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# Evaluation of global warming impacts on the carbon budget of terrestrial ecosystems in monsoon Asia: a multi-model analysis

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**Abstract** This study assesses the potential impacts of future global warming on the carbon budget of terrestrial ecosystems across monsoon Asia using the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP) dataset. We used simulation results of two emission pathways (RCP2.6 and RCP8.5), climate projections of five climate models, and seven terrestrial biome models to analyze the changes in net primary production and carbon stocks in the South, Southeast, and East Asian subregions during the period 1981–2099. The simulations indicated that by the end of the 21st century, net primary production would increase by 9–45 % and ecosystem carbon storage would increase by 42–86 Pg C. The clearest climatic impacts were found when using the adaptation-oriented emission scenario (RCP8.5), which assumes a greater CO<sub>2</sub> increase and a larger change in climatic conditions. Substantial disparities in temporal trajectories and spatial patterns were found in the estimated changes, owing to the uncertainties in the emission scenarios, climate projections, and ecosystem models. We attempted to derive consistent patterns throughout the simulations to specify potential hotspots of climatic impacts (e.g., soil carbon change in the southern Tibetan Plateau). Finally, we discuss changes to the climatic characteristics in the study region (e.g., a change in the rainy season), the implications for ecosystem services, and the need for collaborative field monitoring studies.

**Keywords** Climate change · ISI-MIP · Monsoon Asia · Terrestrial carbon cycle · Uncertainty

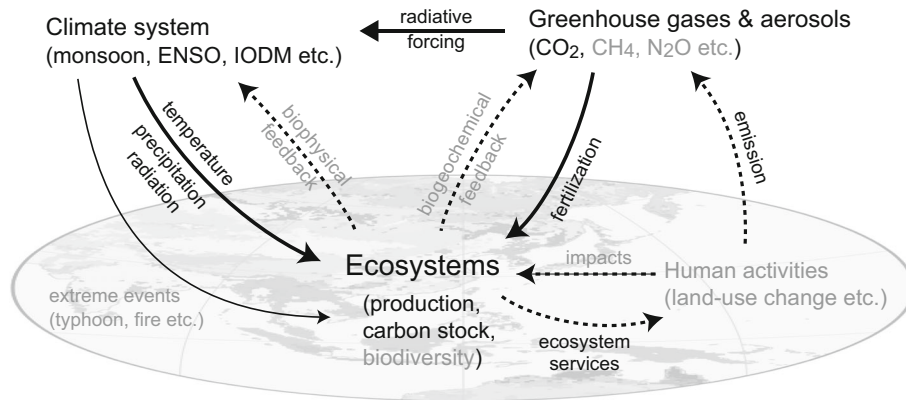
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## Introduction

Terrestrial ecosystems are key components of the Earth system, and are expected to have considerable feedback effects on human-induced climate change. Vegetation biomass and soil organic matter are estimated to store 450–650 and 1500–2400 Pg C (Pg = 10<sup>15</sup> g), respectively, and their total storage is more than double the amount of carbon in atmospheric greenhouse gases [Intergovernmental Panel on Climate Change (IPCC) 2013]. However, our understanding of the climatic impact on terrestrial ecosystems and their impact on their vulnerability and resilience needs to be improved.

Terrestrial ecosystems in monsoon Asia have remarkable characteristics compared with other regions at similar latitudes (i.e., Central to North America and the Mediterranean region of Europe). Biogeographical studies have revealed that the climax vegetation of this region is continuous forest coverage, ranging from tropical rainforests around the equator to boreal coniferous forests in Siberia (Kira 1991; Ohsawa 1995). The lack of subtropical arid zones (i.e., “horse latitudes” made by the Hadley circulation) may be attributed to the plentiful water supply during the rainy season as a result of the monsoon circulation. Meteorological studies have revealed that the land–ocean contrast across the Asian continent plays an essential role in generating the Asian monsoon (Webster et al. 1998; Zhisheng et al. 2015). In addition, large-scale meteorological events such as the El Niño/Southern Oscillation (ENSO) and the Indian Ocean Dipole Mode (IODM) cause clear interannual variation in climatic conditions in monsoon Asia (Ropelewski and Halpert 1987; Saji et al. 1999). Moreover, the strong winds and heavy rains of tropical cyclones are often accompanied by local disturbances such as wind throw and flooding (Boose et al. 1994). These climatic factors have mutual interactions in monsoon Asia (e.g., Ailikon and Yasunari 2001), which introduces considerable complexities to predicting climatic conditions in this region.



**Fig. 1** Schematic diagram of global climate change impacts on ecosystems in Monsoon Asia. This study focused on the components shown in *black solid lines*. Processes shown by *dotted lines* are not directly included in this study

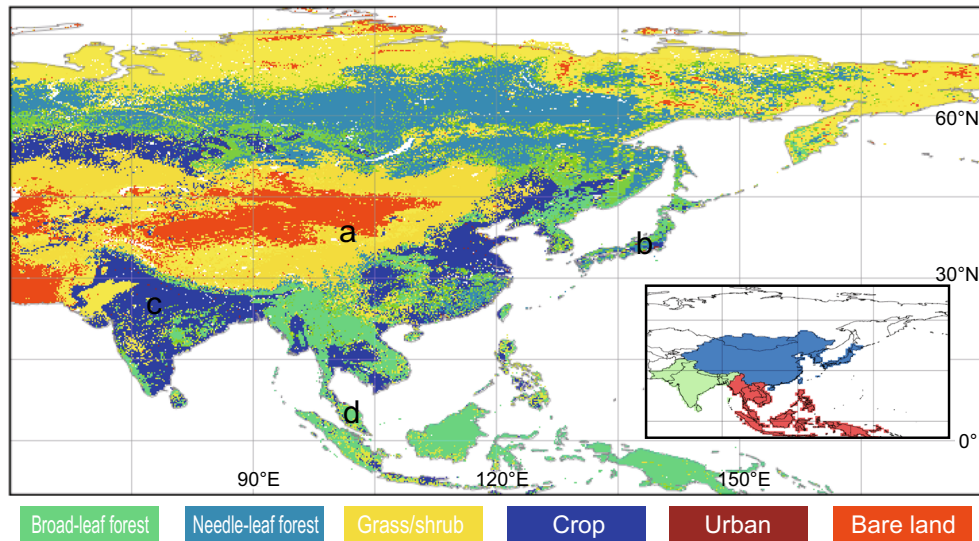
The unique climatic conditions, in turn, foster the unique flora and fauna of this region. Monsoon Asia contains many biodiversity hotspots, including Sundaland, Indo-Burma, Himalaya, Wallacea, the Philippines, the mountains of southwestern China, Japan, and the Western Ghats and Sri Lanka (Myers et al. 2000; Sodhi et al. 2010). The broad areas of humid forests store a substantial amount of carbon as biomass and soil organic matter (Pan et al. 2011), and play an important role in the global carbon cycle. The terrestrial ecosystems in monsoon Asia provide various services to human societies, supporting approximately four billion people (Yasunari et al. 2013). The ecosystem services in this region include not only provision of water and products such as food and fiber but also prevention or reduction of the impact of disasters such as floods and landslides.

In this region, the monsoon regime is predicted to change under global warming (Fu 2003; Werth and Avissar 2005; Takata et al. 2009; Xu et al. 2012). Several studies have predicted that the Asian monsoon will be weakened in the future, leading to decreased precipitation and greater dryness in the region (e.g., Tanaka et al. 2005; Annamalai et al. 2013). In contrast, Hsu et al. (2012) and Kitoh et al. (2013) reported that monsoon-related precipitation would increase, as a result of enhanced atmospheric convergence. The ENSO and IODM regimes are also predicted to change with global warming, but there is substantial uncertainty associated with these estimates (Timmermann et al. 1999; Latif and Keenlyside 2009; Cai et al. 2014). The occurrence of extreme weather events such as tropical cyclones is also predicted to change in the future (Webster et al. 2005; Yamada et al. 2010), potentially leading to increased disaster risks (Peduzzi et al. 2012).

Climate change is expected to influence terrestrial ecosystems in monsoon Asia, although direct human interventions such as deforestation are also likely to have local and immediate impacts. Model prediction and analysis should be an effective approach for

assessing the future impacts of global change, but only a few regional modeling studies have considered the future climatic impacts on monsoon Asian ecosystems. For example, Esser (1995) applied the High-Resolution Biosphere Model to investigate the carbon budget of monsoon Asia from 1990 to 2050. Oikawa and Ito (2001) applied a simulation model of carbon cycle in land ecosystems to monsoon Asia using three climate scenarios that assume a doubling of atmospheric CO<sub>2</sub> concentration. Tian et al. (2003) applied the Terrestrial Ecosystem Model to the region, but only during the historical period from 1860 to 1990. The results of these studies implied that terrestrial ecosystems in monsoon Asia play an important role in the global carbon cycle, and future global change would exert considerable influences on these ecosystems. However, these studies each used a single terrestrial model and a small number of climate scenarios, making it difficult to capture the range of estimation uncertainty. Model intercomparison studies have revealed that existing terrestrial ecosystem models provide widely different estimates (e.g., Todd-Brown et al. 2013; Nishina et al. 2014; Tian et al. 2015), because of the different forcing data, assumptions, and intrinsic biases of each model. Therefore, to obtain less biased and more reliable results, it is desirable to use multiple model simulations.

In this study, we conduct a regional analysis of the impacts of future climate change on terrestrial ecosystems mainly located in monsoon Asia, using multiple scenarios and terrestrial ecosystem model simulations. For brevity and clarity, we focused on metrics representing ecosystem functions and services in the study region: net primary production (NPP), vegetation biomass, and soil carbon stock (Fig. 1). In terms of ecosystem services (Millennium Ecosystem Assessment 2005), NPP is an indicator of ecosystem functioning and can be related to fundamental ecosystem services such as carbon cycling. By serving as a sink of CO<sub>2</sub>, carbon storage in biomass and soil may represent a climate regulation service. We then specified hot spots of



**Fig. 2** Land cover of the study area of monsoon Asia based on SYNMAP data (Jung et al. 2006) produced from satellite data for the study period (1981–2000). Symbols *a–d* show site location for

ecosystem change in the region, where a certain magnitude of impact is expected to occur with high confidence. Finally, we discuss the future need for collaborative research, involving both models and field observations, for the early detection of climatic impacts and reduction of estimation uncertainty.

## Methods

### Study area

In this study, monsoon Asia was defined as the area between 10°S and 80°N and between 60°E and 180°E (land area  $37.03 \times 10^6 \text{ km}^2$ ). In particular, we focused on three subregions (Fig. 2, inset): South Asia, Southeast Asia, and East Asia, which cover 4.86, 4.48, and  $11.45 \times 10^6 \text{ km}^2$ , respectively. According to a land-cover map synthesized from multiple satellite products (Jung et al. 2006), the vegetation coverage of these three subregions is as follows: 14.2 % evergreen broad-leaf forests, 10.4 % grasslands, 7.7 % evergreen needle-leaf forests, 8.0 % bare land (e.g., deserts), 7.9 % shrubs and grasses, 5.7 % shrubs and bare lands, 3.7 % mixed forests, 3.4 % deciduous conifer forests, and 3.2 % deciduous broad-leaf forests. In terms of human land use, this area is occupied by 20.4 % croplands and 0.2 % urban area.

### Data

This study used a dataset from the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP) organized by the Potsdam Institute for Climate Impact Research (Warszawski et al. 2014). This project began in 2012,

Fig. 11a–d, respectively. *Inset*: the South Asia (green), Southeast Asia (red), and East Asia (blue) subregions

with the aim of contributing to assessments of climate change impacts, especially those conducted by the IPCC. For each sector [e.g., agriculture, water, human health, and ecosystems (biome)], model simulations were conducted using a standardized protocol and forcing dataset of historical and future climate. In the first stage, the biome sector included seven models:

1. Hybrid version 4 (Friend and White 2000): the fourth version of a dynamic global vegetation model including interactions between individual trees and the herbaceous layer, developed at Cambridge University, United Kingdom;
2. JeDi (Pavlick et al. 2013): the Jena Diversity model, including a biodiversity component, developed at the Max Planck Institute for Biogeochemistry, Germany;
3. JULES (Clark et al. 2011): the Joint UK Land Ecosystem Scheme developed at the Center for Ecology and Hydrology, Meteorological Office Hadley Centre, and University of Exeter, United Kingdom;
4. LPJmL (Sitch et al. 2003; Bondeau et al. 2007): the Lund-Potsdam-Jena model, including dynamic vegetation and land management, developed at the Potsdam Institute for Climate Impact Research, Germany;
5. ORCHIDEE (Krinner et al. 2005): the ORganized Carbon and Hydrology In Dynamic Ecosystems model developed at the Institut Pierre Simon Laplace, France;
6. SDGVM (Woodward and Lomas 2004): the Sheffield Dynamic Global Vegetation Model developed at the University of Sheffield, United Kingdom;
7. VISIT (Ito and Inatomi 2012): the Vegetation Integrative Simulator for Trace gases, focusing on atmosphere–ecosystem biogeochemical interactions,

developed at the National Institute for Environmental Studies, Japan.

These models are based on different principles and differ in complexity and environmental responsiveness (Friend et al. 2014; Nishina et al. 2014, 2015); however, they all simulate the terrestrial carbon cycle, including productivity and carbon stock.

In addition to the differences between biome models, we also considered the uncertainties associated with greenhouse gas emission scenarios and climate projections. We used two greenhouse-gas emission and concentration scenarios, both of which were representative concentration pathways (RCPs; Moss et al. 2010; Meinshausen et al. 2011) derived from socio-economic assumptions and models. RCP2.6 represents a mitigation-oriented scenario with low atmospheric greenhouse gas concentrations and a low radiative forcing target ( $2.6 \text{ W m}^{-2}$  in 2100), whereas RCP8.5 represents an adaptation-oriented scenario with a higher radiative forcing target ( $8.5 \text{ W m}^{-2}$  in 2100 and  $12 \text{ W m}^{-2}$  in 2300). The two scenarios also differ in  $\text{CO}_2$  concentration pathways: 443 ppmv for RCP2.6 and 541 ppmv for RCP8.5 in 2050, and 421 ppmv for RCP2.6 and 927 ppmv for RCP8.5 in 2099. Thus, they differ in their temporal trajectories: in RCP2.6  $\text{CO}_2$  concentration stabilizes after the 2040s, whereas in RCP8.5 it shows a continuous increase. For each RCP scenario, future climate was predicted by climate models, which include not only atmospheric and oceanic circulation patterns but also carbon-cycle feedbacks (so-called Earth system models). Under the ISI-MIP protocol, five climate-model projections from the fifth stage of the Climate Model Intercomparison Project (CMIP5; Taylor et al. 2012) were used to span the range of climate projection: Geophysical Fluid Dynamics Laboratory, version CM3 (hereafter GFDL), Hadley Centre Global Environmental Model, version ES (hereafter HadGEM), Institut Pierre Simon Laplace, version CM5A-LR (hereafter IPSL), Model for Interdisciplinary Research on Climate, version ESM-CHEM (hereafter MIROC), and Norway Earth System Model, version 1-M (hereafter NorESM). The ten scenarios obtained by combining the two RCPs and five climate-model projections represent the range of uncertainties in future environmental change.

Each biome model was driven from 1980 to 2099 after a sufficient length of stabilization (spin-up) and a transition period from 1951 to 1980 using the bias-corrected meteorological data (Hempel et al. 2013). Because the ORCHIDEE model provided simulation outputs for the HadGEM climate projections only, we obtained a total of 62 simulation time-series datasets. Most models adopted a spatial resolution of  $0.5^\circ \times 0.5^\circ$  in latitude and longitude; however, JeDi and JULES had a lower resolution ( $2.5^\circ \times 2.5^\circ$ ) and were thus interpolated using the nearest neighbor method.

## Analyses

We used the results of NPP, vegetation biomass carbon stock (CVeg), and soil carbon stock (CSoil) from the ISI-MIP dataset. Future change (denoted by  $\Delta$ ) was calculated as the difference from the present state (mean of 1981–2000). Note that the biome models used in this study differ in their inclusion of natural disturbances such as wildfire (Friend et al. 2014). Several global vegetation dynamics models predicted a future change in biome distribution, whereas others used a prescribed (model-specific) land-cover map. The first stage of ISI-MIP focused on direct climatic impacts, and human land-use conversion was not taken into account.

Using the 62 simulation results, we specified hot spots in monsoon Asia in which a certain magnitude of impact was simulated with high consistency. We then examined the frequency distributions of the different magnitudes of ecosystem change, focusing on the occurrence of extreme impacts. Further, to derive monitoring objectives, we compared observable metrics such as seasonality in net ecosystem  $\text{CO}_2$  flux and annual NPP in the 2000s, 2040s, and 2090s in several grids containing field sites.

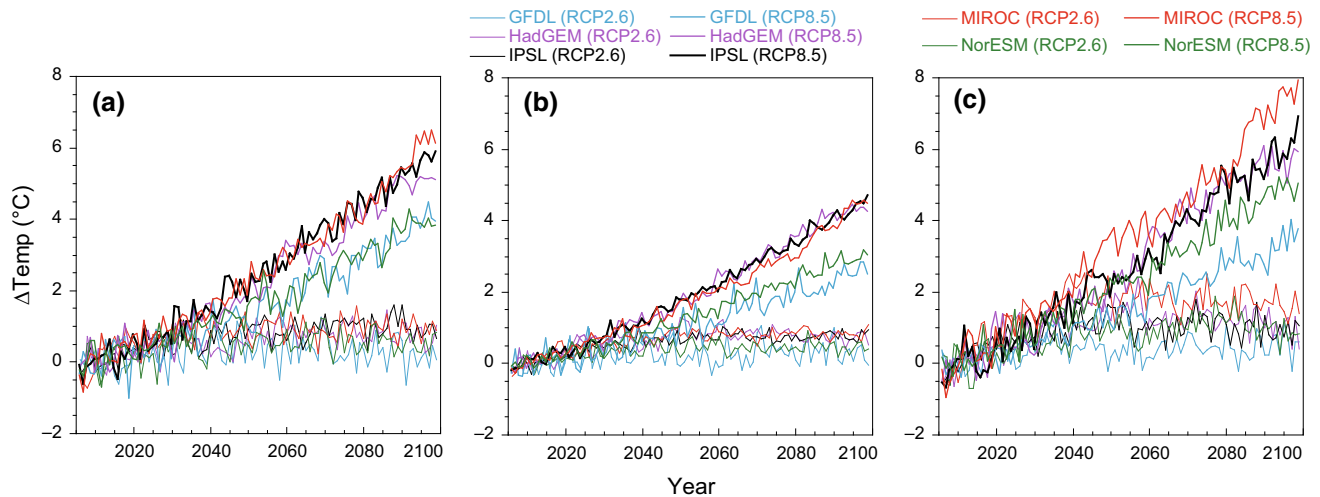
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## Results

### Projected climate change in monsoon Asia

According to the ISI-MIP climate data, the annual mean temperature during the present period in the South, Southeast, and East Asian subregions was 24.0, 26.4, and 7.1 °C, respectively. South and Southeast Asia experience tropical to subtropical climatic conditions, whereas East Asia, containing the Tibetan Plateau, has largely temperate climatic conditions. Annual precipitation in the South, Southeast, and East Asian subregions was 1064, 2394, and 634 mm year<sup>-1</sup>, respectively. Precipitation during the typical rainy season (June–August) in South, Southeast, and East Asian subregions was 632 mm (59.4 % of annual precipitation), 694 mm (29.0 % of annual precipitation), and 318 mm (50.2 % of annual precipitation), respectively. Thus, Southeast Asia experiences a humid climate, whereas South and East Asia have moist to dry conditions, and water input into South and East Asia is heavily dependent on rainfall in summer.

As a result of global warming, the temperature in monsoon Asia is predicted to rise until the end of the 21st century. As shown in Fig. 3, annual mean air temperature will rise, but the rate of this increase varies between the RCP scenarios, among climate projection models, and among subregions. In South Asia, annual mean temperature was predicted to rise by  $0.67 \pm 0.42$  °C for RCP2.6 and  $4.84 \pm 0.91$  °C for RCP8.5 (mean  $\pm$  standard deviation among the climate models), from the 2000s to the 2090s. In Southeast Asia, annual mean temperature was predicted to rise by



**Fig. 3** Time-series of changes in annual mean temperature based on the ISI-MIP forcing climate dataset for the three subregions: **a** South Asia, **b** Southeast Asia, and **c** East Asia. GFDL,

HadGEM, IPSL, MIROC, and NorESM denote the names of climate models (see “Methods” section), with two emission pathways (RCP2.6 and RCP8.5)

$0.62 \pm 0.29$  °C for RCP2.6 and  $3.65 \pm 0.80$  °C for RCP8.5. Finally, in East Asia, it was predicted to rise by  $1.00 \pm 0.49$  °C for RCP2.6 and  $5.42 \pm 1.39$  °C for RCP8.5. In each subregion, the temperature increases estimated in the RCP2.6 scenario were lower than those in RCP8.5 and stabilized after the 2040s. A larger temperature rise was projected in East Asia, which contains alpine and boreal ecosystems.

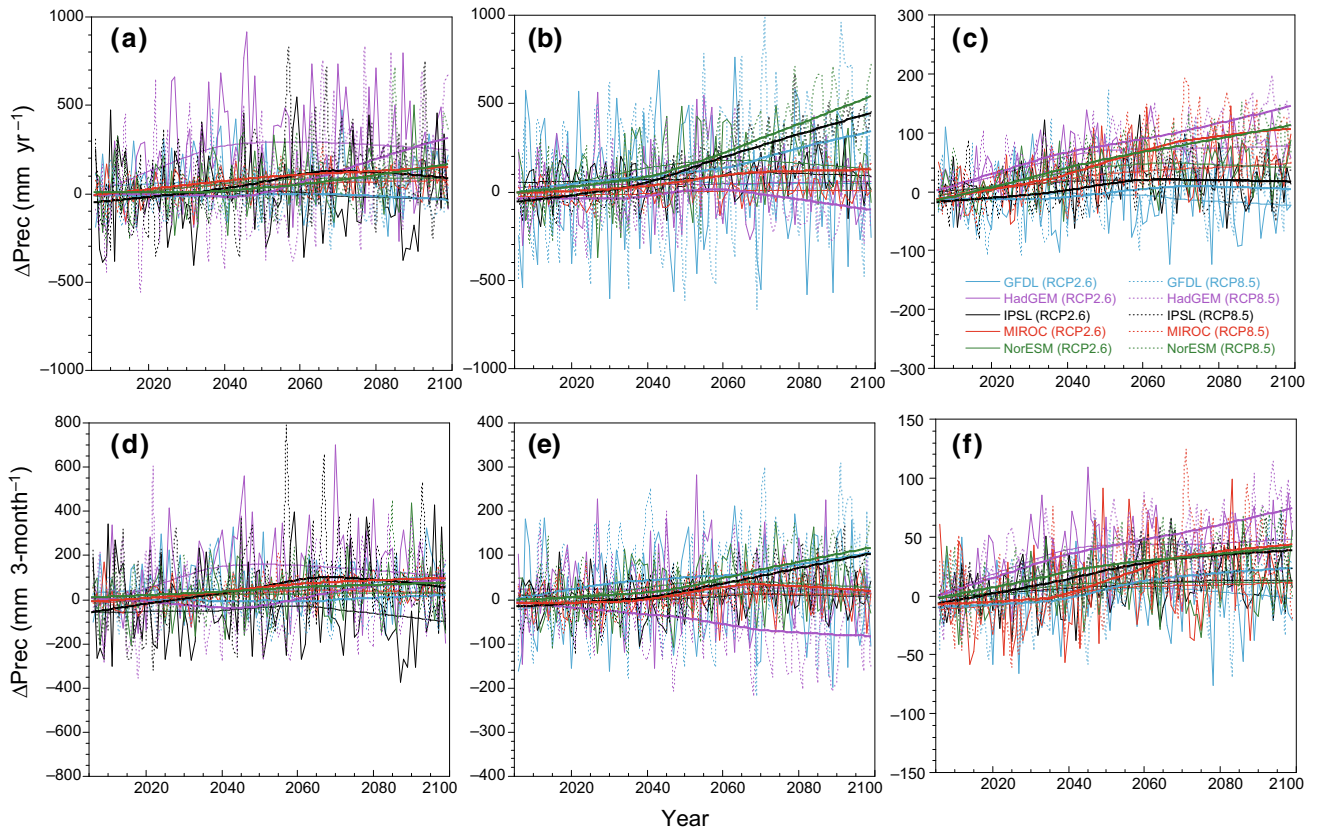
Predicted precipitation changes in monsoon Asia showed a wide range of inter-annual variability (Fig. 4), and long-term trends were not as clear as those for the temperature rise. On average, in the South Asian subregion, annual precipitation was estimated to increase by  $118.3 \pm 172.3$  mm year<sup>-1</sup> for RCP2.6 and  $124.0 \pm 226.4$  mm year<sup>-1</sup> for RCP8.5, from the 2000s to the 2090s. In Southeast Asia, annual precipitation was estimated to increase by  $71.9 \pm 185.9$  mm year<sup>-1</sup> for RCP2.6 and  $267.6 \pm 289.8$  mm year<sup>-1</sup> for RCP8.5. Some climate models (GFDL, IPSL, and NorESM) showed clear trends of precipitation increase in this subregion for both RCP2.6 and RCP8.5. In East Asia, annual precipitation was estimated to increase by  $34.2 \pm 34.1$  mm year<sup>-1</sup> for RCP2.6 and  $73.2 \pm 63.1$  mm year<sup>-1</sup> for RCP8.5. Within each subregion, the differences between the two RCP scenarios were not clear. Some of the climate models estimated a long-term decrease in precipitation (e.g., HadGEM in Southeast Asia and GFDL in South Asia and East Asia). In most cases, precipitation during the rainy season showed similar tendencies to those of annual precipitation, although HadGEM estimated a clearer decreasing trend in rainy-season precipitation in Southeast Asia.

The climate projections indicated that downward shortwave radiation at the ground surface will change over time. However, note that the climate models also

consider the change in natural and anthropogenic aerosol emissions, and therefore it is not easy to attribute the radiation change to climate change alone. In East Asia, climate models predicted that shortwave radiation would increase by  $5.1 \pm 2.2$  and  $2.7 \pm 2.7$  W m<sup>-2</sup> for RCP2.6 and RCP8.5, respectively, between the 2000s and 2090s. In South and Southeast Asia, there was no consistent trend in shortwave radiation (from  $-2.3 \pm 5.3$  to  $2.9 \pm 2.7$  W m<sup>-2</sup> for both RCPs), with a broad range of variability among climate models.

#### Changes in the regional carbon budget

The biome models simulated reasonable primary production and carbon storage in the terrestrial ecosystems of monsoon Asia (Table 1). Based on the average of the biome models’ estimates, vegetation in the South, Southeast, and East Asian subregions were estimated to have NPPs of  $0.40 \pm 0.16$ ,  $0.85 \pm 0.29$ , and  $0.42 \pm 0.05$  kg C m<sup>-2</sup> year<sup>-1</sup>, respectively, in the 2000s. Thus, Southeast Asia, which contains tropical rainforests, had a higher area-based productivity than the other subregions. The total NPP in the three subregions was estimated as  $12.5$  Pg C year<sup>-1</sup>, of which 44.2 % was in Southeast Asia. The carbon stock in vegetation biomass in the South, Southeast, and East Asian subregions was estimated as  $3.4 \pm 1.7$ ,  $12.5 \pm 4.0$ , and  $4.5 \pm 1.7$  kg C m<sup>-2</sup>, respectively, in the 2000s. The total amount in the three subregions is  $152.1$  Pg C, of which 53.3 % was in Southeast Asia. Similarly, the carbon stock in soil organic matter in the South, Southeast, and East Asian subregions was estimated as  $6.7 \pm 3.2$ ,  $10.1 \pm 7.2$ , and  $11.9 \pm 3.1$  kg C m<sup>-2</sup>, respectively. In this case, the East Asian subregion had a



**Fig. 4** Time-series of changes in **a–c** annual and **d–f** rainy-season precipitation based on the ISI-MIP forcing climate dataset for the three subregions: **a, d** South Asia; **b, e** Southeast Asia; **c, f** East Asia. Rainy-season precipitation represents the total for June, July, and August. *Thick lines* show smoothed trends. GFDL, HadGEM, IPSL, MIROC, and NorESM denote the name of climate models (see “Methods” section), with two emission pathways (RCP2.6 and RCP8.5)

**Table 1** Regional carbon budget simulated by the ISI-MIP biome models in three subregions of monsoon Asia

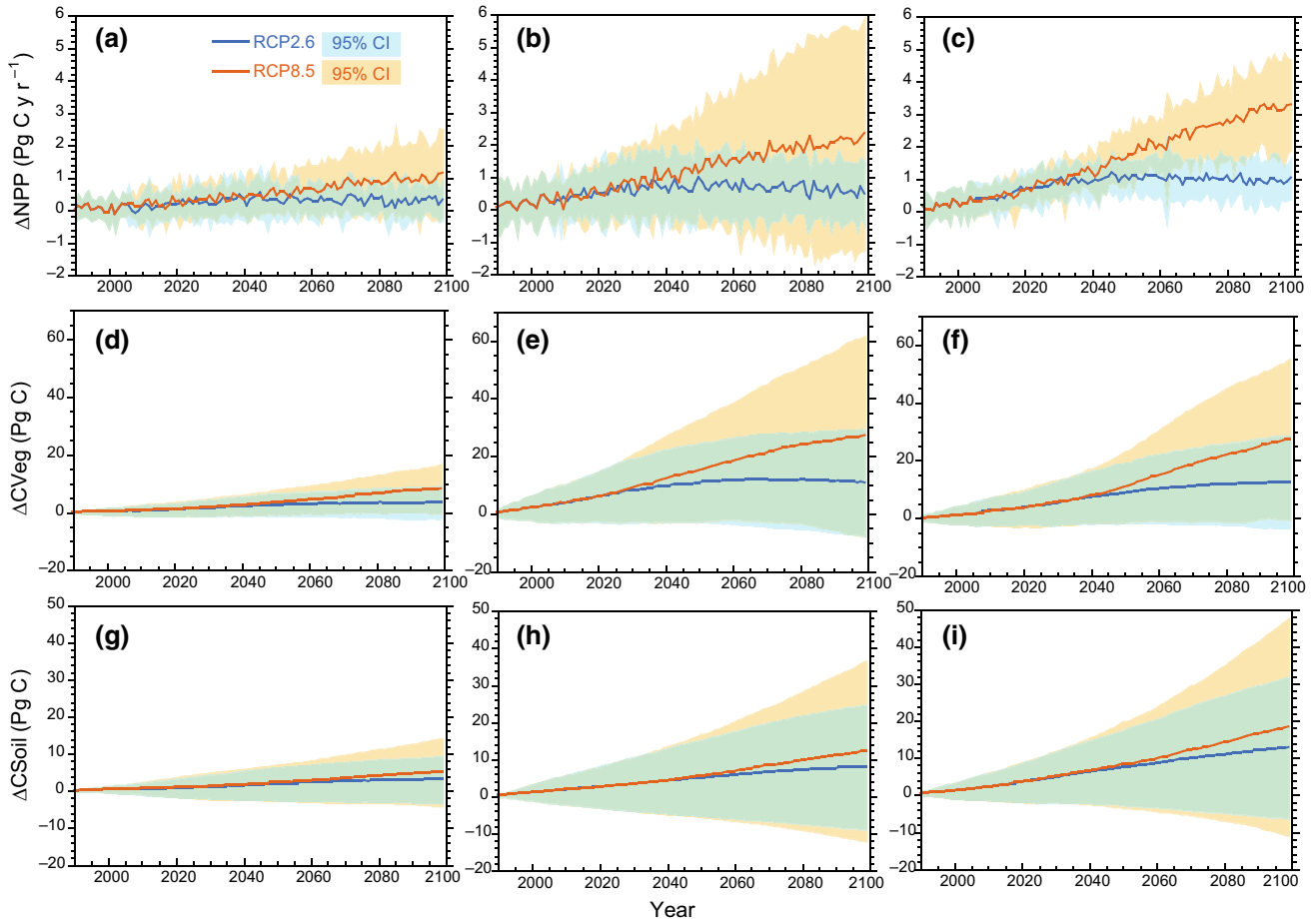
Carbon budget	RCP2.6						RCP8.5			
	2000s		2040s		2090s		2040s		2090s	
Subregions	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
<b>NPP (Pg C year<sup>-1</sup>)</b>										
East Asia	5.0	0.6	5.8	0.6	5.6	0.6	6.6	0.7	7.9	0.8
Southeast Asia	5.5	1.9	6.0	2.1	5.8	2.1	6.7	2.6	7.4	3.4
South Asia	1.9	0.7	2.2	0.8	2.2	0.8	2.4	0.9	2.8	1.1
<b>CVeg (Pg C)</b>										
East Asia	54.9	20.1	62.8	22.8	65.7	23.8	65.9	24.3	79.4	28.6
Southeast Asia	81.1	26.0	89.4	28.3	89.4	28.1	94.9	31.0	104.6	36.5
South Asia	16.1	8.2	18.5	9.5	19.0	10.3	19.6	9.7	23.4	11.4
<b>CSoil (Pg C)</b>										
East Asia	143.7	37.6	150.0	40.3	154.4	41.7	150.9	41.0	159.4	45.4
Southeast Asia	65.5	46.5	69.6	50.3	72.0	52.8	70.3	50.6	75.8	55.7
South Asia	32.1	15.3	33.6	16.6	34.5	17.1	33.9	16.9	36.3	18.1

Means and standard deviations (SD) of 31 simulations based on different climate projections and biome models are shown for the RCP2.6 and RCP8.5 scenarios

*NPP* net primary production, *CVeg* vegetation biomass carbon, *CSoil* soil organic carbon

higher area-based and total carbon stock, representing 59.6 % of the total regional soil carbon stock of 241.4 Pg C.

As a result of the atmospheric CO<sub>2</sub> rise accompanying climate change, the terrestrial carbon budget in monsoon Asia was projected to experience substantial



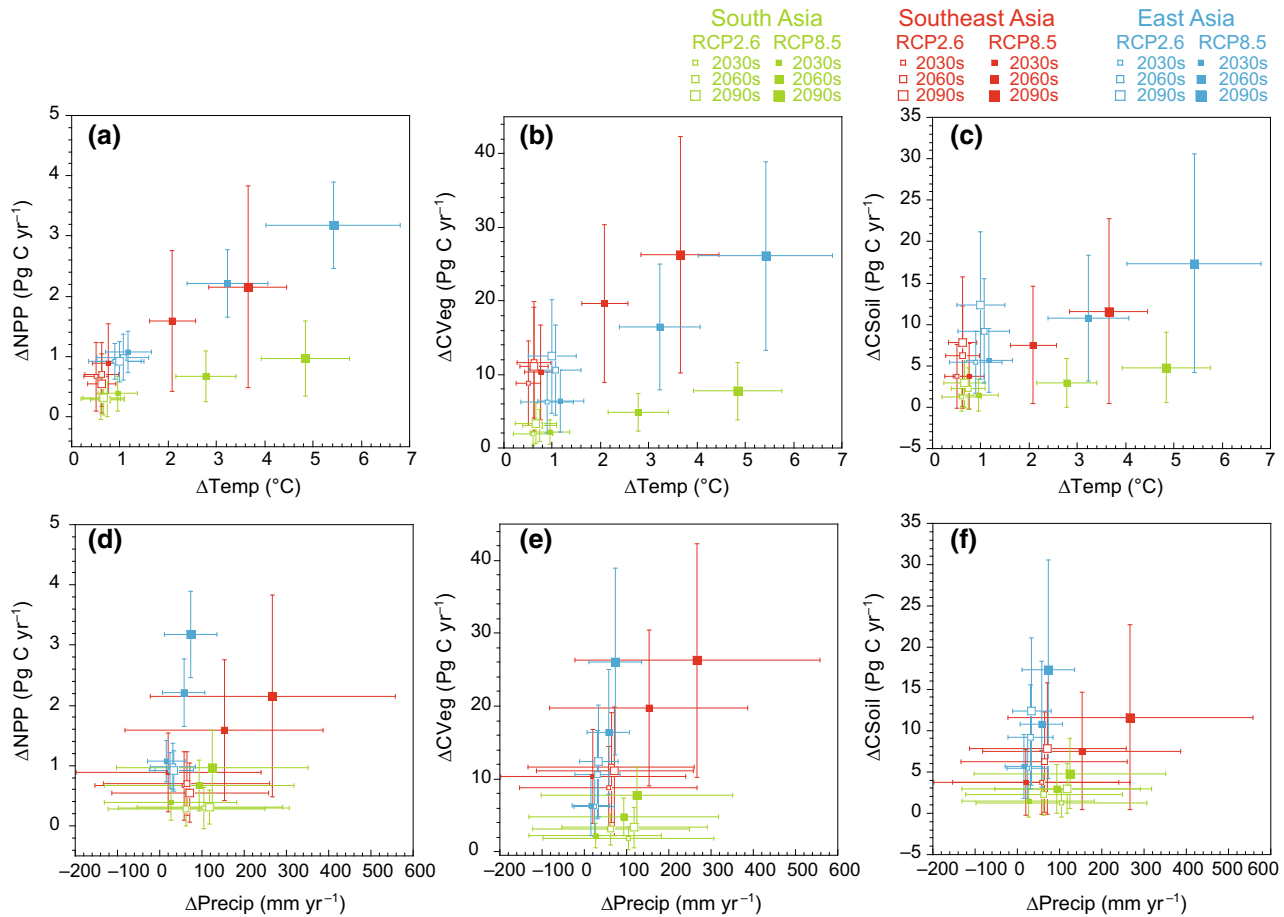
**Fig. 5** Time-series of the simulated carbon budget change in Monsoon Asia: (*top*) net primary production ( $\Delta\text{NPP}$ ), (*middle*) vegetation biomass ( $\Delta\text{CVeg}$ ), (*bottom*) soil organic carbon ( $\Delta\text{CSoil}$ ). **a, d, g** South Asia, **b, e, h** Southeast Asia, and **c, f,**

**i** East Asia. *Lines* show the ensemble-mean of the 31 simulations for each RCP scenario, and *shaded zones* represent 95 % confidence intervals

impacts. Figure 5 shows the evolution of  $\Delta\text{NPP}$ ,  $\Delta\text{CVeg}$ , and  $\Delta\text{CSoil}$  through time ( $\Delta$  denotes the deviation from the present state). In addition to model and scenario ensemble trajectories, there was an expanding trend in the range of the 95 % confidence intervals around the estimates. Note that negative values in the simulated responses were partly attributable to the interannual variability in the climatic conditions. For the RCP2.6 and RCP8.5 scenarios, total regional NPP was estimated to increase to  $13.6 \text{ Pg C year}^{-1}$  (on average, +12.4 % from the 2000s) and  $18.1 \text{ Pg C year}^{-1}$  (+45.4 %) by the 2090s, respectively. The magnitude of relative change was more evident in the East Asian subregion (+58 % in the 2090s for RCP8.5) than in the other two subregions: +44 % in South Asia and +33 % in Southeast Asia. Because of the leveling-off of atmospheric  $\text{CO}_2$  and temperature in RCP2.6 after the 2040s (Fig. 3),  $\Delta\text{NPP}$  in the RCP2.6-based simulations also plateaued in each region. In contrast, the estimated  $\Delta\text{NPP}$  in the RCP8.5-based simulations showed steeper increasing trends until the end of the simulation period (Fig. 5). Similarly, vegetation biomass was estimated to increase to  $174.1 \text{ Pg C}$  (+14.5 %) and  $207.4 \text{ Pg C}$  (+36.4 %) for the

RCP2.6- and RCP8.5-based simulations, respectively. In this case, the South and East Asian subregions showed relatively higher responses (both +45 % in the 2090s for RCP8.5), than those in Southeast Asia (+28.9 %). Although the relative magnitude of soil carbon change was smaller than those of  $\Delta\text{NPP}$  and  $\Delta\text{CVeg}$ , total  $\Delta\text{CSoil}$  remained substantial. Soil organic carbon was estimated to increase to  $260.9 \text{ Pg C}$  (+8.1 %) and  $271.5 \text{ Pg C}$  (+12.5 %) for the RCP2.6- and RCP8.5-based simulations, respectively. In this case, the Southeast Asian subregion showed a larger response (+15.6 %) than those in the South (+13.3 %) and East Asian (+10.9 %) subregions. Overall, Monsoon Asian region was estimated to be a net carbon sink by the end of the 21st century, with values of  $41.6 \pm 24.4$  and  $85.5 \pm 39.1 \text{ Pg C}$  (on average,  $0.2\text{--}1.2 \text{ Pg C year}^{-1}$  of net uptake from the atmosphere to ecosystems) for the RCP2.6 and RCP8.5 scenarios, respectively.

Figure 6 shows the relationships between regional climate change and the estimated changes in the terrestrial carbon budget. Note that the simulated ecosystem changes were at least partly attributable to the atmospheric  $\text{CO}_2$  fertilization effect. In each subregion, the



**Fig. 6** Relationships between climate change and the simulated changes in the carbon budget of monsoon Asia from the 2000s to the 2030s, 2060s, and 2090s, for **a–c** annual mean temperature and **d–f** annual precipitation. **a, d** Net primary production ( $\Delta\text{NPP}$ ), **b,**

**e** vegetation biomass ( $\Delta\text{CVeg}$ ), and **c, f** soil organic carbon ( $\Delta\text{CSoil}$ ). Error bars represent standard deviations of (*x*-axis) the climate projection and (*y*-axis) the simulated carbon budget

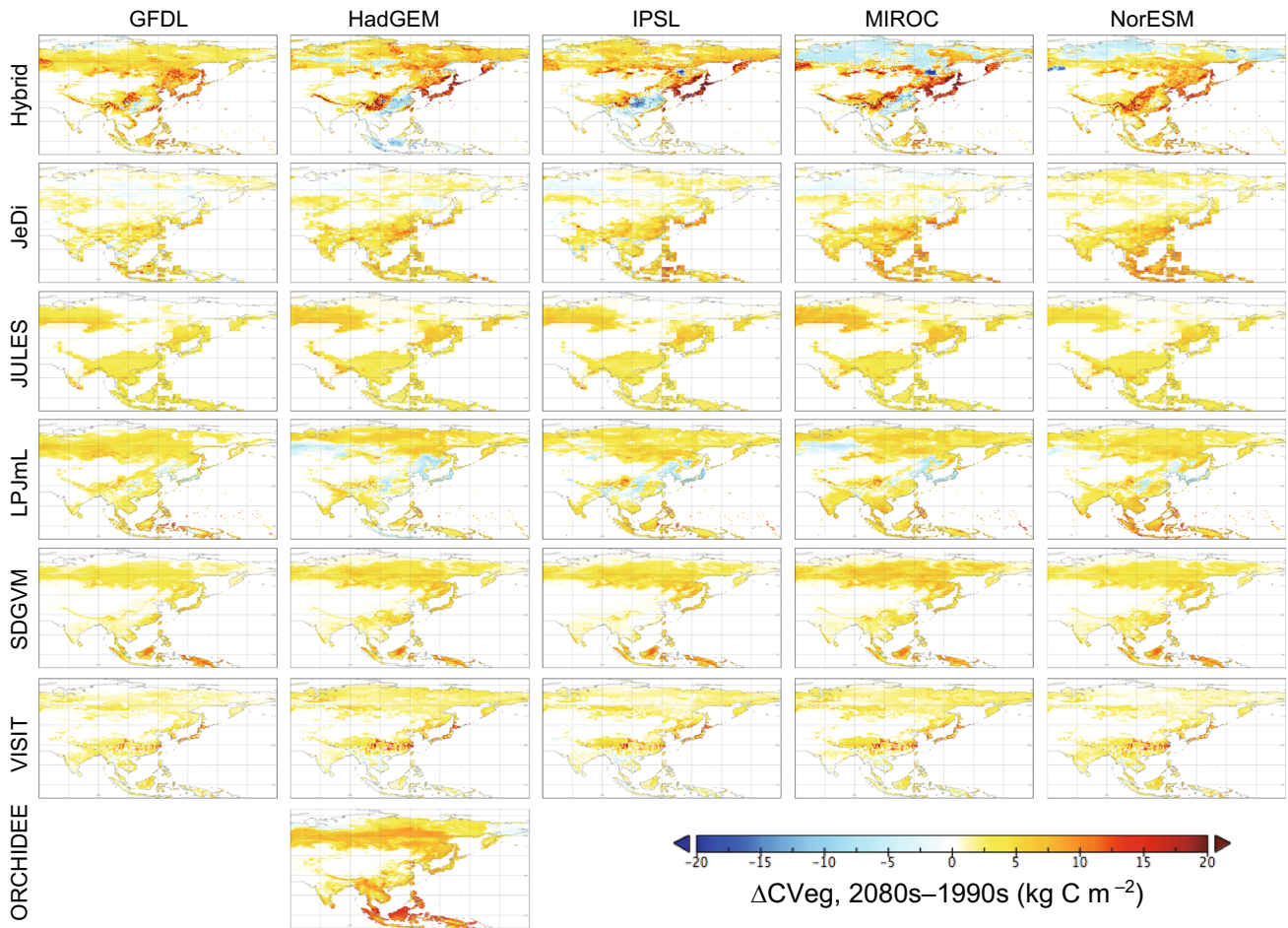
estimated changes in the terrestrial carbon budget for RCP8.5 simulations were positively correlated with temperature change. East Asia, the subregion with the largest area, and Southeast Asia, the subregion with the highest NPP, showed comparable responsiveness to temperature change. Note that Fig. 6 shows the total NPP and carbon stocks in each subregion and that South Asia, the subregion with the lowest land area, had a considerable responsiveness per unit land area, which was similar to values for the larger subregions. Such a relationship was less clear in the RCP2.6 simulations, because the magnitude of temperature change was much less evident than that of RCP8.5. In terms of the response to precipitation change, a stronger increase was found in the RCP8.5-based results in each region, whereas in the RCP2.6-based cases, precipitation change and its impact on the carbon budget was less clear.

#### Spatial patterns: heterogeneity and hotspots

The simulated changes in the regional terrestrial carbon budget varied widely among scenarios and biome models.

Under the RCP8.5 scenario, the spatial distributions of  $\Delta\text{CVeg}$  (Fig. 7) and  $\Delta\text{CSoil}$  (Fig. 8) differed markedly among models and climate projections; however, the results for RCP2.6 showed similar patterns but with smaller magnitudes (not shown). In the Hybrid simulations,  $\Delta\text{CVeg}$  showed high heterogeneity, ranging from a moderate decrease in Southeast Asia to a large increase in East Asia. It is noteworthy that under the MIROC and Nor-ESM climate projections, the biome models simulated decreases in  $\text{CVeg}$  and  $\text{CSoil}$  in Siberia. In the JeDi simulations,  $\text{CVeg}$  increased mainly in the Southeast and East Asian sub-regions, and this model simulated a considerable magnitude of increase in  $\text{CSoil}$  from Southeast Asia to Siberia. In the JULES simulations,  $\text{CVeg}$  showed moderate increases in the three subregions with comparable magnitudes, whereas  $\Delta\text{CSoil}$  was apparently heterogeneous, ranging from moderate decreases in western South Asia to large increases in northern East Asia. In the LPJmL simulations, the magnitude of simulated  $\Delta\text{CVeg}$  was moderate compared with the other models, but it showed characteristic patterns such as decreases in northern East Asia and increases in Southeast Asia. It is also noteworthy that LPJmL simulated exten-





**Fig. 7** Spatial distributions of the simulated change in vegetation biomass ( $\Delta CVeg$ ) by the seven biome models using five climate projections under the RCP8.5 scenario. GFDL, HadGEM, IPSL, MIROC, and NorESM denote the names of climate models (see

“Methods” section). Hybrid, JeDi, JULES, LPJmL, ORCHIDEE, SDGVM, and VISIT denote the names of biome models. Each panel shows the study area from 10°S to 80°N and from 60°E to 180°E

sive decreases of CSoil in northern areas. In the SDGVM simulations, CVeg increased mainly in Southeast Asia, whereas changes in East and South Asia were less evident. The simulated  $\Delta CSoil$  was nearly homogeneous (i.e., small increase) across the study area and throughout the climate projections. In the VISIT simulations, CVeg increased mainly in the southern East Asian subregion and the changes in CSoil were moderately heterogeneous, ranging from decreases in humid East Asia to increases in inner dry lands. In the ORCHIDEE simulation, increases in CVeg were evident in the Southeast Asian subregion and Eurasian boreal forests. The magnitude of  $\Delta CSoil$  was moderate, ranging from decreases in northern ecosystems to increases in southern ecosystems. The LPJmL and VISIT models simulated a large magnitude of  $\Delta CSoil$  on the Tibetan Plateau, which is discussed later.

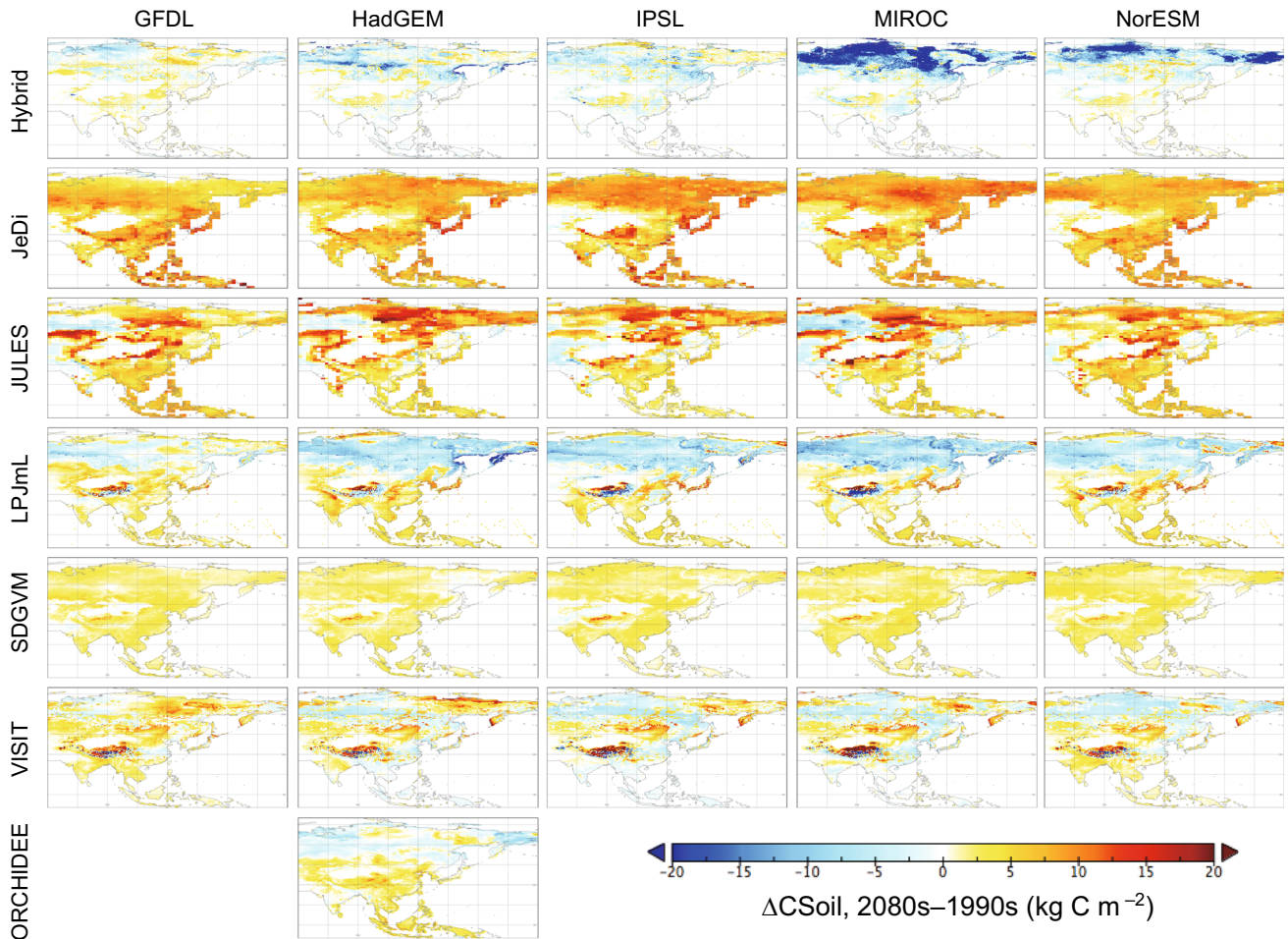
Based on the simulation results of multiple scenarios and models, we identified areas with consistent changes in the terrestrial carbon budget. Figure 9 shows the areas in monsoon Asia that were projected to have  $\pm 30\%$  or greater change between the 2000s and 2080s (i.e., hotspots). In the RCP2.6 simulations, this magni-

tude of  $\Delta NPP$  and  $\Delta CSoil$  occurred in limited areas, including the southern Tibetan Plateau and western South Asian subregion. In contrast, this magnitude of  $\Delta CVeg$  occurred consistently in large areas of South and East Asia at northern latitudes in the majority of simulations. In the RCP8.5 simulations,  $\Delta NPP$  and  $\Delta CVeg$  of more than  $\pm 30\%$  occurred consistently in the East Asian subregion and parts of the South and Southeast Asian subregions, whereas in other parts of the Southeast Asian subregion, changes were inconsistent among simulations. The pattern of  $\Delta CSoil$  was different from those of  $\Delta NPP$  and  $\Delta CVeg$ . Consistent change was found only in limited areas of the southern Tibetan Plateau and western South Asia.

## Discussion

Importance of monsoon Asia in the global carbon cycle

The multi-model simulations confirmed that the terrestrial ecosystems in monsoon Asia are an important



**Fig. 8** Spatial distributions of the simulated change in soil organic carbon ( $\Delta\text{CSoil}$ ) by the seven biome models using five climate projections under the RCP8.5 scenario. GFDL, HadGEM, IPSL, MIROC, and NorESM denote the names of climate models (see

“Methods” section). Hybrid, JeDi, JULES, LPJmL, ORCHIDEE, SDGVM, and VISIT denote the names of biome models. Each panel shows the study area from 10°S to 80°N and from 60°E to 180°E

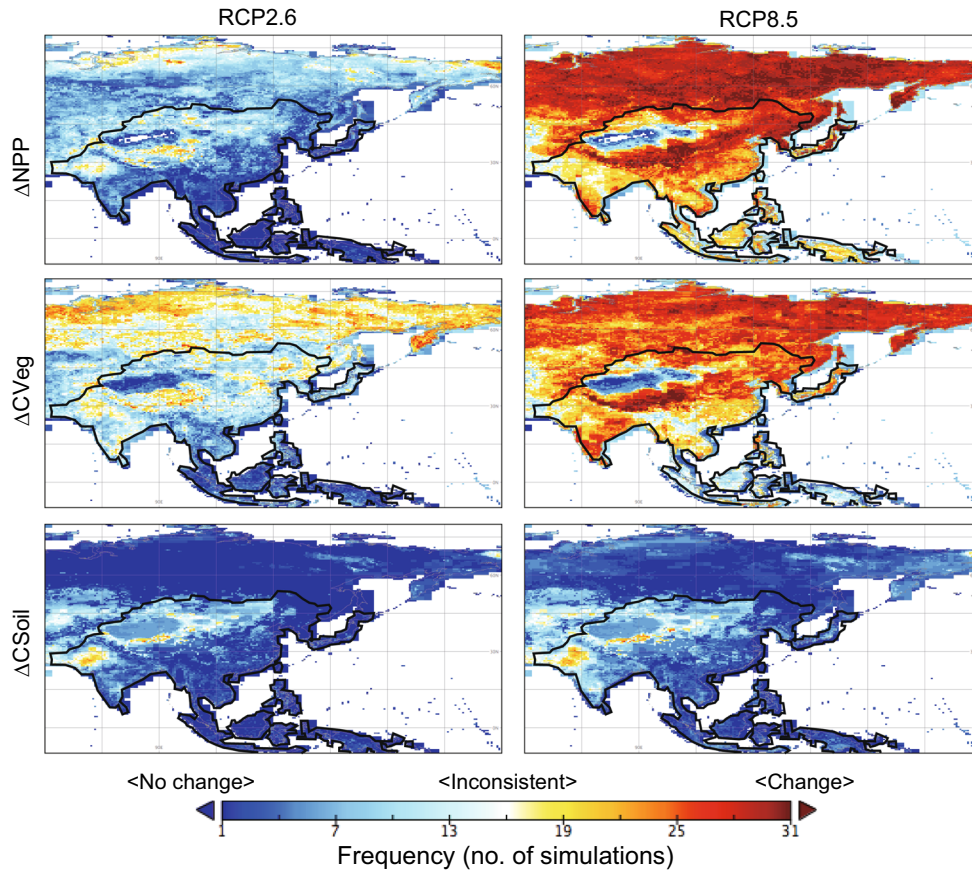
component of the global carbon cycle. The simulated total NPP of the three subregions, on average 12.4 Pg C year<sup>-1</sup> in the 2000s (Table 1), is about 22 % of the global terrestrial NPP of 56.4 Pg C year<sup>-1</sup> (Ito 2011). The simulated total CVeg of 152.1 Pg C is about 30 % of the global total biomass stock of 500 Pg C (IPCC 2013), and the simulated total CSoil of 241.3 Pg C is about 16 % of the global total of 1502 Pg C (in 0–1 m; Jobbágy and Jackson 2000). Note that this estimate of soil carbon stock is only for the three subregions (Fig. 2, inset); the total soil carbon for the whole study area, including Eurasian high-latitude ecosystems, was estimated as  $638 \pm 201$  Pg C (about 42 % of the global total) in the 2000s.

These results are comparable with previous model estimates in this region. Tian et al. (2003) estimated that the total base-line (i.e., natural) vegetation carbon stock in the same region of monsoon Asia was 151.7 Pg C, which is relatively close to our mean value. In contrast, the soil carbon stock of 109.4 Pg C estimated by Tian et al. (2003) is lower than our mean value but within the range of estimates from the ISI-MIP biome models.

Specifically, the estimated soil carbon storage differed markedly among the biome models, ranging from 97.6 Pg C for Hybrid to 351.2 Pg C for JULES, as found in other model intercomparison studies (e.g., Todd-Brown et al. 2013). The models used in this study differ in structure and environmental responsiveness of the decomposition rate and thus the mean residence time of carbon, implying that further research is needed to constrain model behavior.

#### Impacts of climate change

The magnitudes of temperature rise in the three subregions by the end of the 21st century (+0.62 to +1.0 °C for RCP2.6 and +4.84 to +5.42 °C for RCP8.5) are comparable to the global land average:  $+1.2 \pm 0.6$  °C for RCP2.6 and  $+4.8 \pm 0.9$  °C for RCP8.5 (IPCC 2013). Our analysis based on multiple scenarios and biome models indicated that vegetation productivity and ecosystem carbon stock in monsoon Asia is likely to increase, on average, as a result of the projected climate



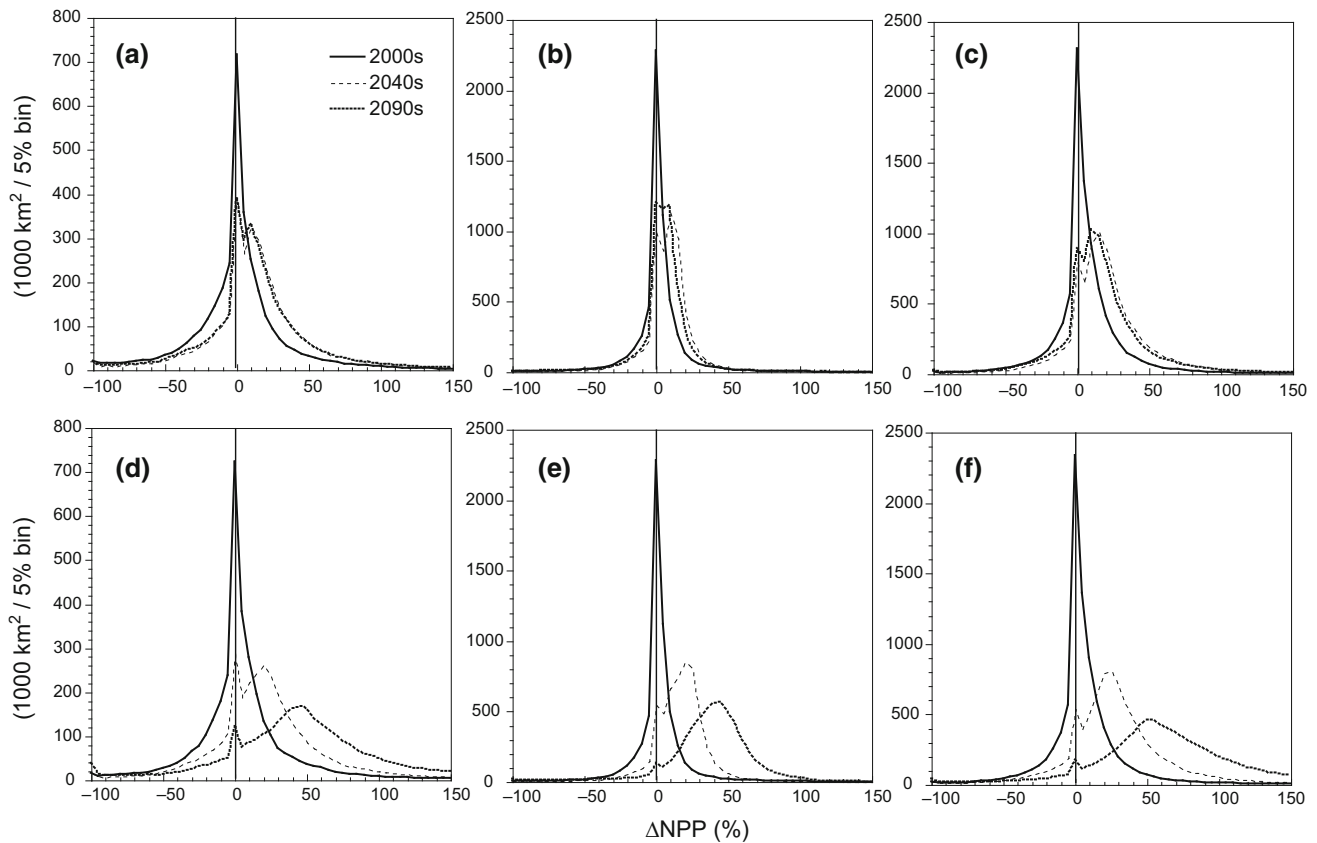
**Fig. 9** Spatial distributions of the consistency (i.e., agreement among the simulations) in terms of changes greater than  $\pm 30\%$  (i.e., both increase and decrease) from the 1990s to the 2080s. *Red areas* indicate significant change with high consistency, *blue areas* indicate no significant change with high consistency, and *pale blue*

to *yellow areas* show inconsistency (disagreement; change found in approximately 10–20 simulations). *Each panel* shows the study area from  $10^{\circ}\text{S}$  to  $80^{\circ}\text{N}$  and from  $60^{\circ}\text{E}$  to  $180^{\circ}\text{E}$ , and *thick lines* define the focal subregions (cf. Fig. 2 inset)

change and elevated atmospheric  $\text{CO}_2$  level. Notably, the ISI-MIP analyses were conducted in an off-line manner to clarify the impacts of climate change, so the feedback loops between the atmosphere and ecosystems (e.g., forest die-back and carbon emissions in the Amazon; Cox et al. 2004) were not directly included. Nevertheless, the present analyses using multiple scenarios did not indicate the occurrence of serious ecosystem collapse in monsoon Asia. Several models simulated climate-induced decreases in vegetation biomass across limited areas (Fig. 7), implying only a slight degradation of vegetation structure and functions. Even under the RCP8.5 scenario, in which the temperature increased markedly, terrestrial ecosystems in monsoon Asia were projected to act as a net carbon sink in the majority of simulations. The magnitude of net carbon sequestration from the 2000s to 2090s was larger in the RCP8.5-based simulations ( $+85.5 \pm 39.1$  Pg C) than those in the RCP2.6-based simulations ( $+41.6 \pm 24.4$  Pg C), implying that the terrestrial productivity and carbon stock in the region will respond positively to elevated  $\text{CO}_2$  concentration and climate change. Because the RCP2.6 scenario assumes that global warming will

be kept below a dangerous level (i.e.,  $+2^{\circ}\text{C}$ ; Meinshausen et al. 2011), the natural carbon sink simulated here is meaningful.

Recent studies have considered the responses of terrestrial ecosystems to extreme conditions such as heat waves, droughts, fires (e.g., Reichstein et al. 2013; Zscheischler et al. 2014), because such events are important for the long-term carbon budget. Based on the simulation results used in the present study (Fig. 5), we next discuss the future change in the variability of the terrestrial carbon budget in the region. Figure 10 shows the grid-based frequency distribution of NPP anomalies (i.e., deviation from the average) simulated in the three subregions. The simulated NPP clearly increased over time, accompanied by expanded variability, especially in the RCP8.5-based simulations (Fig. 10d–f). As a result, we may expect not only increases in NPP above average conditions but also severe decreases in NPP to occur with higher frequency. The wider range of variability in the simulated future NPP is, at least partly, attributable to enhanced meteorological variability, including extreme conditions (for meteorological analysis, see Kitoh et al. 2013). In recent decades, terrestrial



**Fig. 10** Area-based frequency distributions of the changes in simulated net primary production ( $\Delta$ NPP) in the 2000s, 2040s, and 2090s for the three subregions: **a, d** South Asia; **b, e** Southeast Asia; **c, f** East Asia. **a–c** Results for RCP2.6, and **d–f** results for

RCP8.5. The  $x$ -axis represents the difference from the regional average NPP in the 2000s, and the  $y$ -axis indicates the area for each 5 % bin

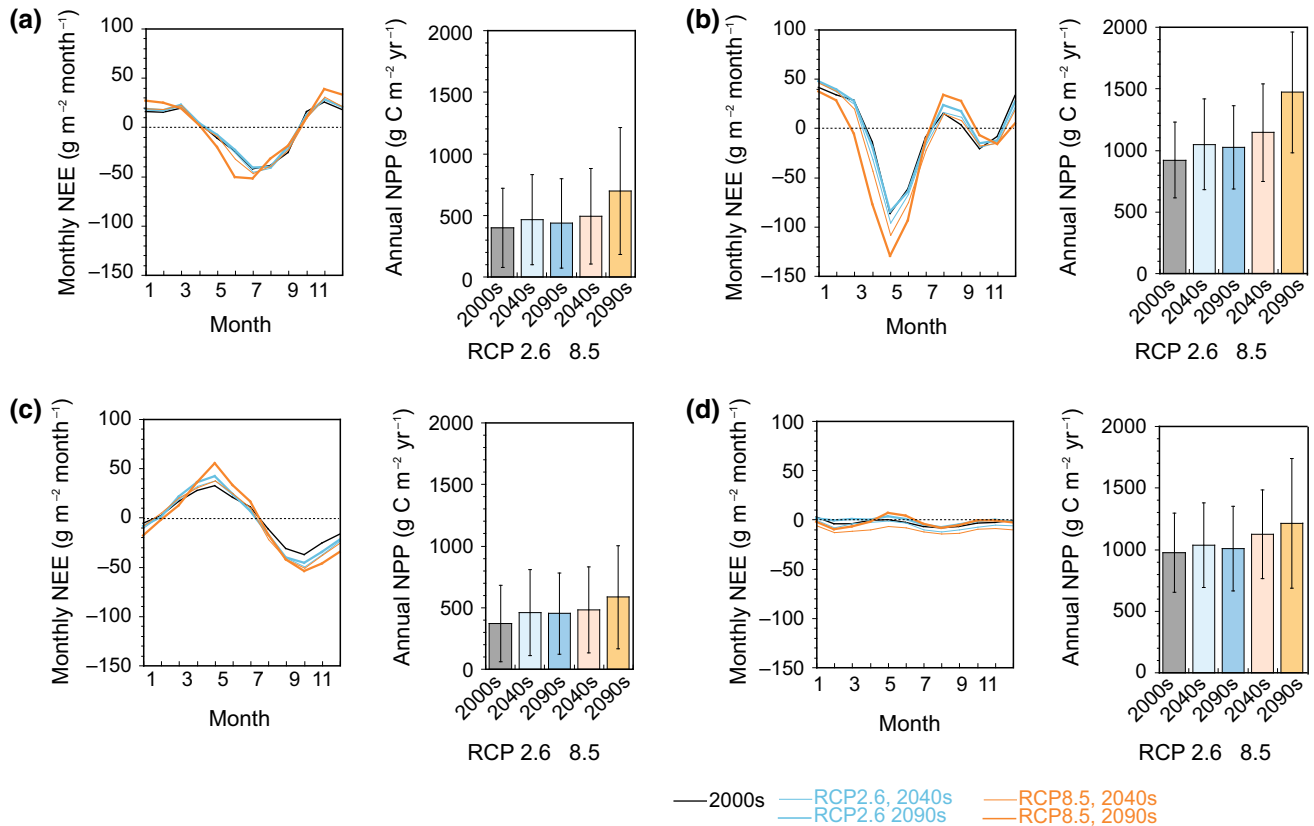
ecosystems in monsoon Asia have experienced severe meteorological events, such as the drought in Southeast Asia in 1997/1998, which was caused by the strong ENSO. An ecohydrological study by Kumagai and Porporato (2012) showed that tree mortality (i.e., biomass decrease) in Southeast Asia would be increased by predicted future drought stress. In addition, a model study by Ito and Oikawa (2000) implied that the high temperature and low precipitation during such warm and dry periods would strongly influence the carbon budget of monsoon Asia. Although it is still difficult to simulate future weather patterns with the present models (Turner and Annamalai 2012), researchers should consider to the impacts of extreme conditions on terrestrial ecosystems in monsoon Asia in more detail.

#### Implications for observational studies

Our results imply that climatic changes will have pronounced impacts on vegetation productivity and biomass (Fig. 9). Early detection of such climatic impacts is important for planning effective adaptation options. With recent advancements, satellite remote sensing is especially effective for monitoring vegetation structure and functions and for detecting changes in these prop-

erties over a wider area. For example, Poulter et al. (2013) used satellite-derived data of the fraction of absorbed photosynthetically active radiation to analyze forest dynamics in Inner Asia. Ichii et al. (2013a) analyzed a similar dataset to examine temporal changes in gross primary production in Asia. Furthermore, Saatchi et al. (2011) developed a broad-scale high-resolution map of vegetation biomass using satellite laser imaging detection and ranging data for the entire tropics, including South and Southeast Asia. Indeed, these remote sensing results have been used as benchmarking data for terrestrial ecosystem models, and such data-model collaboration will enable us to more effectively detect the impact of climate change in this region.

In turn, model simulations can inform fieldwork by researchers. Several hot spots were identified by the present analyses, with implications for field studies. Even under the mitigation-oriented RCP2.6 scenario, substantial changes in vegetation biomass were consistently predicted by multiple simulations (Fig. 9). For example, substantial biomass change (in this case, larger than  $-30$  % from the present state) was predicted in northern East Asia and the southern Tibetan Plateau. These areas appear to be as sensitive to climate change as northern ecosystems, which are also limited by low temperatures. The detection of climatic impacts on the



**Fig. 11** Simulated changes in monthly net ecosystem CO<sub>2</sub> exchange (NEE) and annual net primary production (NPP; error bars show standard deviations) from the ISI-MIP dataset at selected locations

close to representative field sites: **a** Haibei and **b** Takayama sites in East Asia, **c** Betul site in South Asia, and **d** Pasoh site in Southeast Asia. See Fig. 2 for the location of each site

soil carbon stock is likely to be difficult in most areas; in western South Asia and the southern Tibetan Plateau, substantial impacts were predicted with moderate consistency. Because of the increasing importance of issues related to global climate change, increasing numbers of field studies are being conducted in Asia. For example, Kwon et al. (2010) found that the Asian monsoon has considerable influences on the carbon budget of two ecosystems in South Korea. At the regional scale, several studies analyzed micrometeorological flux data and correlated them with climatic factors such as rainy season anomalies (Hirata et al. 2008; Kato and Tang 2008; Saigusa et al. 2010). Such field- to regional-scale studies provide us with insights into the processes and mechanisms of ecosystem response to climate change, and modeling studies can help us to identify high-priority areas for observations by showing predicted hot spots of climatic impacts.

Figure 11 shows the simulated changes in net ecosystem CO<sub>2</sub> exchange and NPP at several points in the grid that contain field sites. At East Asian sites, changes in the seasonal cycle of net ecosystem CO<sub>2</sub> exchange, especially during the early growing season (i.e., April–June), would be easy to observe. This may justify the need for continuous observation of leaf phenology and flux measurements in East Asia (e.g., Nasahara and

Nagai 2015). In contrast, at Southeast Asian sites, it would be difficult to detect the climatic impacts from observed CO<sub>2</sub> fluxes, and researchers may need to apply alternative strategies such as detecting trends from long-term productivity and biomass data (e.g., Ito 2012). Such synergies between field and modeling studies will also help to improve our understanding of ecological processes (Ito et al. 2015).

#### Remaining issues and uncertainties

We used ISI-MIP data to focus on the impacts of climate change on natural ecosystems in monsoon Asia. Therefore, we did not include direct human interventions such as land-use change. In reality, however, land-use changes such as conversion from forest to cropland, which is associated with human-induced biomass burning and urbanization would have significant impacts on the carbon budget and other ecosystem functions in monsoon Asia (e.g., Zhao et al. 2006; Tao et al. 2013). For example, broad areas of tropical forests are being converted into oil palm plantations, leading to large carbon emissions from residual detritus (e.g., Koh et al. 2011). In East Asia, considerable areas of rangeland and cropland have been converted into forest (Fang et al.

2001; Pan et al. 2011), leading to carbon sequestration for a certain regrowth period. Future projection of land-use change is technically difficult, because it is affected by complex human factors such as population increase, economic growth, and conservation strategies. In the ongoing second phase of ISI-MIP, we are considering future land-use change based on appropriate scenarios.

The present terrestrial ecosystem models have various intrinsic biases as shown by model intercomparison studies (Piao et al. 2012; Ichii et al. 2013b). Such estimation uncertainties may be attributed to several factors, the largest being that the models differ markedly in environmental responsiveness, especially to future climate change. Although some experimental studies in Asia have examined ecosystem responses to elevated atmospheric CO<sub>2</sub> and global warming (Eguchi et al. 2008; Chung et al. 2013), they covered only a fraction of the total biomes and possible climatic conditions in this region. Fortunately, observational networks in Asian terrestrial ecosystems (e.g., Yu et al. 2006; Mizoguchi et al. 2009) are steadily increasing and are expected to provide indispensable data for examining and constraining terrestrial models (e.g., Piao et al. 2013).

### Concluding remarks

This study showed that climate change in the monsoon Asian region may have considerable impacts on the carbon budget of terrestrial ecosystems. These simulated impacts were not seriously adverse, but it is important to note that changes in ecosystem productivity and structure (represented by carbon stock in this study) are associated with the alteration of ecosystem services (cf. Fig. 1). Although the present study ignored several important ecosystem factors, such as nutrients and biodiversity, the simulation results can be related to fundamental, provisioning, and regulation ecosystem services. For example, changes in the ecosystem water budget as a result of ecophysiological responses are likely to influence the amount of water available for human activities. Therefore, we need more interdisciplinary research among fields such as ecology, meteorology, agronomy, hydrology, and social sciences. Indeed, several projects have assessed natural–social systems in monsoon Asia (Kohyama 2005) such as the Terrestrial Ecosystems in Monsoon Asia project and the Monsoon Asia Integrated Study. In addition, regional research activities are ongoing (Yasunari et al. 2013), including AsiaFlux, a regional network of micrometeorological flux measurement towers, and the Asia–Pacific Biodiversity Network. Furthermore, in the second phase of the ISI-MIP, interactions and trade-offs among different sectors (e.g., agriculture, water, humans, and biomes) will be assessed in an integrated manner. Through these collaborations, we may obtain more credible (i.e. less uncertain) predictions and make better

contributions to achieving sustainable ecosystems under the changing global environment.

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