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Projection of the East Asian westerly jet under six global warming targets

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ABSTRACT

This study investigates the projected changes in the East Asian westerly jet (EAJ) under six global warming targets (1.5°C, 2.0°C, 2.5°C, 3.0°C, 3.5°C, and 4.0°C) relative to the present climate, using the outputs of CMIP5 models. The results show that the westerly tends to weaken slightly under the 1.5°C warming target. Under the 2.0°C target, it is projected to intensify south of the EAJ's axis (approximately 40°N) and decay north of the axis. This change becomes increasingly evident under the 2.5°C and higher warming targets, which suggests that the EAJ's axis will move farther and farther southward, but its intensity will change little with increasing global warming. Further analyses suggest that the change in the EAJ is closely related to the inhomogeneous rising rate of air temperature in the mid–upper troposphere. The relatively slow-rising air temperature in the mid–upper troposphere over the EAJ's entrance and exit regions will lead to a negative (positive) meridional temperature gradient to the south (north), and will then accelerate (decelerate) the westerly on the EAJ's south/north side.

摘要

东亚高空急流(简称急流)对夏季东亚地区的天气和气候有着重要影响。本文利用CMIP5的历史 气候模拟试验和RCP8.5路径下的未来气候变化预估试验数据,预估了急流在6个全球变暖阈值 (1.5℃, 2.0℃, 2.5℃, 3.0℃, 3.5℃和4.0℃)下相对于当代气候的变化情况。结果表明东亚高空西 风在1.5℃阈值下略微减弱。在2.0℃阈值下,西风在急流轴(约40°N)南侧增强,北侧减弱。这种 变化趋势在2.5℃和更高的变暖阈值下愈加明显,使急流轴逐渐向南移动,但急流强度变化不大。 研究表明,在急流的入口和出口区,对流层中上层大气升温速度相对较慢,导致在急流轴南(北)侧 出现向南(北)的负(正)经向温度梯度,使西风在南(北)侧增强(减弱).

1. Introduction

The East Asian westerly jet (EAJ) is a dominant component of the East Asian summer (June–July–August) monsoon. The EAJ is located north of the East Asian subtropical rainy belt in summer, and its intensity and location significantly affect the precipitation over East Asia (Xuan, Zhang, and Sun 2011; Lu, Lin, and Zhang 2013). Thus, the future behavior of the EAJ under global warming is of great concern.

Many studies have projected the changes in the EAJ due to global warming. The CMIP3 future warming scenarios suggested an intensified and southward-migrated EAJ in the 21st century (Zhang and Guo 2010). Its interannual variability is also projected to be enhanced in the future (Lu and Fu 2010; Fu 2013). By analyzing the outputs of CMIP5 models, both Dai and Lu (2013) and Ren et al. (2016) claimed that the interannual variability in the EAJ would intensify in the 21st century, and the relationship between East Asian summer rainfall and the EAJ would be stronger compared to that in the present day.

Moreover, the possible responses of the EAJ to different warming targets have received less attention. The Paris Agreement aims to maintain the rise in global

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关键词

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temperature well below 2.0°C above preindustrial levels and to pursue efforts to limit this even further to 1.5°C. However, it is expected that a global warming target of even 4.0°C-5.0°C will be reached by the end of the 21st century under a high emission scenario (Guo et al. 2016; Xu et al. 2017; Fu, Lu, and Guo 2018; Wang, Jiang, and Lang 2018). Thus, it is imperative that researchers investigate the variations in the EAJ under various warming targets (i.e. 1.5°C, 2.0°C, 2.5°C, 3.0°C, 3.5°C, and 4.0°C) in comparison with the present climate.

The rest of the paper is organized as follows: section 2 describes the data and methods; section 3 displays the selection of the models and the projected changes in the EAJ under the global warming targets; and a summary is provided in section 4.

2. Data and methods

The results of 28 CMIP5 models were downloaded for their historical climate simulation (referred to as HIST hereafter, 1850–2005) and future climate projection under Representative Concentration Pathway 8.5 (RCP8.5, 2006–2100). Only one member (the first member) was

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selected for each model. All simulations were interpolated onto a common $2.5^{\circ} \times 2.5^{\circ}$ grid to enable the multi-model ensemble (MME) and median analyses. Table 1 lists key information about the models. Following the 1.5°C Special Report (IPCC 2018), the 51-year (1850–1900) global mean surface temperature (GMST) was used as the guasipreindustrial baseline. The warming was defined as the GMST anomaly relative to the average of the preindustrial baseline. An 11-year-window moving mean of the anomalous GMST was used to find the years in which global warming reached the targets. Once the time was determined for a model, the 11-year (5 years before and after) mean was taken as the climatic state under the warming target. Under a warming target, the MME result was obtained by simply averaging the climatic state in the individual models with equivalent weight. Additionally, the 20-year (1986-2005) simulation of HIST was used to represent the present climate. The projected change was calculated by the difference between variables under the warming target and those in the present climate.

3. Results

3.1 Model evaluation and selection

The individual CMIP5 models exhibit a large inter-model discrepancy in simulating the EAJ (Lin, Fu, and Lu 2019). Therefore, agreement between the simulated and observed zonal wind at 200 hPa over (20°–60°N, 60°–180°E) during the period 1986–2005 is evaluated using Taylor diagrams (Taylor 2001) (Figure 1). As we can see, most

models can sufficiently reproduce the observed character of zonal wind at 200 hPa. The centralized distribution implies a small inter-model spread. With the exception of four models (GISS-E2-H, GISS-E2-R, IPSL-CM5A-LR, and MIROC-ESM-CHEM), nearly all of the models have correlation coefficients with the observations larger than 0.90, normalized standard deviations between 0.75 and 1.25, and RMSEs lower than 0.50.

On the other hand, three models (BCC-CSM1-1-M, BNU-ESM, and FGOALS-s2) reach the 1.5°C global warming target before the year 2010, and seven models (FGOALS-g2, GFDL-ESM2G, GFDL-ESM2M, GISS-E2-H, GISS-E2-R, MIROC5, and MRI-CGCM3) do not project the 4.0°C warming by the end of the 21st century (Table 1). These models are excluded from the subsequent investigation.

Therefore, the outputs of 16 models (BCC-CSM1-1, CESM1-CAM5, CCSM4, CanESM2, CNRM-CM5, FIO-ESM, GFDL-CM3, HadGEM2-AO, HadGEM2-CC, HadGEM2-ES, IPSL-CM5A-MR, MIROC-ESM, MPI-ESM-LR, MPI-ESM-MR, NorESM1-ME, and NorESM1-M) are used in the following analyses.

3.2 *Projected changes in the EAJ under the six global warming targets*

The zonal wind at 200 hPa is projected to change little under the 1.5°C warming target (Figure 2(a)). Around the axis of the EAJ (approximately 40°N), the westerly is projected to decrease at a rate of only approximately 0.2–0.4 m s⁻¹, which suggests a weakened EAJ under the 1.5°C target. At the same time, the EAJ's axis shows

Table 1. Basic information of the CMIP5 models used in this study and their global warming target times.

Model	Affiliation and country	Resolution	1.5℃	2.0°C	2.5°C	3.0°C	3.5℃	4.0°C
BCC-CSM1-1	BCC, China	128 × 64	2018	2035	2050	2060	2070	2084
BCC-CSM1-1-M	BCC, China	128×64	2010	2028	2048	2059	2068	2084
BNU-ESM	GCESS, China	128×64	2009	2023	2035	2047	2055	2065
CESM1-CAM5	NCAR, USA	288 × 192	2028	2041	2047	2057	2067	2078
CCSM4	NCAR, USA	288 × 192	2015	2030	2045	2058	2068	2077
CanESM2	CCCMA, Canada	128×64	2015	2028	2040	2049	2059	2069
CNRM-CM5	CNRM-CERFACS, France	256 × 128	2029	2044	2055	2066	2077	2088
FGOALS-g2	IAP, China	128×60	2031	2045	2061	2075	2089	-
FGOALS-s2	IAP, China	128×60	1997	2011	2025	2036	2048	2054
FIO-ESM	FIO, China	128 × 64	2028	2045	2055	2068	2078	2086
GFDL-CM3	NOAA GFDL, USA	144×90	2025	2036	2048	2055	2064	2071
GFDL-ESM2G	NOAA GFDL, USA	144×90	2037	2055	2068	2078	2092	-
GFDL-ESM2M	NOAA GFDL, USA	144×90	2036	2051	2067	2078	2094	-
GISS-E2-H	NASA GISS, USA	144×90	2019	2036	2051	2066	2080	-
GISS-E2-R	NASA GISS, USA	144×90	2032	2053	2072	2086	-	-
HadGEM2-AO	MOHC, UK	192 × 145	2037	2046	2054	2062	2072	2078
HadGEM2-CC	MOHC, UK	192 × 145	2029	2041	2051	2058	2063	2073
HadGEM2-ES	MOHC, UK	192 × 145	2022	2035	2048	2056	2065	2073
IPSL-CM5A-LR	IPSL, France	96 × 96	2014	2028	2040	2047	2057	2066
IPSL-CM5A-MR	IPSL, France	144×143	2015	2031	2043	2051	2058	2068
MIROC-ESM-CHEM	MIROC, Japan	128 × 64	2019	2029	2042	2049	2058	2068
MIROC-ESM	MIROC, Japan	128 × 64	2020	2031	2041	2052	2062	2071
MIROC5	MIROC, Japan	256 × 128	2033	2051	2059	2072	2082	-
MPI-ESM-LR	MPI-M, Germany	192 × 96	2014	2038	2050	2061	2072	2083
MPI-ESM-MR	MPI-M, Germany	192 × 96	2021	2040	2051	2060	2071	2085
MRI-CGCM3	MRI, Japan	320 × 160	2041	2054	2063	2078	2087	-
NorESM1-ME	NCC, Norway	144 × 96	2033	2048	2058	2070	2081	2092
NorESM1-M	NCC, Norway	144 × 96	2033	2049	2061	2072	2086	2095



Figure 1. Taylor diagrams of zonal wind at 200 hPa over (20°–60°N, 60°–180°E) between NCEP reanalysis data and CMIP5 model outputs during the period 1986–2005. The solid lines indicate the RMSE; the dashed lines indicate the normalized standard deviation; the dotted lines indicate the correlation coefficients of 0.6 and 0.9.

almost no meridional movement. Additionally, there is little agreement in most changes in two-thirds of the models, indicating a large inter-model uncertainty.

Under the 2.0°C warming target, the westerly tends to accelerate south of the EAJ's axis and decelerate north of the axis, both at a rate of approximately 0.6–0.8 m s⁻¹ (Figure 2(b)), showing a different spatial pattern compared with that under the 1.5°C target. This pattern causes a slight southward displacement of the EAJ's axis. It appears that the changes occur mainly at the entrance (approximately west of 90°E) and exit (approximately east of 120°E) regions of the EAJ. The changes are in agreement in approximately two-thirds of the selected models, indicating a greater consistency among the models compared to that under the 1.5°C target.

Under the 2.5°C and higher warming targets, the spatial pattern of the changes in the westerly that increase south of the axis and decrease north of the axis, will become increasingly evident and the amplitude of changes will intensify with increasing targets (Figure 2(c-f)). In the meantime, the EAJ's axis will move farther and farther southward with global warming, though the EAJ's intensity will change little. Generally, there are two positive centers south of the axis and two negative centers north of the axis. These positive/negative pairs of changes appear at the entrance and exit regions of the EAJ, respectively. By the 4.0°C global warming target, the westerly is projected to accelerate/

decelerate at a rate of approximately 2.0 m s⁻¹ on the south/north side of the EAJ's axis, and the axis will move southward by approximately 2.0° of latitude (Figure 2(f)). More than approximately two-thirds of the models project the same trend and the inter-model consistency tends to be greater under warmer targets.

To facilitate the quantitative estimation of the projected changes in the EAJ, the intensity and shift indices are defined. Figure 3(a) shows the changes in the EAJ's intensity index, which is defined as the area-averaged zonal wind at 200 hPa over $(30^\circ-50^\circ\text{N}, 70^\circ-150^\circ\text{E})$, following Lin, Fu, and Lu (2019). The intermodel median results suggest that the intensity will exhibit few changes under all six warming targets, which are caused by opposite changes in the westerly on the two sides of the EAJ's axis (Figure 2).

Figure 3(b) shows the projected changes in the EAJ's shift index, which is defined as the difference between the 200-hPa zonal wind averaged over $(30^\circ-40^\circ N, 120^\circ-150^\circ E)$ and $(40^\circ-50^\circ N, 120^\circ-150^\circ E)$, following Lu and Fu (2010). A positive (negative) EAJ shift index indicates a southward (northward) displacement of the EAJ. The inter-model median result indicates that the EAJ's axis will move southward increasingly clearly, when global warming is higher than 2.0°C. The displacement shows an approximately linear trend with increasing warming targets, though the axis tends to move northward under the 1.5°C warming target. The axis will move southward displacement of the axis can be found in approximately three-quarters of the models.

3.3 *Possible interpretation for the projected changes in the EAJ*

The change in the EAJ is closely related to the variation of tropospheric temperature due to the thermal wind relationship (Kuang and Zhang 2005; Zhang and Guo 2010). This relationship can be expressed as a linear relationship between the change in zonal wind and the meridional air temperature gradient. For the EAJ, the thermal wind adjustment is mainly toward the anomalous temperature field. If the atmospheric temperature is anomalously colder (warmer) in the north and anomalously warmer (colder) in the south, the westerly will increase (decrease).

Under the 1.5° C warming target, the change in air temperature in the mid–upper troposphere is approximately uniform over the East Asia region and approximately 1.2° C warmer than the present temperature (Figure 4(a)). According to the thermal wind relationship, the warming has a weak horizontal temperature gradient, which leads to a weak change in the westerly (Figure 2(a)).



Figure 2. MME projected changes in zonal wind at 200 hPa under the six global warming targets (yellow shades indicate an increase and blue a weakening). The solid line indicates the position of the EAJ's axis in HIST, and the dashed line indicates the position under each warming target. Black dots indicate that more than two-thirds of the models show the same trend. Units: m s⁻¹.

In addition, the role played by the changes in air temperature in the lower troposphere is hard to find because of the large inter-model diversity (figure not shown for brevity). The diversity is mainly caused by the lower horizontal resolutions used by current CMIP5 models, which are not sufficient to represent the complexity of the geomorphology, especially over the Tibetan Plateau.

Under the 2.0°C warming target, a slow warming center appears over the entrance region of the EAJ (Figure 4(b)). This suggests that at the south (north) flank of the entrance region that is located south (north) of approximately 40°N, the temperature is anomalously colder (warmer) in the north and anomalously warmer (colder) in the south, which causes a negative (positive) meridional temperature gradient (∇T_y) to the south (north), and in turn accelerates (decelerates) the westerly on the south (north) side of the EAJ's axis (Figure 2(b)). Simultaneously, a trough of warm air appears over the exit region because of the fast warming on its poleward (north of 40°N) and equatorward (south of 40°N) sides (Figure 4(b)). Similarly, the westerly also increases on the south side of the EAJ's axis and decreases on the north side over the exit region (Figure 2(b)). The opposite changes lead to a southward displacement of the EAJ's axis (Figure 3(b)).

Under the 2.5°C and higher warming targets, the inhomogeneous warming patterns of air temperature in the mid-upper troposphere are increasingly clear (Figure 4(c-f)). According to the thermal wind



Figure 3. (a) Boxplot of changes in EAJ intensity index under the six warming targets (units: $m s^{-1}$). Positive (negative) values indicate an increase (decrease) in the EAJ's intensity. The short black lines indicate the multi-model median changes of the individual models; red boxes indicate the lower and upper quartiles of the changes; and blue lines indicate their minimum and maximum. (b) As in (a), but for the EAJ shift index. Positive (negative) values indicate a southward (northward) displacement of the EAJ's axis.

relationship, the increasing negative (positive) meridional temperature gradients to the south (north) increase (decrease) the westerly on the EAJ's south (north) side with the increasing warming targets (Figure 2(c-f)). Therefore, the EAJ's intensity will change little (Figure 3(a)), and its axis will move farther and farther southward with global warming (Figure 3(b)).

4. Summary

This study investigates the projected changes in the EAJ under six global warming targets (1.5°C, 2.0°C, 2.5°C, 3.0°C, 3.5°C, and 4.0°C) in comparison with the EAJ in the present climate, using the outputs of 28 CMIP5 models in HIST and RCP8.5. Sixteen models that project global warming reaching 4.0°C and that have the highest skills in simulating the present zonal wind at 200 hPa were selected.

The projected zonal wind at 200 hPa will weaken slightly under the 1.5°C target. Under the 2.0°C target, the westerly tends to intensify south of the EAJ's axis and decay north of the axis. This spatial pattern will become increasingly evident under the 2.5°C and higher warming targets. That is, the increase of the westerly on the south side and decrease on the north side will intensify with increasing global warming targets. This implies that the EAJ's intensity will exhibit few changes, and the EAJ's axis will move farther and farther southward with global warming. Movement of up to approximately 2.0° of latitude will occur by the 4.0°C warming target.

The change in the westerly is closely associated with the inhomogeneous rising rate of air temperature in the mid–upper troposphere. Under the 1.5°C target, the change in air temperature exhibits a weak meridional gradient. Under higher warming targets, the air temperature rises slowly over the EAJ's entrance and exit



Figure 4. MME projected changes in the averaged air temperature between 500 and 200 hPa under the six global warming targets, and the color shading shows the changes in meridional temperature gradient (∇T_y) (yellow shades indicate an increase and blue a weakening). The contour line interval is 0.1. Black dots indicate that more than two-thirds of the models show the same trend. Units: °C.

regions, which causes a negative meridional temperature gradient to the south and a positive gradient to the north, in turn accelerating the westerly on the EAJ's south side and decelerating it on the north side.

Disclosure statement

No potential conflict of interest was reported by the authors.

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