Analysis of the Baiu Precipitation and Associated Circulations Simulated by the MIROC Coupled Climate System Model

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Abstract

The major features of Baiu simulated by the climate model (MIROC_Hires) are examined by analyzing the differences between simulations and the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis data during 1981–2000, focusing on the evaluation of the model performances in reproducing the Baiu precipitation climatology as well as the associated 3-dimensional circulation systems, the relationship with Indian Summer Monsoon (ISM) and the configuration of upper and lower level jets. The results show that the model can reproduce heavy precipitation centers over the Yangtze-Huai River Basin during the Baiu period. The horizontal and vertical structures of the circulation systems during the Baiu period are also well simulated, such as an intensive meridional gradient of moisture and its equivalent potential temperature, the strong low-level southwesterly flow in the lower troposphere over East China, the location of the westerly jet in the upper troposphere, the strong ascending motion over heavy rainfall area (HRA) and compensatory descending motion over the northern and southern sides of HRA. However, obvious discrepancies occur in the overestimated precipitation over southeastern China during the Baiu period. In addition, our study suggests that the biases of the ISM and the configuration of upper and lower level jet results in deficiencies in the evolution of Baiu. The simulated onset of ISM is one pentad later than the reanalysis data, while the onset day of simulated Baiu is one pentad later than the reanalysis data, as well. The simulation showed southward shifting of the upper level jet and the stronger, lower level jet. These location and intensity biases essentially favor excess precipitation in southeastern China. Therefore, it is necessary for the coupled model to improve the configuration of upper and lower level jets in simulating the Baiu.

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1. Introduction

China is greatly affected by summer monsoons and their associated rainfall. A notable example of the sever-

ity and duration of rainfall is called Meiyu in China, Baiu in Japan and Changma in Korea (hereafter referred to as the Baiu). This rain concentration is in a nearly east–west-elongated rainbelt during June and July, which stretches for many thousands of kilometers, affecting China, Japan, Korea, and the surrounding seas. During Baiu season, the Yangtze-Huai River basin (YHRB, 110°E–122°E, 28°N–34°N) is vulnerable to floods and droughts due to the relative concentration and severity of the rainfall (Chen and Chang 1980; Tao and Chen 1987; Lau et al. 1988; Ding 1992). Thus, the Baiu plays an important role in the East Asia climate variation. It is necessary to study the Baiu systems for disaster prevention in East Asia.

During the Baiu period, several significant features within large-scale circulations can be found. In the upper-troposphere, the position and strength of the subtropical westerly jet over East China place it around 37°N and 30 m s⁻¹, respectively. The intensity of the westerly jet over the Asian continent weakens and the core of the westerly jet over the western Pacific splits up and intensity reduces, eventually disappearing after the end of Baiu (Du et al. 2008). In the mid-troposphere, the westward extension of the western Pacific subtropical high (WPSH) is an important feature. The WPSH ridge stays steady at 20°N–25°N (Ding et al. 2007). At 850 hPa, warm and moist southwest monsoon airflows, coming from the Indo-China Peninsula, the South China Sea, and the western Pacific Ocean, are mainly over East China (Huang et al. 1998; Zhou and Yu 2005). Moreover, the strong meridional gradients of moisture and the equivalent potential temperature (θ_e) are found over YHRB. In all, the Baiu is generally characterized by a low-level jet stream, strong meridional gradients of moisture and θ_e , and moist neutral stratification (Matsumoto et al. 1971; Ninomiya 1984). Thus, the Baiu is closely related with the monsoon trough, the low level jet, the upper level jet, the WPSH, strong meridional gradients of moisture and other large-scale atmosphere circulations.

It is well known that climate models have been powerful tools in studies on past, present and future climate change. A few reports indicate that simulating the Baiu is difficult in an Atmospheric General Circulation Model (AGCM) with low resolution (T42L21; the maximum zonal wave-number is 42 in triangular wave truncation, and the number of vertical levels are 21) (Sugi et al. 1995). Sperber et al. (1994) compared the ability of the European Centre for Medium-Range Weather Forecasts (ECMWF) model to simulate the Indian and East Asian monsoons at four different horizontal resolutions: T21, T42, T63, and T106. The results indicate

T106 best captures both the spatial and temporal characteristics of East Asian monsoons when compared with the lower resolution models. Based on the higher resolution models, Kawatani and Takahashi (2003) showed that a T106L20 model can simulate Baiu precipitation over Japan in certain periods. Min and Juhn (2010) indicated the higher resolution model (T106) effectively simulates the monthly precipitation pattern over wide areas across the East Asian region including the monsoonal rain band, although it shows a stronger rain band than observations. Thus, the higher resolution models have the ability to identify Baiu precipitation.

In most previous studies, the distribution of simulated Baiu precipitation has been discussed for June or July (based on monthly data) across wide areas in the East Asia region without focus on the 3-dimension circulations (Kar et al. 1996; Kawatani and Takahashi 2003; Li et al. 2008; Ninomiya et al. 2008; Zhou et al. 2008; Ninomiya 2009; Min and Juhn 2010). In general, Baiu mostly occurs from mid-June to mid-July, but with large interannual variability (Hu and Ding 2010), e.g., “Early Baiu” and “Second Baiu”. Kitoh and Uchiyama (2006) defined the onset and withdrawal dates of the summer rainy season using normalized pentad precipitation without considering the associated circulations. However, it is well known that during different periods of Baiu, the features of corresponding circulations are significantly different (Zhu et al. 2000). An accurate reproduction of large-scale circulation systems is important for the simulation of Baiu precipitation. Furthermore, a few numerical experiment studies indicate that whether the simulated Baiu precipitation and its associated circulation are reasonable or not will directly affect the precipitation simulation in the East Asian monsoon region (Li et al. 2008; Zhuo et al. 2010). Because most of previous studies discussed the reproducibility of Baiu using monthly and seasonal average data, the simulated Baiu period was not fully compared with observations. Therefore, identifying the exact Baiu period is necessary before evaluating the model ability of Baiu systems. The simulated Baiu period, as well as 3-dimensional circulation fields, should be verified against observations with time scales shorter than monthly and seasonal.

A large number of coordinated experiments using the new generation of coupled climate models have been conducted for the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) (Meehl et al. 2004; Meehl et al. 2005). Concerning these model outputs, great effort has been devoted to evaluating the model performance in order to improve model ability (Zhou and Yu 2006; Guo et al. 2008; Zhou

Fig. 1. (a) Seasonal evolution of area-averaged precipitation over the YHRB (110°E – 120°E , 28°N – 34°N) (unit: mm d^{-1}) (b) Annual time series of area-averaged precipitation over YHRB is sorted in ascending order (unit: mm d^{-1}) (c) Latitudes of the WPSH ridge.

Fig. 2. The average height field at 500 hPa during Baiu period (unit: degpm). (a) NCEP/NCAR reanalysis data (b) simulations Observation uses pentad 36–38 averages and simulation uses pentad 37–39 averages, same in Fig. 4–8.

et al. 2009). However, little attention has been paid on the AR4 simulations for studying the Baiu systems over YHRB.

In this study, we attempt to examine the simulated features of Baiu precipitation and 3-dimensional circulations during Baiu period over YHRB using an AR4 simulation with relatively high horizontal resolution. The aim of this paper is to answer the following questions:

- (1) Can the model capture the Baiu period and the 3-dimensional circulation over YHRB in pentad scale?
- (2) What is the key process for improving Baiu systems simulation?

The paper is structured as follows: Section 2 provides a brief description of the model and data. The detail definitions of Baiu period and Baiu precipitation are illustrated in Section 3. Section 4 addresses the horizontal and vertical features of Baiu circulations. Possible factors for improving the Baiu simulation are discussed in Section 5. Conclusions are in the final section.

2. Data

The coupled climate models used in this study have been developed jointly by the Atmosphere and Ocean Research Institute (AORI) of the University of Tokyo; National Institute for Environmental Studies (NIES);

Table 1. The ISM index in NCEP/NCAR and simulations during the 25th–35th pentads, respectively. (The bold number means the changing point from negative to positive of ISM.)

Time (Pentad)	NCEP/NCAR	Model
25th pentad	−0.849849	−0.94449
26th pentad	−0.675024	−0.65141
27th pentad	−0.50451	−0.6277
28th pentad	−0.343944	−0.44176
29th pentad	−0.160419	−0.15118
30th pentad	0.0188431	−0.05339
31th pentad	0.43934	0.248282
32th pentad	0.80879	0.591994
33th pentad	1.23505	0.567426
34th pentad	1.26225	0.806125
35th pentad	1.16719	0.835916

and the Frontier Research Center for Global Change, Japan Agency for Marine–Earth Science and Technology (FRCGC/JAMSTEC) of Japan, called MIROC (Model for Interdisciplinary Research On Climate). Two versions of the model have been developed: a high-resolution version (MIROC_Hires) and a medium-resolution version (MIROC_Medres).

As pointed out by Kimoto et al. (2005), the higher-resolution model better simulates mean and frequency distribution of precipitation in East Asian summer monsoon (EASM) region. Particularly, it is already known that T106 spectral truncation effectively captures both spatial and temporal characteristics of the East Asian monsoon (Sperber et al. 1994). Moreover, the MIROC_Hires shows relatively good performance in reproducing the circulation systems in East Asia, e.g., the frequency and intensity of precipitation (Sun et al. 2006; Zhu et al. 2009), the climatology structure of East Asian subtropical westerly jet (Zhang et al. 2008) and EASM (Min and Juhn 2010). Thus, the higher-resolution models could provide more credible results for projection of the Baiu systems than the lower-resolution models. In this study, we use high-resolution simulation (MIROC_Hires).

The MIROC_Hires has an atmospheric horizontal resolution of T106 spectral truncation (~ 100 km transform grid, 1.125° (longitude) $\times$ 1.125° (latitude)) and 56 vertical levels with relatively finer vertical resolution in the planetary boundary layer and around the tropopause, $1/4^\circ$ (longitude) $\times$ $1/6^\circ$ (latitude) with 47 levels for the ocean and sea ice and a $0.5625^\circ \times 0.5625^\circ$ grid with 5

Fig. 3. Seasonal evolution of averaged ISM index during 1981–2000. (The time serial is measured in units of its respective standard deviation.)

soil layers for land. More details are described by the K-1 model developers (2004).

We use 20 year daily mean data for the present-day (1981–2000) for the 20th century climate simulations (20C3M) in IPCC AR4. The 20th century climate simulations are generated using various combinations of forcings, including greenhouse gases (GHGs), sulfate aerosols, ozone, volcanic aerosols and solar variability.

The National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis data (Kalnay et al. 1996) for wind, temperature, vertical velocity and specific humidity from January 1981 to December 2000 is used to compare with the MIROC_Hires simulations. Moreover, the daily precipitation data within the period, 1981–2000, from the National Meteorological Information Center of China is used in this study. Although the simulation period is 1870–2000, our study is mainly focused on the period 1981–2000, since reanalysis data are relatively reliable.

3. Baiu precipitation distribution

Three criteria are used to define Baiu period (Zhuo et al. 2010): (1) the ridge line of WPSH is steadily located at 20°N – 25°N ; (2) the pentad mean precipitation amount over the YHRB exceeds the designated threshold value, the precipitation is ranked in ascending order, and the threshold value is defined as the 95th percentile of the sorted series; (3) the Baiu period exceeds continuous two pentads.

As shown in Fig. 1b, the precipitation threshold value of the observation and simulation is 6.8 mm d^{-1} and 7.5 mm d^{-1} , respectively. In Fig. 1c, the WPSH ridge line in reanalysis data occurs steadily at 15°N from January to May, jumps northward apparently at the end of May, and then locates along 20° – 25°N from the middle

Fig. 4. Distribution of the mean precipitation during Baiu period (unit: mm d^{-1}). (a) observation (b) simulations. Precipitation greater than 6 mm d^{-1} is shaded. The box indicates YHRB. The contour interval is 1 mm d^{-1} (a, b).

of June to the middle of July. The simulated ridge line begins to migrate northward nearly at the same time as in reanalysis data, and resides along 20° – 25°N from the middle of June to the end of August. Clearly, the simulated intensity of WPSH is weaker than NCEP/NCAR. As shown in Fig. 1a, the erroneous model peak in May (nearly the 25–30th pentad) is found in simulations, while the position of the simulated WPSH ridge line agrees with the observed position during this period. Thus, this simulated precipitation peak occurring in May is not Baiu period. In all, under the definition, the observed Baiu period is in the 36–38th pentads (from 25th June to 9th July) (Fig. 1a), which is in accordance with the results from previous research (Zhou 1996; Ding et al. 2007). In the simulation, the Baiu period is in the 37–39th pentad (from 30th June to 14th July), which is consistent with observation. However, the simulated Baiu period is one pentad later than the reanalysis data.

To examine the Baiu period, the geographical distribution of height at 500 hPa during Baiu period is given in Fig. 2. Clearly, the model effectively reproduces the WPSH pattern. The WPSH ridge (5880 and 5860 line) is nearly along 22°N and 20°N in NCEP/NCAR reanalysis and simulations, respectively, which is accordance with the significant characteristics of the WPSH during the Baiu period mentioned in the second paragraph of the Introduction. This is also evidence for confirming the Baiu period. However, the simulated intensity of WPSH is weaker than NCEP/NCAR reanalysis data, which is in accordance with the results given from Fig. 1c. Therefore, the periods of the 36th–38th pentad and the 37th–38th pentad can represent the Baiu period in observation and simulations, respectively.

It has been well documented that there is a close relationship between the position and features of Baiu and EASM (Ding 1992). In the EASM, the relationship between the Indian summer monsoon (ISM) and Baiu precipitation have been thoroughly studied (Ding 1999; Wu et al. 2000; Wang and LinHo 2002; Zhang et al. 2003). Suda and Asakura (1955) suggested that the onset of the ISM will lead the Baiu season. Recently, Liu and Ding (2008) indicated that the data concerning ISM onset over Kerala in the southwestern coast of the Indian Peninsula is about two weeks earlier than the beginning of the Meiyu over the YHRB. A dynamic index for the ISM is defined by Wang et al. (2001) using the difference in the 850 hPa zonal winds between a southern region of 5°N – 15°N , 40°E – 80°E and a northern region of 20°N – 30°N , 70°E – 90°E . The index changing from negative to positive indicates onset of the monsoon. The 25th–35th pentad ISM index is given in Table 1, apparently, the changing point is around the 30th and 31st pentad in NCEP/NCAR reanalysis and simulations. As shown in Fig. 3, the onset of Baiu period in simulation is one pentad later than the reanalysis data, which is also in good agreement with the difference in ISM period onset between simulations and reanalysis data. If the formations of simulated circulation systems (e.g., ISM, WPSH, low-level jet) delay, the onset and withdrawal of Baiu period will delay as well. This implies that the delay in ISM might be the cause of the delay of the Baiu period in the model.

Figure 4 shows the precipitation distribution during Baiu period for both the observation and simulations. In Fig. 4a, a heavy rainfall of 8 – 12 mm d^{-1} occurs over YHRB. The rain belt is mainly oriented from west to east along the mid-lower reaches of the YHRB, while

Fig. 5. During Baiu period, the fields of mean wind velocity (unit: m s^{-1}) (a, b), mean θ_e (unit: K) fields at 850 hPa (c, d) and mean zonal winds (unit: m s^{-1}) at 200 hPa (e, f). (a, c, e) NCEP/NCAR reanalysis data, (b, d, f) simulations. The dark shaded regions (a, b) are the meridional velocity above 5 m s^{-1} . The bold solid line (b, d) and the gray shaded regions in (a, c) indicate terrains above 1500 m. The dash-dot line (e, f) is the westerly jet.

rainfall less than 6 mm d^{-1} occurs in southeastern China (Fig. 4a). Clearly, the model reproduces the maximum precipitation center located over YHRB (Fig. 4b). The spatial correlation between the simulation and observation is 0.54 over YHRB. However, there still exist obvious discrepancies, such as the overestimated precipitation in southeastern China.

4. Associated circulation distributions

It has been well documented that the Baiu is associated with the monsoon trough, the low level jet, the upper level jet, the WPSH and other large-scale atmosphere circulations (Saito 1966; Asakura 1971; Yoshino 1971; Akiyama 1973, 1975; Tao and Chen 1987). To clearly indicate the circulations during Baiu period, we choose a horizontal structure, such as the low-level jet illustrated by wind velocity at 850 hPa, the upper level

jet described by zonal wind at 200 hPa, low-level moisture identified by θ_e at 850 hPa, and a vertical structure containing θ_e , specific humidity and vertical velocity.

Figure 5 shows the wind velocity at 850 hPa, θ_e at 850 hPa and zonal winds at 200 hPa for reanalysis data and simulations. At 850 hPa, a westerly from the Indo-China peninsula converging with the airflow on the southern flank of the WPSH reaches YHRB and Japan. The low-level winds show a considerable convergence zone over YHRB, which may be identified by the abrupt digression of strong southerlies along 30°N (Fig. 5a). In Fig. 5b, the simulated strong southwesterly wind along the rim of the west Pacific subtropical anticyclone is in good agreement with the reanalysis data. Whereas, the shaded regions (meridional wind larger than 5 m s^{-1}) in simulations are larger than the reanalysis data, which means the intensity of the simulated low level jet is

Fig. 6. Latitude-height cross sections of vertical velocity (unit: Pa s^{-1}) averaged from 110°E to 130°E (units: Pa s^{-1}). The vertical axis is height by pressure (a) NCEP/NCAR reanalysis data, (b) simulations. (The arrowhead means the direction of the movement.) The shaded area indicates the regions of YHRB.

Fig. 7. Longitude-height cross sections of meridional winds averaged from 27.5°N to 32.5°N (unit: m s^{-1}) (a, b); Longitude-height cross section of the vertical velocity averaged from 27.5°N to 32.5°N (unit: Pa s^{-1}) (c, d). NCEP/NCAR reanalysis data (a, c); simulations (b, d).

stronger than reanalysis data. Since the strong southwesterly wind provides a lot of warm and humid air for Baiu precipitation, the intensity biases may result in bias related to simulated precipitation distribution.

The Baiu front is generally characterized by strong meridional gradients in moisture and the θ_e wet tongue. As shown in Fig. 5c, a wet tongue extends from southwestern China to Japan at 850 hPa. An intensive θ_e gra-

Fig. 8. Latitudinal-height cross sections of specific humidity (unit: $\times 10^{-3} \text{ g kg}^{-1}$, dashed line) and θ_e (unit: K, solid line). (a) reanalysis data, (b) simulations averaged from 110°E to 130°E . The vertical axis is height by pressure (unit: hPa). The black bar indicates the region of heavy precipitation.

dient belt is located over the northern side of YHRB and the humidity is discontinuous over heavy rain region (figure omitted). The model effectively simulates discrete humidity in the Baiu front zone. The θ_e wet tongue and strong gradient zone at 850 hPa are realistically reproduced over YHRB. However, the wet tongue is slightly stronger, and shifts northward in simulations (Fig. 5d).

Compared with the reanalysis data, the intensity of the westerly jet at 200 hPa is well reproduced over the continent (Figs. 5e, f). However, it is underestimated over the ocean. Moreover, the jet clearly shifts southward, especially east of 110°E . Zhang and Kuang (2006) examined the performance of a Chinese climate system model (FGCM0) in simulating the seasonal variation of East Asian subtropical westerly jets in the upper troposphere. The results indicated that the simulated unrealistically heavy precipitation center is related to the location and intensity biases in the subtropical westerly jet, which directly affect the maximum precipitation center during Baiu period (Du et al. 2008). Thus, the southward shift may be associated with positive anomalies in precipitation in southeastern China during Baiu period.

As shown in Fig. 6, the vertical structure of Baiu systems has been investigated by analyzing θ_e , specific humidity and vertical velocity. During Baiu period, the simulations indicate a strong ascending motion over the heavy precipitation area (along $28^\circ\text{--}30^\circ\text{N}$) and compensatory descending motions are found over the northern and southern sides along the heavy precipitation belt. In all, the upward and downward motions are in good

agreement with the reanalysis data.

As shown in Fig. 7, meridional and vertical winds averaged from 27.5°N to 32.5°N within the simulations are in accordance with reanalysis data, especially from 110°E to 130°E . Consequently, the Baiu precipitation is well simulated over YHRB. However, over the Tibetan region (shaded area), the meridional and vertical winds in simulations are stronger than in the reanalysis data, which may be associated with the unrealistic precipitation simulated in the eastern area of Tibetan Plateau. This is probably related to the inappropriately resolved topography of Tibetan Plateau in the model (Qian and Shen 1990; Qian 2000; Zhang et al. 2006).

Figure 8 shows the latitudinal-vertical profile of θ_e and specific humidity averaged from 110°E to 130°E . In reanalysis data (Fig. 8a), the large θ_e gradient belt extends from surface to 600 hPa over the northern side of heavy rainfall area, and a high moist air column is found to the south of the large θ_e gradient belt. As shown in Fig. 8b, the model effectively reproduces the θ_e distribution with high value in the lower layer, especially along the heavy rainfall zone and the relatively low value in the middle layer. In the simulations, the meridional θ_e gradient is large in the Baiu rain belt and slightly weakens to the south in the middle and lower troposphere. Moreover, the model basically reproduces the characteristics of a quasi symmetric saddle type of θ_e .

From the analysis mentioned above, it is obvious that MIROC-Hires accurately reproduces the major features of Baiu period, precipitation and its associated circulations. The obvious discrepancies in the simulations are a southward shift of the subtropical westerly jet

Fig. 9. The latitude-temporal variation of zonal winds at 200 hPa (a, c) and at 850 hPa (b, d) averaged between 110°E – 130°E in simulations (a, b) and NCEP/NCAR reanalysis data (c, d) (unit: m s^{-1}). The values above 30 m s^{-1} (a, c) and 6 m s^{-1} (b, d) are shaded. The contour interval is 10 m s^{-1} (a, c) and 2 m s^{-1} (b, d), respectively.

and overestimated southwesterly winds from the Indo-China peninsula.

5. Discussion

Obvious discrepancies are revealed between the simulations and NCEP/NCAR reanalysis data on the features of Baiu systems, indicating the model overestimates the Baiu precipitation in southeastern China. In this section, we try to find possible reasons for the discrepancies by analyzing the coupled structure of the upper and lower level jet.

Several previous studies have related the Baiu to the lower and upper level jets (e.g., Simmonds et al. 1999; Zhou and Yu 2005; Zhang and Kuang 2006; Ding et al. 2007; Du et al. 2008; Liu and Ding 2008; Zhang and Kuang 2008). Du et al. (2008) found that the changes in the location and intensity of the westerly jet were not only associated with the start and end of Baiu period, but also associated with the spatial distribution and intensity of Baiu precipitation in YHRB. Based on observational analysis, Zhang and Kuang (2008) indicated the south-north location of the westerly jet impact the

variation within the rain belt during the Baiu period through the East Asian summer monsoon. Liu and Ding (2008) and Ding et al. (2007) mentioned the intensity of the lower level jet as associated with the ascending motion and transport of water vapor. Moreover, the coupled structure of the upper and lower level jet is one of the important circulations beneficial to strong precipitation occurring over YHRB during Baiu period (Zhou and Yu 2005; Zhang and Kuang 2006). As mentioned in Section 4, the wind bias between simulations and reanalysis data is largest in the Baiu systems. Thus, the main cause of the model biases in Baiu precipitation may be the unrealistic meandering within the upper-level subtropical jet and the intensity of the lower-level jet. Figure 9 shows the evolution of the upper and lower level jet. Clearly, in regards to the latitude-time variation of the upper level jet, the seasonal structure is well simulated in cold season (September–December). However, during Baiu period, the model underestimates the intensity of the upper level jet and cannot reproduce the northern tilting structure. In the simulations, the intensity of the upper level jet arrives at maximum along 30°N , while

in reanalysis data, it occurs around 40°N. On the evolution of the lower level jet, the model overestimates the intensity of the lower level jet, especially during Baiu period. Furthermore, the model simulates a larger center within the lower level jet located over the southern part of China during Baiu period. In this study, we find the location of the simulated upper level jet shifts southward, which will result in the southward movement of the rain belt during Baiu period. The model overestimates the intensity of the lower level jet, which benefits bringing sufficient water vapor to southeastern China. Thus, the configuration between the upper and lower level jets (e.g., southward shifting of the upper level jet and the stronger lower level jet in southeastern China) simulated by the models benefits rainfall over southeastern China, which is one of the possible reasons for overestimation of Baiu precipitation in southeastern China.

6. Conclusions

In this study, the performance of AORI/NIES/FRCGC coupled climate system model in simulating Baiu systems is evaluated. The main conclusions are as follows:

- (1) The climatic Baiu period is the 36–38th and 37–39th pentads in reanalysis data and simulations, respectively. The simulated onset of Baiu period tends to delay by about one pentad compared with that of observation. Similarly, the simulated onset of ISM tends to delay by about one pentad compared with that of observation. In the model, the delay of ISM might be the cause for delay in Baiu period.
- (2) During the Baiu period, the model has good performance in simulating the Baiu precipitation distribution, especially over YHRB. However, the model overestimates the Baiu precipitation over southeastern China. The simulated horizontal and vertical circulations associated with Baiu systems are in good agreement with reanalysis data. However, the simulated westerly jet shifts southward and the intensity of low level jet is stronger than reanalysis data.
- (3) The southward shifting of the upper level jet affected the southward movement of the rain belt during Baiu period. The simulated stronger lower level jet brings sufficient water vapor to southeastern China.
- (4) Under the described configuration of the upper and lower level jets, the simulated larger Baiu precipitation center locates over southern China, which

results in the bias of Baiu precipitation between simulations and reanalysis data. In all, the variation of ISM and the configuration of upper and lower level jet may be one of the key processes in the MIROC-Hires model to be improved for the simulation of Baiu.

This study only focuses on the climatological Baiu period and associated circulations. The atmospheric dynamic processes also need to be studied in following research. Because of the model dependence, the performance of the other models participating IPCC AR4 in simulating Baiu precipitation and its associated circulations need to be evaluated in the future.

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