ADVANCES IN ATMOSPHERIC SCIENCES, VOL. 36, JUNE 2019, 614–622

• Original Paper •

Intermodel Diversity in the Zonal Location of the Climatological East Asian Westerly Jet Core in Summer and Association with Rainfall over East Asia in CMIP5 Models

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(Received 14 October 2018; revised 23 January 2019; accepted 1 February 2019)

ABSTRACT

The East Asian westerly jet (EAJ), an important midlatitude circulation of the East Asian summer monsoon system, plays a crucial role in affecting summer rainfall over East Asia. The multimodel ensemble of current coupled models can generally capture the intensity and location of the climatological summer EAJ. However, individual models still exhibit large discrepancies. This study investigates the intermodel diversity in the longitudinal location of the simulated summer EAJ climatology in the present-day climate and its implications for rainfall over East Asia based on 20 CMIP5 models. The results show that the zonal location of the simulated EAJ core is located over either the midlatitude Asian continent or the western North Pacific (WNP) in different models. The zonal shift of the EAJ core depicts a major intermodel diversity of the simulated EAJ climatology. The westward retreat of the EAJ core is related to a warmer mid–upper tropospheric temperature in the midlatitudes, with a southwest–northeast tilt extending from Southwest Asia to Northeast Asia and the northern North Pacific, induced partially by the simulated stronger rainfall climatology over South Asia. The zonal shift of the EAJ core has some implications for the summer rainfall climatology, with stronger rainfall over the East Asian continent and weaker rainfall over the subtropical WNP in relation to the westward-located EAJ core.

Key words: zonal location, East Asian westerly jet, summer rainfall, intermodel diversity, CMIP5

Citation: Lin, Z. D., Y. H. Fu, and R. Y. Lu, 2019: Intermodel diversity in the zonal location of the climatological East Asian westerly jet core in summer and association with rainfall over East Asia in CMIP5 models. *Adv. Atmos. Sci.*, **36**(6), 614–622, https://doi.org/10.1007/s00376-019-8221-z.

Article Highlights:

- The zonal shift of the EAJ core depicts a major intermodel spread of the simulated summer EAJ climatology.
- The westward retreat of the EAJ core is related to the warmer temperature in the midlatitudes.
- The zonal shift of the EAJ core implies opposite change in the simulated rainfall climatology between East Asia and the subtropical WNP.

1. Introduction

The East Asian westerly jet (EAJ) in the upper troposphere is a crucial midlatitude system of the East Asian summer monsoon. In summer, the EAJ is located north of the East Asian subtropical rainy belt and its variability significantly affects the climate over East Asia (Liang and Wang, 1998; Lau et al., 2000; Lu, 2004; Lin and Lu, 2009; Xuan et al., 2011; Lu et al., 2013). In addition, seasonal northward jumps of the EAJ in early summer lead to the onset of the rainy season in East Asia (Yeh et al., 1958; Li et al., 2004). In midsummer, the westward retreat of the EAJ core to the Asian continent from the western North Pacific (WNP) and the northward jump of the EAJ to Northeast China ends the Meiyu season (Zhang et al., 2006; Du et al., 2008; Lin and Lu, 2008). Understanding the variability and improving the simulation of the EAJ, therefore, is vital to better understand and predict climate anomalies over East Asia.

Several studies have investigated the performance of individual models in simulating the EAJ. They found that current models can generally capture the summer EAJ (Song and Zhou, 2013; Du et al., 2017; Zhao et al., 2018) and its relationship to rainfall over East Asia (Hirahara et al., 2012; Dai and Lu, 2013); however, the simulated EAJ also shows a large bias in its intensity and location, which may be one reason

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behind the failure to capture the East Asian subtropical rainy belt (Zhang and Guo, 2005) and the surface air temperature cooling in mid-eastern China in the late 1970s (Wang et al., 2013).

Based on 14 CMIP5 climate models, Huang et al. (2013) reported that the multimodel ensemble (MME) mean reasonably simulated the intensity and location of the summer EAJ climatology in reanalysis data. However, they also revealed a large intermodel spread in the simulated EAJs, which may affect the uncertainty in the simulated East Asian summer rainfall climatology. Ma et al. (2015) investigated the meridional position bias of the EAJ in 20 CMIP5 models and highlighted the important role of the sea surface temperature over the Kuroshio–Oyashio Extension region related to different ocean model resolutions. However, to date, it remains unclear what the major characteristics are of the intermodel uncertainty in the simulated summer EAJ and how it relates to summer rainfall diversity.

The objective of this study is to identify the major uncertainty in the simulated EAJ climatology in the present-day climate and investigate its relation to summer rainfall in East Asia. The text is arranged as follows: Section 2 describes the data used in the study. Section 3 presents the characteristics of the intermodel diversity of the simulated EAJ in the present-day climate, focusing on the zonal shift of the EAJ core. Possible mechanisms and implications for summer rainfall of the uncertainty in the simulated EAJ are explored in section 4. Conclusion and discussion are given in section 5.

2. Data

We use the historical-simulation data from 20 models in the CMIP5 multimodel archive. The historical experiment is forced by time-varying natural and anthropogenic forcings and is run from the preindustrial period to the present day (1850–2005) (Taylor et al., 2012). Table 1 lists the key features of the models, and additional details are documented at http://cmip-pcmdi.llnl.gov/cmip5/index.html?submenuheader=0. Also used are atmospheric circulation data from ERA-Interim (Dee et al., 2011) and global precipitation data from the GPCP (Huffman et al., 1997; Adler et al., 2003). The ERA-Interim and GPCP data, considered as the observation, are used to evaluate the reproducibility of the summer EAJ and its relation to South Asian rainfall in the CMIP5 models.

All the simulation data have been interpolated onto a horizontal 2.5° × 2.5° grid to enable comparison between individual simulations. The present-day climatology is calculated as the 20-year mean of variables averaged over 1981–2000. Only one realization is chosen for each model. The MME mean is calculated simply as the 20-model mean with equal weights. The same analysis was conducted with the 30-year mean climatology during 1971–2000 and similar results were obtained. In this study, we only present the results based on the 20-year mean climatology.

Table 1. Atmospheric resolutions of the 20 CMIP5 models used in this study.

	Model	Atmospheric resolution
(1)	CCSM4	288×192, L17
(2)	NorESM1-M	144×96, L17
(3)	MIROC-ESM-CHEM	128×64, L35
(4)	BCC_CSM1	128×64, L17
(5)	MIROC-ESM	128×64, L35
(6)	MIROC5	256×128, L17
(7)	FGOALS-s2	128×108, L17
(8)	CSIRO Mk3.6	192×96, L18
(9)	HadGEM2-ES	$192 \times 145/144$, L17
(10)	CNRM-CM5	256×128, L17
(11)	HadGEM2-CC	$192 \times 145/144$, L23
(12)	MPI-ESM-LR	196×96, L25
(13)	GFDL-ESM2M	144×90, L17
(14)	GFDL-ESM2G	144×90, L17
(15)	GFDL CM3	144×90, L23
(16)	IPSL-CM5A-LR	96×96, L17
(17)	MRI-CGCM3	320×160, L25
(18)	FGOALS-g2	128×60, L17
(19)	GISS-E2-H	144×89, L17
(20)	GISS-E2-R	144×89, L17

3. Intermodel diversity in the zonal location of the summer EAJ core

To understand the intermodel diversity of the summer EAJ climatology, we first evaluate the features of its MME mean. Figure 1a shows the MME mean of the climatological summer zonal winds at 200 hPa (U200). A strong westerly jet prevails in the midlatitudes over East Asia, with the maximum exceeding 25 m s^{-1} over the Asian continent at approximately 40°N. The location of the simulated EAJ core is similar to the observed in the reanalysis data (Fig. 1b) but the intensity is weaker—the same result as that of Huang et al. (2013). The pattern correlation coefficient between the observational and MME mean U200 climatology is 0.99 over the region (10°–70°N, 65°–180°E). We also calculated the pattern correlation coefficient of the U200 climatology for each model with the observation, and found it to range from 0.85 to 0.99 (Fig. 2). The result suggests that the models generally capture the basic features of the EAJ climatology.

However, the individual models also exhibit large discrepancies in the longitudinal location of the EAJ core (Fig. 2) despite the similarity between the MME mean and the reanalysis data. The EAJ core, defined as the U200 exceeding 25 m s^{-1}, is concentrated over the mid-latitude Asian continent in the first eleven models. In the other models, the strong westerly extends eastward to the WNP. Moreover, there are four models (MRI-CGCM3, FGOALS-g2, GISS-E2-H, and GISS-E2-R) in which the maximum U200 is situated over the WNP. The longitudinal difference is more clearly revealed by

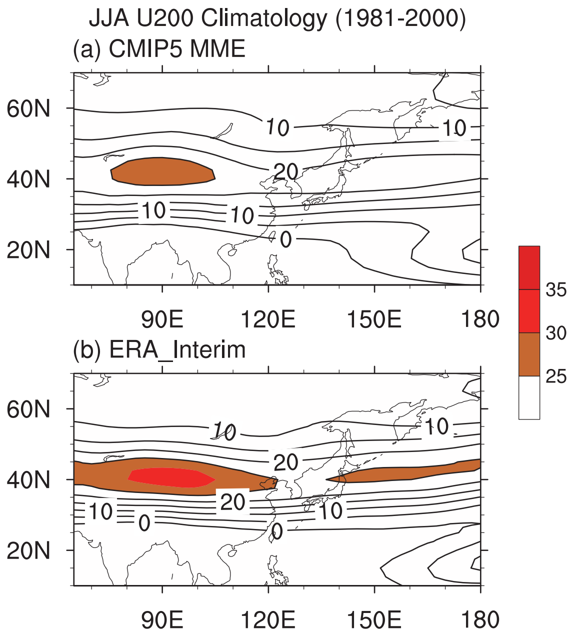


Fig. 1. (a) MME mean of 20 CMIP5 models and (b) the observation (ERA-Interim) of climatological summer zonal winds at 200 hPa (U200; units: m s^{-1}) averaged over 1981–2000. Shading depicts regions with U200 exceeding 25 m s^{-1}.

the center of the EAJ core (Fig. 3). The center refers to the location with maximum U200 over the domain (20°–60°N, 65°–180°E). Among the 20 models, there are 16 with centers located over the midlatitude Asian continent at approximately 90°E, close to the location of the observational EAJ core, and four with centers over the WNP east of 140°E. On the other hand, in comparison with the longitudinal change, the difference in the latitudinal location of the EAJ core is much smaller (Fig. 3). The EAJ cores are located at approximately 40°N, consistent with that in the MME mean and observation (Fig. 1), but they also show some discrepancies, especially among the models with an EAJ core over the Asian continent varying between 40°–45°N.

To quantify the longitudinal difference in the EAJ core, we define a zonal shift index (ZSI) as the zonal difference in the average U200 between the Asian continent (30°–50°N, 70°–120°E) and the WNP (30°–50°N, 120°–170°E). The ZSI values in the 20 models are shown in Fig. 4. A positive ZSI indicates that the EAJ core is located over the Asian continent and a negative ZSI indicates it is over the WNP. The positive ZSIs in the first 16 models and the negative ZSIs in the last four models are consistent with the westward-located EAJ core in the first 16 models and eastward-located core in the last four (Figs. 2 and 3). Meanwhile, we also calculated

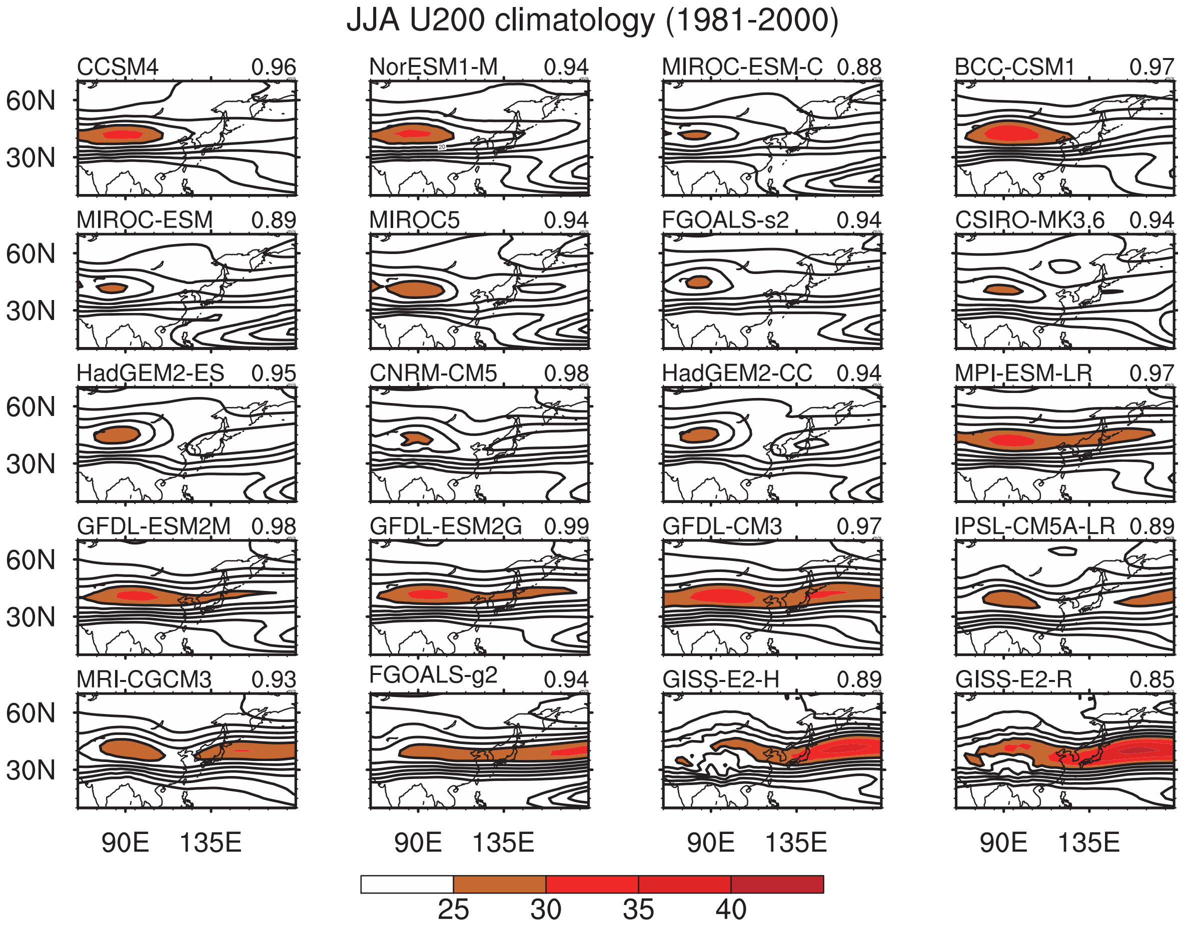


Fig. 2. As in Fig. 1a, but for the 20 individual CMIP5 models. The pattern correlation coefficient with observation over the region (10°–70°N, 65°–180°E) is given in the top-right corner.

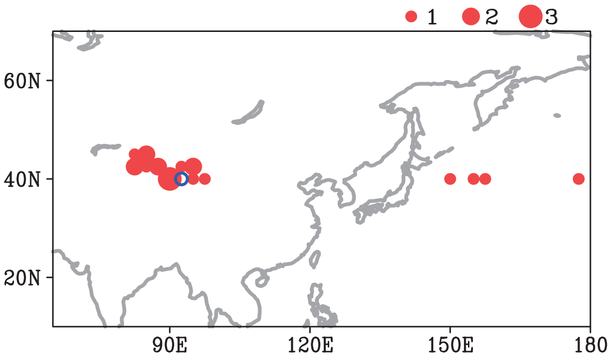


Fig. 3. Locations of the climatological summer EAJ core in the 20 models (red filled circles) and the observation (blue open circle), where the U200 is maximum over the domain (20°–70°N, 65°–180°E). Size of each dot depicts the number of models.

the ZSI based on the ERA-Interim data (the observation). The observational ZSI value is 2.1 m s^{-1}, which is consistent with the westward location of the EAJ core over the Asian continent (Fig. 3). Therefore, the ZSI is appropriate to depict the zonal location of the EAJ core. To compare the difference between the zonal-shifted models, the first six westward-located models with the ZSI being larger than 4 m s^{-1} and the last four with the ZSI being less than 0 are chosen. In the following composite analyses, these 10 selected models are employed, with the mean of the westward-located models minus the eastward-located models.

Figure 5 shows the composite EAJ and its difference. The composite EAJ core is located over the Asian continent with the center at (42.5°N, 90°E) in the positive phase of the ZSI and over the WNP with the center at (40°N, 160°E) in the negative phase—in good agreement with the zonal locations of the EAJ core in individual models (Figs. 2 and 3). The difference shows a strong negative U200 anomaly over the midlatitude WNP and a weak positive anomaly over the Asian continent. The strengthened westerly jet over the continent and the weakened westerly jet over the WNP correspond to the westward shift of the EAJ core. Also of note is the southward and westward extension of the easterly anomaly from the WNP to the subtropical Asian continent to the south of the EAJ core.

The zonal shift of the EAJ core indeed represents the major intermodel difference of the summer U200 climatology over East Asia. To analyze the dominant modes of intermodel variations in the climatological EAJ, we performed an intermodel empirical orthogonal function (EOF) analysis on the summer U200 climatology of the 20 models over the domain (20°–60°N, 60°–180°E). The intermodel EOF method has been employed previously to investigate the diversity of tropical sea surface temperatures and precipitation (Li and Xie, 2012, 2014; Ma and Xie, 2013; Wang et al., 2014) and East Asian summer circulation and rainfall (Kosaka and Nakamura, 2011; Qu, 2017). Figure 6 shows the first intermodel EOF mode. The EOF mode accounts for most (64%) of the total intermodel variance. It is characterized by a negative anomaly over the WNP, which extends westward and southward to the subtropical Asian continent with reduced magnitude, and a positive anomaly over the midlatitude Asian continent (Fig. 6a). The EOF pattern is similar to the composite U200 difference between the positive and negative phase of the ZSI (Fig. 5). Their pattern correlation coefficient over the domain (20°–60°N, 60°–180°E) is 0.97. Moreover, the values of the corresponding principal component (PC1) are larger than 0.5 for the selected six models with the EAJ core over the Asian continent, except for MIROC5, in which the PC1 value is slightly smaller (0.41). Also, the PC1 values are less than −0.5 for the last four models with the EAJ core over

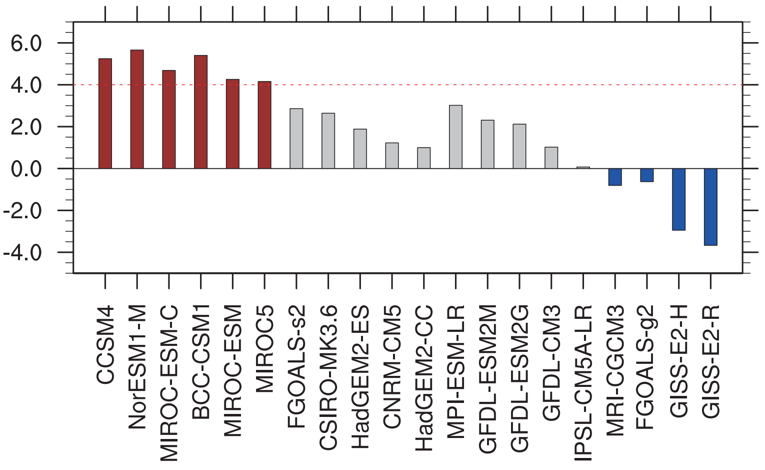


Fig. 4. ZSI of the climatological summer EAJ core in the 20 models. The ZSI is defined as the zonal difference in the U200 climatology along the EAJ averaged over the domains (30°–50°N, 70°–120°E) and (30°–50°N, 120°–170°E). A positive index depicts a westward shift of the EAJ core, and vice versa. Six models (red bars) in the positive phase, with the ZSI being positive and larger than 4 m s^{-1}, and four models (blue bars) in the negative phase, are chosen for the following composite analysis. The grey bars are for the rest.

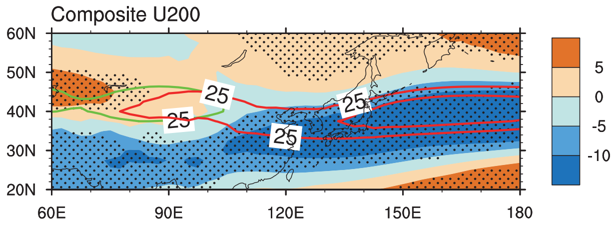


Fig. 5. Composite summer U200 climatology in the positive (green line) and negative (red line) phases and their difference (shading). Locations with a significant difference at the 95% confidence level are dotted.

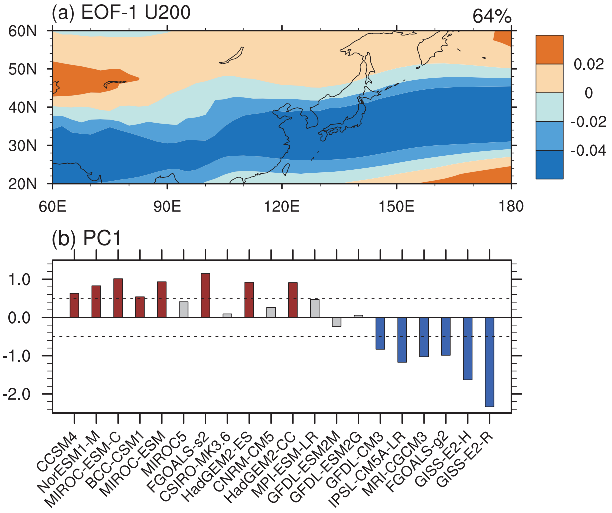


Fig. 6. (a) First intermodel EOF mode of the summer U200 climatology over the domain (20°–60°N, 60°–180°E) and (b) the associated normalized principal component (PC1). The EOF mode explains 64% of the total intermodel variance. The red bars depict models with PC1 values larger than 0.5, the blue bars those with PC1 values less than −0.5, and the grey bars in between in (b).

the WNP. In addition, the PC1 values are also less than −0.5 for GFDL-CAM3 and IPSL-CM5A-LR, in which the second core with U200 exceeding 25 m s^{-1} is evident over the WNP, though it is weaker than the one over the Asian continent (Fig. 2). Meanwhile, we also calculated the composite U200 based on PC1 (figure not shown), with the criterion of ±0.5 standard deviations, and obtained a similar result as in Fig. 5. The results above indicate that the zonal shift of the EAJ core depicts a major intermodel diversity of the simulated climatology of the summer EAJ. In the next section, we try to explore the possible mechanism underlying the intermodel diversity of the zonal shift of the EAJ core, which may help in understanding the model deficiencies in simulating the location of the EAJ core.

4. Possible interpretation and implications

4.1. *Possible interpretation for the diversity in the zonal shift of the EAJ core*

The change in the observational EAJ is closely related to variations of tropospheric temperature due to the thermal wind balance (Kuang and Zhang, 2005; Zhang and Guo, 2010). To reveal if there is a similar relation in the model simulations, Fig. 7a shows the composite difference in averaged air temperature in the mid–upper troposphere. Clearly, the westward retreat of the simulated EAJ core is associated with a midlatitude warmer air temperature extending northeastward from Southwest Asia to Northeast Asia and the northern North Pacific. The tropospheric warming decreases its meridional gradient to the south (Fig. 7b) and, consequently, decelerates the westerly jet (Fig. 5) over subtropical Asia and the midlatitude WNP. Meanwhile, the tropospheric warming over Southwest Asia (Fig. 7a) also increases its meridional gradient to the north (Fig. 7b) and accelerates the westerly jet over midlatitude Asia (Fig. 5). Accordingly, in the midlatitudes, the westerly anomaly over Asia and the easterly anomaly over the WNP cause the westward retreat of the EAJ core.

The difference in tropospheric air temperature is probably attributable to different intensities of simulated summer rainfall over South Asia (Fig. 8). The latent heat release in relation to South Asian rainfall can trigger a westward-extended Rossby wave response, which in midlatitudes develops downstream (Rodwell and Hoskins, 1996; Enomoto et al., 2003). The stronger South Asian rainfall might cause a stronger anticyclone response and downstream-propagated midlatitude wave train in the mid–upper troposphere, leading to the warmer tropospheric air temperature over Southwest Asia, Northeast Asia and the northern North Pacific. As shown in Fig. 8a, the westward retreat of the EAJ core corresponds to more rainfall over South Asia. The mean summer rainfall climatology over the South Asian region (10°–30°N, 65°–90°E) is 8.3 mm d^{-1} for the first six models—more than twice the 3.7 mm d^{-1} for the last four models (Fig. 8b). For each model, generally, a similar result is obtained, with stronger rainfall over South Asia for the models with

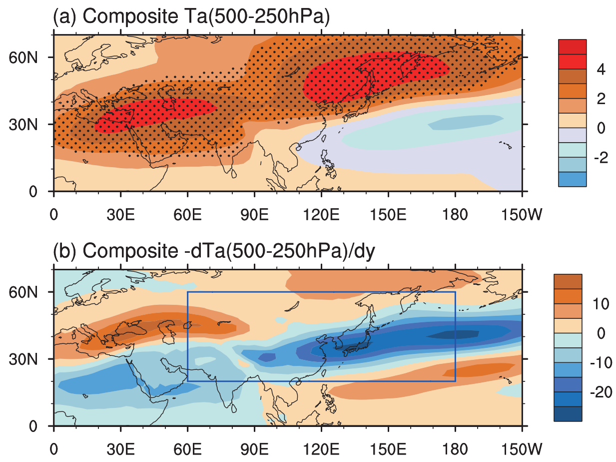


Fig. 7. As in Fig. 5, but for the composite difference in (a) average air temperature (units: °C) in the mid–upper troposphere between 500 and 250 hPa and (b) its meridional gradient (units: K). Locations with a significant difference at the 95% confidence level are dotted in (a), and the blue box in (b) depicts the same region as that used for the EOF analysis in Fig. 6.

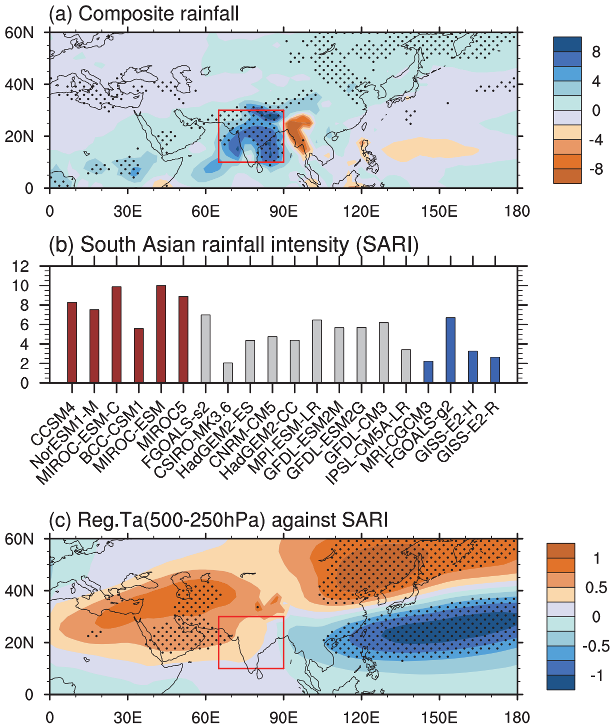


Fig. 8. (a) As in Fig. 5, but for composite difference in the summer rainfall climatology (units: mm d^{-1}). (b) Mean of the climatological summer rainfall intensity (SARI) over the South Asian region (10°–30°N, 65°–90°E). The red bars are for the six models chosen to represent the westward retreat of the EAJ core, the blue bars for the four models with an eastward shift of the EAJ core, and the grey bars for the rest, identical to Fig. 4. (c) Intermodel anomalies of tropospheric air temperature in the mid–upper troposphere regressed against the SARI. Locations with a significant difference are dotted at the (a) 95% and (c) 90% confidence level. The red box in (a, c) depicts the South Asian region.

a westward retreat of the EAJ core, and weaker rainfall for those with an eastward shift of the EAJ core. For the observation, the rainfall climatological value using the GPCP data is 5.7 mm d^{-1}, which lies between the two groups of models and is consistent with the observational ZSI value (2.1 m s^{-1}) that falls between the two groups (ZSI > 4 m s^{-1} and ZSI < 0) in Fig. 4. The rainfall–temperature relationship is further confirmed by the regressed air temperature in the mid–upper troposphere against the South Asian rainfall intensity (Fig. 8c). Related to the stronger climatological South Asian rainfall, the tropospheric air temperature is warmer over Southwest Asia, Northeast Asia and the northern North Pacific, as expected, resembling that related to the westward retreat of the EAJ core (Fig. 7a). The result suggests that the uncertainty of the simulated South Asian rainfall may partially contribute to the intermodel diversity in the zonal shift of the EAJ core. In addition, colder air is seen over the subtropical WNP, which further increases the meridional temperature gradient and decreases the westerly jet to the north over the midlatitude WNP.

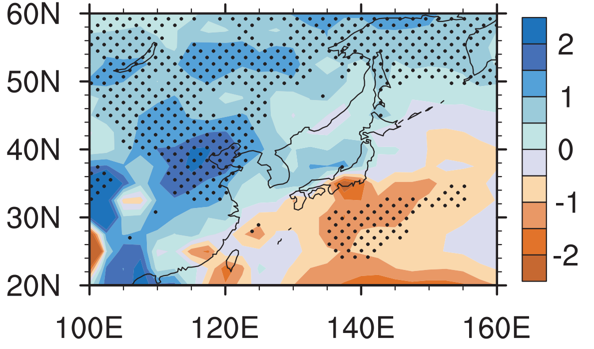
4.2. *Implications for uncertainty in the summer rainfall climatology over East Asia*

A few studies have noticed uncertainty in the simulated summer rainfall climatology in East Asia among CMIP5 models (Huang et al., 2013; Chen and Frauenfeld, 2014; Qu, 2017). Qu (2017) proposed that uncertainty in the meridional position of the ITCZ over the tropical WNP may be one source of the intermodel uncertainty in the climatological summer rainfall over East Asia. Additionally, observational analysis has revealed that the zonal shift in the EAJ core is closely related to summer rainfall variations over East Asia (Du et al., 2008; Sampe and Xie, 2010; Xie et al., 2015). In this section, we explore the possible relation of the diversity in the EAJ to the simulated uncertainty of the summer rainfall climatology over East Asia.

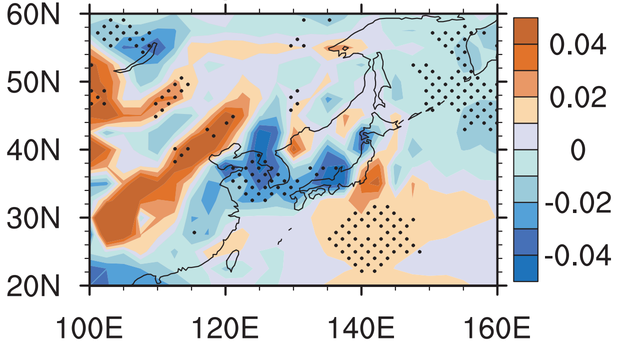
Based on the 10 selected models, we calculated the composite difference in the summer rainfall climatology over the East Asia–WNP domain (Fig. 9a). Related to the westward shift of the EAJ core, more rainfall occurs over the East Asian continent and less rainfall over the subtropical WNP south of Japan. This is similar to the observed rainfall change in relation to the subseasonal evolution of the westward retreat of the EAJ core in late June (Du et al., 2008; Xie et al., 2015). Over the subtropical WNP, the rainfall–EAJ relationship may be associated with a two-way interaction mechanism. On one hand, the simulated climatological rainfall difference is possibly attributable to the intermodel difference in vertical motion (Fig. 9b) due to the differing mid-tropospheric temperature advection by the various westerly jets over the WNP and Asian continent (Sampe and Xie, 2010; Wang and Zuo, 2016; Wang et al., 2018). The suppressed vertical motion over the subtropical WNP south of Japan is consistent with the in-situ reduced rainfall. On the other hand, summer rainfall may also feed back to the EAJ through latent heat release (Zhang et al., 2006; Lu and Lin, 2009). Therefore, the intermodel difference in the climatological summer rainfall, which is probably due to, for example, different descriptions of the physical processes and resolutions in models, may also affect the uncertainty in the EAJ climatology. Over the East Asian continent, the stronger rainfall is, however, more likely related to the lower-tropospheric southerly anomaly (Fig. 9c), which enhances the East Asian summer monsoon and transports more moisture northward towards the East Asian continent, favoring rainfall there.

5. Conclusion and discussion

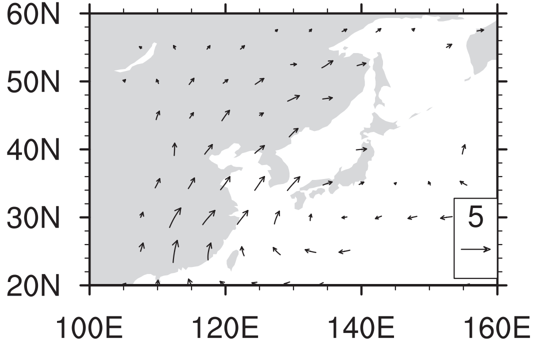
This study investigates the intermodel diversity in the zonal shift of the simulated summer EAJ climatology in the present-day climate among 20 CMIP5 models. There are 16 models with an EAJ core over the midlatitude Asian continent and four with it over the WNP. The zonal shift in the EAJ core depicts a major intermodel diversity in the simulated EAJ. The diversity of the zonal location of the EAJ core has some implications for the simulated rainfall climatology over East Asia. More rainfall occurs over the East Asian



(a) Composite rainfall



(b) Composite W500



(c) Composite uv850

Fig. 9. As in Fig. 8a, but for composite difference in the summer climatology of (a) rainfall (units: mm d^{-1}), (b) pressure vertical velocity at 500 hPa (units: Pa s^{-1}), and (c) horizontal wind vector at 850 hPa (units: m s^{-1}) over East Asia. Only significant wind anomalies are plotted in (c), at the 95% confidence level.

continent and less rainfall over the WNP south of Japan in the models with an EAJ core over the Asian continent, in contrast with the models with an EAJ core over the WNP.

The possible reason for the uncertainty in the EAJ core is explored. Compared with the eastward-located EAJ, the westward shift of the EAJ core is related to warmer tropospheric temperatures in the midlatitudes, with a southwest–northeast tilt extending from Southwest Asia to Northeast Asia and the northern North Pacific. The warmer air temperature increases the meridional temperature gradient and accelerates the westerly jet to the north over midlatitude Asia and decreases the meridional temperature gradient and decelerates the westerly jet to the south over subtropical Asia and the midlatitude WNP. The accelerated westerly over midlatitude Asia and the decelerated westerly over the midlatitude WNP then cause the westerly shift in the EAJ core. Moreover, we propose that the tropospheric warming is partially due to the simulated stronger summer rainfall climatology over South Asia. However, the detailed physical processes involved still need to be studied further.

The present study focuses on the performance of models in simulating the summer EAJ climatology and its association with rainfall. On the other hand, the EAJ also exhibits strong interannual variability observationally (Lu, 2004; Lin and Lu, 2005; Lu et al., 2013). Meanwhile, Lu and Fu (2010) noticed that climate models can reproduce well the tight correlation between the meridional displacement of the EAJ and East Asian summer rainfall. But, how well models can reproduce the interannual variability of the zonal shift in the EAJ and its impact on summer rainfall remains unclear. This open question requires further investigation.

Acknowledgements. We thank the three reviewers and the editor for their valuable comments, which greatly improved our manuscript. We acknowledge the World Climate Research Programme's Working Group on Coupled Modelling, which is responsible for CMIP, and we thank the climate modeling groups listed in Table 1 for producing and making available their model output. Zhongda LIN was supported by the National Natural Science Foundation of China (Grant No. 41775062) and the Youth Innovation Promotion Association (Grant No. CAS 2017105), and Yuanhai FU was supported by the National Key R&D Program of China (Grant No. 2017YFA0603802) and the National Natural Science Foundation of China (Grant No. 41675084).

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