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Has the East Asian Westerly Jet Experienced a Poleward Displacement in Recent Decades?

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ABSTRACT

Previous studies have suggested a poleward shift of the zonally averaged jet stream due to rapid warming over continents. However, the regional characteristics of the change in the jet stream are not yet understood. Here, we present evidence suggesting that the East Asian westerly jet did not shift poleward in past decades (1980–2004 relative to 1958–1979), both in winter and summer. Rather, the jet axis has moved southward in summer, but its meridional position is steady in winter. The main change of the jet stream in winter is the enhancement of its intensity. These changes in both summer and winter are consistent with the corresponding changes in the large meridional tropospheric temperature-gradient zone. Based on these results, we suggest that the changes of the jet stream over East Asia are unique and are different from the zonal mean jet stream over the Northern Hemisphere and over the North Atlantic region.

Key words: East Asian westerly jet, meridional displacement, decadal changes

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1. Introduction

The East Asian westerly jet stream (EAWJ), defined as a narrow and strong westerly belt with large horizontal and vertical wind shears in the upper troposphere and lower stratosphere over the East Asia, plays an important role in the East Asian climate change. Variation in the EAWJ is characterized by prominent seasonal evolution, by interannual to decadal variability in its intensity, and by meridional location. On the seasonal time scale, the EAWJ axis experiences meridional migration from winter to summer, which is closely related to the monsoon climate in East Asia (Tao et al., 1958; Yeh et al., 1958; Liang and Wang, 1998; Li et al., 2004; Zhang et al., 2006). On interannual and decadal time scales, the meridional shift of EAWJ is also associated with the shift in the rain band over the East Asian monsoon region (Yu and Zhou, 2004; Lu, 2004; Lin and Lu, 2005; Li et al., 2005).

The change of the jet stream under global warming has been a popular topic because of its climatic impacts. Previous studies have suggested that the faster atmospheric warming in the subtropics pushes jet streams poleward (Seidel and Randel, 2007; Solomon et al., 2007). For example, a trend toward a deeper polar vortex and an Icelandic low associated with a positive phase of the Northern Hemisphere Annular Mode (NAM) in winter (Hurrell, 1995; Thompson et al., 2000; Ostermeier and Wallace, 2003) was accompanied by intensification and poleward displacement of the Atlantic polar frontal jet and by associated enhancement of the Atlantic storm activity (Chang and Fu, 2002; Harnik and Chang, 2003). Analogous trends have also been found in the southern hemisphere (Kushner et al., 2001; Gallego et al., 2005). As indirect evidence, the IPCC AR4 (Solomon et al., 2007) mentions that poleward shifts in storm location and the mean latitudes of extratropical cyclones, with storm and cyclone intensity increasing over the North Pacific and North Atlantic, occurred in the second half of the 20th century. Yin (2005) presented a consistent poleward and upward shift and intensification of zonal mean storm track in a 15-member multi-model ensemble of the upper midlatitude troposphere and lower stratosphere. In addition, Fu et al. (2006) made an inference that a poleward shift of the jet stream occurred $\sim 1^{\circ}$ from the temperature change, based on satellite-borne microwave sounding unit (MSU) data

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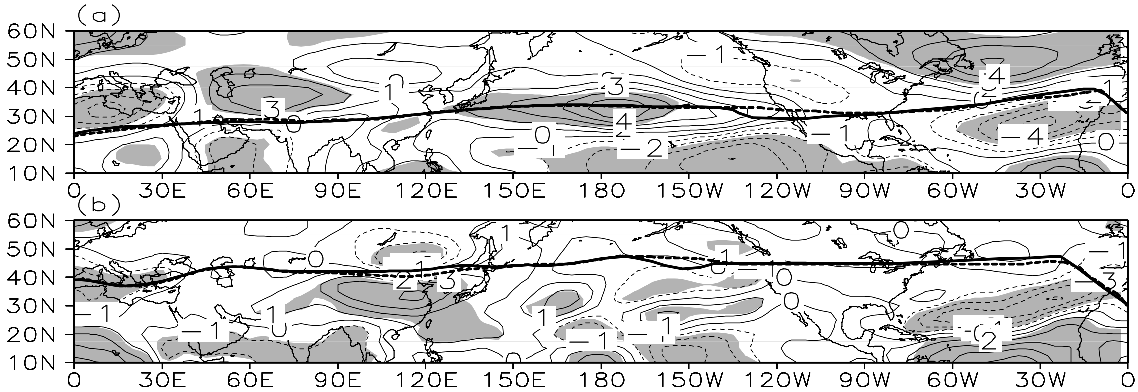

Fig. 1. Mean 200-hPa zonal wind changes for (a) winter (DJF) and (b) summer (JA) (1980–2004 mean minus 1958–1979 mean; units: m s^{-1}). The solid and dashed bold lines represent the westerly jet axis, i.e. the location of mean maximum wind speed at each longitude, during 1958–1979 and 1980–2004, respectively. The shaded areas indicate statistical significance at the 95% confidence level.

from 1979 to 2005. They found an enhanced stratospheric cooling and tropospheric warming in the 15°–45° (latitude) belts of both hemispheres, relative to other latitudes, inferring that the downward slope of the pressure surfaces toward the poles was increasing on the poleward flanks of the jet streams and decreasing on the equatorward flanks. Such a reshaping of the pressure surfaces is associated with the poleward shift of the jet streams.

These studies mainly focused on the jet stream over subtropical oceans; less effort has been devoted to the jet stream over East Asia. There is limited evidence to indicate that the zonal wind south to the EAWJ axis has been increasing, accompanying a distinctive, strong, tropospheric cooling trend over East Asia during July and August, which results in a tendency toward increased droughts in northern China and floods along the Yangtze River valley (Yu et al., 2004). Apparently, there is no consensus on the variation of the westerly jet in the subtropical region. Due to the special features of monsoon climate in East Asia, the EAWJ variation may be different from that over other regions. In this study, both the location and intensity changes of the EAWJ axis of the upper troposphere in winter and summer were investigated using NCEP/NCAR reanalysis data (Kalnay et al., 1996). The main objective was to examine whether the EAWJ axis has experienced a poleward displacement during recent decades. The results suggest a southward rather than northward displacement of the westerly jet axis over East Asia in summer, which is different from the zonal mean jet stream globally and over the North Atlantic sector in particular. During winter, the westerly jet stream has intensified in strength but has not shown any meridional displacement in the axis. Analyses based on the ERA40 data (Uppala et al., 2005) have revealed highly consistent results, adding fidelity to the robustness of the results. For brevity, here we only present the results derived from NCEP/NCAR reanalysis.

2. Results

2.1 *Change of the EAWJ in winter*

Because the strong westerly wind over midlatitudes is located at 200 hPa throughout the year, the EAWJ is normally defined as the 200-hPa westerly wind stronger than 30 m s^{-1}, and the EAWJ axis is normally defined as the location of maximum wind speed at each longitude (Zhang et al., 2006). Previous studies have revealed an interdecadal shift of the eastern Asian climate around the end of 1970s (Hu, 1997; Yu and Zhou, 2004; Li et al., 2005; Xin et al., 2006). To identify the interdecadal change of the EAWJ axis over East Asia and its peculiarity in comparison with other regions, the mean 200-hPa zonal wind changes in winter (December–January–February, DJF; the 1980–2004 mean minus the 1958–1979 mean) are shown in Fig. 1a. The westerly wind is dominant in middle-high latitudes over East Asia in winter, and the EAWJ axis is situated around 30°N, with the maximum zonal wind speed exceeding 60 m s^{-1} over the ocean to the southeast of Japan (Zhang et al., 2006). The difference between the mean zonal winds during 1980–2004 and 1958–1979 shows an obvious enhancement of the westerly jet intensity along the jet axis at the exit region of the EAWJ over the central north Pacific. These differences are significant at the 95% confidence level. However, the EAWJ axis has not demonstrated any meridional displacement during the past two decades, except over the eastern Pacific, where the jet axis shifts northward. Over the Atlantic sector and western Asia, the zonal wind intensifies to the north of the jet axis and weakens to the south of the axis. This evidence indicates that the interdecadal change of the wintertime EAWJ axis is inconsistent with the change in zonal mean location of the westerly jet axis and in the Atlantic region, suggesting that the climate change in East Asia may be different from that in other regions.

2.2 *Change of the EAWJ in summer*

Because the EAWJ core occurs most frequently over the East Asian continent in July and August (Zhang et al., 2006), the mean zonal wind for July and August was used to analyze the interdecadal change of the EAWJ axis in summer. The mean 200-hPa zonal wind changes in summer (July–August, JA) (the 1980–2004 mean minus the 1958–1979 mean) are given in Fig. 1b. Apparently, the changes of the intensity and the location of the EAWJ in summer are different from that in winter. The difference between the mean zonal winds in summer during 1980–2004 and 1958–1979 shows an enhancement of the westerly jet at the southern side of the EAWJ axis over eastern China and a weakening of the westerly jet at the northern side, both of which are significant at the 95% confidence level. The EAWJ axis exhibits an obvious southward displacement during the past two decades. Over the eastern Pacific and the Atlantic Ocean, the westerly wind intensifies at the northern side of the jet axis and weakens at the southern side of the jet axis, leading to a northward shift of the westerly jet axis. To contrast the meridional displacement of the westerly jet stream in summer between the East Asia, the zonal mean and the North Atlantic, the latitude–time cross sections of 200-hPa zonal winds averaged along different longitudes are shown in Fig. 2. A prominent southward displacement of the EAWJ axis from the end of 1970s is evident in Fig. 2a, indicating that interdecadal change in the EAWJ occurred in the late 1970s, which is consistent with the regime shift of the atmospheric circulation and oceanic condition in the East Asian and Pacific regions (Zhang et al., 1997; Mantua et al., 1997). However, the meridional displacements of the westerly jet stream, averaged globally and over the Atlantic sector, are different from those over East Asia, where the westerly jet axes shift poleward apparently (Figs. 2b and c), consistent with the storm track changes over these regions (Yin, 2005; Solomon et al., 2007). Therefore, the interdecadal climate change over East Asia may be unique, relative to other regions in the globe. Moreover, obvious changes in the westerly jet location and intensity over East Asia that occurred after the 1990s can be seen in Fig. 2a. The strong zonal wind extends northward at the

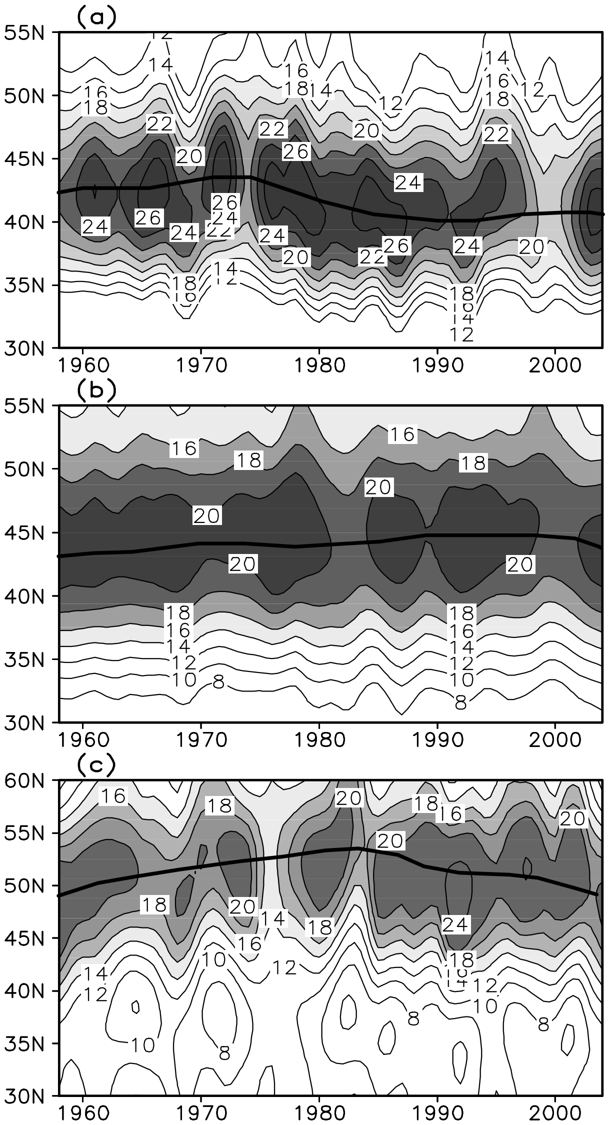

Fig. 2. The latitude-time cross sections of 200-hPa zonal wind in summer (units: m s^{-1}): (a) East Asian sector averaged from 100°E to 130°E, (b) global zonal mean and (c) Atlantic sector averaged from 0°E to 30°E, respectively. The solid bold lines represent the westerly jet axis.

beginning of 1990s, then the westerly jet weakens at the end of 1990s and intensifies from early 2000s. Recently, Ding et al. (2008) found that the summer rainfall in eastern China has experienced two decadal shifts, one in the late 1970s, and the other at the beginning of 1990s. The changes in the westerly jet location and intensity at the beginning of 1990s are probably associated with the shift in rainfall pattern that occurred in 1992 (identified by Ding et al., 2008). To further analyze the differences between the zonal winds between two periods of 1993–2004 and 1979–1992, the

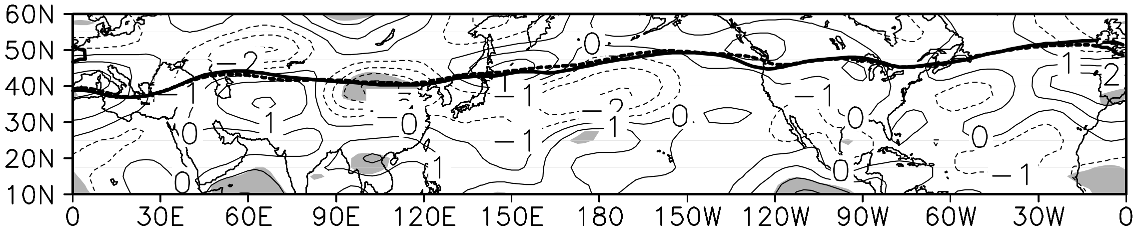

Fig. 3. Mean 200-hPa zonal wind changes for summer (JA) (1993–2004 mean minus 1979–1992 mean; units: m s^{-1}). The solid and dashed bold lines represent the westerly jet axis during 1979–1992 and 1993–2004, respectively. The shaded areas are statistically significant at the 95% confidence level.

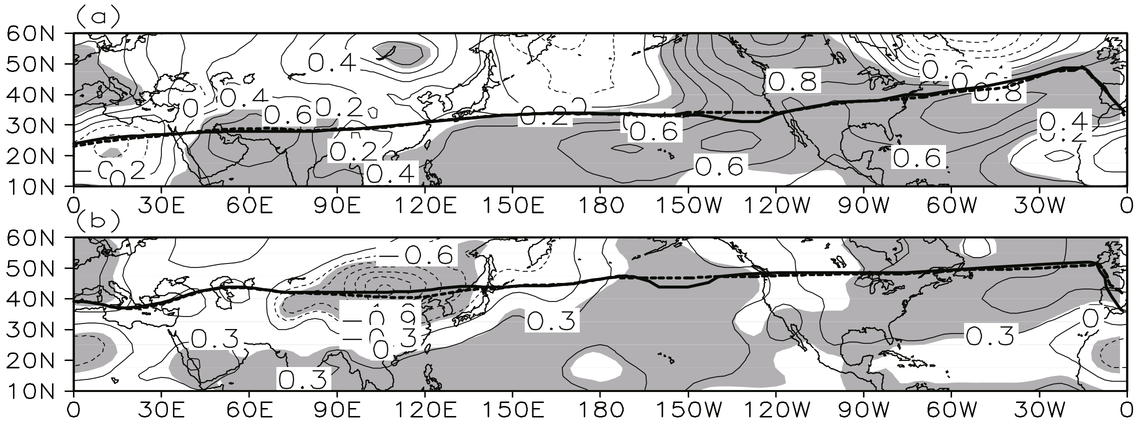

Fig. 4. (a) Winter and (b) summer temperature differences (1980–2004 mean minus 1958–1979 mean) averaged from 850-hPa to 200-hPa. The solid and dashed bold lines are the same as in Fig. 1 in (a) and (b). The contour interval is 0.1°C. The shaded areas are statistically significant at the 95% confidence level.

mean 200-hPa zonal wind changes for summer (JA) are shown in Fig. 3. Apparently, the westerly jet stream over East Asia weakens after 1992, and the westerly jet axis did not experience a meridional shift. Thus, the westerly jet changes are quite different during these two periods. Further investigation of this issue is beyond the scope of this study.

2.3 *Change of the temperature gradient in the upper troposphere*

The upper tropospheric westerly jet formation is associated with the meridional temperature gradient below the jet stream. Based on the principle of thermal wind, if the air temperature is decreased poleward, the westerly increases or the easterly decreases with altitude; on the contrary, if the air temperature increases poleward, the westerly weakens or the easterly intensifies, and the intensity of jet stream is directly proportional to the meridional temperature gradient (MTG; Wallace and Hobbs, 2005; Zhang et al., 2006). Figures 4 and 5 present the temperature changes and the MTG changes, averaged from 850 hPa to 200 hPa, between the 1980–2004 mean and the 1958–1979 mean in winter and summer (Figs. 4a and b), as well as the latitude-height cross section averaged over the longitudes between 90°E and 130°E during summer (Fig. 6). The MTG was calculated using the air temperature in the south minus that in the north, with a 2.5° (latitude) interval. A weak warming in winter can be seen along the westerly jet axis over western Asia and the subtropical Pacific and Atlantic, except for a weak cooling over the northern Africa (Fig. 4a). The maximum MTG increase occurs along the westerly jet axis (Fig. 5a), corresponding to the enhancement of the westerly jet intensity at the exit region of the EAWJ over the central North Pacific, as shown in Fig. 1a. Because the area of maximum MTG is located along the westerly jet axis over the central North Pacific, it cannot change the location of the westerly jet axis, but it can change the westerly jet intensity at the exit region of the EAWJ over the central North Pacific.

Statistically significant cooling during summer can be seen over an extensive region of the Eurasian continent during the past two decades in Fig. 5b, with the cooling center over North China, which is located near the EAWJ axis, whereas a weak warming occurs

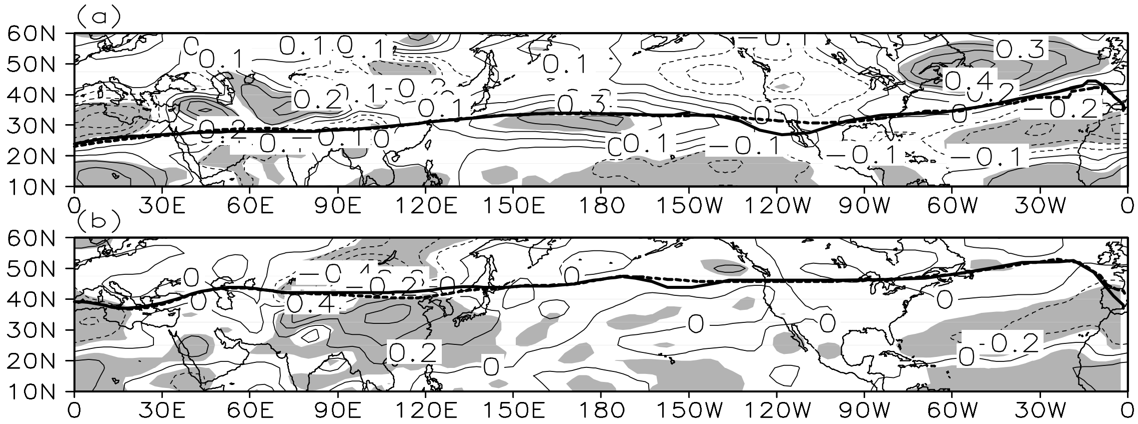

Fig. 5. Same as Fig. 4, but for MTG differences.

over the north Pacific and Atlantic. A previous study has suggested that this cooling is unique, relative to the global warming in the surface temperature (Yu et al., 2004). The MTG changes in summer indicate that an increase in the meridional temperature gradient occurs to the south of the cooling center and the westerly jet axis, whereas a decrease in the meridional temperature gradient appears to the north of the cooling center and the westerly jet axis (Fig. 5b). These differences are significant at the 95% confidence level. As a result, the maximum increase in zonal wind is found south of the westerly jet axis, and the largest decrease of zonal wind occurs to the north of the westerly jet axis (Fig. 1b), corresponding to a southward displacement of the 200-hPa westerly jet axis over East Asia in summer. The latitude-height cross section of the temperature and MTG changes (Fig. 6) clearly shows that the largest MTG increase occurs around 300 hPa to the south of the westerly jet axis, which is associated with the maximum cooling in upper troposphere near 300 hPa, and an obvious MTG decrease is seen to the north of the westerly jet axis, with the maximum center in the lower troposphere.

3. Summary and concluding remarks

The location and intensity of changes of the East Asian westerly jet axis in the upper troposphere in winter and summer were investigated using the NCEP/NCAR reanalysis data. A unique southward displacement of the westerly jet axis over East Asia in summer has occurred during the past two decades. This feature is quite different from the change in the zonal mean location of the westerly jet axis and in the Atlantic region, indicating that climate change on the interdecadal scale in East Asia may be unique, relative to other region in the globe. The southward shift of the westerly jet axis in summer is consistent with the corresponding change of the large meridional tropospheric temperature gradient zone over East Asia. In

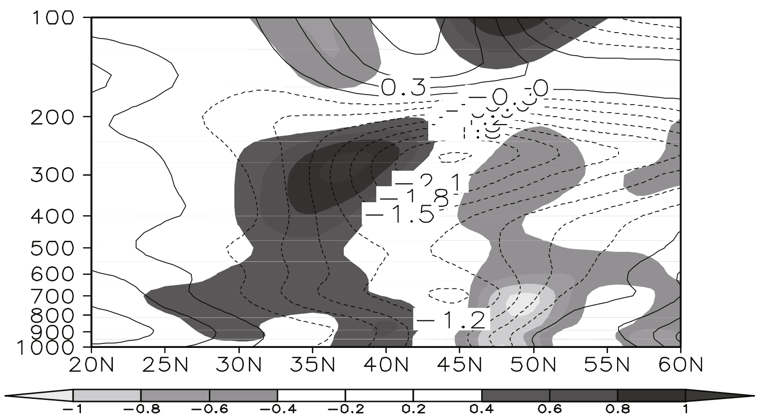

Fig. 6. Latitude–height cross section of temperature (contours) and MTG (shading) differences averaged over the longitudes between 100°E and 130°E for summer (JA; contour interval 0.3°C).

winter, the westerly jet intensity intensifies over the central north Pacific, but the location of the EAWJ axis has remained almost unchanged during the past two decades.

We have shown that the southward shift of the westerly jet axis in summer is consistent with the increased meridional tropospheric temperature gradient over East Asia. However, the cause of this increased meridional tropospheric temperature gradient remains elusive. The upper tropospheric cooling over northern China is a likely contributor (Yu et al., 2004). A recent examination of 19 WCRP-CMIP3 coupled models driven by historical greenhouse gases and sulfate aerosols found that barely any model could reproduce the observed cooling trend over East Asia (Zhou and Yu, 2006), leaving the mechanism of external forcing a problem open for investigation. Probably, the local thermal anomalies (e.g., surface sensible heat flux, condensation heat release, and snow cover over the Tibetan Plateau) also make significant contributions; additional research is needed to understand their potential mechanisms. In addition, momentum balance from mean circulation and transient eddies also play an important role in the changes of westerly jet, but these dynamics are beyond the scope of this work. Further effort should be devoted to this kind of research. One possible topic of research is the jet stream change associated with tropical ocean anomaly via meridional circulation (Hadley cell). In addition, the westerly jet changes also differed during two periods, 1993–2004 and 1979–1992, when the decadal rainfall patterns changed. The reason for these different changes requires further study.

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