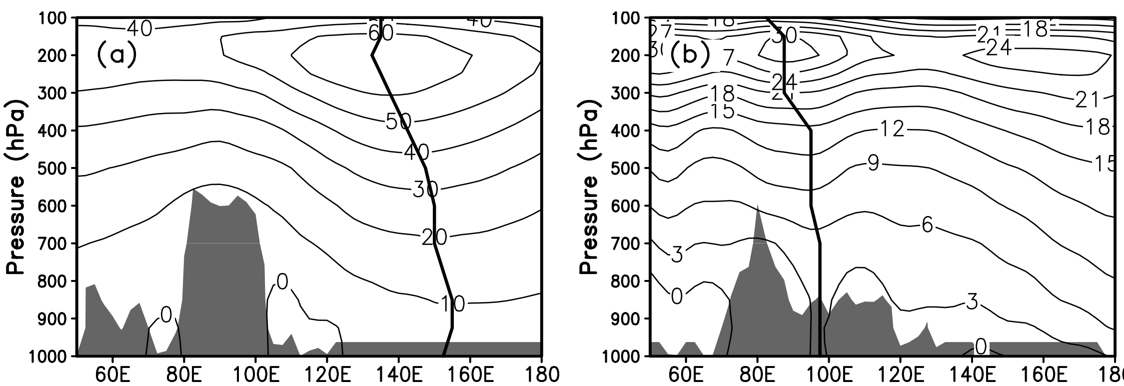

Fig. 2. The longitude-altitude sections of zonal wind speed (a) along 30°N in winter and (b) along 42°N in summer. The bold solid line represents the vertical westerly axis. The shaded areas represent topography. (Units: m s^{-1})

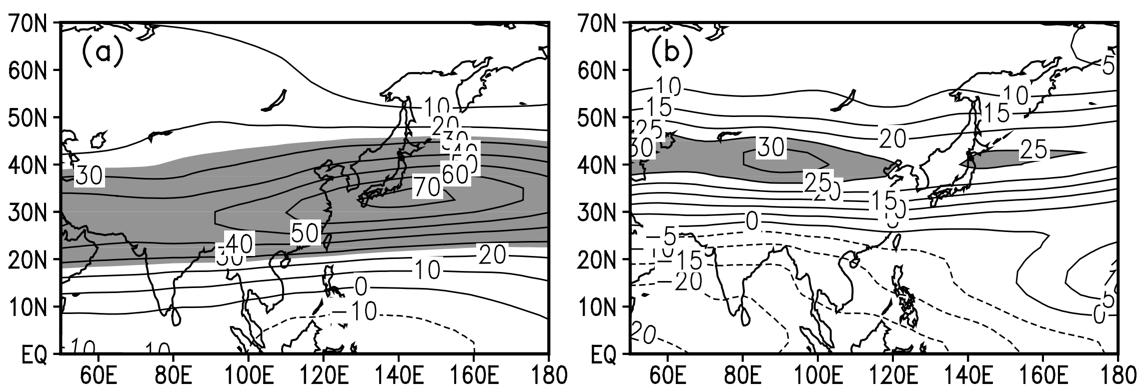

Fig. 3. The distributions of the zonal wind speed at 200 hPa (a) in winter and (b) in summer (Units: m s^{-1}; values exceeding 25 m s^{-1} are shaded).

3.3 *Annual cycle of EAWJ axis*

The location of the rain-belt in East Asia is closely related to the meridional shift of EAWJ (Lu, 2004), so we focus on the annual cycle of the EAWJ axis in this section. The seasonal meridional shift of the EAWJ axis can be divided into three periods (Fig. 4): stationary period, northward migration, and southward withdrawal. The first period is from January to March during which the EAWJ axis is steadily located near 30°N, which is somewhat more northward in the east than in the west. From April to August is the northward migration period. In April the eastern segment of the EAWJ axis over the ocean moves northward first while the western part of the EAWJ axis over the Eurasian continent is still stationary. The first integral northward jump of the EAWJ axis with a magnitude of about 5° of latitude occurs from April to May, which is consistent with the onset of the South China Sea summer monsoon (Li et al., 2004), and the amplitude of the shift over land is larger than that over the ocean. In June, the segment to the west of 100°E moves northward swiftly but the eastern segment seems stationary. From June to July, the second integral northward jump of the EAWJ axis occurs, which is thought to be closely related to the "Mei-yu" in East China (Li et al., 2004). In August, the EAWJ axis to the east of 100°E continues to move northward and reaches the northernmost position of the year. September to December, i.e. the retreat period of the EAWJ axis, is mainly characterized by the integral withdrawal of the EAWJ. To sum up, there is obvious longitudinal inconsistency in the northward migration and in-phase southward retreat of the axis in the annual cycle of the EAWJ evolution.

4. The mechanism of the EAWJ seasonal variation

Based on the principle of thermal wind:

$$\frac{\partial U}{\partial p} = \left(\frac{R}{fp}\right)\frac{\partial T}{\partial y}\,,$$

the variation of zonal wind (U) with altitude depends on the meridional gradient of air temperature (T). If the air temperature is decreased poleward, the westerly increases or the easterly decreases with altitude; on the contrary, if the air temperature is increased poleward, the westerly weakens or the easterly intensifies. Therefore, strong zonal winds normally appear over the frontal area of the troposphere, and the intensity of the zonal winds is directly proportional to the intensity of the meridional gradient of air temperature.

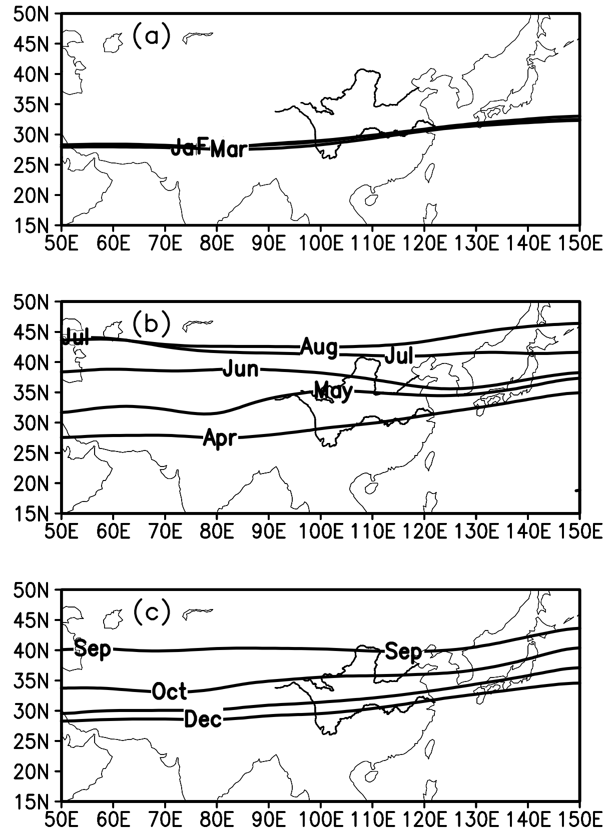

Fig. 4. The annual cycle of the EAWJ axis (a) from January to March, (b) from April to August, and (c) from September to December.

Figure 5 shows the distribution of meridional differences of air temperature (MDT) averaged between 500 hPa and 200 hPa. The MDT field is calculated by using the air temperature in the south minus that in the north with a 2.5° of latitude interval, so the positive MDT means it is relatively warmer in the south and colder in the north. Note that the distribution patterns of MDT in Fig. 5 match very well with the zonal wind distributions in Fig. 3. In winter, the values of MDT are positive over most regions of East Asia, and the maximum center is located at 140°E and 32°N with a magnitude of about 3.5°C, where the EAWJ center is just situated and the EAWJ intensity reaches its annual maximum. In summer, the values of MDT are negative over the low latitudes to the south of 25°N, where the easterly is dominant, and positive over the mid-high latitudes, with an MDT center in the region to the north of the Tibetan Plateau, corresponding to the EAWJ center.

Figure 6 illustrates the longitude-month variation of mean MDT between 500 hPa and 200 hPa and the zonal wind at 200 hPa averaged between 30°N and 45°N. The correspondence of MDT and EAWJ can be

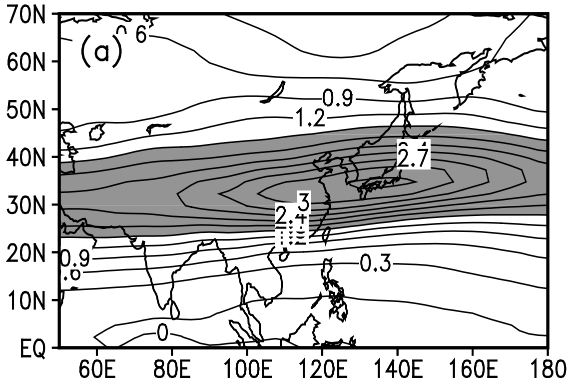

Fig. 5. The meridional differences of air temperature averaged between 500 hPa and 200 hPa (a) in winter and (b) in summer. (Units: °C; values exceeding 1.5°C are shaded.)

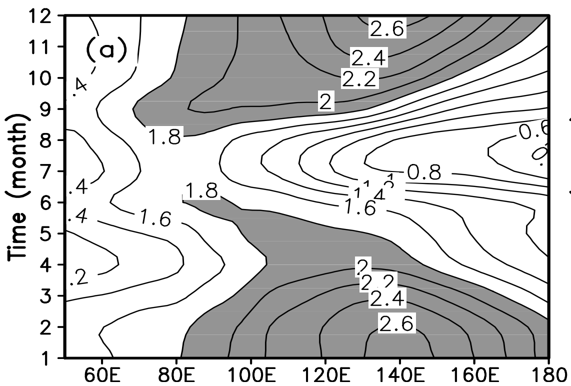

Fig. 6. Longitude-season variations of (a) mean MDT between 500 hPa and 200 hPa (Units: °C; values exceeding 1.8°C are shaded) and (b) zonal wind at 200 hPa (Units: m s^{-1}; values exceeding 30 m s^{-1} are shaded) averaged between 30°N and 45°N.

clearly seen in the figure. Note that due to the strong cooling of the land from January to March, the values of MDT are relatively large during the whole year. The maximum value of more than 2.2°C occurs near 140°E. The EAWJ center also appears at this position and its intensity becomes the strongest out of the whole year. In April, due to the gradual increase of air temperature, the MDT is reduced, and the EAWJ intensity over the region to the south of Japan weakens too and the location of the center moves westwards. In May and June, the MDT is reduced further and is merely in the range 1.0°C–2.0°C, and the EAWJ weakens evidently. In July and August, the MDT reaches its minimum value of the whole year, which is only 0.5°C–1.8°C, but due to the heating effect of the Tibetan Plateau, the maximum MDT appears between 70°E and 90°E. This matches very well with the facts that the westerly jet attains its weakest value of the whole year and the jet center migrates to the north of the Tibetan Plateau. After September, the MDT increases, and the EAWJ gradually intensifies and migrates eastwards again. Therefore, the EAWJ intensity and east-west migration correspond to the MDT distribution very well.

Comparison of the MDT axis seasonal migration with that of the EAWJ axis shows that the seasonal variations of EAWJ intensity and location are in good accordance with the variations of MDT. This indicates that the MDT variation is the basic reason for the EAWJ seasonal evolution.

5. Relationship between EAWJ and the heating fields

As mentioned above, the EAWJ seasonal variation is determined by the MDT in the mid-upper troposphere, which is basically associated with the air temperature changes at different latitudes. According to the thermodynamics equation, the local temperature change is the integrated results of temperature horizontal and vertical advection, and the diabatic heating, which includes solar radiation, sensible heat, latent heat and so on. In this paper, we only focus on the relationship between the diabatic heating, particularly the surface sensible heating (SH) and latent heating (LH), and the variation of the MDT field, which is the basic reason for the variation of the EAWJ.

5.1 *Definitions of the EAWJ indices*

Because the EAWJ seasonal variation is mainly characterized by the jet intensity change and location shift, four indices are defined in this section to quantitatively depict the EAWJ variation. As the EAWJ center is over the western Pacific Ocean in winter and migrates to the north of the Tibetan Plateau in summer, the correlations between the zonal wind speed at the base point of the EAWJ center (winter: 32°N, 140°E, and summer: 40°N, 90°E) and that at every point at 200 hPa are calculated, and the areas with relatively larger correlation coefficients are selected to define the EAWJ indices. The EAWJ intensity index in winter (IIW) is defined as the mean zonal wind speed within the area (30°–40°N, 120°E–160°E) at 200 hPa, and the EAWJ location index in winter (ILW) is defined as the mean EAWJ axis location (latitude) between 120°E and 160°E in winter. Likewise, the EAWJ intensity index in summer (IIS) is the same as IIW but within the area (30°–45°N, 75°–115°E), and the EAWJ location index in summer (ILS) is the same as ILW but between 75°E and 115°E in summer. Figure 7 shows the interannual variations of the four indices. It can be seen that obvious interannual variations exist in the four indices, and there is a good relationship between IIS and ILS with a correlation coefficient of −0.759.

5.2 *Correlation analysis*

From the distributions of mean SH and LH in winter and in summer(not shown), several strong heating centers are selected for the following analysis: SH in the Kuroshio Current area in the western Pacific (20°–40°N, 120°–160°E) in winter; SH in the north of the Tibetan Plateau (35°–45°N, 80°–110°E) in summer; LH in the Kuroshio Current area in the western Pacific (20°–40°N, 120°–160°E) in winter; LH in the Arabian Sea (5°–15°N, 50°–70°E) and the Bay of Bengal (5°–15°N, 80°–100°E) in summer. The simultaneous correlations between the indices and the SH and LH of the heating centers are given in Table 1. In winter there exists a significant relationship between the EAWJ intensity and the sensible heat and latent heat

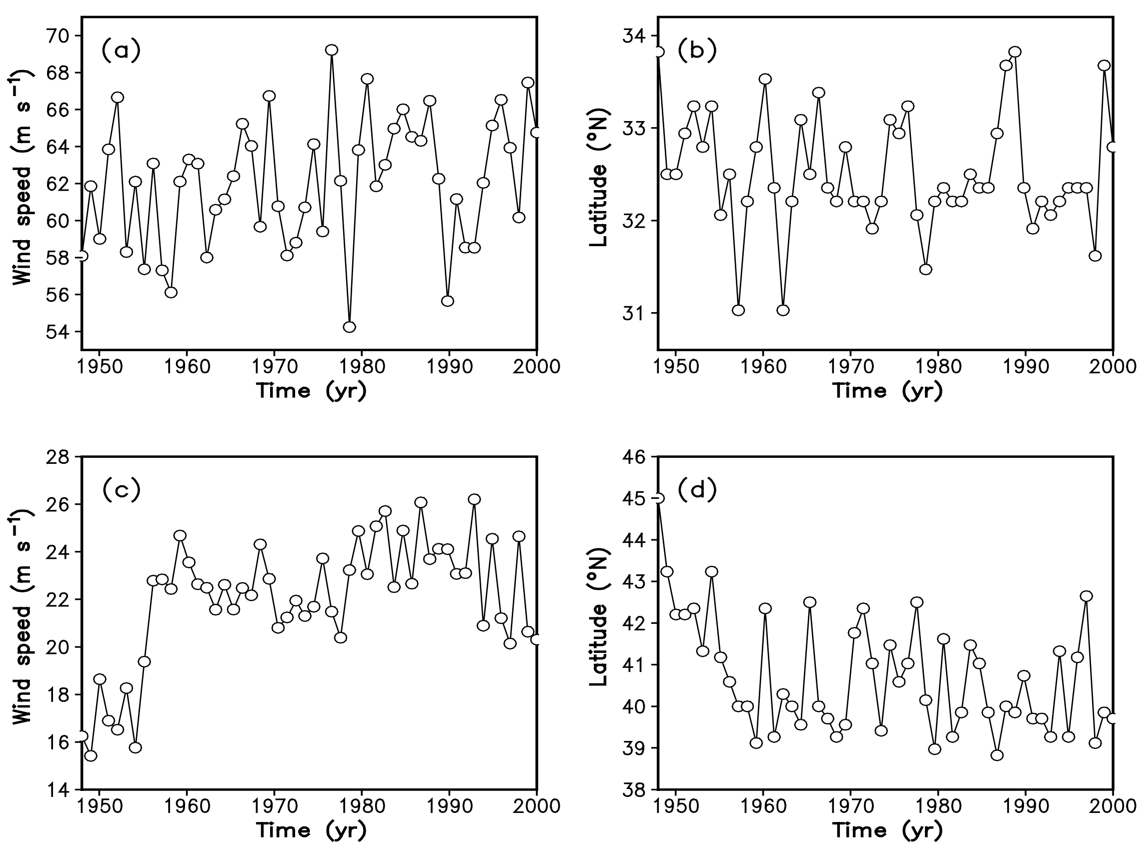

Fig. 7. The year-to-year variations of the EAWJ indices: (a) intensity index in winter, (b) location index in winter, (c) intensity index in summer, and (d) location index in summer. (Units of intensity index: m s^{-1}; Units of location index: °N).

Table 1. Simultaneous correlations between the indices and the SH and LH of the heating centers.

Index	Winter		Summer		
	Sensible heat flux	Latent heat flux	Sensible heat flux	Latent heat flux	
	Kuroshio Current area (20°–40°N, 120°–160°E)	Kuroshio Current area (20°–40°N, 120°–160°E)	North of Tibetan Plateau (35°–45°N, 80°–110°E)	Arabian Sea (5°–15°N, 50°–70°E)	Bay of Bengal (5°–15°N, 80°–100°E)
IIW	0.636	0.579			
ILW	0.007	0.075			
IIS			0.698	0.552	−0.264
ILS			−0.468	−0.431	0.145

flux in the area of the Kuroshio Current to the south of Japan, where the correlation coefficients reach above 0.636 and 0.579 respectively. This means that a larger (smaller) heating in the regions corresponds to a stronger (weaker) EAWJ. However the location index is not well correlated with the heat flux fields in this region. In summer, the correlations between the intensity index and location index of the EAWJ and the surface sensible heat flux in the north of the Tibetan Plateau reach 0.698 and −0.468 respectively, and both exceed the 99% confidence level, suggesting a significant relationship between the sensible heating of the Tibetan Plateau and the EAWJ. Strong sensible heating in the Tibetan Plateau corresponds to the EAWJ strengthening and southward shift, while weak sensible heating in the Tibetan Plateau results in EAWJ weakening and northward migration. From Table 1, the latent heating in the Arabian Sea also shows the apparent connection with the EAWJ, which is similar to the SH in the north of the Tibetan Plateau. Figure 8 gives the simultaneous correlation between the intensity index of EAWJ and the sensible heat flux in winter and in summer. The noticeable relationships between the heating in the Kuroshio Current area and the SH in the Tibetan Plateau with the EAWJ are clearly identified.

The above analyses reveal the significant relationships between SH and LH in East Asia and the EAWJ statistically. Based on the analysis in section 4, the seasonal variation of EAWJ corresponds to the change of MDT, so it can be reasonably assumed that the heating fields first influence the temperature structure, then result in the changes of the MDT and the pressure, thus leading to the adjustment of the wind to the pressure field. Figure 9 shows the simultaneous correlations between SH in the Kuroshio Current area in winter and that in the north of the Tibetan Plateau in summer with the MDT field averaged between 500 hPa and 200 hPa. We can see that the correlations between SH in the Kuroshio Current area and MDT show a −/+/− pattern from low latitudes to high latitudes, and the positive correlation center with a value exceeding 0.7 corresponds to the EAWJ center. This indicates that the stronger heating in the regions leads to the larger MDT in the mid-latitudes and the weaker MDT in the low and high latitudes, resulting in the intensification of the EAWJ. As for the case in summer, the correlation distribution shows an out-of-phase variation on the two sides of the location of the EAWJ axis. In the north is a negative correlation area while

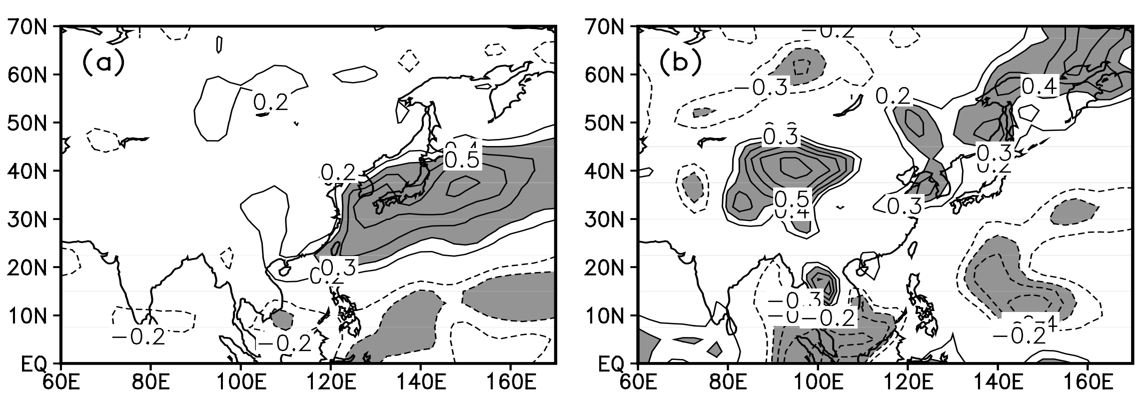

Fig. 8. Simultaneous correlations between the intensity index of the EAWJ and sensible heat flux (a) in winter and (b) in summer (values exceeding the 99% confidence level are shaded; contours with an absolute value smaller than 0.2 are not shown).

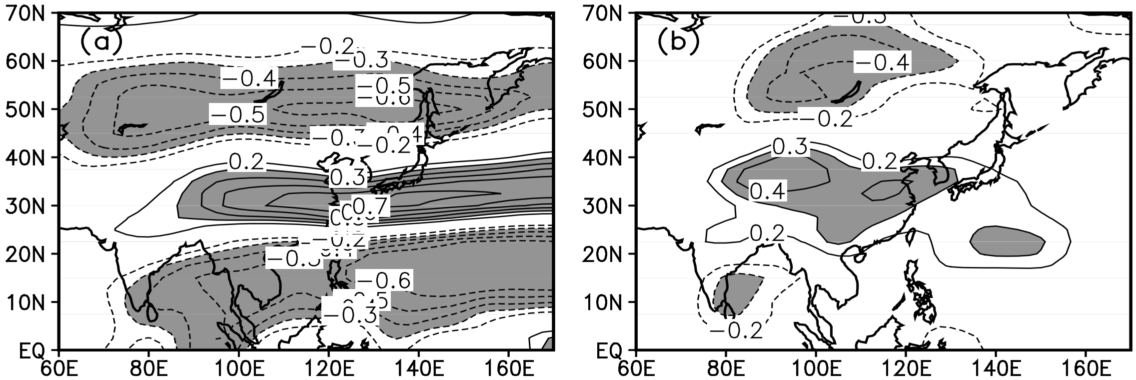

Fig. 9. Simultaneous correlations between sensible heat flux (a) in the area of the Kuroshio Current in winter, (b) in the north of the Tibetan Plateau in summer and the MDT field averaged between 500 hPa and 200 hPa (values exceeding the 99% confidence level are shaded; contours with an absolute value smaller than 0.2 are not shown).

in the south is a positive correlation area. This means that the strong SH of the Tibetan Plateau leads to the MDT decrease over high latitudes to the north of the Tibetan Plateau and an increase over the Plateau regions, which results in the southward shift of the EAWJ.

6. Conclusions

The structure and seasonal variation of the East Asian Subtropical Westerly Jet and their associations with the heating fields over East Asia are investigated. There exist significant differences in intensity and location of the structure of the westerly wind in different regions and seasons due to the ocean-land distribution and the seasonal thermal contrast, as well as the dynamic and thermodynamic impacts of the Tibetan Plateau. In winter, the jet center is situated over the western Pacific Ocean and the intensity of the westerly is gradually reduced from east to west over East Asia. In summer, the EAWJ center is located over the north of the Tibetan Plateau and the intensity is reduced significantly compared with that in winter. The seasonal meridional shift of the EAWJ axis can be divided into three periods: stationary period, northward migration and southward withdrawal, and the obvious longitudinal inconsistency of the northward migration and in-phase southward retreat of the EAWJ axis occur in the annual cycle of the EAWJ evolution.

Seasonal variations of EAWJ intensity and location are in accordance with variations of meridional differences of air temperature, which indicates that the meridional difference of air temperature is the basic reason for the seasonal variation of EAWJ. According to the correlation analyses on the relationship between the heating fields and the EAWJ, the Kuroshio Current region to the south of Japan is the key area for the EAWJ intensity variation in winter. The larger the heating in the regions is, the stronger the EAWJ intensity is. Otherwise, the westerly jet intensity weakens. In summer, SH in the north of the Tibetan Plateau and LH in the Arabian Sea have similar significant correlations with the EAWJ intensity and location. When sensible heating to the North of the Tibetan Plateau is strong, the EAWJ is strengthened and shifts southward; when sensible heating in this region is weak, the EAWJ weakens and migrates northward.

The significant correlation between the heating field and MDT indicates that the heating field first influences the temperature structure, then results in the changes of the MDT and the pressure field, thus leading to the adjustment of the wind field and the variation of the EAWJ. The above analyses are mainly based on data analysis, so our future work is to use a numerical model to verify the above conclusions and further study the thermal mechanism of the EAWJ.

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