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ORIGINAL PAPER

Consistent responses of East Asian summer mean rainfall to global warming in CMIP5 simulations

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Abstract East Asia summer rainfall is of great social–economic importance. Based on observations, reanalysis and simulations of 16 Coupled Models Intercomparison Project phase 5 (CMIP5) models, the responses of East Asia summer precipitation, as well as some relevant features, to global warming are investigated. The CMIP5 historical simulation reasonably reproduces the climatology of summer rainfall, the associated circulation, the moisture and its transportation, and the mid-troposphere horizontal advection of temperature as well. Under global warming, the rainfall enhancement is robustly projected in the state-of-the-art models over North China, Northeast China, northern coast of Japan and the Kuroshio. As well, the total summer rainfall over East Asia is consistently increased in the models. For the consistent responses, the moisture budget analysis based on the simulations shows that two factors are responsible: one is increased moisture. As East Asia is a climatological ascent region in northern summer, increased moisture induced by global warming leads to more moisture transported upward and thus the rainfall rise. The other is enhanced evaporation, which may be caused by surface warming and provides more precipitable water to the atmosphere column. Furthermore, the results may provide some implications to the long-term variability of East Asia summer rainfall over the last several decades.

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1 Introduction

Northern summer is the major rainy season of the vast populated region—East Asia. Not only does the rain provide necessary water for local lives, but also bring weather disasters, exerting great social–economic influences. On the attribution to rainfall, massive studies have been carried out. The causes may trace to ocean temperature (e.g., Huang et al. 2011; Qu and Huang 2012; Wu and Wang 2002), Tibetan orography (e.g., Liu et al. 2007; Zhang et al. 2002), atmosphere internal variability (e.g., Liang and Wang 1998; Ding and Wang 2005; Kosaka et al. 2011), etc. while, two factors directly affect the rain: one is the southerly, which bring moisture to East Asia (Huang et al. 1998), the other is the westerly jet induced warm advection, which induces upward motion and transports the moisture upwards (Sampe and Xie 2010; Kosaka et al. 2011).

Since the industrial revolution, greenhouse gases have been steadily increasing, causing a rise in global surface temperature. The warming, however, is inhomogeneous due to the different properties of the earth's surface. This may result in an inhomogeneous response in the atmosphere. In turn, this may provide feedback on the temperature. Besides, the warming leads to the melting of snow cover, glaciers and sea ice. So rather sophisticated are the influences of global warming on climate, including East Asia summer rainfall. So far, a relatively reasonable way to detect those effects is comparing the Coupled Models Intercomparison Project (CMIP) outputs under different greenhouse gas emissions. Based on the

CMIP results, amounts of results emerge. Using ten CMIP phase 3 models, Chou et al. (2009) did a global survey of precipitation response and suggested that climatological wet regions get wetter under global warming. Similar results are obtained in the studies specialized in East Asia summer rainfall. Kripalani et al. (2007) did a systematic survey on the rainfall change and found that the rainfall increases are significant over the Korea–Japan peninsula and the adjoining North China region under global warming. Consistent conclusions are found in Bueh (2003), Lu and Fu (2010), Kim and Byun (2009), and Sun and Ding (2010). The rainfall change may be attributed to the intensification of the north Pacific subtropical high, Meiyu frontal zone, the associated influx of moist air from the Pacific inland (Kripalani et al. 2007; Sun and Ding 2010).

However, the above results are based on CMIP phase 3 or 2. In 2011, CMIP phase 5 (CMIP5) was released. It assembled the state-of-the-art coupled models with finer resolutions relative to previous CMIPs. Besides, carbon cycle is taken into consideration in some of the models. So question arises whether the updates in models yield new results on East Asia summer rainfall. Previous studies mainly focus on the multi-model mean results while present study devote to the exploration of the consistent responses among the models.

The paper is organized as follows: Section 2 introduces the data and methods used in the study. Section 3 evaluates the performance of the CMIP5 models. Section 4 explores some robust responses of East Asia summer rainfall to global warming. Section 5 diagnoses the causes to the rainfall response. Section 6 provides the conclusion and discussion.

2 Data and method

This investigation is based on CMIP5 outputs. The information for the CMIP5 models is listed in Table 1. The experiments used in this study are historical and RCP45 scenario simulations. The historical experiments were conducted based on observed anthropogenic and natural forcing from the mid-nineteenth century to about 2005. The RCP45 experiments were conducted from 2006 to at least 2099 driven by prescribed forcing (Thomson et al. 2011). For detailed information, readers are referred to the following web site: http://cmip-pcmdi.llnl.gov/cmip5/.

The performance of the CMIP5 models are evaluated against: (1) the National Centers for Environmental Prediction–National Center for Atmosphere Research (NCEP-NCAR) atmospheric reanalysis with a horizontal resolution of 2.5°×2.5° (Kalnay et al. 1996) and available from 1948 to the present and (2) the Center for Climate Prediction Merged Analysis of Precipitation (CMAP) with a horizontal resolution of 2.5°×2.5° (Xie and Arkin 1997) and available from 1979 to the present.

The difference between climatology of future (2069–2098) and present-day simulations (1975–2004) is used to represent the model responses to global warming. Only the run "r1i1p1" of each model is analyzed. The multi-model ensemble (MME) approach is used to reduce natural variability and systematic biases in the models. The model outputs are interpolated onto a 1.0°×1.0° grid using a bilinear interpolation technique. The analysis is focused on summer (i.e., June–July–August) mean and is based on monthly data. Besides, the present study focuses on the consistent response of the models. Here, if more than 75 % of total models show the same sign response as the MME does at the grid, the response is treated as "significant."

Table 1 Climate models used in the present study

Model ID	Country	Spatial correlation coefficients based on rainfall$_{[20–50° N, 100–150° E]}$
CanESM2	Canada	0.67
CNRM-CM5	France	0.71
CSIRO-Mk3-6-0	Australia	0.70
FGOALS-s2	China	0.66
GFDL-CM3	US	0.62
GFDL-ESM2G	US	0.69
GISS-E2-R	US	0.69
HadGEM2-ES	UK	0.79
inmcm4	Russia	0.70
IPSL-CM5A-LR	France	0.76
MIROC-ESM	Japan	0.26
MIROC-ESM-CHEM	Japan	0.35
MIROC5	Japan	0.65
MPI-ESM-LR	Germany	0.73
MRI-CGCM3	Japan	0.77
NorESM1-M	Norway	0.45
MME		0.80

The third column displays the spatial correlation coefficients of East Asia summer mean rainfall between CMAP and each model

To diagnose the contribution of the factors (e.g., circulation and moisture) to precipitation response, moisture budget is analyzed in the present study. The moisture budget equation in response to global warming is as follows:

$$P' = \langle -\overline{\omega}\partial_p q' \rangle + \langle -\omega' \partial_p \overline{q} \rangle + \langle -\omega' \partial_p q' \rangle + \langle -\overline{V} \cdot \nabla q' \rangle + \langle -V' \cdot \nabla \overline{q} \rangle + \langle -V' \cdot \nabla q' \rangle + E' \quad (1)$$

where the $\overline{()}$ means climatology in 1975–2004 in the historical run. The $()'$ means the departure from the climatology of 1975–2004. P, ω, q, V, E represent the precipitation, pressure velocity, specific humidity, horizontal wind and evaporation, respectively. The values in $\langle\rangle$ means a mass integration from the surface to 100 hPa, that is:

$$\langle X \rangle = -\frac{1}{g}\int_{surface}^{100hPa} X dp \quad (2)$$

3 Present-day climate in simulations

Before analyzing the response of the rainfall to greenhouse gas emission, we examine the performance of models based on the CMIP5 MME. Figure 1a and b compares the climatology of the precipitation between CMAP and the CMIP5 historical simulation in 1979–2004 during which all the observational data, reanalysis and historical simulations are available.

Over East Asia, the summer precipitation features a southeast–northwest gradient and a rain belt extending from the estuary of the Yangtze River to the Northern Pacific via south of Japan (Fig. 1a). Both features are reproduced by the CMIP5 MME (Fig. 1b). Spatial correlation coefficients between the observation and each of the CMIP5 models are calculated based on the summer rainfall over the domain [20–50° N, 100–150° E], and the results are given in Table 1. The spatial correlation displays a large spread, with correlation coefficients spanning from 0.26 to 0.79. The MME, with its spatial correlation coefficient 0.80, shows a more reasonable representation of the East Asia summer precipitation pattern.

In addition, the background features which breeds the East Asia rainfall is reasonably reproduced by the CMIP5 MME. In the upper troposphere, the South Asian High and the westerly jet stream are two of the most prominent features near East Asia. The former is a huge anticyclone centering over the Bay of Bengal and Tibetan Plateau; the latter is a strong westerly belt lying over 40° N of Asia, the North Pacific region (Fig. 1c). The two large-scale features are well reproduced by the CMIP5 MME (Fig. 1d). In mid-troposphere, the northern Pacific subtropical high is a phenomenon tightly associated with East Asia summer precipitation (Huang and Sun 1992; Tao and Chen 1987). The westerly in its north flank may lead to upward motion. The geopotential gradient from the Yangtze River to the Northern Pacific via the south of Japan is well simulated (Fig. 1c, d), which yields the reasonable westerly. Moisture is an important factor of precipitation. In northern summer, East Asia is wetter than neighbouring regions besides

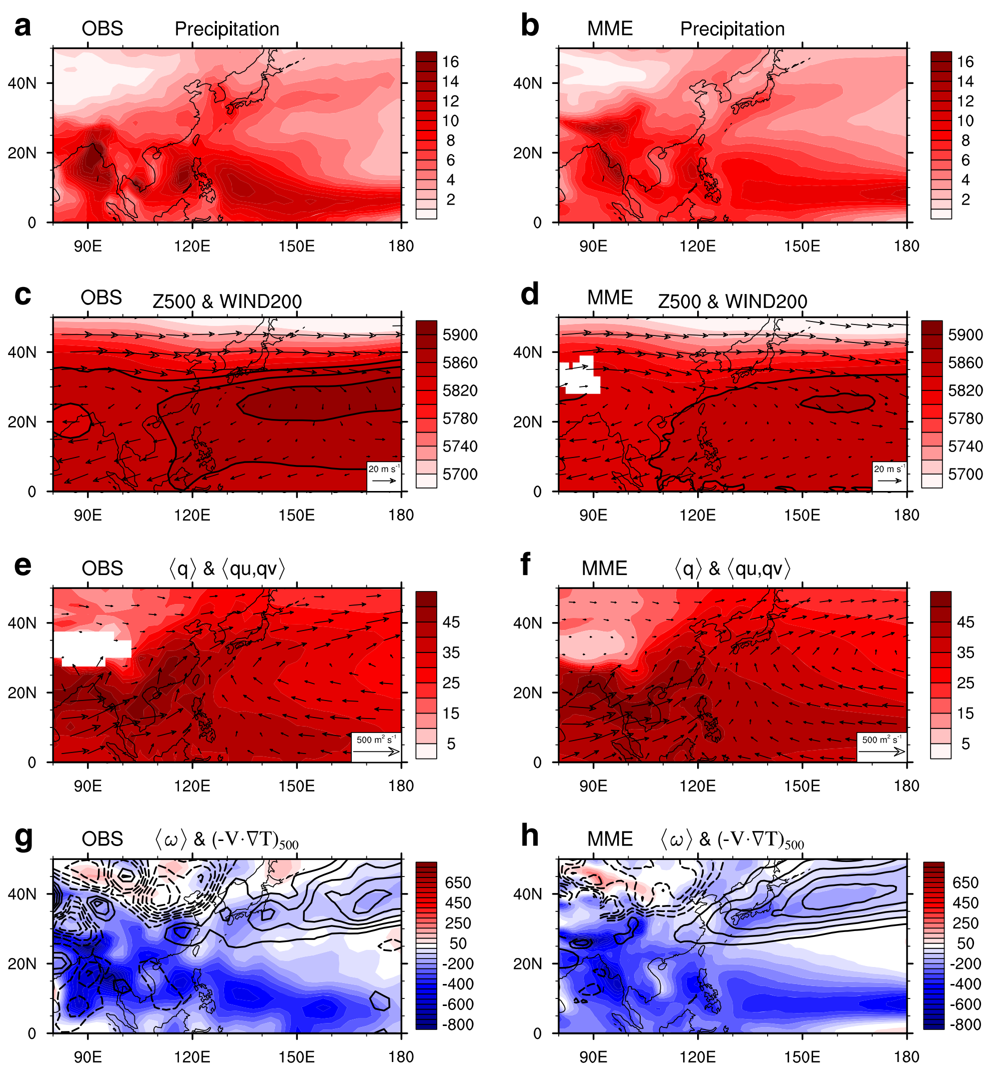


Fig. 1 The climatology of **a**, **b** precipitation (*color shaded*, unit: millimeters per day). **c**, **d** Geopotential height (*color shaded*, unit: meters; geopotential height for 5,840, 5,860 and 5,880 m are shown in *contours*) and 200 hPa wind (v). **e**, **f** Integration of specific humidity (*color shaded*, unit: kilograms per meter per kilogram) and moisture transport (*vector*), and **g**, **h** integration of p velocity (*color shaded*, unit: Pascal per meter per second) and 500 hPa horizontal advection of temperature (*contour*, interval: 2×10^{-6} K s^{-1}; contours for zero are omitted; negative contours are shown in *dash contours*) during 1979–2004. **a**, **c**, **e** and **g** are the results of NCEP-NCAR reanalysis or CMAP, **b**, **d**, **f** and **h** are the results of the CMIP5 MME. The reference vectors are shown in the *bottom right corners* of each figure

South Asia (Fig. 1e). It mainly results from the southerly along East Asia coast, for it transports moisture from the tropics (Fig. 1e). Also, the moisture feature is reproduced in simulation (Fig. 1f). Besides the moisture transportation, another important forcing is the westerly induced warm horizontal advection of temperature to the east of the Tibetan Plateau. It leads to the formation of the Meiyu-Baiu rain and brings the major rainy season in East Asia in the boreal summer (Sampe and Xie 2010). In mid-troposphere, prominent warm advection is found over the downstream of the Yangtze River Valley, Japan and the Northern Pacific (Fig. 1g). The warm advection leads to ascent motion (Fig. 1g). The corresponding features are reasonably represented in the CMIP5 MME, too (Fig. 1h).

Overall, reasonably reproduced are the East Asia summer precipitation as well as the related large-scale features by the CMIP5 MME. Thus, the discussion of East Asia summer rainfall by using the CMIP5 MME is credible.

4 Consistent responses

Under the RCP45 scenario, the wind associated with East Asia summer rainfall does not display consistent responses in individual models. As the horizontal advection of temperature is an important environmental forcing of East Asia summer precipitation, its response to global warming is analyzed. The MME climatology shows cold anomaly over the climatological position of the Meiyu-Baiu rain belt under RCP45 relative to historical climatology, while the amplitude is small relative to individual models and the behaviors in individual models are spread (figure not shown). Furthermore, alike the horizontal advection response of temperature, individual models do not project consistent response in the responses of the 850 hPa wind, 200 hPa wind and integration of p-velocity, either (figures not shown).

In mid-troposphere, the north Pacific subtropical high stretches far westwards in response to global warming. In historical simulation, the geopotential height greater than 5,840 m resides south of Japan and southeast of China; while, under RCP45 scenario, the corresponding northern boundary extends to about 40° N (Fig. 2). In each model, similar extension is found (figures not shown), although the characteristic isoline of the subtropical high may not be 5,840 m. It is mainly led by the atmospheric warming-induced geopotential rise according to hydrostatic balance. Based on the behavior of the subtropical high, it may be speculated that a drier summer over South and Central China under global warming.

However, the state-of-the-art models generally project an enhancement of the rainfall under global warming. Figure 3 shows the precipitation response of the CMIP5 models and MME over East Asia region. The anomalous rainfall patterns of the individual models are diverse. But intensified rainfall is found over the whole region of East Asia in MME. Interestingly, the enhancement is projected in most of the models over the following regions (last figure of Fig. 3): North China, Northeast China, seaboard of Huaihe River Valley, northern coast of Japan and the Kuroshio. The results are consistent with those in Kripalani et al. (2007). Even the models developed by the same modeling center yield different results (e.g., MIROC-ESM, MIROC-ESM-CHEM and MIROC5). It may be caused by carbon cycle, natural variability or initial condition. For the summer rainfall over East Asia region [20–50° N, 100–140° E], the total rainfall is enhanced in all the models (Fig. 4). Among the models, the total rainfall increases most in GFDL-CM3 and least in GISS-E2-R. Furthermore, paradox exists in the responded north Pacific subtropical high and rainfall. It indicates that the frequently used characteristic isoline of 500 hPa geopotential height (e.g., 5,840 or 5,880 m) may not be suitable for precipitation prediction under a warmer scenario.

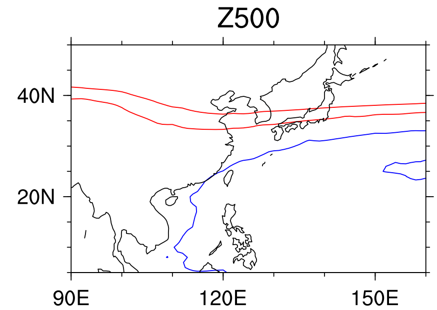


Fig. 2 Contours of 500 hPa geopotential height for 5,840 and 5,860 m in historical (*blue*) and RCP45 (*red*) simulations. Unit is meters

As the circulation change could not explain the consistent enhancement of the rainfall, the other factor—moisture—is investigated. Figure 5 gives the response of integrated humidity of the atmosphere column. Robust is the enhancement of the humidity under RCP45 scenario in the CMIP5 models. In MME, the maximum of the anomalous humidity resides over Southeastern China. The anomalous humidity declines sharply to its northwest. In addition, to the northeast, decaying gradient is found but more smoothly. In individual models, most models yield the MME-like response pattern, except for MIROC-ESM and MIROC-ESM-CHEM, featuring a wet tongue stretching from Southeast China to Japan. Again, it implies that carbon cycle, natural variability or initial condition may affect the responses. The consistent behaviors of humidity in the CMIP5 models could be explained by the Clausius–Clapeyron equation, follow which moisture increases as the air temperature rises (Fig. 6).

5 Moisture budget

To better interpret the influences of the moisture-induced processes on the rainfall change, moisture budget analysis is

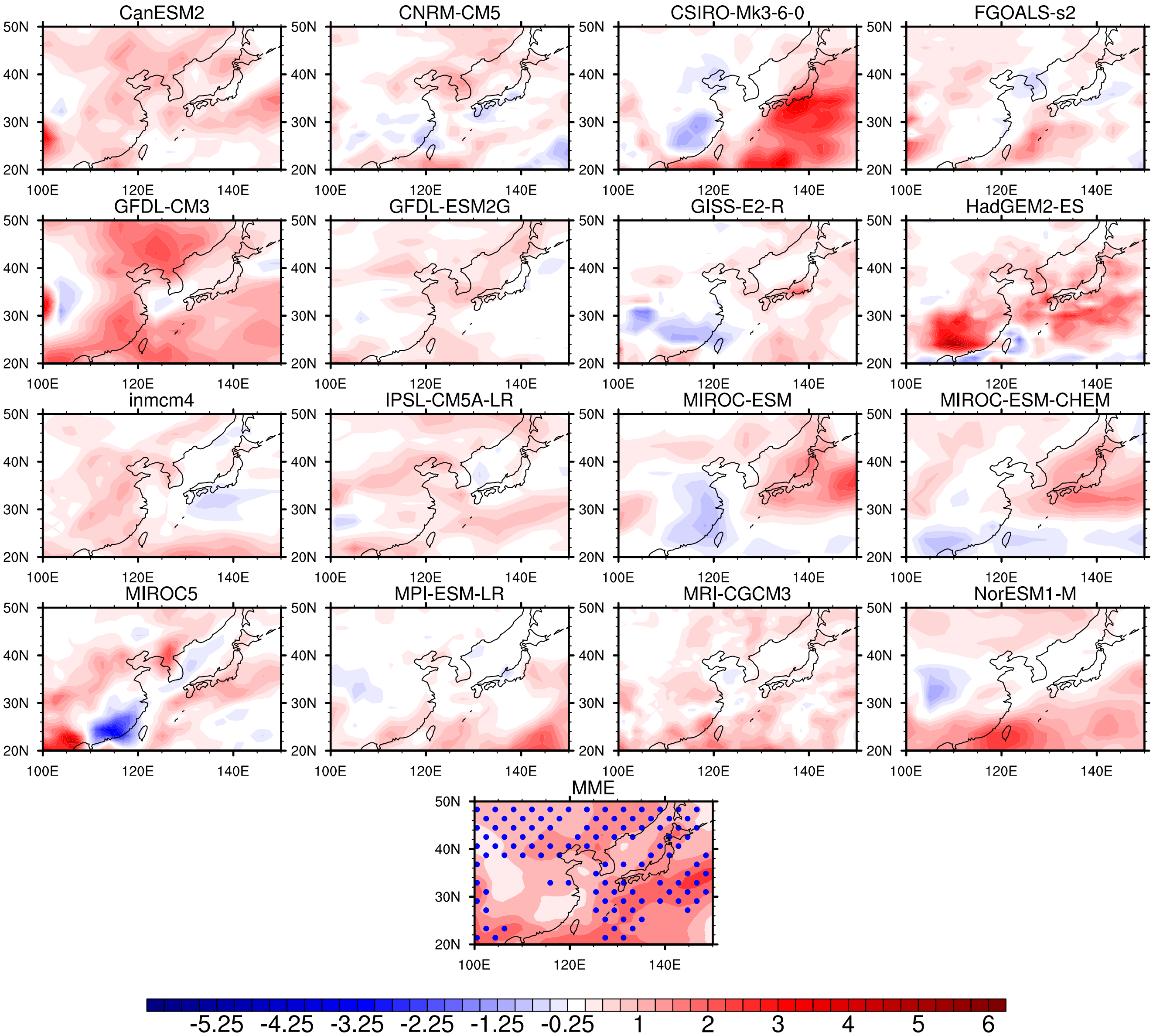
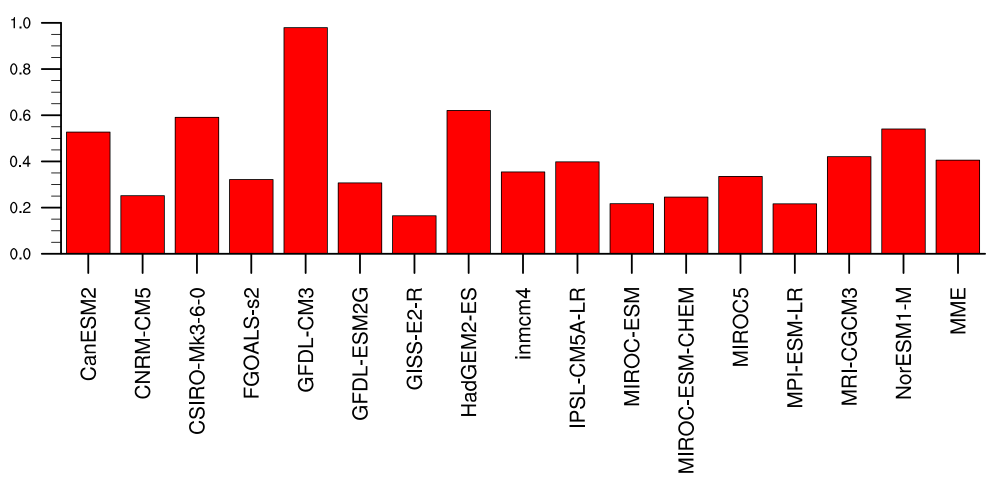


Fig. 3 The difference of precipitation (unit: millimeters per day) between RCP45 and historical runs. The model names are shown on the top of each figure. *Dots* in the bottom figure mean that more than 12 models show the same sign responses with the MME on the grids

Fig. 4 The difference of regional mean summer rainfall over [20–50° N, 100–140° E] between RCP45 and historical simulations in the CMIP5 models and MME. The unit is millimeters per day



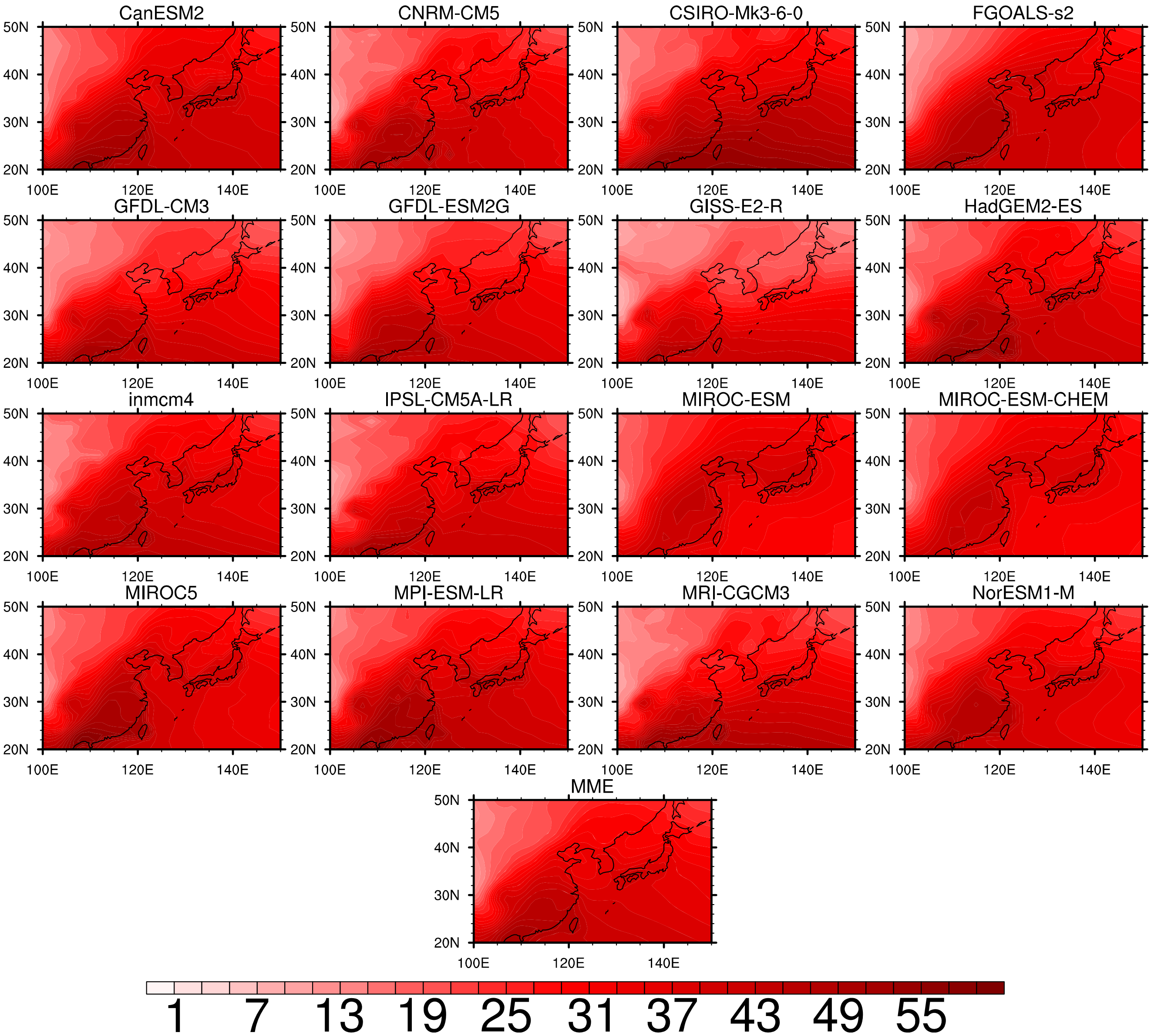


Fig. 5 The difference of vertical integrated humidity (unit: meters) between RCP45 and historical runs. The model names are shown on the top of each figure

performed. The detailed information of the moisture budget equation is introduced in Section 2. Figure 7 shows the responses of each moisture budget terms. In the MME results, the rainfall change over East Asia is mainly attributed to the anomalous vertical gradient of humidity transported by mean vertical motion ($\langle -\overline{\omega}\partial_p q' \rangle$) and evaporation change (), with the former larger than the latter. The contributions of the other terms are rather small. Interestingly, the aforementioned two terms in the individual models both show a positive response. The signs of the other terms in the CMIP5 models are diverse. In individual models, the dominant terms are not the same structure as those in MME. For instance, GFDL-CM3 simulates positive responses in most of the terms and its largest contribution term is evaporation change. Nevertheless, among the processes influencing the overall rainfall over East Asia, increased $\langle -\overline{\omega}\partial_p q' \rangle$ and enhanced evaporation are certain.

Furthermore, the spatial structures of the two dominant terms are examined. For $\langle -\overline{\omega}\partial_p q' \rangle$, over western China or east of the Tibetan Plateau, positive responses are found in most of the CMIP5 models; negative anomaly is seen northeast of the Tibetan Plateau (Fig. 8a). Over the mentioned regions, the model responses are robust. The increase mainly locates over the climatological rainy areas; the decline is found over climatological less rainy area (Fig. 1b). Over the climatological ascent region, the increased humidity causes more moisture being transported from the lower to the upper atmosphere, arising more rainfall locally; on the contrary, more moisture is transported downwards to the surface and less rainfall occurs

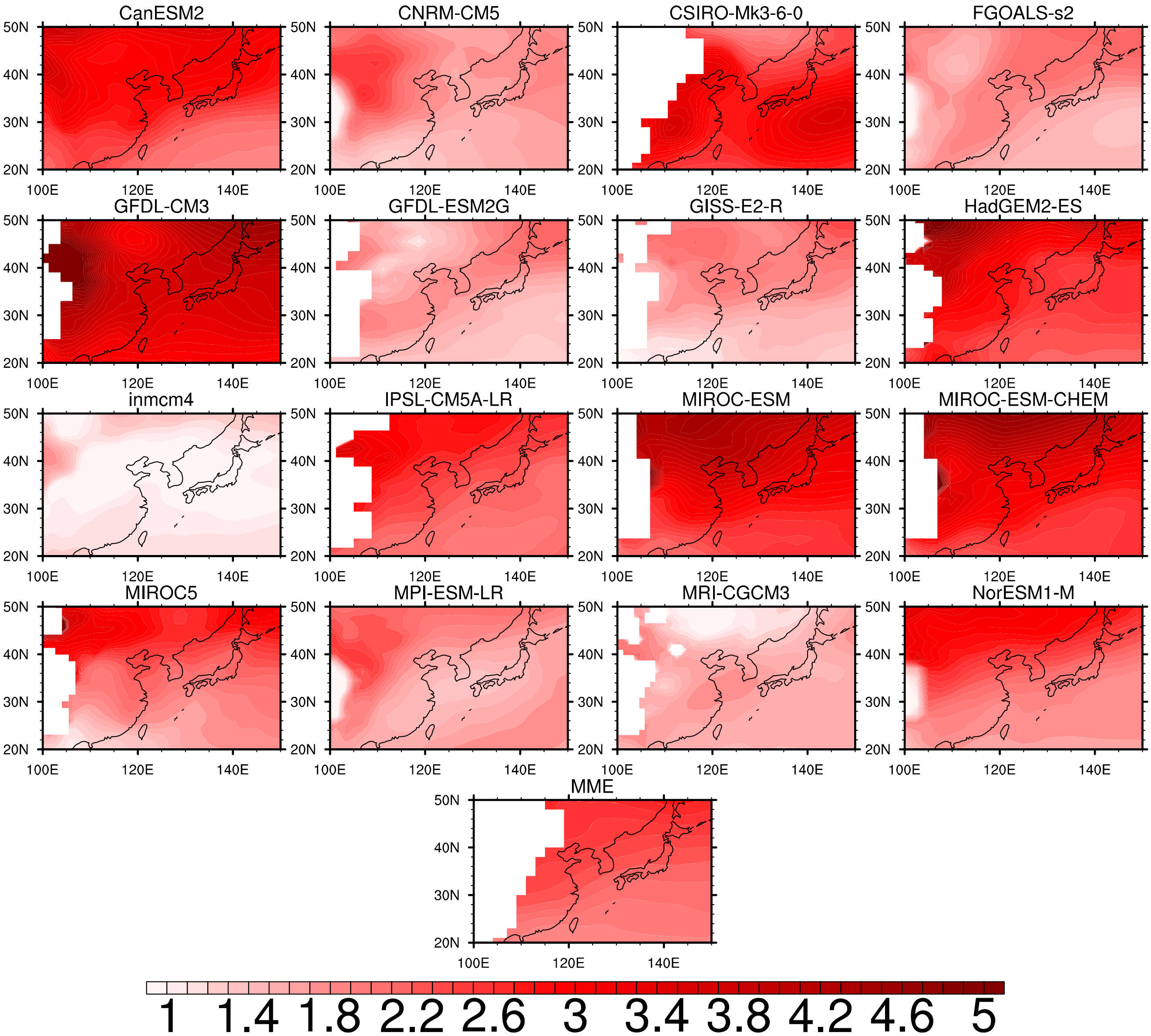


Fig. 6 The same as Fig. 5, but for 850 hPa air temperature (unit: Kelvin)

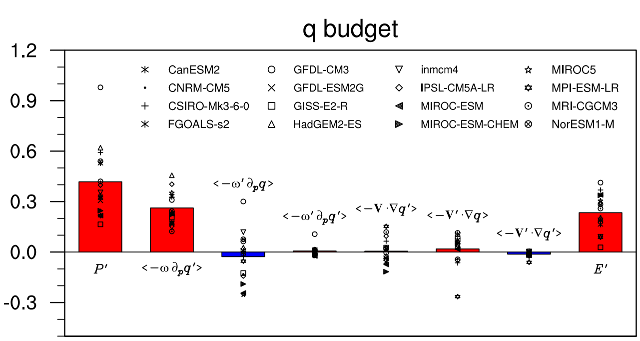


Fig. 7 The responses of regional mean moisture budget terms over the domain [20–50° N, 100–140° E]. The MME results are shown in *red* and *blue bars* and individual results are shown in *markers*. The unit is millimeters per day

over climatological decent region. It is the "wet-get-wetter" mechanism proposed by Chou and Neelin (2004) and Chou et al. (2009). In individual models, the responses do not all show the same pattern as MME, but respectively resemble the climatological precipitation pattern of its own (not shown), which can also be explained by the "wet-get-wetter" mechanism.

For the evaporation, prominent enhancement is mainly found over Northeast China and Yellow Seas (Fig. 8b). Furthermore, most of the CMIP5 models simulate a similar increase over East Asia except Southeast China and northeast of Japan. The global warming-induced surface temperature increase favors the intensified evaporation. While, the causes to the pattern of the anomalous evaporation structure are not clear. Also, diverse are the patterns in individual models.

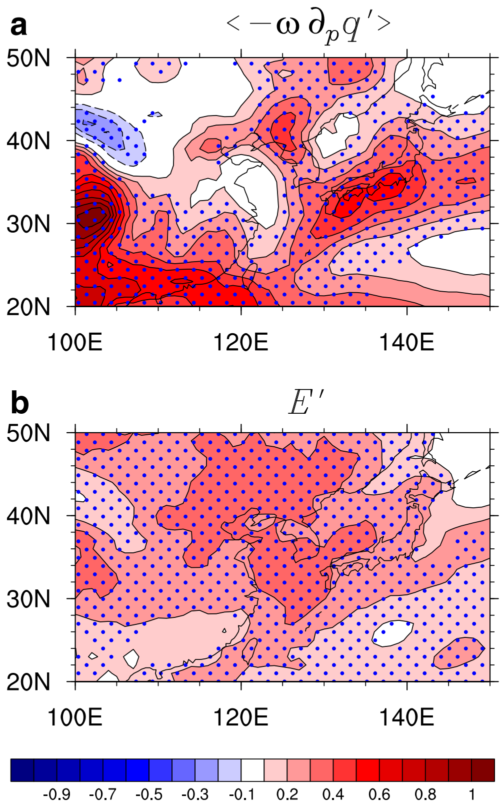


Fig. 8 $\langle -\overline{\omega}\partial_p q' \rangle$ (**a**) and the responses of evaporation between RCP45 and historical simulations (**b**). The units are millimeters per day. *Dots* in the figures mean that more than 12 models show the same sign responses with the MME on the grids

In the MME, the term $\langle -\overline{\omega}\partial_p q' \rangle$ is dominant over evaporation change over South China, North Korea, the adjoining north China region, Japan and its south, while evaporation change is dominant over North China, Northeast China and Yellow Seas. The uncertainty in the rainfall response over South and Central China (Fig. 3) may stem from the diversity of the evaporation change. In individual models, the dominant terms are complex in spatial distribution (not shown).

Overall, it is certain that under global warming, two processes are responsible for the wetter summer over East Asia: (1) moisture increase, East Asia is mainly a climatological ascent region in northern summer, more moisture is transported upward and yields more rainfall; (2) enhanced evaporation, it provides more precipitable water in the atmosphere column.

6 Conclusion and implications

Based on the NCEP–NCAR reanalysis, CMAP and simulations of 16 CMIP5 models, present study investigates the responses of East Asia summer precipitation to greenhouse gas emission and some associated consistent responses as well. The CMIP5 historical simulation reasonably reproduces the climatological pattern of summer rainfall, the circulation in the upper and middle troposphere, the moisture and its transportation and the mid-troposphere horizontal advection of temperature as well.

Under global warming, the rainfall is robustly enhanced over North China, Northeast China, northern coast of Japan and the Kuroshio in the CMIP5 models. Also, the regional averaged summer rainfall rises over East Asia in all the models. To the consistent rainfall enhancement, wind response could not be the cause as the response is not uniformly projected by the CMIP5 models. Though the north Pacific subtropical high is projected westward with good agreements in the CMIP5 models, it contradicts the rainfall enhancement.

For the robust rainfall rise, two attributions are responsible: (1) increased moisture. According to the Clausius–Clapeyron equation, global warming induces moisture enhancement in the atmosphere. As East Asia is mainly a climatological ascent region in northern summer, increased moisture leads to more rainfall transported upward via vertical motion, resulting in enhanced rainfall locally. This process yields a "wet-get-wetter" pattern, which is robust over the whole of East Asia except North China, Huaihe River Valley, the northern Sea of Japan and northeast of Japan. (2) Enhanced evaporation: warming in surface favors intensified evaporation, which provides more precipitable water to the atmosphere column. The enhancement is robust over the whole of East Asia, but Southeast China and northeast of Japan, and peaks over Northeast China and Yellow Seas.

Large amounts of evidence (e.g., Huang et al. 2007; Zhou et al. 2009) suggested that since the 1950s the summer rainfall over East Asia experiences decadal changes, with a decrease over Southeast and North China and increase over the Yangtze and Huaihe River Valley. The feature is also named a "tripole" pattern. The occurrence of global warming over the decades makes it hard to distinguish the effects of global warming and natural variability on it. The present study shows that under global warming, over 75 % of the CMIP5 models simulate an enhancement of the summer rainfall over North China. It implies that the historical long-term rainfall change over the region may be due to natural variability. Furthermore, over South China, our results give the hint that the rainfall change there may not result from global warming. However, over the seaboard of Huaihe River Valley, the historical rainfall change is the same sign as those in most of the CMIP5 models. It indicates that the rainfall increase is, or partly, led by global warming.

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