Theoretical and Applied Climatology (2019) 137:2187–2201
https://doi.org/10.1007/s00704-018-2720-1

ORIGINAL PAPER

Projections of East Asian summer monsoon under 1.5 °C and 2 °C warming goals

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Received: 28 May 2018 / Accepted: 18 November 2018 / Published online: 12 December 2018

Abstract

Based on 1.5 °C and 2.0 °C warming experiments of Community Earth System Model, this study documents future changes in the East Asian summer monsoon (EASM) and associated monsoon precipitation. The model reproduces reasonably well the climatology of East Asian summer rainfall. All ensemble means show an increase in EASM intensity and associated precipitation over most parts of the East Asian region in 1.5 °C "never-exceed" (1.5degNE), 1.5 °C "overshoot" (1.5degOS), and 2.0 °C (2.0degNE) experiments. There is no significant difference in the future changes in EASM intensity, EASM precipitation, and its location among the three scenarios. A moisture budget analysis demonstrates that the increased precipitation over East Asia in three scenarios should be ascribed to the changes in evaporation, vertical motion, and humidity. The contributions of these three dominant terms increase sequentially under 1.5degNE, 1.5degOS, and 2degNE scenarios. However, the differences among the three scenarios are quite small in three dominant terms. Over East Asia, the contributions of evaporation and vertical motion are generally larger than that of humidity to the domain-averaged EASM rainfall in each scenario.

1 Introduction

The East Asian summer monsoon (EASM) has an important influence on weather and climate in East Asia and its adjacent regions as the summer monsoon rainfall provides most of the annual average precipitation (Lei et al. 2011). Many previous studies have indicated that the variability in the advance and retreat of the rain belt has substantial social and economic influence (Huang et al. 1999, 2006, 2007; Jiang et al. 2008; Hu et al. 2011, 2013). Therefore, projection of future changes in EASM and associated precipitation under global warming is one of the central issues relevant to the sustainable development of society and economy.

Many previous studies have investigated future projections of EASM and associated precipitation. A significant change in monsoon rainfall is found in East Asia based on the Coupled Model Intercomparison Project phase 3 (CMIP3) in various scenarios, such as Special Report on Emissions Scenarios (SRES) B1, A1B, and A2 (Lu and Fu 2010; Fu and Jiang 2012; Kusunoki and Arakawa 2012; Jiang and Tian 2013). Recently, based on multi-model results of CMIP5, some studies provide evaluations on projected changes in EASM intensity and precipitation for high-emissions scenarios Representative Concentration Pathway (RCP), such as RCP8.5 (Bao 2012; Li et al. 2014; Kwon et al. 2017), RCP6.0 (Seo et al. 2013), and RCP4.5 (Jiang and Tian 2013; Chen and Sun 2013; Lee and Wang 2014). It is found that both EASM and associated precipitation are projected to strengthen in East Asia during the twenty-first century's different time periods. In addition, compared with other monsoon domains, the changes in extreme precipitation indices are most pronounced over East Asian region in both RCP4.5 and RCP8.5 scenarios (Kitoh et al. 2013).

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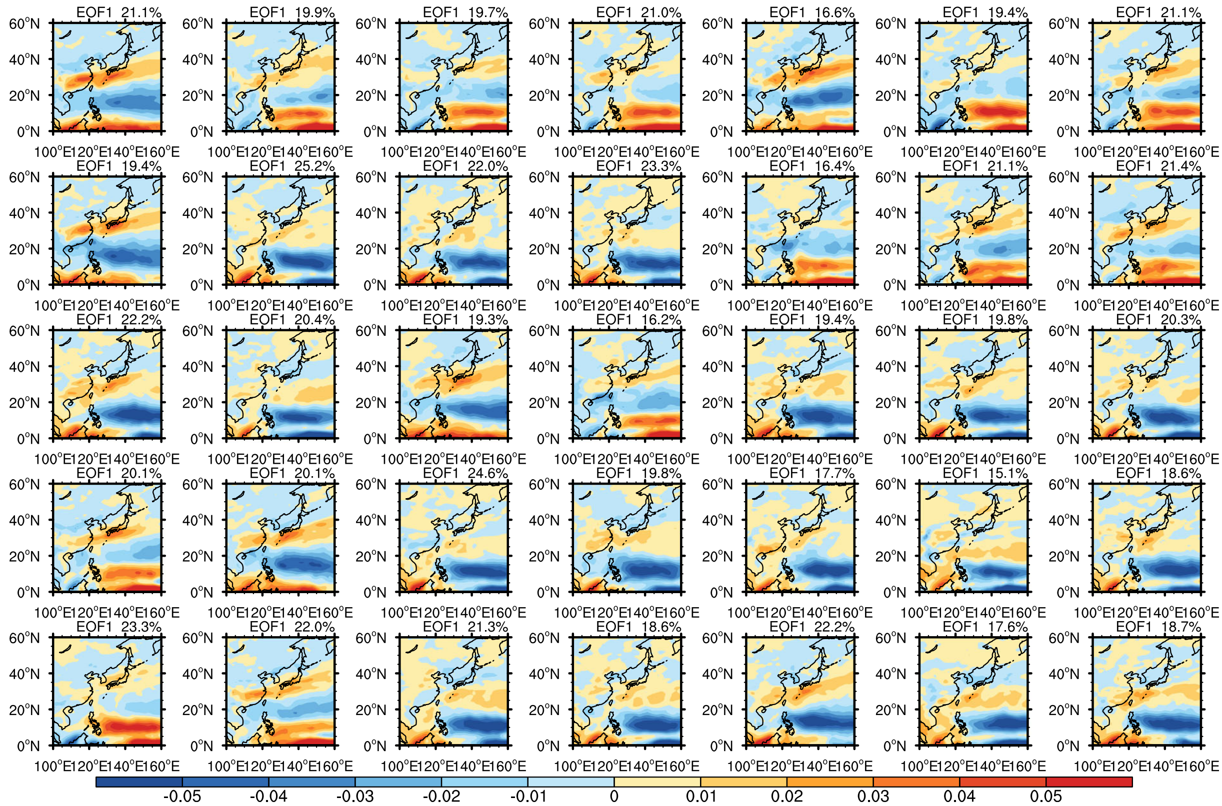


Fig. 1 The leading EOF mode of JJA precipitation anomalies (color shading, unit: mm day^{-1}) over East Asian region during 1958–2005 in each ensemble of CESM historical simulations

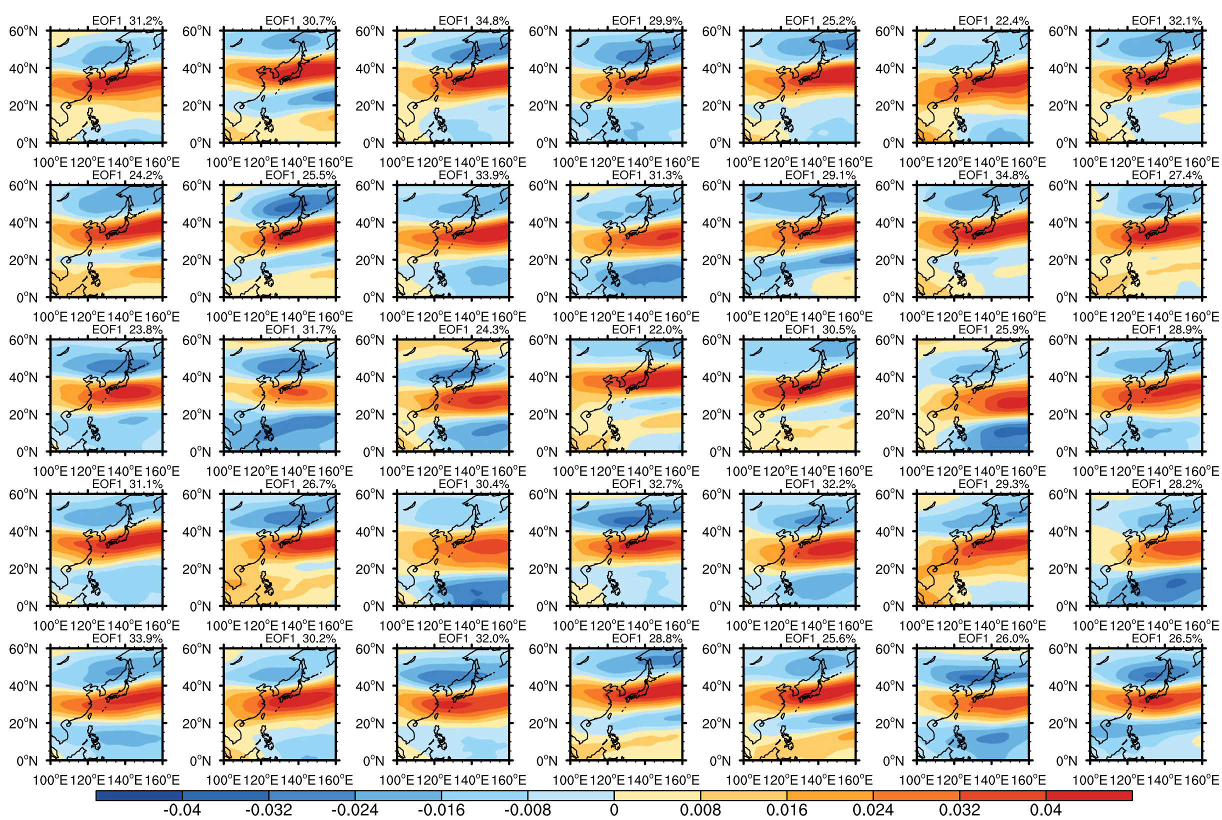


Fig. 2 The leading EOF mode of JJA zonal wind at 200 hPa (color shading, unit: m s^{-1}) over East Asian region during 1958–2005 in each ensemble of CESM historical simulations

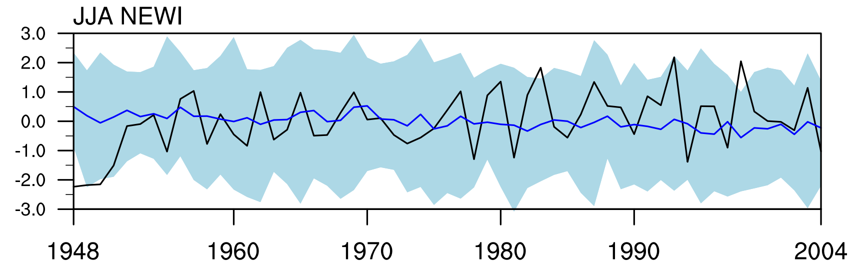


Fig. 3 Ensemble mean of normalized NEWI in CESM for the period 1948–2004 (blue solid line), and normalized NEWI in NCAR-NCEP reanalysis for the period 1948–2004 (black line). The light blue shading indicates the inter-ensemble spread

Because of the continuous increase in greenhouse gases (GHGs) concentration, the problem of global warming becomes more serious (IPCC 2013). The Paris Agreement stated a goal to pursue efforts to keep global temperatures below 1.5 °C above pre-industrial levels on December 2015 (UNFCCC 2015). As a matter of fact, the 1.5 °C warming target is different from previous global warming scenarios. With defined carbon emission pathways, the previous global warming scenarios concentrate on the change of the climate, which belongs to the research field of climate dynamics. Without any given emission pathway, the 1.5 °C target concentrates on temperature rise. It is not only a matter of climate dynamics but also a socioeconomic issue. In addition, for monsoon, the Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX) assessed that the low confidence in projected changes of the monsoon, especially for high-emissions scenarios, is likely associated with uncertainty between models (Seneviratne et al. 2012). And Wartenburger et al. (2017) pointed out that there exist substantial differences in heavy precipitation between 1.5 and 2 °C warming goals. However, projections of changes in EASM under 1.5 and 2 °C warming goals are rarely assessed in the literature so far.

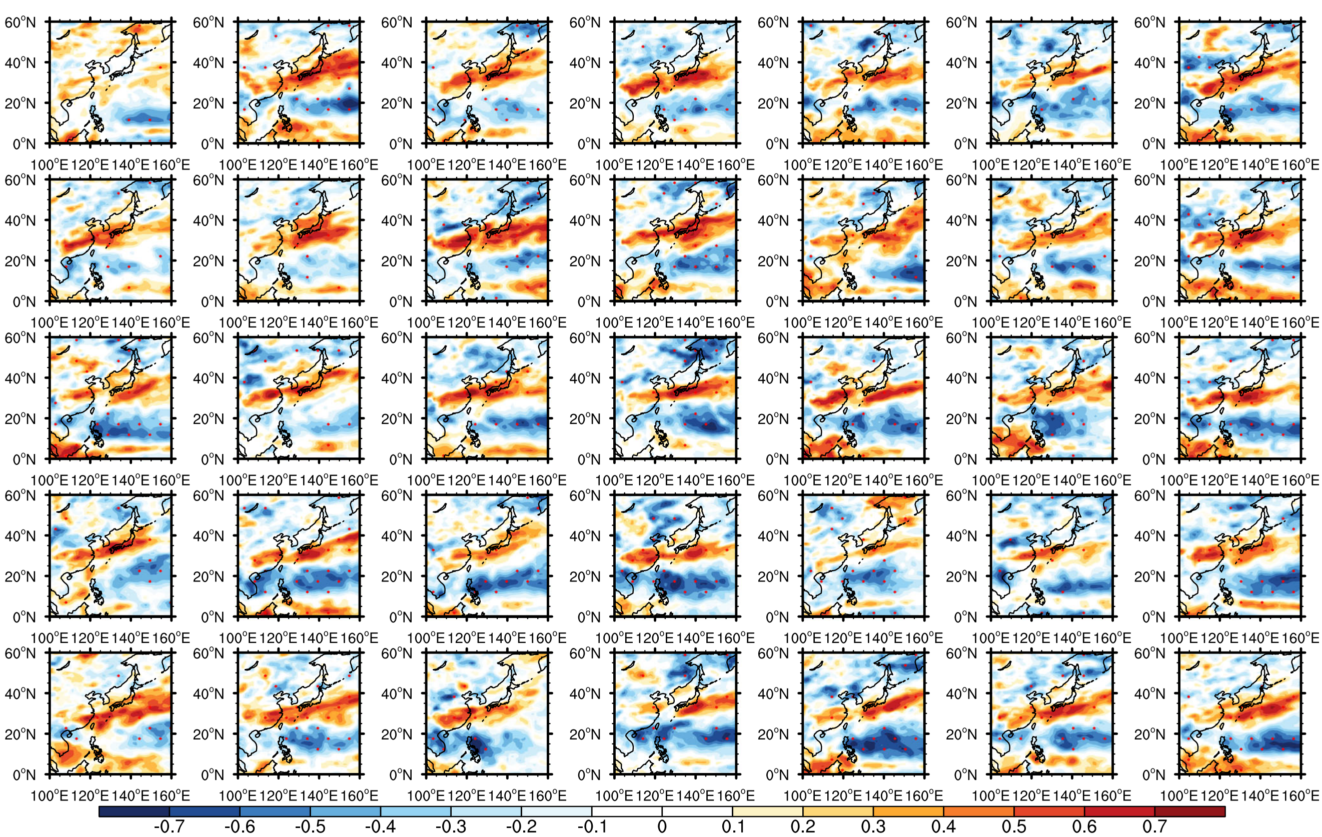


Fig. 4 Correlation (color shading) of precipitation (unit: mm day^{-1}) and the NEWI for the period 1980–2005 in each ensemble of CESM historical simulations. The red dots indicate the correlation reaches the 90% confidence level

Previous studies on EASM and associated precipitation mostly focused on the results under high emission scenarios. However, in order to achieve the 1.5 °C and 2 °C warming targets, greenhouse gases concentration or radiative forcing is required to decrease in the next few decades (Sanderson et al. 2016, 2017; Xu and Ramanathan 2017). Compared with the previous pathways in which the radiative forcing is monotonically increasing, the thermodynamic and dynamical processes in the ocean will be different under pathways in which the radiative forcing is monotonically decreasing. In addition, in response to the radiative forcing, there exists the fast adjustment of ocean mixed layer and the slow response in deeper ocean due to its enormous heat capacity (Held et al. 2010; Chadwick et al. 2013; Long et al. 2014). And the East Asian monsoon is generally affected by the heating effect of the ocean (Zhou et al. 2009; Li et al. 2014; Ueda et al. 2015). Thus, different responses of the oceans may have a significant impact on the response of EASM.

Therefore, the question arises how the EASM and associated precipitation change when the greenhouse gas concentration firstly increases and then decreases in 1.5 °C and 2 °C warming scenarios during different periods of the twenty-first century. At present study, numerical simulation is relatively feasible. Nevertheless, only Community Earth System Model (CESM, version 1; Hurrell et al. 2013) is in agreement with 2 °C and 1.5 °C warming goals. Hitherto, this model has not yet been used to analyze changes of East Asian summer monsoon. Based on above statement, this paper intends to use this experimental result to analyze the changes in the EASM and monsoon rainfall under 1.5 °C and 2 °C warming targets and provide relevant diagnostic analysis. The rest of the paper is organized as follows. Section 2 describes the data as well as the methods used in the study. Section 3 evaluates the simulation capacity of the CESM model. Section 4 displays future changes in the EASM and associated monsoon rainfall under 1.5 °C and 2 °C warming goals, respectively. Section 5 diagnoses the causes of the EASM precipitation changes. And the summary and discussion are provided in Section 6.

2 Data and methods

The projection is based on CESM Low Warming runs: 10 ensembles for scenarios 1.5 °C “never-exceed” (1.5degNE) and 2.0 °C (2.0degNE) and 5 ensembles for scenario 1.5 °C “overshoot” (1.5degOS). The simulations for these three scenarios were all derived from Kay et al. (2015) in 2006, running through 2100. The detailed definition of 1.5degNE, 1.5degOS, and 2.0degNE scenarios and their emission pathways are given by Sanderson et al. (2017). A 35-member ensemble is conducted with the CESM1-Community Atmosphere Model (version 5, CAM5) (Hurrell et al. 2013) BGC Large Ensemble for 1920–2005. The focused period is 1980–2005.

The reproducibility of the CESM is estimated against reanalysis data. In this paper, we use the monthly atmospheric reanalysis data available from 1948 to the present with a horizontal resolution of 2.5° × 2.5° (Kalnay

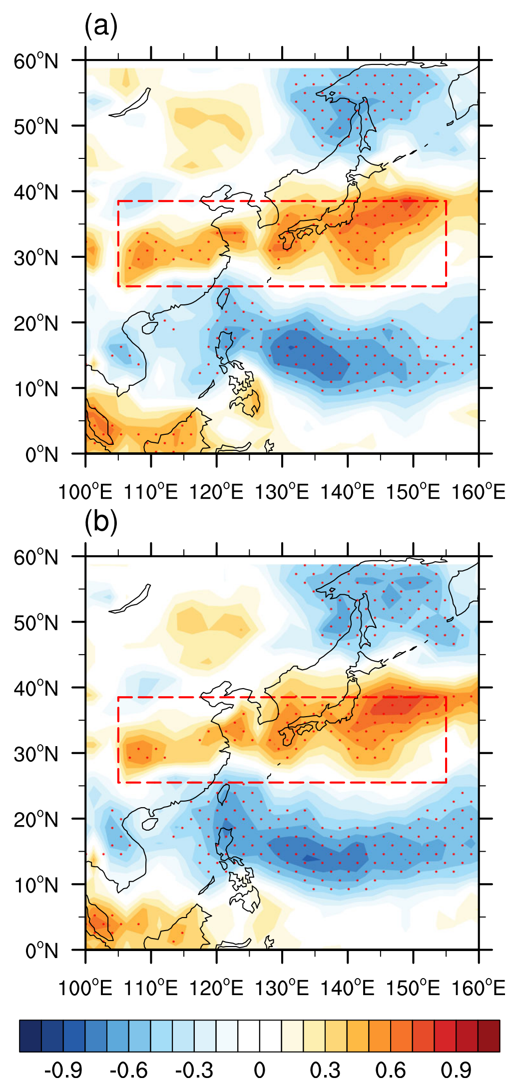


Fig. 5 Same as in Fig. 4, but the results from the **a** GPCP and **b** CMAP. The area [25.5° N–38.5° N, 105° E–155° E] in red frame is highly correlated positive area. The red dots indicate the correlation reaches the 95% confidence level

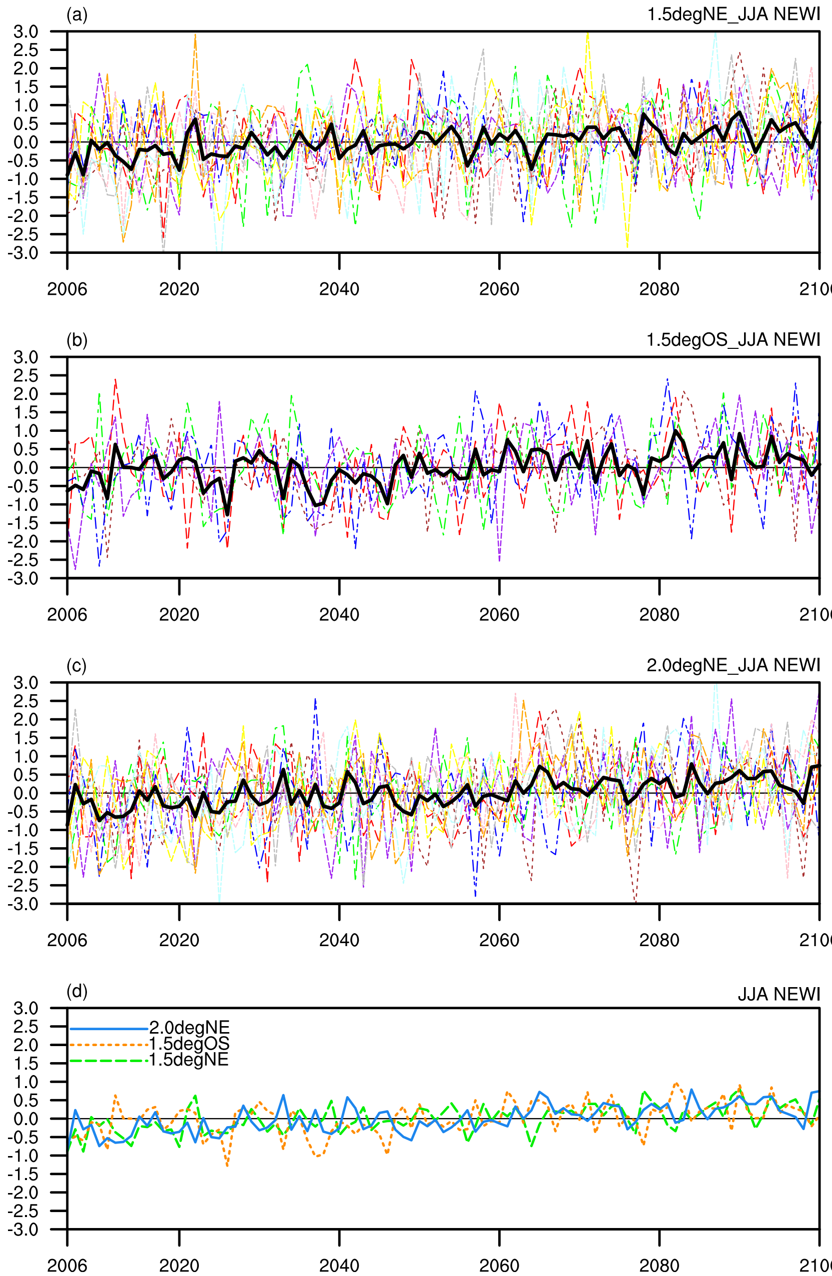


Fig. 6 The NEWI under: **a** 1.5degNE, **b** 1.5degOS, and **c** 2.0degNE. The results in each scenario are subtracted by corresponding 2006–2100 mean. The corresponding ensemble mean is displayed as thick black lines. The results of each ensemble are displayed as color lines. **d** The ensemble mean for each scenario

et al. 1996). And the monthly global Precipitation data from Center for Climate Prediction Merged Analysis of Precipitation (CMAP; Xie and Arkin 1997) during 1979–2008 and the Global Precipitation Climatology Project (GPCP; Huffman et al. 2009) for the period 1979–2009 were also utilized. Both of these two data sets have a horizontal resolution of 2.5° × 2.5°.

To measure the intensity of EASM, the NEW index (NEWI) used in this study was proposed by Zhao et al. (2015), which reflects well main features associated with EASM variability. Hence, our study uses NEWI to measure the EASM.

$$NEWI = Nor\left[\begin{array}{l} u(2.5^{o}\text{–}10^{o}N, 105^{o}\text{–}140^{o}E) \\ -u(17.5^{o}\text{–}22.5^{o}, 105^{o}\text{–}140^{o}E) \\ +u(30^{o}\text{–}37.5^{o}N, 105^{o}\text{–}140^{o}E) \end{array}\right] \quad (1)$$

Where *Nor* represents standardization and *u* refers to the average of June, July, and August (JJA) zonal wind at

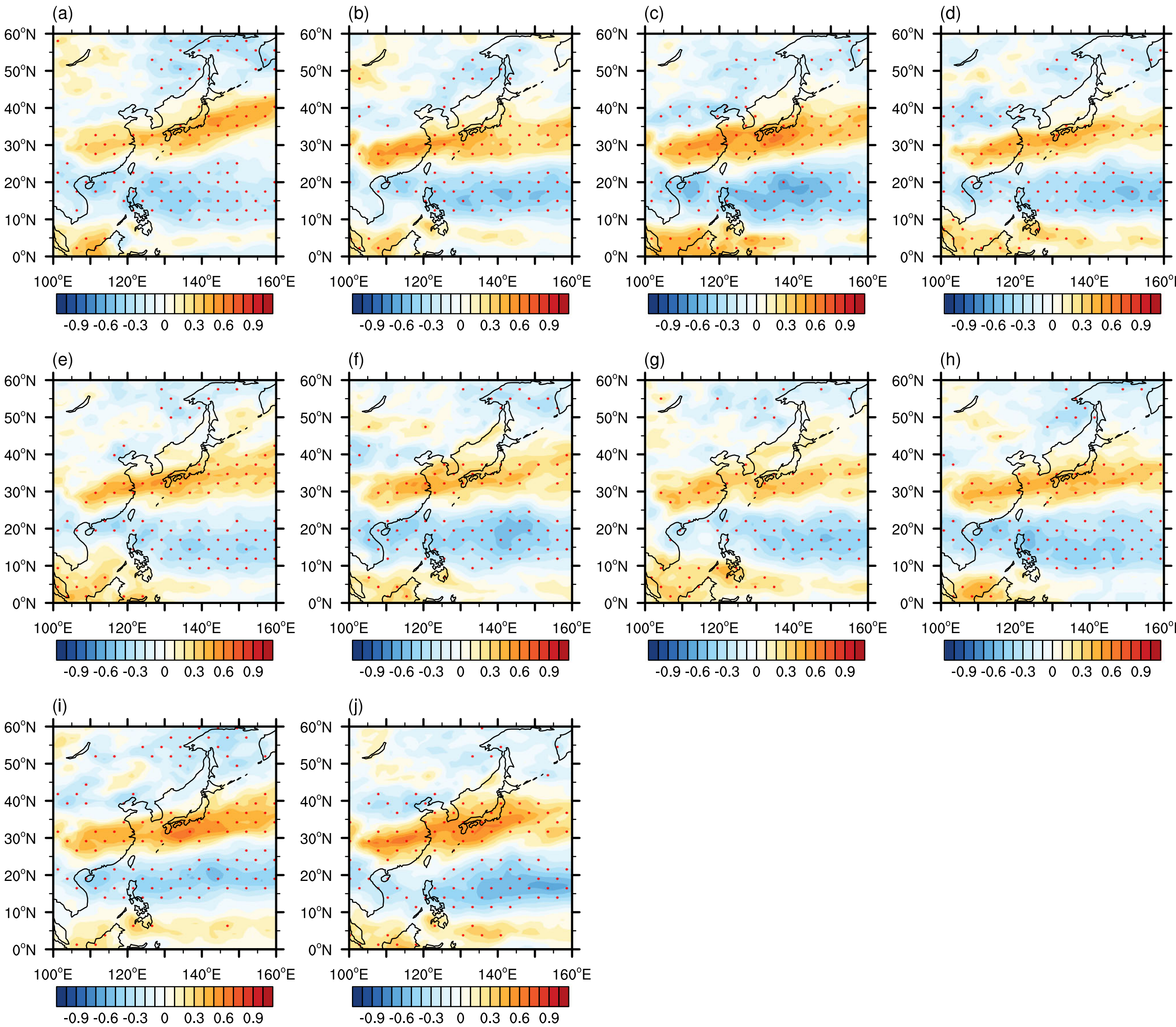


Fig. 7 Correlation (color shading) of precipitation (mm day^{-1}) and the NEWI based on a set of 10 simulations of 1.5degNE scenario for the period 2006–2100. The red dots indicate the 95% confidence level

200 hPa. The index NEWI represents the strength of EASM. When easterly anomalies appear at the middle area (about 20°N), and westerly anomalies appear at southern (about 5°) and northern (about 35°N) areas of zonal wind at 200 hPa in East Asia, the NEWI is positive, and the EASM is stronger.

To interpret the causes of the rainfall changes over the East Asian region, the moisture budget analysis is given as follows:

$$P' = \langle -\overline{\omega}\,\partial_p q' \rangle + \langle -\omega'\partial_p \overline{q} \rangle + \langle -\omega'\partial_p q' \rangle + \langle -\overline{V}\cdot\nabla q' \rangle + \langle -V'\cdot\nabla\overline{q} \rangle + \langle -V'\cdot\nabla q' \rangle + E' \quad (2)$$

Where the overbars mean climatology in present-day (1980–2005). And ' means the departure from the present-day value. Here, P, ω, q, V, and E represent the precipitation, pressure velocity, specific humidity, horizontal wind, and evaporation, respectively. The operator $< >$ means a mass integration from the surface to 100 hPa.

In this paper, multi-ensemble mean is used to analyze present-day (1980–2005) climate and diagnose causes of the rainfall change in future (2006–2100). And the Student's t test is used to estimate the level of the significance for differences between the mean values of the two groups of samples.

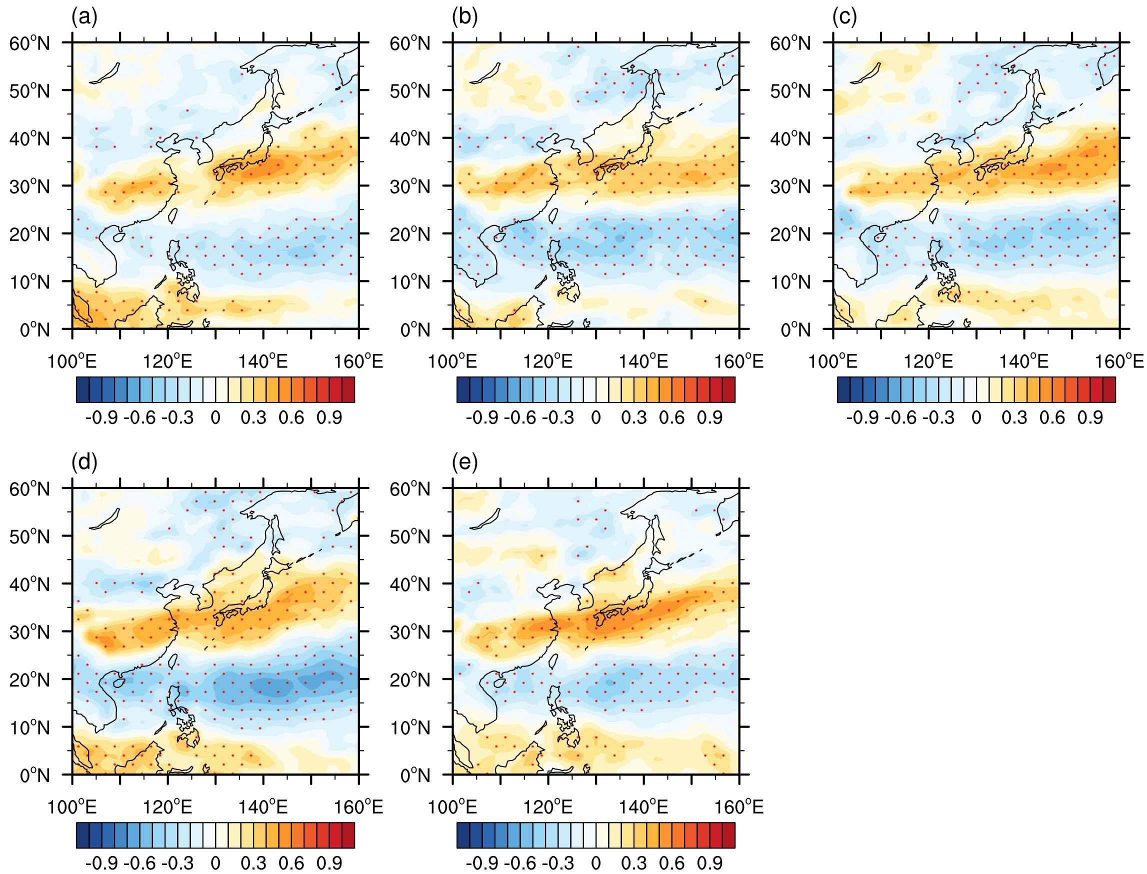


Fig. 8 Same as Fig. 7, but based on a set of 5 simulations in 1.5degOS scenario

3 EASM in present-day climate

The reproducibility of EASM variability in the CESM is estimated before investigating changes in precipitation. First, the leading EOF mode of the JJA precipitation in CESM historical simulations over the domain (0–60° N, 100–160° E) areas is shown in Fig. 1. The leading EOF of the summer rainfall over East Asia-Northwestern Pacific features the Meiyu–Changma–Baiu rain belt and tropical Philippine Sea rain belt, which is consistent with the observations in Zhao et al. (2015). Thus, CESM can capture the main features of the year-to-year rainfall variability over the East Asian region.

Figure 2 shows the leading EOF mode of the JJA zonal wind at 200 hPa. The CESM historical simulation reproduces reasonably the distinct tripole pattern, and the centers of positive–negative–positive anomalies appear about 5°, 20°, and 35°N, respectively. These results are consistent with Zhao et al. (2015). Hence, the model has a reasonable performance in simulation of the changes of NEWI. The observational NEWI fluctuation is within the spread of 35 CESM historical ensembles (Fig. 3). There is the possibility that one of the ensembles display close variation to observational NEWI, indicating that CESM has capability to produce reasonable variation of NEWI. We examine the correlations between precipitation and NEWI based on CESM. The obtained correlation based on the ensemble mean is shown in Fig. 4. A dipole rain belt structure is found over East Asia-Northwestern Pacific region. The structure is consistent with results in GPCP and CMAP (Fig. 5).

Therefore, CESM shows a good performance in simulating the major feature of the variation of summer precipitation and zonal wind at 200 hPa over East Asia-Northwestern Pacific region. In addition, the variation of NEWI and associated rainfall are also reasonably reproduced by CESM. In this sense, it is reasonable to use CESM to study the future change of EASM.

4 Projection of the EASM

Furthermore, we use NEWI to study the changes of EASM based on CESM. Figure 6a–c shows the variation of NEWI

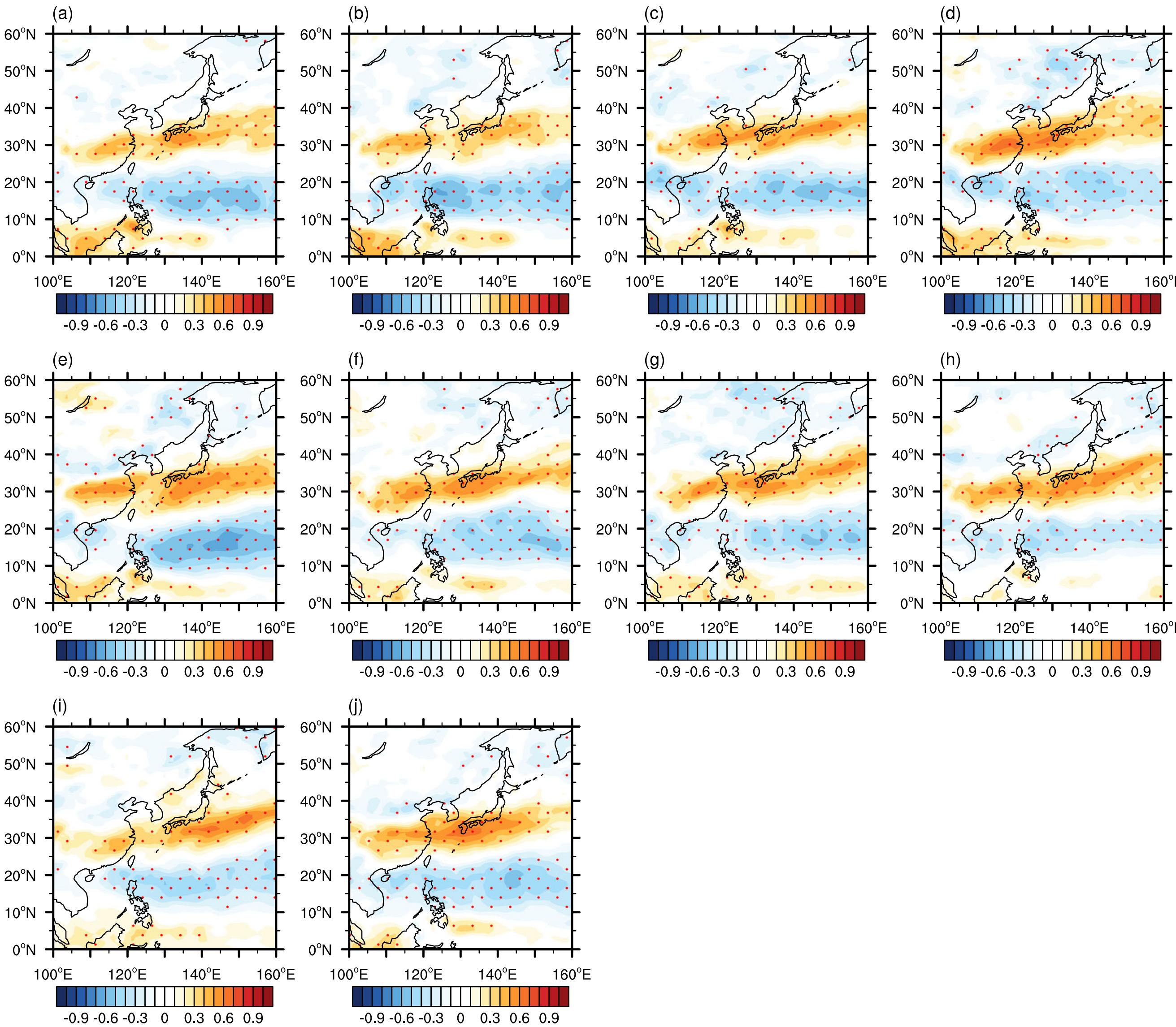


Fig. 9 Same as Fig. 7, but based on a set of 10 simulations in 2degNE scenario

from 2006 to 2100 under 1.5degNE, 1.5degOS, and 2degNE scenarios, respectively. The changes of NEWI in all ensemble means show a slightly increase in the three scenarios. These results suggest that the increasing trend of EASM is not significant. In addition, Fig. 6d displays the ensemble mean of each scenario. The differences among the ensemble means are not significant and do not reach the 90% confidence level.

Figures 7, 8, and 9 display the correlation between precipitation and NEWI under three scenarios during the period of 2006–2100. The patterns of the summer rainfall over East Asia associated with the NEWI also display dipole structure, similar to that of historical simulation in Fig. 4. It implies that the location of East Asian summer rainfall associated with the intensity of EASM will not change if the global mean temperature changes.

Then, we choose one area that is highly correlated with the NEWI (25.5–38.5°N, 105–155°E) (Figs. 4 and 5) to see the transient response of the rainfall over the key area associated with the EASM. The position of this area is quite similar in both present-day (1980–2005) and future climate (2006–2100). Generally, the variation of EASM rainfall over the key region shows a significant increasing trend under 1.5degNE, 1.5degOS, and 2degNE scenarios, respectively (Fig. 10a–c). Although all ensemble means show that the increasing trend of EASM rainfall in

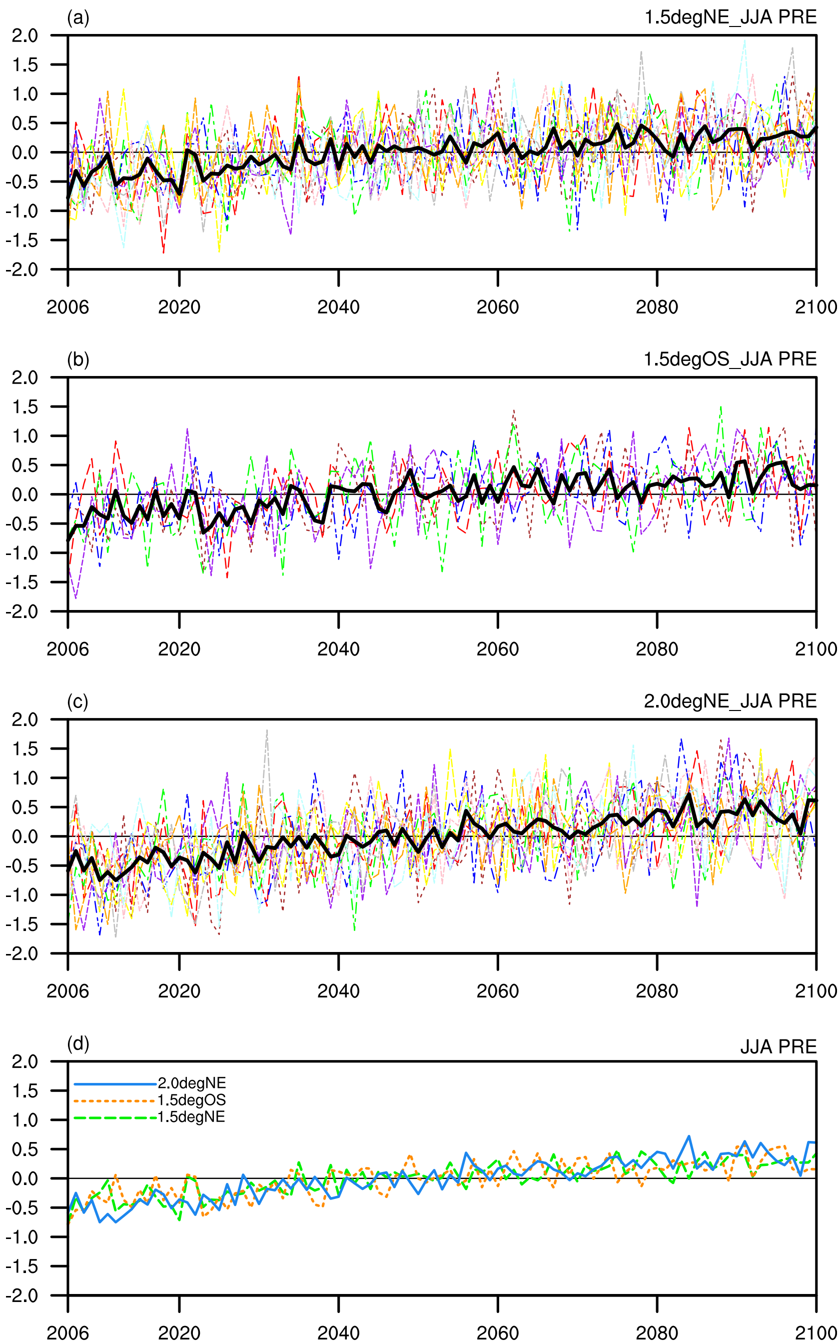
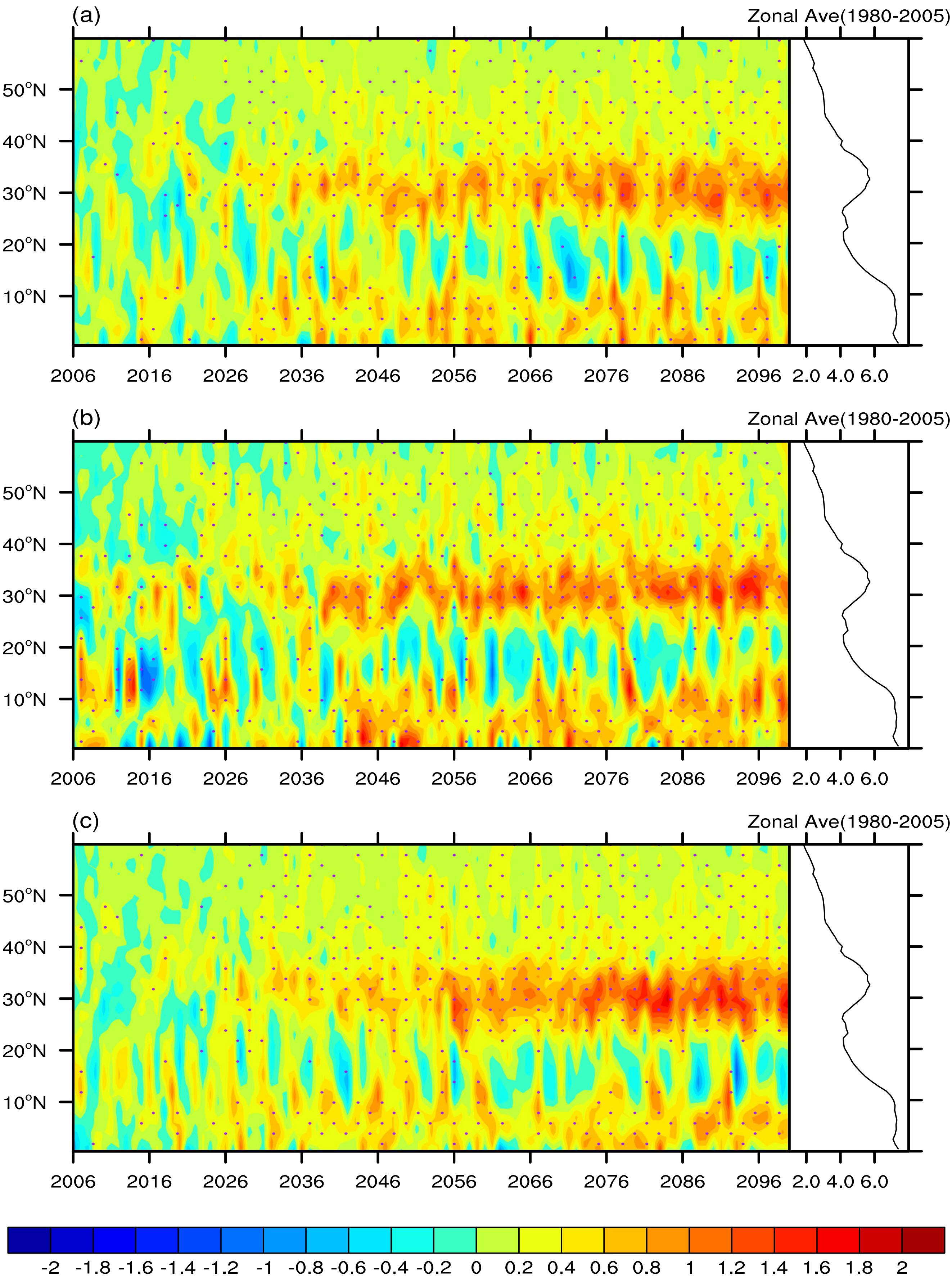


Fig. 10 Area average of JJA precipitation over [25.5° N–38.5° N, 105° E–155° E] for the period 2006–2100: **a** 1.5degNE, **b** 1.5degOS, and **c** 2.0degNE. The results in each scenario are subtracted by corresponding 2006–2100 mean. The corresponding ensemble mean is displayed as thick black lines. The results of each ensemble are displayed as color lines. **d** The ensemble mean for each scenario. The units are millimeter per day

2degNE is slightly obvious, each scenario does not show distinct differences and the differences do not reach the 90% confidence level (Fig. 10d).

Figure 11 shows the response of zonal average precipitation under the three scenarios for the period 2006–2100. We can see that the anomalies of zonal average precipitation all increase with time under the three scenarios. Furthermore, the location of key area of anomalies of zonal average precipitation in the future is quite similar to that in present-day. It also confirms that no distinct change occurs in the meridional location of rain belt during 2006–2100.

Briefly, the changes in EASM intensity and the associated monsoon rainfall are projected to strengthen in most of the ensembles of 1.5degNE, 1.5degOS, and 2degNE scenarios. These results generally in agreement with previous research based on CMIP3 or CMIP5 (Lu and Fu 2010; Bao 2012; Kusunoki and Arakawa 2012; Chen and Sun 2013; Qu et al. 2014; Jiang and Tian 2013; Li et al. 2014; Lee and Wang 2014; Kwon et al. 2017).


(a)
Zonal Ave(1980-2005)
50°N
40°N
30°N
20°N
10°N
2006 2016 2026 2036 2046 2056 2066 2076 2086 2096
2.0 4.0 6.0
(b)
Zonal Ave(1980-2005)
(c)
Zonal Ave(1980-2005)
-2 -1.8 -1.6 -1.4 -1.2 -1 -0.8 -0.6 -0.4 -0.2 0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2

◀ **Fig. 11** Zonal average [100–160° E] of JJA precipitation (color shading; unit: mm day^{-1}) during 2006–2100 relative to the ensemble mean of CESM historical simulation during 1980–2005: **a** the ensemble mean of 1.5degNE scenario, **b** the ensemble mean of 1.5degOS scenario, and **c** the ensemble mean of 2.0degNE scenario. The red dots indicate the 95% confidence level. To facilitate the comparison, the zonal average [100–160°E] of ensemble mean JJA precipitation (black lines) during 1980–2005 in CESM is attached to the right of each panel. The units are millimeter per day

And the enhancement is more clearly in the ensemble mean results of each scenario. In addition, compared with present-day, the location of rain belt has no significant change in three warming scenarios. However, it is still not clear what contributes to the strengthening of EASM precipitation. To answer the question, the moisture budget is performed in the following section.

5 The moisture budget

To explore the causes of the strengthening of EASM rainfall under the 1.5degNE, 1.5degOS, and 2degNE warming scenarios, moisture budget diagnosis is performed (see Section 2).

Under the warming scenarios, the increased precipitation over the domain (25.5–38.5°N, 105–155°E) may be attributed to three terms: increases in evaporation change ($E^{'}$), anomalous vertical motion change ($<\omega^{'}\partial_p\overline{q}>$), and vertical gradient of humidity change ($<\overline{\omega}\partial_p q^{'}>$). Among them, the evaporation change contributes most (Fig. 12). In addition, the differences of the moisture budget terms among 1.5degNE, 1.5degOS, and 2degNE scenarios are quite small (Fig. 12d–f). Then, the time-series of the three dominant terms are given by Fig. 13. The fluctuation of vertical motion ($<\omega^{'}\partial_p\overline{q}>$) in orange line is larger than the other two terms in all the three scenarios. One possible reason is that this term more subjects to internal variability. In the last half of the twenty-first century, the change of evaporation generally overwhelms the other two terms under 1.5degNE and 1.5degOS scenarios. In 2.0degNE scenario, the change of evaporation is generally comparable to vertical motion ($<\omega^{'}\partial_p\overline{q}>$) in the last half of the twenty-first century. Whatever in which scenario, the changes in evaporation and vertical motion are larger than humidity ($<\overline{\omega}\partial_p q^{'}>$) during the last half of the twenty-first century.

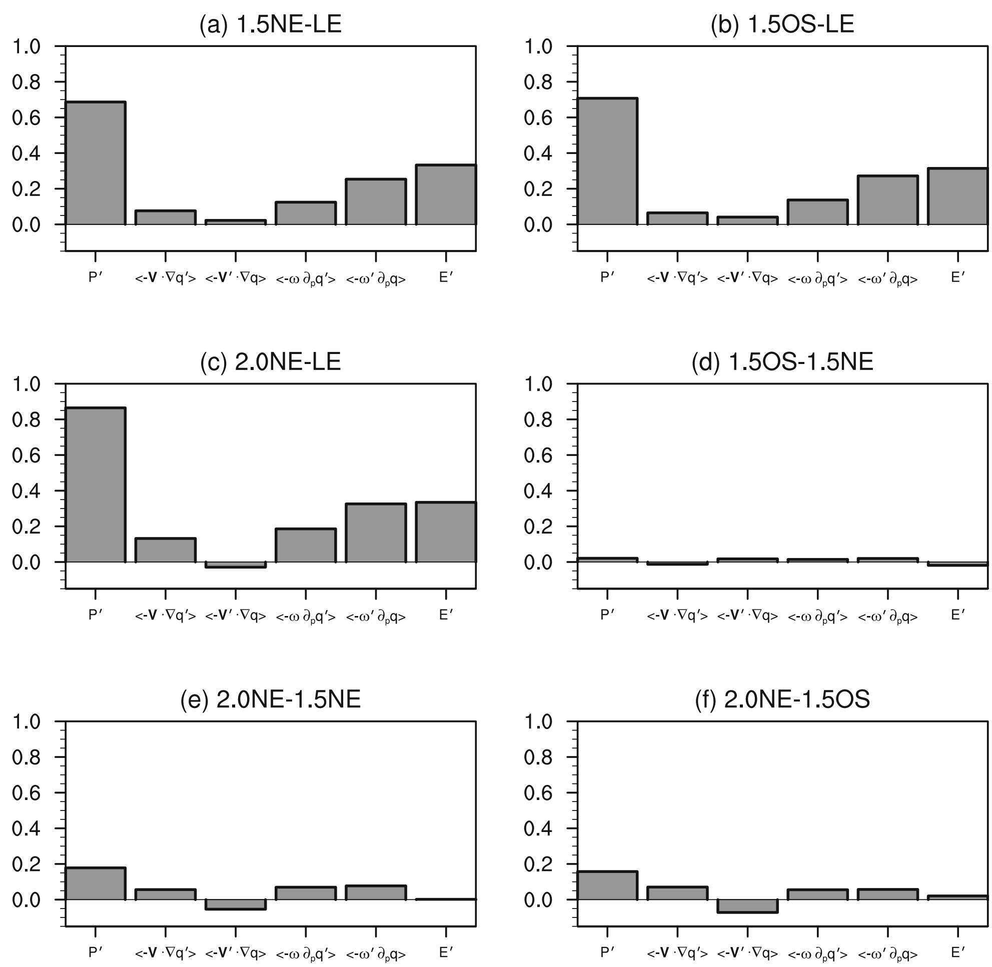


Fig. 12 The area-averaged terms of the moisture budget equation associated with EASM precipitation in comparison of given two experiments: **a** 1.5NE relative to LE; **b** 1.5OS relative to LE; **c** 2.0NE relative to LE; **d** 1.5OS relative to 1.5NE; **e** 2.0NE relative to 1.5NE; **f** 2.0NE relative to 1.5OS. The terms are display in x-axis. The units are millimeter per day

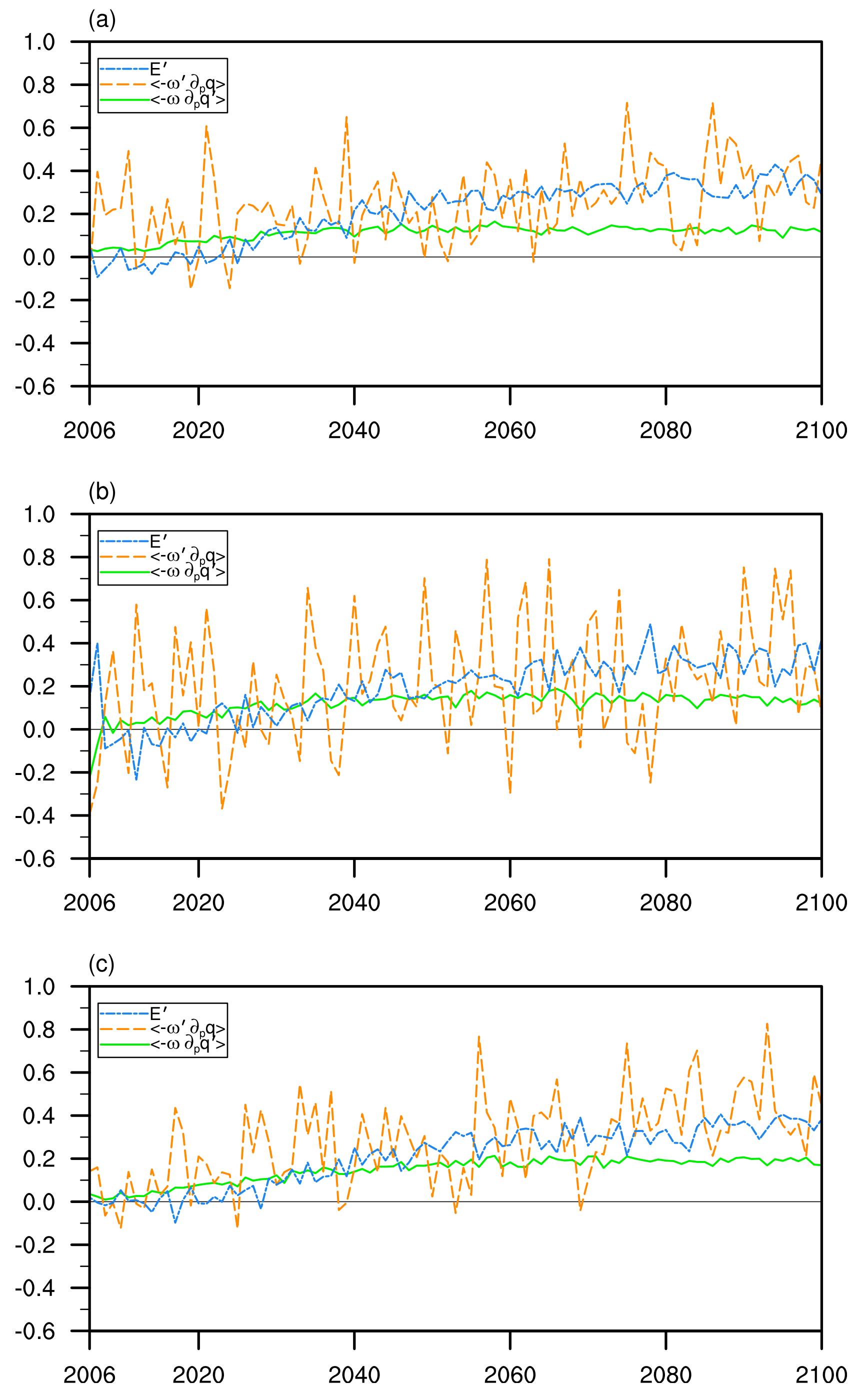


Fig. 13 The area average of $<\overline{\omega}\partial_p q^{'}>$, $<\omega^{'}\partial_p \overline{q}>$, and the evaporation change over area [25.5°N–38.5°N, 105°E–155°E] under 1.5degNE (**a**), 1.5degOS (**b**), and 2degNE (**c**) scenarios. The units are millimeter per day

We further analyze the patterns of the three dominant terms. From Fig. 14, we can see that the contributions of three dominant terms increase sequentially under 1.5degNE, 1.5degOS, and 2degNE scenarios. For $<\overline{\omega}\partial_p q^{'}>$, there are distinct positive responses in the climatological rainy areas over northeastern of China, North Korea, and of South Japan. This term reflects "wet-get-wetter" or "rich-get-richer" mechanism (Chou and Neelin 2004; Chou et al. 2009; Held et al. 2010), with the upward motion in the climatological rain belt leads to plenty of moisture increase near the surface. For $<-\omega^{'}\partial_p \overline{q}>$, positive responses are found in EASM associated key rainfall area (25.5–38.5° N, 105–155° E), indicating the enhancement of rainfall due to strengthening of the ascendance; while distinct negative responses are mainly located in north of the key rainfall area, where the rainfall decreases due to the weakening of the ascendance. As for $E^{'}$, it displays uniform

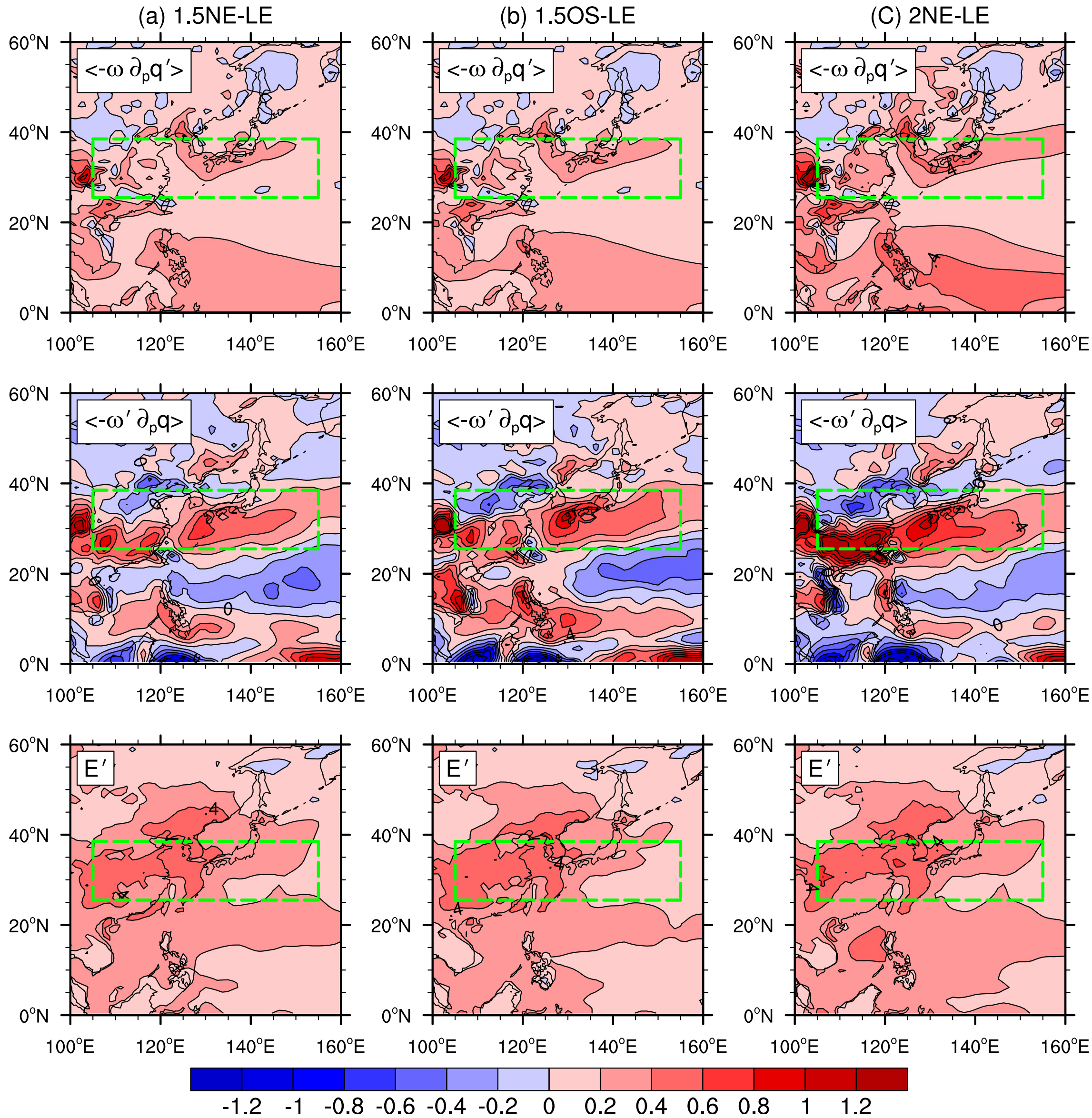


Fig. 14 $<\overline{\omega}\partial_p q'>$, $<\omega'\partial_p\overline{q}>$, and the evaporation change under 1.5degNE, 1.5degOS, and 2degNE scenarios. The units are millimeter per day. The area [25.5° N–38.5° N, 105° E–155° E] in green rectangle is EASM-associated key rainfall area

enhancement over East Asia-Northwestern Pacific region. The enhancement maximums are mainly located over Yellow Seas and Northeast China. And the intensified evaporation is intimately associated with the increase in surface temperature by global warming. However, we are not able to diagnose the evaporation changes due to the absence of surface wind data.

Briefly, the increased rainfall over the key area of East Asia is mainly ascribed to the changes in evaporation, vertical motion, and humidity in 1.5degNE, 1.5degOS, and 2degNE scenarios. And the contributions of these three dominant terms increase sequentially in the three scenarios. One of the greatest contributions among the three terms is evaporation in each scenario. Although the effects of changes in evaporation and upward motion are almost the same as in 2.0degNE, their contributions are still larger than humidity.

6 Summary and discussion

In this study, we present the changes in EASM intensity and the associated rainfall by 1.5 °C and 2.0 °C warming experiments of CESM. First, the model reproducibility is evaluated. The CESM reasonably reproduces the main features of the year-to-year rainfall variability over East Asia-Northwestern Pacific region. Thus, we can use CESM to predict the changes in EASM intensity and the associated precipitation over the twenty-first century.

Under 1.5degNE, 1.5degOS, and 2degNE warming scenarios, both EASM intensity and the associated rainfall are projected to increase in most ensembles in the future. The changes in EASM intensity have no significant differences among the three scenarios. And these results are more obvious in the ensemble mean for each scenario. In addition, the position of key rainfall region (25.5–38.5° N, 105–155° E) of EASM-associated precipitation in future is quite similar to that in present-day. Although the EASM precipitation has more significant increasing trend in 2degNE scenario, there is no significant difference among the three scenarios. One possible reason is that the differences of the radiation force in low warming experiments are quite small among the three scenarios. Besides, the insignificant differences among the three scenarios are probably associated with large natural variability which may has a great influence on the changes of monsoon rainfall. Therefore, it is difficult to see the differences among the three scenarios.

Our moisture budget analysis reveals the increased precipitation over East Asia should be attributed to the changes in evaporation, vertical motion, and humidity during 2071–2100 in 1.5degNE, 1.5degOS, and 2degNE scenarios. And the contributions of the three dominant terms increase sequentially in three scenarios, while the differences among the three scenarios are quite small in three dominant terms. In all the three scenarios, the contribution of evaporation is the greatest in the changes of total precipitation. Only in 2degNE scenario, the contribution of vertical motion is almost the same as evaporation. However, the contributions of evaporation and vertical motion are greater than that of humidity in all three scenarios. These results are further to be confirmed in time-series of the three dominant terms. In all patterns of three dominant terms, positive responses are mainly found in the key rainfall area.

Besides, other factors, especially oceanic factors, contribute to East Asian climate anomalies (Ueda et al. 2015; Fan et al. 2018; Zhang et al. 2018). Compared with monotonically increasing radiative forcing pathways, the oceanic heating will be different to that during the radiative forcing is decreasing (Held et al. 2010; Chadwick et al. 2013; Long et al. 2014). Consequently, the East Asian summer monsoon may also display different responses. However, the detailed causes of EASM changes need further study.

Acknowledgments We sincerely thank the Editor and the anonymous reviewer for their valuable comments and suggestions to improve the quality of this manuscript. We gratefully acknowledge the NCAR for the release of the CESM low warming experiment products.

Funding information This work was supported by the Strategic Priority Research Program of Chinese Academy of Sciences (XDA20060501), the National Natural Science Foundation of China (41831175, 41425019, 41721004 and 41661144016).

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