Analysis of the East Asian Subtropical Westerly Jet Simulated by CCSR/NIES/FRCGC Coupled Climate System Model

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Abstract

The major features of the East Asian subtropical westerly jet (EASWJ) in the upper troposphere simulated by the two versions of CCSR/NIES/FRCGC climate system model (MIROC_Hires and MIROC_Medres) are examined by analyzing the differences between the coupled model 20th century simulations and the NCEP/NCAR reanalysis, focusing on the evaluation of the model performances in reproducing the mean EASWJ structures, the seasonal evolution, interannual variability, and the relationship among the EASWJ seasonal evolution, the meridional temperature gradient and the diabatic heating in the upper troposphere.

The mean EASWJ vertical and horizontal structures, the seasonal evolution, and the correspondence of the EASWJ location to the meridional temperature gradient in the upper troposphere are well simulated in the coupled models. The increase in model resolution can improve the simulation of the EASWJ structures, seasonal evolution and interannual variability. However, both coupled models overestimate the EASWJ intensity in winter, and underestimate the jet intensity in summer, relative to the NCEP/NCAR reanalysis. The biases in model EASWJ intensity are found to be associated with biases in meridional temperature gradients in the troposphere, and furthermore with the surface sensible heat flux in summer and convective condensation heating in winter as well as the meridional heat transport gradient. The coupled models simulate well the seasonal evolution of the diabatic heating averaged between 30°N–45°N, and its association with the westerly jet. However, the simulated maximum diabatic heating in summer is located eastward compared with the reanalyzed position, with a relatively weak diabatic heating intensity, especially in MIROC_Hires, while the MIROC_Medres model reproduces relatively strong diabatic heating near 130°E in winter. This study suggests that the condensation latent heating over the western Pacific in winter, the surface sensible heating over the northern side of the Tibetan Plateau in summer and the meridional heat transport gradient determine the EASWJ intensity, location and structure as well as its seasonal evolution. Thus the reasonable reproductions of the meridional heat transport gradient and the surface diabatic heating are the key points for improving the EASWJ simulation by the MIROC model.

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1. Introduction

In the upper troposphere and lower stratosphere, there exists a narrow and strong westerly belt with large horizontal and vertical wind shears over the subtropical East Asia, which is referred to the East Asian Subtropical Westerly Jet (EASWJ). Accompanying the transition of atmospheric circulation during the period of pre-onset to post-onset of the East Asian monsoon, the EASWJ is characterized by prominent seasonal evolutions in the intensity and location, and intimately related to the monsoon climate in East Asia (Yin 1949; Yeh and Zhu 1955; Yeh et al. 1958; Tao et al. 1958; Lau et al. 1988; Ding 1992; Liang and Wang 1998; Yang et al. 2002; Li et al. 2004; Zhang et al. 2006). On interannual and decadal time scales, the shift of EASWJ is also associated with the rainfall shift over the East Asian summer monsoon region (Yu et al. 2004; Liao et al. 2004; Lu et al. 2004; Zhou and Yu 2005; Lin and Lu 2005; Li et al. 2005). Thus, the EASWJ plays an important role in the East Asian climate variation.

It is well known that climate models have been powerful tools in the past, present and future climate change studies. Recently, a large number of coordinated experiments by the new generation of coupled climate system models have been conducted for the IPCC Fourth Assessment Report (AR4) under the leadership of the Joint Scientific Committee (JSC)/Climate Variability and Predictability (CLIVAR) of the World Climate Research Programme (JSC/CLIVAR) Working Group on Coupled Modelling (WGCM) (Meehl et al. 2004; Meehl et al. 2005). Up to now, nearly 20-coupled models worldwide have finished the 20th and 21st century coupled model integrations (Kripalani et al. 2006). Based on these valuable multimodel outputs, great efforts should be devoted to evaluating the models’ ability to reproduce the modern climate and project the future climate induced by anthropogenic activities (Knutson et al. 2006; Johns et al. 2006; Meehl et al. 2006; Ueda et al. 2006; Hori et al. 2006). Reasonable performances of coupled climate models in reproducing current state of global and regional climate are the bases for developing credible geographical distributions of future climate change through IPCC scenario simulations. However, the performance of these models in simulating the EASWJ has never been evaluated systematically. A few numerical experiment studies indicate that the simulated wind field biases can affect the precipitation simulation in the East Asian monsoon region, and especially, the shift of the simulated EASWJ location and the bias of the westerly jet intensity are closely associated with the precipitation amount in eastern China (Liang et al. 2001; Zhang et al. 2005). Therefore, it is very important to analyze and diagnose the model deficiencies in simulating the EASWJ for the improvement of climate model system.

Although the multimodel ensemble (MME) approach has been widely applied to assess the model performance and project future climate change in order to reduce the uncertainties from internal variability and inter-model difference (Giorgi et al. 2002; Gillett et al. 2002; Min et al. 2004), the MME method is limited in that its performance critically depends on that of the individual participating models (Min et al. 2006). To improve the credibility of climate change projection results from the MME, it is also necessary to understand the specific characteristics of each participating model in detail. The main motivation of this paper is to examine the coupled model’s performance of MIROC3.2 in simulating the detailed structure, seasonal evolution as well as interannual variation of the EASWJ in the second half of 20th century, and to understand the key points for improving the MIROC model in EASWJ simulation from the viewpoint of thermal dynamics. The reason for using this model is that two versions of the MIROC3.2 show relatively good performance in reproducing the frequency and intensity of precipitation (Sun and Solomon et al. 2006), and provide us with a good example to investigate the effects of model resolution on the simulation of westerly jet stream characteristics. The paper is structured as follows. Section 2 provides a brief description of the model and the data used. The detailed structures of the EASWJ as well as meridional temperature gradients are depicted in Section 3, while Section 4 addresses EASWJ seasonal evolution. The EASWJ interannual variability and possible influencing factors on the EASWJ simulation are presented in Section 5 and Section 6, respectively. Conclusions are given in Section 7.

2. Data

We use monthly mean data for 40 years at the present-day (1961–2000) of the 20th century climate simulations (20C3M) for IPCC AR4. The 20th century climate simulations are made with various combinations of forcings, including greenhouse gases.
(GHGs), sulfate aerosols, ozone, volcanic aerosols and solar variability. The coupled climate models used in this study have been developed jointly by the Center for Climate System Research (CCSR) of the University of Tokyo, the National Institute for Environmental Studies (NIES), and Frontier Research Center for Global Change, Japan Agency for Marine-Earth Science and Technology (FRCGC) of Japan (K-1 Model Developers 2004), which is called MIROC (Model for Interdisciplinary Research On Climate). It has five independent submodels for the atmosphere, ocean, land, river, and sea-ice, coupled by a flux coupler. Two versions of the model have been developed: one a high-resolution version (MIROC_Hires) and the other a medium-resolution version (MIROC_Medres). The MIROC_Hires has atmospheric horizontal resolution of T106 spectral truncation (~100 km transform grid) and 56 vertical levels with relatively finer vertical resolution in the planetary boundary layer and around the tropopause, 1/4° × 1/6° and 48 levels for the ocean and sea ice, and a 0.5° × 0.5° grid and 5 soil layers for the land. The MIROC_Medres consists of T42 (~300 km grid), 20-level atmosphere and 1° × 1.4° 44-level ocean and sea ice. The land model of the Mid-CGCM shares the same grids as the atmosphere. The component models are equipped with the state-of-the-art physics package and their details are described by the K-1 Model Developers (2004).

The NCEP/NCAR reanalysis data of wind, temperature, outgoing longwave radiation (OLR), and surface sensible heat flux from January 1961 to December 2000 were used to compare with the MIROC model results (Kalnay et al. 1996). Although the period simulated is 1870–2000, our analysis is focused mainly on the period 1961–2000 when anthropogenic external forcing is large, and the reanalysis data are relatively reliable.

3. Structures of the EASWJ

3.1 Vertical structure

To evaluate the model performance in simulating the westerly jet stream over different region of East Asia, the NCEP/NCAR reanalyzed and simulated latitude-height cross sections of the zonal winds and meridional temperature gradients along 90°E, 115°E, and 140°E in winter (December–January–February) are presented in Fig. 1, where the underlying surface is the Tibetan Plateau, flat orography, and ocean, respectively. The locations (height and latitude) of the winter westerly jet stream simulated by MIROC_Hires and MIROC_Medres are in good agreement with the NCEP/NCAR reanalysis. The westerly jet intensity is strongest along 140°E, and gradually becomes weaker westward. Around the Tibetan Plateau the westerly jet core is located at the southern side of the Plateau in winter, and the bifurcation of the jet stream along the two sides of the Plateau at 90°E below 600 hPa is well reproduced in MIROC_Hires and MIROC_Medres. There also exist obvious deficiencies in the westerly jet simulation. Both models reproduce much stronger zonal wind along three longitudes, with westerly jet centers 10 m s⁻¹ stronger in MIROC_Hires than that in the NCEP/NCAR reanalysis along 140°E and 115°E, and in MIROC_Medres along 90°E. In terms of thermal wind principle, the zonal wind is proportional to the horizontal temperature gradient. Figure 1 also shows the corresponding meridional temperature gradients, which is calculated by using the air temperature in the south minus that in the north with 2.5° latitude interval. It is clearly indicated that the simulated meridional temperature gradient patterns are similar in structure to their reanalyzed counterparts, with the exception that the simulated meridional temperature gradients are larger than that in NCEP/NCAR reanalysis, which are associated with the stronger westerly jet intensity in MIROC_Hires and MIROC_Medres.

Analyses of the simulated and reanalyzed zonal winds along 90°E, 115°E, and 140°E in summer (June–July–August), as shown in Fig. 2, indicate that the major features of the simulated summer westerly jet are similar to the NCEP/NCAR reanalysis. Compared with the results in winter, the westerly jet location in summer migrates northward to 40°N apparently, and the westerly intensity is reduced significantly, with the strongest at 90°E and the weakest at 140°E, which is opposite to the case in winter. The simulations show 5–10 m s⁻¹ weaker westerly jet intensities in two models. Comparisons of the simulated meridional temperature gradients with the reanalysis, as shaded in Fig. 2, show that there are similar patterns of the meridional temperature gradients for the models and reanalysis, with positive temperature gradients below 200 hPa and negative temperature gradients above 200 hPa. A clear discrepancy between reanalysis and models is the weaker than reanalyzed meridional temperature gradients along three longitudes, which may be partly related to the weaker westerly jet intensity in two models.
Fig. 1. The latitude-height cross sections of zonal wind and meridional temperature gradient (shaded) along 90°E, 115°E, 140°E in winter (DJF). (Units: m s$^{-1}$) NCEP/NCAR (a, b, c; upper panel), MIROC_Hires (d, e, f; middle panel), MIROC_Medres (g, h, i; lower panel).
Fig. 2. Same as Fig. 1, but for summer (JJA).
Figure 3 shows the longitude-altitude cross-sections of zonal wind speed and meridional temperature gradient along 32°N in winter and along 42°N in summer, respectively. Clearly, two models reproduce the longitude-altitude patterns of zonal wind and meridional temperature gradient along these two latitudes well. During wintertime the westerly wind over the ocean is markedly stronger than that over the land, with a westerly jet center at 200 hPa situated over the ocean. The model simulated westerly jet intensities are quite similar to that in the reanalysis, with exception that MIROC_Hires reproduces slightly stronger jet intensity, which is associated with the extended meridional temperature gradients below the jet center. Over the western side of the Tibetan Plateau, the MIROC_Hires simulated westerly jet intensity and location are in good agreement with the reanalysis, whereas MIROC_Medres reproduces stronger westerly wind in this area. In summer, two westerly centers at 200 hPa can be found in NCEP/NCAR reanalysis, the stronger one located over the Tibetan Plateau, and the other situated at 50°E near Iranian Plateau. In comparison with the reanalysis, the MIROC_Hires model reproduces the EASWJ vertical structures very well, indicating that the increase of model resolution can improve the simulation of the EASWJ vertical structures.

3.2 Horizontal structure

The results mentioned above show that the maximum westerly wind occurs at 200 hPa in winter and summer over different underlying surface. Thus the zonal wind at 200 hPa is used to analyze the horizontal structure of the westerly jet stream. Figure 4 shows the reanalyzed and simulated zonal wind distributions at 200 hPa and the meridional temperature gradients averaged between 500 hPa and 200 hPa over East Asia in winter and summer. Apparently, both the intensity and the location of the EASWJ in summer are different from that in winter. In comparison with the reanalysis, the simulated location of the westerly jet core and the orientation of the jet axis in MIROC_Hires and MIROC_Medres are in good agreement with that in NCEP/NCAR reanalysis, but MIROC_Hires reproduces a stronger westerly jet intensity of 80 m s⁻¹ in winter, whereas the simulated winter westerly jet intensity in MIROC_Medres is similar to the reanalysis. In summer MIROC_Hires reproduces major features of the EASWJ intensity and location, although there is a clear jet location shift westward to 50°E. However, MIROC_Medres simulates weaker westerly jet intensities in summer.

Comparison of the simulated meridional temperature gradients averaged between 500 hPa and 200 hPa with the NCEP/NCAR reanalysis, as shown in Fig. 4 (shaded areas), indicates that there are similar patterns of the meridional temperature gradients for the models and reanalysis. The large value of meridional temperature gradients from 500 hPa to 200 hPa matches well with the 200 hPa westerly jet center shown in Fig. 4, thus the 200 hPa westerly jet always follows the larger meridional temperature gradients from 500 hPa to 200 hPa. The meridional temperature gradient in winter is stronger than that in summer, which is related to the westerly jet intensity change between winter and summer. Thus the change of the meridional temperature gradient determines the shift of the EASWJ core position. Clear deficiencies of the models are the stronger meridional temperature gradients along the westerly jet stream in winter, and weaker in summer, compared with the reanalysis. These discrepancies in meridional temperature gradient simulations are responsible for the biases in the simulation of the westerly jet, which can also be seen in the vertical structures of the meridional temperature gradients.

It is obvious that MIROC_Hires and MIROC_Medres can reproduce the major features of the EASWJ vertical and horizontal structures. The apparent discrepancy of the model results is stronger than reanalyzed jet intensity in winter and weaker in summer, which is related to the simulated meridional temperature gradient biases. As the westerly jet intensity and location over the China Mainland are associated with the migration of the rain belt in eastern China (Zha 1983), the westerly jet simulation bias is possibly related to the rainfall simulation bias in a climate model.

4. Features of the EASWJ seasonal evolution

The above analyses on the EASWJ horizontal and vertical structures indicate that the westerly jet intensity and location in winter are different from that in summer. Accompanying the shifts of the westerly jet patterns from winter to summer, the EASWJ exhibits apparent seasonal evolutions in the intensity and location. This section compares the simulated EASWJ seasonal variation features in MIROC with those in NCEP/NCAR reanalysis.
Fig. 3. The longitude-height cross sections of zonal wind and meridional temperature gradient (shaded) along 30°N and 42°N in winter and summer respectively. (Units: m s$^{-1}$) NCEP/NCAR (a, b; upper panel), MIROC_Hires (c, d; middle panel), MIROC_Medres (e, f; lower panel).
Figure 5 shows the latitude-time cross sections of the simulated and reanalyzed zonal winds at 200 hPa and the meridional temperature gradients averaged between 500 hPa–200 hPa (shaded) in winter and summer. (Unit: m s$^{-1}$) NCEP/NCAR (a, b; upper panel), MIROC_Hires (c, d; middle panel), MIROC_Medres (e, f; lower panel).

Figure 5 shows the latitude-time cross sections of the simulated and reanalyzed zonal winds at 200 hPa and the meridional temperature gradients averaged between 500 hPa–200 hPa (shaded) in winter and summer. (Unit: m s$^{-1}$) NCEP/NCAR (a, b; upper panel), MIROC_Hires (c, d; middle panel), MIROC_Medres (e, f; lower panel).

Figure 4. The zonal wind at 200 hPa and the corresponding meridional temperature gradient averaged between 500 hPa–200 hPa (shaded) in winter and summer. (Unit: m s$^{-1}$) NCEP/NCAR (a, b; upper panel), MIROC_Hires (c, d; middle panel), MIROC_Medres (e, f; lower panel).

The westerly jet center along 90°E in NCEP/NCAR reanalysis occurs steadily at 28°N from January to April, and jumps apparently to nearby 32°N from April to May, then migrates northward to 40°N till southward retreat from August. The MIROC_Hires simulated westerly jet center appears nearby 30°N along 90°E from January to April, then jumps to 40°N from April to May and keeps stationary near 40°N until gradual southward retreat of the jet from August, while MIROC_Medres captures the major features of the jet seasonal evolution along 90°E, compared
with MIROC_Hires. Along 115°E, the simulated seasonal evolutions of the westerly jet center by two models are in good agreement with that in NCEP/NCAR reanalysis, only with obvious discrepancy shown in MIROC_Hires being much more abrupt two jumps of the jet center northward from April to May and from June to July. Along 140 °E, the seasonal variation of the simulated westerly jet center is consistent with that of the NCEP/NCAR reanalysis, and MIROC_Hires appears to have a better performance in reproducing the jet seasonal evolution feature than MIROC_Medres does. Overall, the coupled models can reproduce the southward retreat feature of the westerly jet much better than the northward jump feature during the atmospheric circulation transition periods over East Asia. As the EASWJ northward jump is associated with the seasonal transition of the atmo-
spheric circulation, monsoon onset, as well as the rainy season beginning over East Asia (Yeh et al. 1958; Tao et al. 1958; Li et al. 2004), the model performance in simulating the seasonal evolution of the westerly jet is important for the simulations of the East Asian monsoon and the rain belt movements over East Asia. This is an important issue which needs to be addressed for the model improvement in the future.

The simulated meridional temperature gradients averaged from 500 hPa to 200 hPa along 90°E, 115°E and 140°E are also compared with the reanalysis in Fig. 5. A notable feature in Fig. 5 is that the larger meridional temperature gradients match well with the westerly jet stream, thus the westerly jet always follows the larger meridional temperature gradient from 500 hPa to 200 hPa. As a result, the change of the meridional temperature gradient determines the EASWJ position shift. The coupled models capture the major features of meridional temperature gradient evolution except in summer along 140°E and in winter along these three longitudes, when both models reproduce weaker meridional temperature gradients, leading to a weaker westerly jet.

As shown in the above analyses, the EASWJ seasonal evolution is characterized by the change of the EASWJ core location and intensity. The location and intensity of the EASWJ core can be represented by the position of the maximum westerly and corresponding maximum meridional temperature gradients, leading to a weaker westerly jet.

Fig. 6. Seasonal evolutions of the longitude and latitude positions and zonal wind speed of the westerly jet core. The lines with solid circle, empty circle and plus symbol represent NCEP/NCAR, MIROC_Hires and MIROC_Medres, respectively.

core are shown in Fig. 6. For the NCEP/NCAR reanalysis, the core of the EASWJ is located near 140°E before June and in 80°E in July, indicating a rapid east-west displacement of the EASWJ core between June and July. Two models reproduce early westward movement of the EASWJ cores, especially MIROC_Medres, in which the EASWJ core migrates westward from May, one month earlier, whereas MIROC_Hires simulates slower EASWJ core eastward retreat in September, compared with MIROC_Medres. For the northward shift and southward retreat of the EASWJ core, MIROC_Hires simulated latitude location is consistent with that in NCEP/NCAR reanalysis, while there is a clear deficiency in the latitude location of the EASWJ core during southward retreat period in September and October, showing a more northward tendency than usual in MIROC_Medres. Apart from the jet core location, another important parameter to describe the EASWJ seasonal evolution is the jet intensity. Two models capture the major seasonal evolution features of the EASWJ intensity, but apparent discrepancies occur in the simulated jet intensity, with a stronger and weaker jet stream during winter and summer seasons in both models, respectively, as shown before. This appears to indicate that the increase of model resolution can improve the simulation of the seasonal evolution of the EASWJ core location.

Figure 7 illustrates the simulated and reanalyzed longitude-month variation of the zonal wind at 200 hPa averaged between 30°N and 45°N and the mean meridional temperature gradient between 500 hPa and 200 hPa, which represent the sea-
sonal evolution of the EASWJ east-west displacement. The obvious feature in Fig. 7 is that there is a good correspondence between the meridional temperature gradient and EASWJ through the thermal wind balance, and EASWJ always follows larger meridional temperature gradient during the seasonal evolution. The maximum meridional temperature gradient is located near 140°E from January to March, and the westerly jet stream occurs over this area coincidently with a strong intensity. With the enhancement of the meridional temperature gradient from 80°E to 100°E, the jet stream approaches to this area. Meanwhile, the meridional temperature gradient to the east of 100°E weakens. Two versions of MIROC reproduce very similar and reasonable evolution and distributions of the EASWJ and meridional temperature gradient. In fact, the meridional temperature gradient evolution shown in Fig. 7 represents the land-sea thermal contrast in the longitudinal direction. Good performance in simulating the seasonal evolution of the EASWJ and meridional temperature gradient suggests that the coupled model systems are able to capture the major features of the longitudinal thermal contrast and its seasonal evolution.

5. Interannual variability

A few of the characteristics of model-simulated EASWJ interannual variability are presented in this section. The simulated and reanalyzed standard deviations of 200 hPa zonal wind for winter and summer are given in Fig. 8. Clearly, there is a similar overall pattern of the standard deviation fields for the models and the reanalysis, with enhanced variability along the westerly jet axis, indicating that the year-to-year westerly jet intensity change is a dominant feature of the EASWJ interannual variability. A notable deficiency of the simulations is greater than reanalyzed interannual variability over northern China in winter, but weaker over west Asia and stronger over northwestern Pacific in summer. It is noted that largest interannual standard deviations of 200 hPa zonal wind do not appear within the maximum centers of the zonal wind both in winter and summer, compared with Fig. 4, but occur at the entrance area of the EASWJ. Recently Sato and Takahashi (2006) found that the eastward propagation of the wave packet associated with the East Asian subtropical jet starts in the Middle East, and the internal dynamics are important in determining the statistical features of the appearance of anomalous quasi-stationary waves on the subtropical jet in mid-summer. It is possible that the enhanced zonal wind variability over west Asia is related to the atmospheric internal dynamics in middle latitude (Ogi et al. 2003; Yu and Zhou 2004; Xin et al. 2006). Obviously these

Fig. 7. The longitude-month cross sections of 200 hPa zonal wind (isoline, Units: m s$^{-1}$) and meridional temperature gradients between 30°N and 45°N (shaded area, Units: °C) averaged from 500 hPa to 200 hPa. (a) NCEP/NCAR, (b) MIROC_Hires, (c) MIROC_Medres.
two coupled models reproduce less atmospheric internal variability along the westerly jet over west Asia in summer.

To depict the leading modes of the EASWJ variability in the coupled models, we computed the empirical orthogonal function (EOF) for the simulated and reanalyzed 200 hPa zonal wind in winter and summer. Figure 9 shows the patterns of the eigenvectors and corresponding principal components of the first leading EOF modes for the model outputs and reanalysis in winter. The first leading EOF pattern of 200 hPa zonal wind for the reanalysis in winter, which account for 24% of the total variance, is dominated by a positive anomaly along the westerly jet axis over a region extending from the Tibetan Plateau to the north-west Pacific, and by negative anomalies in the north and south of the jet axis, suggesting that the first leading EOF pattern is related to the variation in EASWJ intensity. This dominant pattern is characterized by the variability on interannual time scales. For the simulated EOF patterns and
principle components, MIROC_Hires reproduces a similar variability pattern except the northward extension of the positive zonal wind anomaly along the westerly jet axis (explaining 25% of variance), whereas MIROC_Medres simulates a southward extension of the zonal wind anomaly (explaining 25% of variance), which is different from the spatial structure for the reanalysis. However, the two models reproduce quite different evolutions of the time series of the principal components with interannual variabilities, compared with the reanalysis. The second leading EOF pattern of 200 hPa zonal wind in winter for the reanalysis (explaining 21% of variance, figure not shown) shows the negative anomaly and positive anomaly in the north and south of westerly jet axis, with a dividing line occurring along the jet axis, indicating that the second EOF pattern is related to the meridional
displacement of the EASWJ. The MIROC_Hires model reproduces the reasonable pattern of the 200 hPa variability (explaining 17% of variance), except for the western Tibetan Plateau, whereas MIROC_Medres simulates an opposite distribution of the variability (explaining 17% of variance), in comparison with the reanalysis.

The patterns of the eigenvectors and corresponding principal components of the first leading EOF modes for the model outputs and reanalysis in summer are shown in Fig. 10. The major feature of the first leading EOF pattern for the reanalysis...
in summer, which account for 17% of the total variance, is characterized by a meridional out-of-phase structure, with positive values in the south extent and negative values in the north extent, and the dividing line is located roughly at the latitudes along the climatological westerly jet axis in summer. This feature signifies that the first leading EOF mode of the reanalysis is closely related to the meridional displacement of the EASWJ. Model results show that MIROC_Hires captures the major pattern of the first EOF mode (explaining 17% of variance), while MIROC_Medres reproduces an opposite variability pattern in spatial distribution, compared with the reanalysis and MIROC_Hires result. In addition, the time evolution of the principal component for the MIROC_Hires model result is similar to that for the reanalysis data, showing variabilities on the interannual time scales, however, MIROC_Medres reproduces the interdecadal scale variabilities, which are apparently different from the reanalysis. A recent analysis on the results of 19 coupled climate models of IPCC AR4 (including the MIROC models) has shown that the prescribed natural and anthropogenic external forcings in the coupled climate models mainly produce the observed warming trends and the decadal to interdecadal scale variations, with poor performances at shorter time scales (Zhou and Yu 2006). Hence there is no correspondence between the observed and the simulated variability at interannual to interdecadal scales. The second leading EOF pattern of 200 hPa zonal wind in summer for the reanalysis (explaining 12% of variance, figure not shown) also shows a feature of meridional displacement of the EASWJ. Both models reproduce the second leading modes of the 200 hPa zonal wind variability in a reasonable manner (explaining 13% of variance in both models).

6. **Possible factors determining the EASWJ seasonal evolution**

The formation of the westerly jet is related to the meridional temperature gradient resulted from nonuniform diabatic heating in troposphere and surface. The nonuniformity of the underlying surface thermal features can result in the seasonal evolution of the meridional temperature gradient, affecting the seasonal evolution of westerly jet (Zhang et al. 2006). Based on the principle of thermal wind, the variation of zonal wind with height depends on the horizontal temperature gradient in meridional direction. Therefore, the seasonal evolution of the westerly jet intensity and location is related to the meridional temperature gradient in troposphere. The possible factors determining the EASWJ seasonal evolution are examined from the viewpoint of thermal mechanism in this section, focusing on the relationship among the EASWJ, surface sensible heat flux and outgoing longwave radiation (OLR).

Zhang et al. (2006) found that the diabatic heating is responsible for the intensity change and location shift of the westerly jet core at the upper troposphere, and the seasonal evolution of the diabatic heating represents the variation of the longitudinal thermal contrast, which is also related to the longitudinal change of the EASWJ core. The time-longitude variation of the simulated diabatic heating rate averaged between 30° N and 45°N, from surface to 200 hPa, are shown in Fig. 11. Similar to the Fig. 5 in the reference of Zhang et al. (2006), the diabatic heating includes
turbulent heating, condensation latent heating and radiative heating. The simulated strong heating is located to the east of 120°E before April, and the westerly jet core occurs over this area coincidently. With the enhancement of the diabatic heating near 100°E, the jet core approaches to this area. Meanwhile, the diabatic heating to the east of 120°E weakens. However, the simulated maximum diabatic heating in summer is located eastward of its reanalyzed position, with a relatively weak diabatic heating intensity, especially in MIROC_Hires, while the MIROC_Medres model reproduces relatively strong diabatic heating near 130°E in winter. Further analysis on the surface sensible heat flux and outgoing longwave radiation (OLR) flux shows that the major contribution to the diabatic heating in summer is attributed to the condensation latent heating near 100°E, where low OLR values occur, and to the surface sensible heat flux over the northwestern Pacific in winter. To examine the reason for the westerly jet simulation biases, the summer outgoing longwave radiation (OLR) distributions at the top of atmosphere in MIROC models and NCEP/NCAR reanalysis are given in Fig. 12. It is shown that there exists a low OLR region over the Bay of Bengal and the IndoChina peninsula in NCEP/NCAR reanalysis, while the low OLR occurs near 30°N, 95°E in MIROC models, which is located to the north in comparison with the reanalysis. As the low OLR value corresponds to heavy precipitation (as shown in Fig. 12 by shaded areas) and larger convective condensation latent heating, the strong condensation latent heating near 30°N, 95°E in MIROC model strengthens the meridional temperature gradient in this area, as a result, affecting the westerly jet location and intensity. Previous researches have indicated that the convective condensation latent heating in the tropical region triggers Kelvin waves, leading to the enhancements of westerly wind to the east of the heating center and of easterly wind to the west of the heating center (Wu et al. 2000), whereas the heating in the subtropical region changes the temperature gradient and basic flow, leading to the enhancements of the westerly wind and easterly wind to the north and to the south of the heating center, respectively (Liu et al. 1999; Liu et al. 2001). Therefore, the low OLR region with heavy precipitation near 30°N, 95°E in MIROC models is directly related to the westerly jet location and intensity in the upper troposphere.

Analysis of the surface sensible heat flux distribution shows that both models reproduce reasonable surface sensible heat flux distribution patterns, with larger sensible heat fluxes over the western side and northern side of the Tibetan Plateau in summer, and over the northwestern Pacific in winter, compared with the NCEP/NCAR reanalysis (figure not shown), but an obvious dis-
crepancy in sensible heat flux appears over the northern side of the Tibetan Plateau in summer, showing less sensible heat flux along 40°N, which is responsible for the weak meridional temperature gradient and westerly jet intensity in summer, as mentioned above. The correlation coefficients between the westerly jet intensity and surface sensible heat flux in winter for the NCEP/NCAR reanalysis and two coupled models are shown in Fig. 13. The winter westerly jet intensity refers to the regional mean wind speed over the area of 110°E–170°E, 30°N–40°N. To remove the influence of the climate drift in the coupled model system, the model output is detrended when the correlation coefficients are calculated. It is shown that there exists a positive correlation between the westerly jet intensity and surface sensible heat flux in winter for the NCEP/NCAR reanalysis over an extensive region of the northwestern Pacific, with a coefficient of 0.54 exceeding 0.01 statistic significance. This correlation pattern illustrates that the sensible heating in the northwestern Pacific is intimately associated with the EASWJ intensity. Both coupled models reproduce the positive correlation pattern between the westerly jet intensity and surface sensible heat flux in winter over the northwestern Pacific, with a higher correlation coefficient in MIROC_Medres than in MIROC_Hires, thus the MIROC_Medres has better performance in simulating the correlation pattern between the westerly jet intensity and surface sensible heat flux in winter over the northwestern Pacific. In summer the westerly jet intensity is defined as the regional mean wind over 80°E–100°E, 35°N–48°N. The NCEP/NCAR reanalyzed correlation between the westerly jet intensity and surface sensible heat flux in summer, as shown in Fig. 14, indicates that a positive correlation area with a value of about 0.36 is located over the northern Tibetan Plateau, Iranian Plateau, as well as the northwestern Pacific. This correlation pattern is in favor of the intensification of the meridional temperature gradient near the westerly jet, resulting in the occurrence of the westerly jet over this region. For the coupled model results, however, these two models are found to be unable to capture the major features of the correlation pattern between the westerly jet intensity and surface sensible heat flux over East Asia. The simulations differ apparently from the reanalysis in East Asia, showing an extensive area with high negative correlation coefficient to the northern Tibetan Plateau, and the unreasonable location of positive correlation coefficient, especially in MIROC_Medres. Therefore, both coupled models have relatively poor performance in simulating the correlation pattern between the westerly jet intensity and surface sensible heat flux in summer over East Asia. This apparent discrepancy may be related to the biases of the meridional temperature gradient in the troposphere as well as the westerly
jet simulation, due to unreasonable simulation of the surface sensible heating over the northern side of the Tibetan Plateau, which is the key point for improving simulation of the EASWJ by the MIROC models in summer.

To further explain the linkage among different diabatic heating processes and the meridional temperature gradient in the atmosphere, the local temperature change, horizontal advection heat transport, vertical heat transport and diabatic heating are calculated based on the thermodynamic equation:

$$\frac{\partial T}{\partial t} = -\mathbf{V} \cdot \nabla T - \omega \left( \frac{\partial T}{\partial \phi} - \frac{R}{C_p} \frac{T}{P} \right) + \frac{Q}{C_p \rho}.$$  

Figure 15 presents the NCEP/NCAR reanalyzed and simulated seasonal variation of the meridional gradient of each component in the thermodynamic equation averaged from 500 hPa to 200 hPa and 30°N to 45°N along 80°E–100°E and 120°E–140°E, respectively. (Units: °C d⁻¹)
Dient of diabatic heating keeps positive values all throughout the year along 80°E–100°E, implying strong diabatic heating to the south of the westerly jet, and the vertical heat transport gradient is positive in winter and negative in other months, whereas the meridional gradient of the horizontal heat transport changes from negative to positive in July. Along 120°E–140°E, the meridional gradients of vertical heat transport and diabatic heating are negative except for July and August, and horizontal heat transport gradient is negative in July and August and positive in other months. Thus, the meridional difference of the diabatic heating is mainly responsible for the formation of the meridional temperature gradient along 80°E–100°E, and the horizontal heat transport plays a role in the formation of the meridional temperature gradient along 120°E–140°E, but in July and August the vertical heat transport has a major contribution.

For the simulated results, both models reproduce the major features of the meridional gradient of heat transport terms along two longitudinal belts. The notable deficiencies of the simulations are greater than reanalyzed vertical heat transport gradient along 80°E–100°E in winter, but weaker along 120°E–140°E in summer. Clearly, these discrepancies are related to the biases of the meridional temperature gradient in the troposphere, as a result, leading to the bias in the westerly jet intensity simulation in winter and summer.

7. Conclusions

In this study the performance of CCSR/NIES/FRGC coupled climate system models (MIROC_Hires and MIROC_Medres) in simulating the intensity, location, structure and seasonal evolution of the East Asian subtropical westerly jet (EASWJ) in the upper troposphere has been evaluated by analyzing the differences between the coupled model results and the NCEP/NCAR reanalysis. This study provides a contribution to the validation of climate models over East Asia from the aspects of the East Asian subtropical westerly jet and thermal mechanism. The main conclusions are as follows:

(1) The simulated vertical and horizontal structures of the westerly jet (e.g., the location and intensity of the westerly jet core and the orientation of the jet axis) by MIROC_Hires and MIROC_Medres in summer and winter are in good agreement with that in NCEP/NCAR reanalysis. The model has good performance in simulating the seasonal variation of the westerly jet location and intensity. The results appear to indicate that the increase of model resolution can improve the simulation of the EASWJ vertical and horizontal structures and its seasonal evolution. However, there also exist obvious deficiencies in the westerly jet simulation. Both models reproduce much stronger zonal wind in winter and weaker westerly jet intensity in summer. The discrepancies in meridional temperature gradient simulations are responsible for the biases in the simulation of the westerly jet.

For the northward shift and southward retreat of the EASWJ core, MIROC_Hires simulated latitude location is consistent with that in NCEP/NCAR reanalysis, while there is a clear deficiency in the latitude location of the EASWJ core during southward retreat period in September and October, showing a more northward than usual tendency in MIROC_Medres.

(2) The coupled MIROC models capture the dominant features of the EASWJ interannual variability, especially MIROC_Hires. There is a similar pattern of the standard deviation fields for the MIROC_Hires model result and the reanalysis. For the simulated EOF patterns and principal components in winter, MIROC_Hires reproduces a northward extension of the positive zonal wind anomaly along the westerly jet axis, whereas MIROC_Medres simulates a southward extension of the zonal wind anomaly, compared with the spatial structure for the reanalysis. In summe, the model results show that MIROC_Hires captures the major pattern of the first EOF mode, while MIROC_Medres reproduces an opposite variability pattern in spatial distribution, compared with the reanalysis. However, there also exist apparent differences between the simulated results and the reanalysis, especially, the principal components (time series). Hence there is no correspondence between the observed and the simulated variability at interannual to interdecadal scales.

(3) The diabatic heating has a strong impact on the atmospheric temperature distribution and meridional temperature gradient in the lower troposphere. The coupled models simulate well the seasonal evolution of the diabatic heating averaged between 30°N–45°N, and its association with the westerly jet. However, the simulated maximum diabatic heating in summer is located eastward of its reanalyzed position, with a relatively weak diabatic heating intensity, especially in MIROC_Hires, while the MIROC_Medres model reproduces rela-
tively strong diabatic heating near 130°E in winter. The contribution of the horizontal advection heat transport, vertical heat transport and diabatic heating to the formation of the meridional temperature gradient is quite different along different longitudinal belts, and the meridional gradient of the diabatic heating is mainly responsible for the formation of the meridional temperature gradient along 80°E–100°E, and the horizontal heat transport plays a role in the formation of the meridional temperature gradient along 120°E–140°E, but in July and August the vertical heat transport has a major contribution. Although both models reproduce the major features of the meridional gradient of heat transport terms along two longitudinal belts, there exist notable deficiencies of the simulations, that is greater than reanalyzed vertical heat transport gradient along 80°E–100°E in winter, but weaker along 120°E–140°E in summer. In addition, the correlation analysis indicates that both coupled models are not able to capture the major features of the correlation pattern between the westerly jet intensity and surface sensible heat flux over East Aisa in summer. These apparent discrepancies in simulating the meridional heat transport gradient and the correlation pattern between the westerly jet intensity and surface sensible heat flux over East Aisa are related to the biases of the meridional temperature gradient in the lower troposphere, as a result, leading to the bias in the westerly jet intensity simulation in winter and summer, which are the key points for improving the simulation of the East Asian subtropical westerly jet by the MIROC model.

In this study it is found that the MIROC model has good performance in simulating the EASWJ three dimensional structure, intensity, seasonal evolution and interannual variability, especially the resolution dependence, and the results appear to indicate that the increase of model resolution can improve the simulation of the EASWJ vertical and horizontal structures and its seasonal evolution as well as interannual variability. As the seasonal evolution of the EASWJ intensity and location is closely associated with the rainfall belt movement and the transition of atmospheric circulation during the period of pre-onset to post-onset of the East Asian monsoon, the accurate simulation of the EASWJ intensity, location and structure is paramount to improving the simulation of the east Asian monsoon for the MIROC model. However, there still exist apparent discrepancies, compared with the reanalysis. These discrepancies are probably related to the inappropriately resolved topography of the Tibetan Plateau and calculation of the surface sensible heating or other diabatic heating such as the atmospheric radiation, convective condensation heat release in the model. It is necessary to improve the simulation of the meridional temperature gradient as well as the diabatic heating field in the troposphere for the improvement of the EASWJ simulation by MIROC model. This study only focuses on the model performance in simulating the EASWJ structure, seasonal and interannual variations. The thermodynamic mechanism is used to explain the merit and deficiency in the EASWJ simulation. The atmospheric dynamic processes have not been analyzed because of the lack of model daily output in this paper. In addition, due to the relationship between the westerly jet location and intensity over the eastern China and rainbelt movement in eastern China, the biases of the simulated westerly jet location and intensity is possibly associated with the precipitation simulation biases in a climate model. This is an important issue to be addressed for the model improvement in the future. Moreover, the performances of the other models participating IPCC AR4 in simulating the East Asian westerly jet need to be evaluated in the following work. However, the new insight and definite information useful to the improvement for the MIROC, as for the Asian monsoon simulation, are not obtained by the present model intercomparison study.

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