A Unique Feature of the Asian Summer Monsoon Response to Global Warming: The Role of Different Land–Sea Thermal Contrast Change between the Lower and Upper Troposphere

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Abstract

Recent studies indicate that the view of a general weakening of the monsoon circulation in a warmer climate cannot be simply applied in the Asian monsoon regions. To understand the Asian summer monsoon response to global warming, idealized multi-model experiments are analyzed. In the coupled model response to increased CO_2, monsoon westerlies in the lower troposphere are shifted poleward and slightly strengthened over land including South Asia and East Asia, while the tropical easterly jet in the upper troposphere are broadly weakened. The different circulation responses between the lower and upper troposphere is associated with vertically opposite changes in the meridional temperature gradient (MTG) between the Eurasian continent and the tropical Indian Ocean, with a strengthening (weakening) in the lower (upper) troposphere. Atmospheric model experiments to separate the effects of CO_2 radiative forcing and sea surface temperature warming reveal that the strengthened MTG in the lower troposphere is explained by the CO_2 forcing. On a global perspective, CO_2-induced enhancement of the land–sea thermal contrast and resultant circulation changes are the most influential in the South Asian monsoon. This study emphasizes an important role of the land warming on the Asian monsoon response to global warming.

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1. Introduction

The Asian monsoon is the most prominent monsoon system around the world, as it is driven by thermal contrast between the largest continent, Eurasia, and the surrounding oceans as well as the elevated heat source of the Tibetan Plateau, forced by the annual cycle of solar insolation; and it is accompanied by a significant seasonal reversal in prevailing winds and associated precipitation (Wang et al. 2006). Abundant precipitation brought by monsoon provides rich water resources to support agriculture, industry, and a population of billions in the Asian monsoon region. Global warming is projected to influence monsoon systems in a regionally varying manner. Therefore, it is desirable to provide a reliable future projection of the Asian monsoon on the basis of physical understanding.

The latest assessment by the Intergovernmental Panel on Climate Change (IPCC) stated that global monsoon precipitation is likely to increase in the 21st century due to increases in moisture flux convergence and local surface evaporation (Christensen et al. 2013). However, there is a large regional variation in projected changes in monsoon precipitation, including remarkable increases in South Asia and East Asia (Kitoh et al. 2013; Lee and Wang 2014). Endo and Kitoh (2014) examined thermodynamic (atmospheric moisture changes) and dynamic (atmospheric mean circulation changes) effects on regional monsoon precipitation changes, and showed that the negative dynamical components in the Asian monsoon regions are less than in other monsoons, resulting in larger increases in precipitation. Thus, the dynamic component plays an important role in regional precipitation responses and their uncertainty (Cherchi et al. 2011; Bony et al. 2013), and it is tightly coupled with sea surface temperature (SST) warming patterns in the tropics (Xie et al. 2010, 2015; Chen and Zhou 2015).

Monsoon circulation is projected to weaken on a global scale (Kitoh et al. 2013), which is explained by an influence of a general weakening of atmospheric overturning circulation in the tropics (Held and Soden 2006; Vecchi and Soden 2007; Chadwick et al. 2013) resulting from the energy balance constraints in the troposphere (Allen and Ingram, 2002; Sugi and Yoshimura 2004). In the South Asian sector, monsoon circulation is projected to weaken on a broad scale (Ueda et al. 2006; Wang et al. 2014). Ueda et al. (2006) attributed the weakening of Asian monsoon circulation to a pronounced warming in the mid-to-upper troposphere over the tropical Indian Ocean and a resultant reduction of the meridional temperature gradient (MTG) between the Asian continent and the tropical ocean. The tropospheric thermal contrast variation has also been regarded as one mechanism for the East Asian summer monsoon variation (Zhou and Zou 2010; Dai et al. 2013).

Recently, however, it is increasingly recognized that low-level monsoon westerlies may be enhanced in subtropical South Asia and East Asia (Ma and Yu 2014; Ogata et al. 2014; Sandeep and Ajayamohan 2015); actually it was pointed out earlier in some studies (Kitoh et al. 1997; Hu et al. 2000). They suggested an important role of the increased land–sea temperature contrast near the surface, while some literatures regarded the near-surface thermal difference as a minor effect (Sun et al. 2010; Dai et al. 2013). Thus, a comprehensive understanding of the Asian monsoon response to global warming is still insufficient.

Separating the coupled model response to increased CO_2 into a fast response associated with CO_2 radiative forcing (which involves direct atmospheric heating and subsequent land warming) and a slow response associated with subsequent SST warming in the abrupt CO_2 increase experiment framework may be a useful approach to promote our understanding of the mechanisms (Bony et al. 2013; Shaw and Voigt 2015). Recent studies have showed that the fast response driven by land warming plays an important role on the total response in terms of atmospheric circulation and regional precipitation (Chadwick et al. 2014; Kamae et al. 2014; Chen and Bordoni 2016). Li and Ting (2017) revealed that the Asian summer monsoon precipitation change is dominated by the fast response through enhanced monsoon circulation.

In this study, we examine the Asian summer monsoon response to increased CO_2 and the relative roles of the CO_2 radiative forcing and SST warming/pattern through idealized model experiments. Furthermore, we try to better understand the mechanisms with focusing on the large-scale land–sea thermal contrast.

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2. Model experiments and analysis method

We analyzed several types of experiments with atmosphere–ocean coupled general circulation models (AOGCMs) and atmospheric general circulation models (AGCMs) in the Climate Model Intercomparison Project phase 5 (CMIP5) framework (Taylor et al. 2009, 2012). All the experiments are summarized in Table 1. We analyzed nine models that provide all the above simulations after they were re-gridded onto a common 2.5° × 2.5° grid (see Text S1, Fig. S1, and Fig. S2 for the details). The AOGCM response to assumed all forcing was given by the difference between RCP8.5 and Historical. The AOGCM response to increased CO_2 was extracted from the difference between the last 20 years (years 121−140) and the first 20 years (years 1−20) of 1pctCO2. The AGCM responses were obtained from the difference with respect to amip.

For quantitative comparison of the AGCM responses with the corresponding 1pctCO2 responses, the AGCM anomalies were scaled to match the CO_2 forcing and SST warming of the 1pctCO2 multi-model average (see Text S2 for details of the scaling). To isolate the effect of SST pattern change, amipPattern is defined as the difference between the scaled amipFuture minus the scaled amip4K. Using the above quantities, we can decompose the total response in 1pctCO2 into three components, similar to Chadwick (2016) (note that he used abrupt4xCO2 as the AOGCM experiment): writing this symbolically,

$$\mathrm{1pctCO2} \fallingdotseq \mathrm{amip4xCO2} + \mathrm{amip4K} + \mathrm{amipPattern}. \qquad (1)$$

Here, amip4xCO2, amip4K, and amipPattern correspond to the effect of CO_2 radiative forcing, uniform SST warming, and SST pattern change, respectively. Note that this relationship is valid only for the ensemble-mean analysis, because the 1pctCO2 changes are different by models in terms of the SST warming amplitude and the spatial pattern.

Table1. Experimental design.

a) AOGCM experiment

Experiment name	CO_2	Other forcing	Analyzed period
Historical	Observed	Observed	1986−2005
RCP8.5	RCP8.5 scenario	RCP8.5 scenario	2080−2099
1pctCO2	1% increase/year	Pre-industorial level	years 1−20 years 121−140

b) AGCM experiment

Experiment name	CO_2	SST	Analyzed period
amip	Observed	Observed	1979−2008
amip4xCO2	Observed × 4	Observed	1979−2008
amip4K	Observed	Observed + 4K	1979−2008
amipFuture	Observed	Observed + 4K with pattern	1979−2008

3. Results

3.1 Asian monsoon response

Figure 1 shows precipitation changes during June–August (JJA) for AOGCM and AGCM simulations. The 1pctCO2 response presents an overall increase in precipitation in the Asian monsoon region, with a decrease around the Maritime Continent and the Mediterranean. The amip4xCO2 enhances land monsoon precipitation with its extension into continental interior, while the amip4K enhances oceanic monsoon precipitation. The amipPattern shows a decrease in South Asia, the western Pacific, and the Maritime Continent, which is probably related to the fact that SST warming is smaller in these regions (Fig. S1; Xie et al. 2010). What makes the monsoon precipitation responses so different among the different forcing?

Figure 2 shows lower-tropospheric circulation changes during JJA. The 1pctCO2 response shows that monsoon westerlies shift poleward and slightly intensify over land including South Asia, East Asia, and the Sahel, with a slight weakening on the whole. The amip4xCO2 response presents an intensifying of the monsoon westerlies over land with a weakening over the ocean, showing a resemblance to the 1pctCO2. In contrast, the amip4K presents a

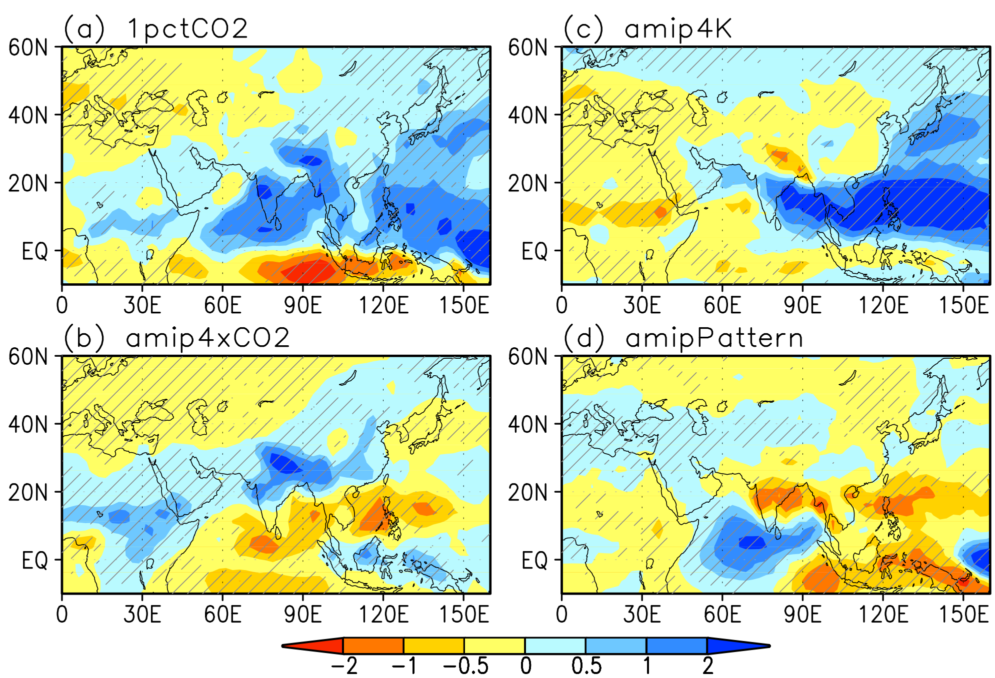

Fig. 1. June–August (JJA) mean precipitation changes (mm day^{-1}) for (a) 1pctCO2, (b) amip4xCO2, (c) amip4K, and (d) amipPattern, based on the nine-model ensemble mean. Hatching shows areas where more than about 80% of models (7 out of 9 models) have the same sign of the change.

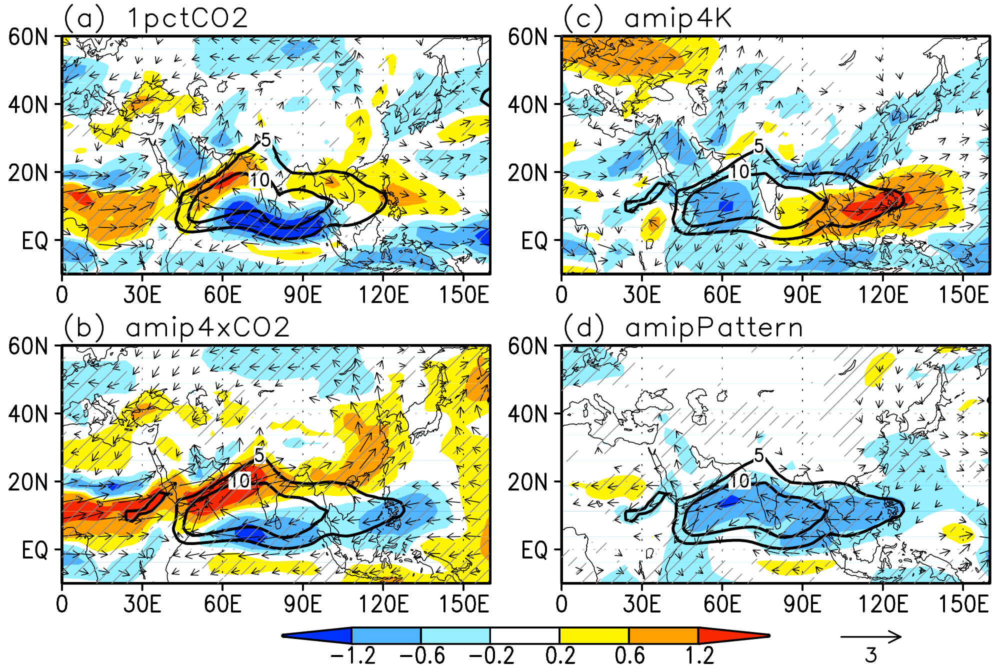

Fig. 2. As in Fig. 1, except for 850-hPa wind changes (m s^{-1}). Arrows indicate change in wind velocity (with magnitude greater than 0.2 m s^{-1}). Shading indicates wind speed change. Thick black contours indicate zonal wind speed in the corresponding control experiment. Hatching shows areas where more than about 80% of models (7 out of 9 models) have the same sign of the change in wind speed.

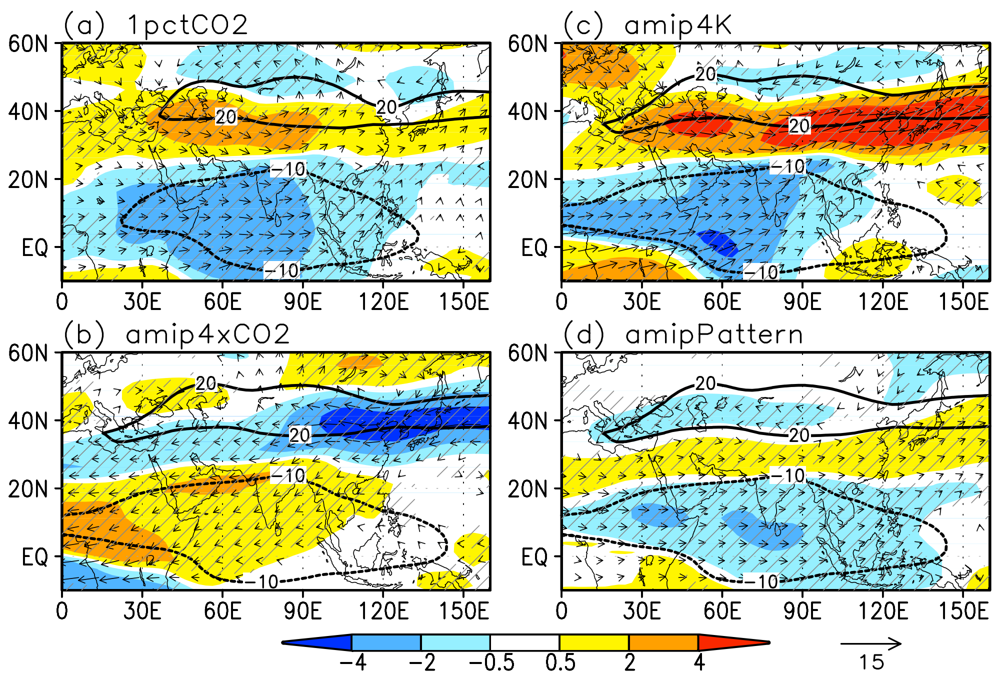

Fig. 3. As in Fig. 2, except for 200-hPa wind changes (m s^{-1}). Arrows indicate wind velocity change (with magnitude greater than 0.5 m s^{-1}).

weakening of the monsoon winds except over the tropical western Pacific. The above results are broadly consistent with Li and Ting (2017). The amipPattern response shows a general weakening of the monsoon westerlies.

Figure 3 shows upper-tropospheric circulation changes. The 1pctCO2 response indicates a weakening of the tropical easterly jet over a wide area, with an equatorward shift of the subtropical westerly jet. The amip4K and amipPattern responses show a similar pattern to the 1pctCO2 with larger anomalies of the amip4K, and they are in contrast to the amip4xCO2 change. Thus, the 1pctCO2 response in the upper troposphere is dominated by the amip4K, which is quite different from the characteristics in the lower troposphere where the amip4xCO2 dominates. This is also clearly suggested in statistics in Table S1.

A comparison of the changes between 1pctCO2, RCP8.5, and amipTotal (defined as the sum of amip4xCO2, amip4K, and

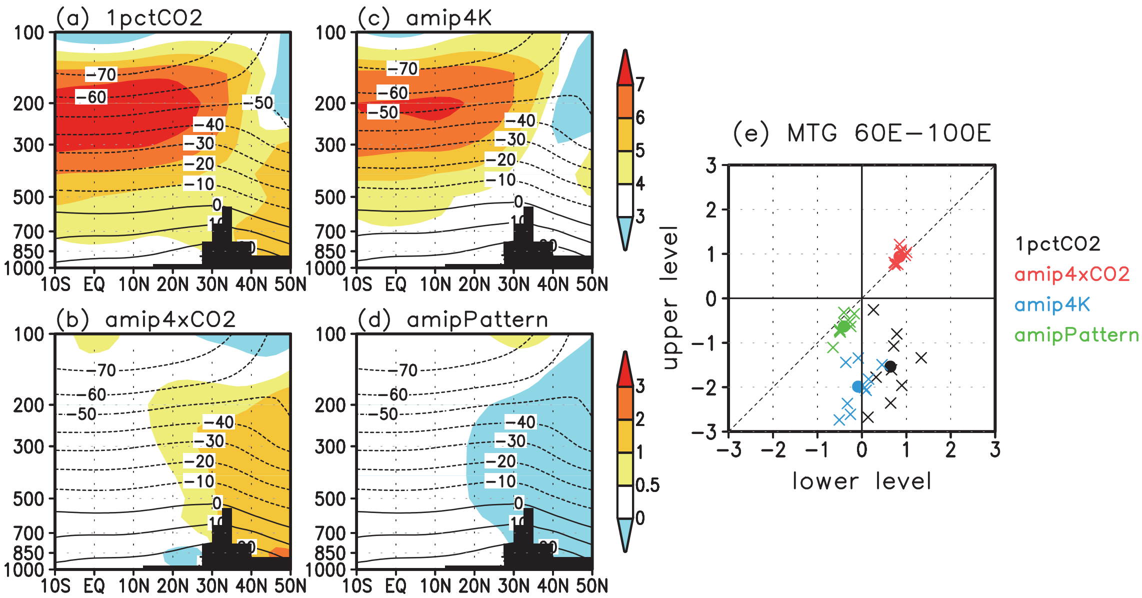

Fig. 4. June–August (JJA) mean tropospheric temperature changes (shading) averaged over 60°E−100°E for (a) 1pctCO2, (b) amip4xCO2, (c) amip4K, and (d) amipPattern, based on the nine-model ensemble mean. Contour indicates temperature in the corresponding control experiment. (e) Scatter plot of changes in the meridional thermal gradient (MTG) averaged in the lower troposphere (surface to 500 hPa; horizontal axis) and the upper troposphere (500 hPa to 200 hPa; vertical axis). MTG is defined as the vertically averaged meridional temperature difference (25°N−45°N minus 10°S−10°N) along the 60°E−100°E sector. Filled circles denote the multi-model averages. All quantities are in Kelvins.

amipPattern) suggests that the Asian monsoon response at the end of 21st century in RCP8.5 scenario can be mostly explained by the 1pctCO2 response, and suggests that the amipTotal response reasonably reproduces the 1pctCO2 response, justifying our approach (See Text S3, Table S2, and Fig. S3 for details).

The South Asian monsoon circulation is driven by the large-scale MTG between the warmer Asian continent and the cooler tropical Indian Ocean (Li and Yanai 1996), which is generated by sensible heating from the land surface as well as latent heating from monsoon-induced precipitation, resulting in a deep-tropospheric structure of the MTG (e.g., Ueda 2014). Based on this perspective, we examine a latitude-height cross section of temperature anomalies over South Asia (Figs. 4a, 4b, 4c, and 4d). The 1pctCO2 response shows a prominent warming in the tropical upper troposphere, where the amip4K response plays a dominant role. The greater warming in the tropical upper troposphere is associated with a decrease in the moist adiabatic lapse rate of temperature in the tropics as the temperature is warmed (Bony et al. 2006). Another aspect of the 1pctCO2 response is a warming throughout the troposphere over the Asian continent, which is explained by the amip4xCO2. The effect of amipPattern cools the troposphere over land, partly offsetting the amip4xCO2 response. Thus, the separation of the 1pctCO2 response into the fast response and the slow response enable us to trace the source of the two warming peaks.

We introduce indices to measure the MTG following previous studies (e.g., Ueda et al. 2006; Dai et al. 2013) and plot their changes in the lower and upper troposphere separately (Fig. 4e). Here, the MTG is defined as the vertically averaged meridional temperature difference (25°N−45°N minus 10°S−10°N) along the 60°E−100°E average. The amip4K response significantly reduces the MTG in the upper troposphere, but it hardly influences the lower-tropospheric MTG, although their magnitudes largely depend on models. The amip4xCO2 response increases the MTG in both levels, with a small inter-model spread. The amipPattern response decreases the MTG, partly cancelling the amip4xCO2 response. A combination of these different effects results in the 1pctCO2 change with a reduced (enhanced) MTG in the upper (lower) troposphere. We note that the results do not depend qualitatively on the area in which the MTG is defined. Thus, the different circulation changes between the upper and lower troposphere in 1pctCO2 are associated with the vertically opposite changes in the MTG (Figs. 2 and 3).

3.2 Global perspective

In this section, we interpret the Asian monsoon response from a global perspective. Figure 5a plots summer precipitation changes in various land monsoon domains. The 1pctCO2 response shows an increase in most regions especially in South Asia (SAS), with large regional variations. This is consistent with the scenario projections with CMIP5 AOGCMs (Kitoh et al. 2013). The amip4xCO2 response shows an increase in most regions. Interestingly, the amip4xCO2 well explains the global monsoon (GLB) response of 1pctCO2 as well as its regional variation, including the largest increase in SAS. An exception is the western North Pacific (WNP), known as the oceanic monsoon (Murakami and Matsumoto 1994), where the amip4K response dominates. The amipPattern response shows a decrease in most regions, including SAS and WNP, although by small amounts. The above features are also found in the case of the percentage change (Fig. S4).

In the amip4xCO2, while the global or tropical annual precipitation is reduced, the global summer monsoon (GLB) precipitation is generally increased (Figs. 5a and S5). The former is caused by a weakening of the overturning circulation due to a reduction of lower-tropospheric radiative cooling by the CO_2 increase (Sugi and Yoshimura 2004). The latter suggest an important role of CO_2-driven land warming and associated atmospheric circulation changes on the monsoon precipitation change. The inter-model spread is generally larger in the amip4K response than the amip4xCO2. Chadwick (2016) noted that this may be because a larger number of processes can cause precipitation change in response to uniform SST warming than direct CO_2 forcing. Note that the amipPattern response is derived from the multi-AOGCM-mean SST anomaly, but actually larger uncertainty would exist on the SST pattern effect since there is a large inter-model spread in projected SST patterns (Mizuta et al. 2014; Chen and Zhou 2015; Chadwick 2016).

Based on a moisture budget analysis, the precipitation change (δP) is separated into the thermodynamic term (δTH), the dynamic term (δDY), and local evaporation change (δE) (see Text S5 for the procedure). Results are shown in Figs. 5b, 5c, 5d, and 5e. In the 1pctCO2 response, δTH has a significant positive effect

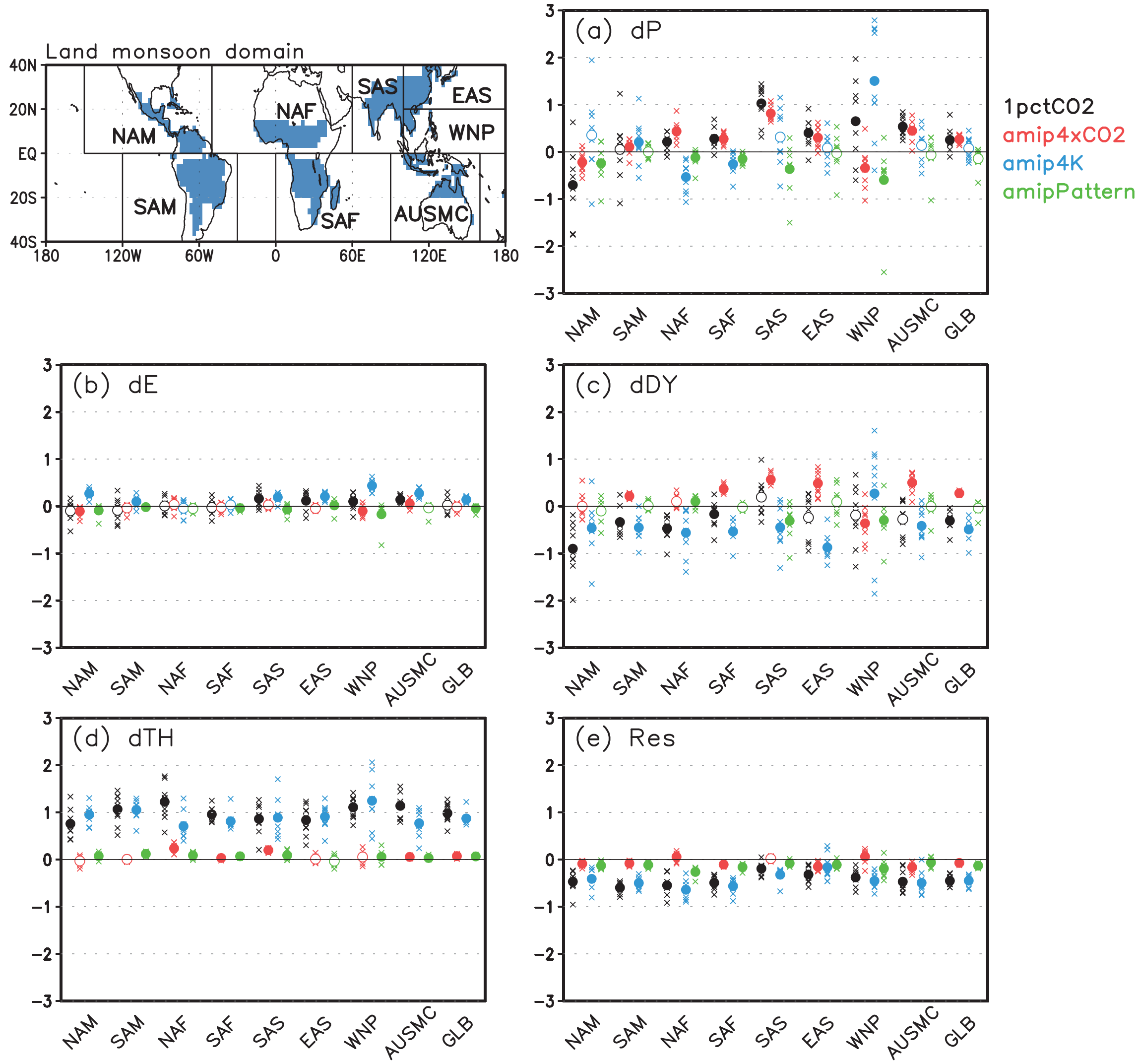

Fig. 5. Monsoon-domain (land only) averaged changes (mm day^{-1}) of the moisture budget terms during the local summer season for 1pctCO2 (black), amip4xCO2 (red), amip4K (blue), and amipPattern (green), based on the nine model ensemble. (a) Precipitation (δP), (b) evaporation (δE), (c) the dynamic term (δDY), (d) the thermodynamic term (δTH), and (e) the residual term (*Res*). Circles denote the multi-model average. The circles are filled in the case of more than about 80% of models (7 out of 9 models) having the same sign of the change. Regional divisions are shown at the top-left of the panel. The local summer season is defined as the period of May–September (November–March) in the Northern (Southern) Hemisphere. See Text S4 for the definition of the monsoon domain.

rather uniformly across the regions, dominated by the amip4K response. In contrast, δDY has a negative effect with an exception in SAS, where δDY tends to be positive but low agreement among models, resulting from the largest positive δDY of amip4xCO2. This is consistent with the intensified low-level monsoon westerlies over South Asia (Fig. 2a). Interestingly, the regional precipitation variations of 1pctCO2 generally follow the amip4xCO2 response, especially its dynamical term. In the amip4K response, δTH and δDY largely cancel, resulting in small precipitation changes, except in WNP. In all the experiments, local evaporation generally plays a minor role. It is noted that the residual term (*Res*) of 1pctCO2 shows negative tendencies with non-negligible amounts, dominated by the amip4K response. The transient eddy component probably contributes to the negative *Res* (Seager et al. 2010; Endo and Kitoh 2014). The other parts of *Res* are from computational errors in the moisture budget analysis, including the use of pressure level data with lower vertical resolution (Seager et al. 2010). The large *Res* limit detailed discussion of the results obtained by the budget analysis.

Next, large-scale fields related to the monsoon circulation changes are examined. In the 1pctCO2 response, the upper tropospheric temperature shows the largest warming in the entire tropics (Fig. 6a), dominated by the amip4K response (Fig. S6), reducing the MTGs between the subtropical continents minus the tropics. In addition, a larger warming in the upper level than the lower act to stabilize the troposphere (Figs. 6a and 6b). These features are common over the monsoon regions worldwide. The lower tropospheric temperature change of 1pctCO2 indicates a larger warming over land especially in the extratropical Northern Hemisphere (Fig. 6b), consistent with the surface temperature change of the CMIP5 projections (Lee and Wang 2014). As a result of this horizontal thermal contrast, sea level pressure (SLP) is characterized by generally negative anomalies over land especially over the western Eurasian continent and northern Africa, contrasted with positive anomalies over the ocean especially the western Pacific (Fig. 6c). These mainly reflect the amip4xCO2 response (Figs. S7 and S8). As suggested by Wang et al. (2014) and Lee and Wang (2014), this continental-scale SLP pattern favor an intensification of low-level winds from the surrounding oceans into the Eurasian continent, which could lead to larger precipitation increases in the Asian monsoon regions and they could be strongly coupled and interactive.

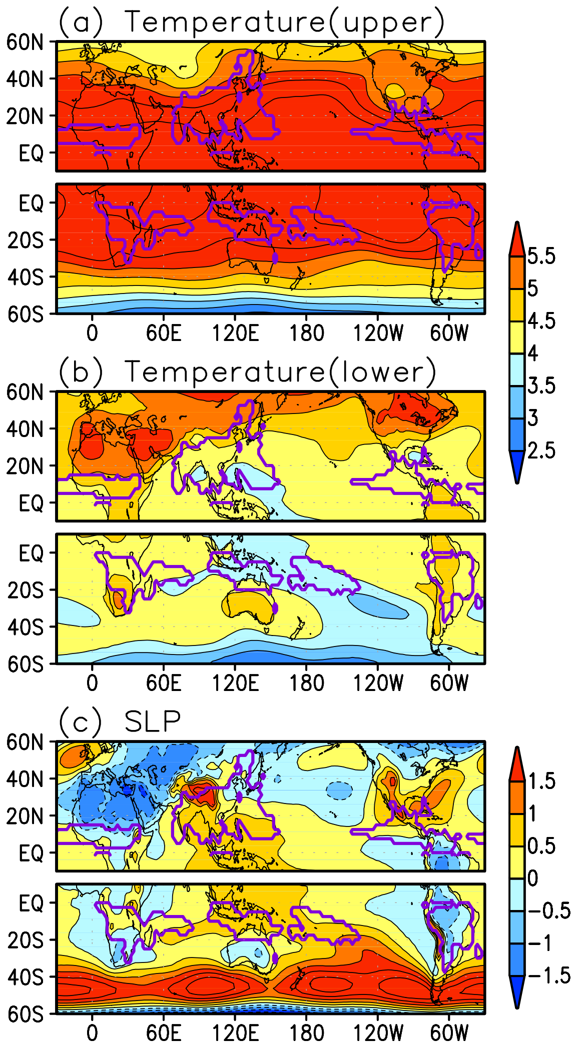

Fig. 6. Summer averaged changes of 1pctCO2 for (a) temperature (K) in the upper troposphere (500 hPa to 200 hPa), (b) temperature (K) in the lower troposphere (surface to 500 hPa), and (c) sea level pressure (hPa), based on the nine-model ensemble mean. The upper (lower) part of each panel shows the changes during May–September (November–March). Purple contours indicate the monsoon domains (See Text S4 for the definition).

4. Concluding remarks

Under a global warming condition, a prominent warming appears in the tropical upper troposphere due to a decrease in the moist adiabatic lapse rate of temperature as the atmosphere is moistened (Bony et al. 2006). The upper-tropospheric warming maximum stabilizes the atmosphere and leads to a general weakening of the overturning circulation in the tropics (Held and Soden 2006). Previous monsoon studies have stressed the effect of the upper-tropospheric warming and suggested a weakening of the monsoon circulation on both global and regional scales (Ueda et al. 2006; Kitoh et al. 2013). On the other hand, this study emphasizes a role of the land warming as a result of the CO_2 radiative forcing, which acts to increase the land–sea thermal contrast and induce a horizontal pressure gradient, strengthening the monsoon circulation and precipitation. In particular, the larger warming over the Eurasian continent and the resultant remarkable negative pressure anomaly could be associated with the largest precipitation increase in South Asia. Thus, the combined effect of the two different warming maximum makes the Asian monsoon circulation response very complicated.

Local factors contributing to the largest response of the Asian monsoon may include the existence of the huge Eurasian continent and the elevated Tibetan Plateau, together with the land–sea distribution, which can help to amplify the land–sea thermal contrast and induce pressure gradient, producing anomalous monsoon circulation. This topic should be pursued further in a future study.

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Supplement

Supplement 1 contains five text sections, two tables, and eight figures.

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