Variations and trends of terrestrial NPP and its relation to climate change in the 10 CMIP5 models

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Using global terrestrial ecosystem net primary productivity (NPP) data, we validated the simulated multi-model ensemble (MME) NPP, analyzed the spatial distribution of global NPP and explored the relationship between NPP and climate variations in historical scenarios of 10 CMIP5 models. The results show that the global spatial pattern of simulated terrestrial ecosystem NPP, is consistent with IGBP NPP, but the values have some differences and there is a huge uncertainty. Considering global climate change, near surface temperature is the major factor affecting the terrestrial ecosystem, followed by the precipitation. This means terrestrial ecosystem NPP is more closely related to near surface temperature than precipitation. Between 1976 and 2005, NPP shows an obvious increasing temporal trend, indicating the terrestrial ecosystem has had a positive response to climate change. MME NPP has increased 3.647PgC during historical period, which shows an increasing temporal trend of $3.9 \text{ gCm}^{-2} \bullet 100 \text{ yr}^{-2}$ in the past 150 years, also indicating that the terrestrial ecosystem has shown a positive response to climate change in past 150 years.

1. Introduction

Net primary productivity (NPP) is the net amount of dry organic material which is produced by ecosystem's green plants in unit time and area, and is an important variable for global carbon cycle and the feedback between terrestrial ecosystems and atmosphere. NPP reflects the ability of plants absorbing atmospheric carbon dioxide and is a key process of carbon cycle (Cramer *et al.* 1999; Runing *et al.* 1999; He *et al.* 2005; Dan *et al.* 2007). NPP integrates climatic, ecological, geochemical, and human influences on the biosphere (Nemani *et al.* 2002, 2003). Spatial and temporal variations in NPP are of great importance to

ecological studies, natural resource management, and terrestrial ecosystem carbon sink estimates (Cao *et al.* 2004).

NPP is highly variable in space and time. Spatial variations of NPP are related to factors such as climate, vegetation distribution, and land use across the planet from local to global scales (Cao *et al.* 2004). Temporal changes in NPP are linked to seasonal variability, atmospheric composition, climatic change, and so on (Cao *et al.* 2004). Though modern ecology could get accurate NPP based on experiments, both in laboratory and in field settings, this approach could not obtain measurements on a large scale, such as global or continental. There are two ways to reach this goal. One of them is

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satellite remote sensing, which could provide large sample sizes. Another is global ecosystem models, which could get a satellite-based estimate of NPP given the variable climate, vegetation distribution, and land use across the planet from local to global scales (Bala *et al.* 2013).

In recent decades, earth system has experienced changes in the energy, momentum, and water exchange between land surface and atmosphere. These changes have caused significant changes in the vegetation growth processes which are closely linked with the terrestrial ecosystem carbon cycle (Dan *et al.* 2007). To describe the vegetation growing processes, the dynamical global vegetation models (DGVM) have been developed and validated worldwide. Furthermore, they are coupled with general circulation model (GCM) in one-way or two-way coupling approaches. Many previous analyses and simulations have proven that climate change plays an important role in terrestrial ecosystem. It is necessary to evaluate and validate NPP variation related to climate change from the GCMs (Dan *et al.* 2007).

The fifth phase of the Coupled Model Intercomparison Project (CMIP5) provides a good platform for coupled model intercomparison research of climate change and terrestrial ecosystem (Taylor *et al.* 2012). The present study compares and validates terrestrial ecosystem NPP simulated by a selection of CMIP5 models with International Geosphere Biosphere Program (IGBP) NPP data. We analyze changes of NPP, explore the relationship between NPP and climatic factors, and discuss the uncertainty or discrepancy of modelled NPP.

2. Models and data

2.1 Models

Ten models were employed for the current study (table 1), which have wide range of spatial resolutions and physical parameterization schemes. Regarding land surface processes, every model includes a DGVM, such as AVIM, CoLM, CTEM, CLM-CN (in CLM4, the user runs the CNDV as a DGVM), LPJ, TRIFFID, ORCHIDEE and SEIB-DGVM, which is coupled to an atmospheric general circulation model (AGCM). All of these DGVMs have been widely used and evaluated either offline or in coupled model studies (Melillo *et al.* 1993; Dan *et al.* 2005, 2007). Specially, three of the 10 models use CLM-CN model, and bcc-csm1-1 and bcc-csm1-1-m have different resolutions but all others are same.

While the selected 10 models contain different DGVM, there are still some similarities in their terrestrial carbon cycle. For example, plants are

Table 1. Description of the CMIP5 models used in this study.

Model	Sponsor and country	Land model	Vegetation model	No. of PFTs	Horizontal resolution	Runs	Reference
bcc-csm1-1	Beijing Climate Center, China	AVIM	AVIM	15	~2.8125° long./lat.	3	Wu <i>et al.</i> (2013b)
bcc-csm1-1-m	Beijing Climate Center, China	AVIM	AVIM	15	~1.125° long./lat.	3	Wu <i>et al.</i> (2013c)
BNU-ESM	GCESS, BNU, Beijing, China	BUN-CoLM3	BUN-DGVM	10	~2.8125° long./lat.	1	Wu <i>et al.</i> (2013a)
CanESM2	Canadian Centre for Climate Modelling and Analysis, Canada	CLASS	CTEM	9	~2.8125° long./lat.	5	Arora <i>et al.</i> (2011)
CCSM4	NCAR, USA	CLM4	CLM4-CN	15	1.25° lat. × 0.9375° long./lat.	6	Gent <i>et al.</i> (2011)
CESM1-BGC	NSF/DOENCAR, USA	CLM4	CLM4-CN	15	1.25° lat. × 0.9375° long./lat.	1	Lindsay <i>et al.</i> (2014)
HadGEM2-ES	Met Office Hadley Centre, UK	JULES	TRIFFID	5	1.875 × 1.25° long./lat.	4	Collins <i>et al.</i> (2011)
IPSL-CM5A-LR	Institute Pierre Simon Laplace, France	ORCHIDEE	ORCHIDEE	12	~3.75 × 1.875° long./lat.	4	Dufresne <i>et al.</i> (2013)
MIROC-ESM	Japan Agency for Marine-Earth Science and Technology, Japan	MATSIRO	SEIB-DGVM	13	~2.8125° lat./long.	3	Watanabe <i>et al.</i> (2011)
NorESM1-M	Norwegian Climate Centre, Norway	CLM4	CLM4-CN	15	~2.5° lat. × 1.875° lat./long.	3	Tjiputra <i>et al.</i> (2012)

categorized in to several different plant function types (PFTs). For each PFT, the processes of photosynthesis (A), maintenance respiration (Rm) and growth respiration (Rg) carbon allocation are similar across the models, though their specific parameters and limiting conditions are different (Shao *et al.* 2013). Gross primary production (GPP) is a measure of carbon absorption by vegetation per unit time (Δt) and space, which is the aggregate amount of A at every time step, and net primary production (NPP) is the difference between GPP and autotrophic respiration (Ra, as the sum of Rm and Rg).

$$\text{GPP} = \sum A \Delta t \quad (1)$$

$$\text{NPP} = \text{GPP} - \text{Ra} = \text{GPP} - \text{Rm} - \text{Rg} \quad (2)$$

Overall, DGVMs simulate well the global terrestrial carbon pool sizes and carbon cycle, and capture the biogeographical distribution of Earth's major biomes (Sitch *et al.* 2003).

Therefore, a GCM-DGVM is a full coupled model, which includes important feedback and responses between biosphere and atmosphere, such that vegetation shifts and changes in the carbon and hydrological cycles affecting climate can be simulated. DGVMs commonly simulate a variety of plant and soil physiological processes. They can reflect the effects and responses of vegetation to climate change and get the actual climate change and changes in the terrestrial ecosystem (Olofsson and Hickler 2008).

2.2 Data

IGBP Global NPP Model Intercomparison Data with the resolution of $0.5^\circ \times 0.5^\circ$, and derived from original data containing gridded average NPP for 17 global biogeochemistry models, are used to evaluate the simulated NPP by CMIP5 models. Table 2 lists some detailed information for comparing the IGBP NPP models and selected CMIP5 land models. The IGBP NPP models were focused on geosphere and biosphere, 16 of 17 models were

offline and without DGVM, and all models were forced by Potsdam Institute of Climate Impact Research (PIK) input data. All selected CMIP5 models were coupled models, which have a DGVM. Fortunately, the 17 models which are selected in this paper are different with the DGVM in GCM. The IGBP NPP data are used widely to compare and validate simulated NPP data (Cramer *et al.* 1999; Dan *et al.* 2007).

The simulated terrestrial ecosystem NPP data and climate factors: precipitation (Pr), near surface temperature (Tas), and surface downwelling shortwave radiation (Rsds) were selected from the historical scenarios of the 10 CMIP5 models, using as many runs as possible (for one model, each run differ in the initial conditions), and table 1 provides more detailed information. Firstly, we calculated an average of all the runs for each model, and then produced a multi-model ensemble (MME) for each variable, thus obtaining an MME result for each variable. Many studies have indicated that MME results produce better estimates of the real value than any particular model taken individually (Dan *et al.* 2007; IPCC 2001, Chapter 9). Therefore, to ensure robust results, the MME results are used in the current analysis.

In climatic research, a popular climatological baseline period is a 30-year 'normal' period, as defined by the WMO, which provides a standard reference for many studies (IPCC 2001, Chapter 3). Herein, we use the period 1976–2005 as the baseline climatology, and correspondingly, we use the simulated NPP during the same period to research the baseline NPP.

3. Results

3.1 Spatial distribution of global NPP

The simulated MME NPP (figure 1a) is similar to the IGBP NPP (figure 1b). The highest NPP is in the tropical rainforest region of Africa, south-east Asia, and Amazonia, which is larger than $1100 \text{ gCm}^{-2}\text{yr}^{-1}$, while intermediate NPP is located

Table 2. Comparing IGBP NPP models and selected CMIP5 models.

	IGBP	CMIP5 (selected)
Model	BIOME3, BIOME-BGC, CARAIB2.1, CASA, CENTURY4.0, DOLY, FBM2.2, GLO-PEM, HRBM3.0, HYBRID3.0, KGBM, PLA10.2, SDBM, SIB2, SILVAN2.2, TEM4.0, TURC	AVIM, BNU-DGVM, CTEM, CLM4-CN, TRIFFID, ORCHIDEE, SEIB-DGVM
Coupled/offline	16 models with offline SIB2 with coupled	All models with coupled
DGVM	HYBRID3.0 with DGVM 16 models without DGVM	All models with DGVM (CNDV)
Forcing	Potsdam Institute of Climate Impact Research (PIK) input data	Solar irradiance, greenhouse gas concentration, CO ₂ emissions, anthropogenic aerosols, sea salt, dust are recommended by CMIP5

Figure 1. Global annual mean NPP over land, with unit of $\text{gCm}^{-2}\cdot\text{yr}^{-1}$ (a) MME NPP; (b) IGBP NPP; (c) the difference of NPP between MME and IGBP; and (d) zonal average of annual mean NPP.

Table 3. Area-averaged annual NPP, units are $\text{gCm}^{-2}\text{yr}^{-1}$.

	Global	60°–30°S	30°S–0	0–30°N	30°–60°N	60°–90°N
IGBP	451.677	461.721	657.259	469.356	378.736	223.217
Ensemble	414.873	290.415	675.664	443.614	297.348	237.798

in temperate regions, and the lowest NPP, which is less than $100 \text{ gCm}^{-2}\text{yr}^{-1}$, is in cold or arid areas. The global spatial patterns of MME and IGBP NPP are rather consistent with some other global or regional observation data (Kicklighter *et al.* 1999; Dan *et al.* 2007). However, the simulated MME NPP exhibits an obviously higher NPP in the Sahel area and along the west coast of South America, while in the south of India and Asia, there also exists a higher simulated NPP. In most areas of Eurasia and North America, the CMIP5 models obtain a lower MME NPP, and there is also a lower MME NPP along the east coast of South America (figure 1c). Zonal mean NPP shows a similar latitudinal variation pattern despite a different magnitude (figure 1d). The simulated MME NPP is very close to the IGBP NPP, except in $35^{\circ}\text{--}30^{\circ}\text{S}$. Generally, between 20°S and 15°N , the simulated MME NPP is larger than the IGBP NPP, while in $45^{\circ}\text{--}20^{\circ}\text{S}$ and $15^{\circ}\text{--}70^{\circ}\text{N}$, the simulated MME NPP is lower than the IGBP NPP.

Table 3 shows the area-averaged annual IGBP and simulated MME NPP at the global and regional scale. The global-averaged IGBP NPP is

$451.677 \text{ gCm}^{-2}\text{yr}^{-1}$, which is almost $55.05 \text{ PgC yr}^{-1}$, and the simulated MME NPP is $414.873 \text{ gCm}^{-2}\text{yr}^{-1}$, which is almost 50.6 PgC yr^{-1} . Comparing the zonal-averaged IGBP NPP, the largest bias appears over $60^{\circ}\text{--}30^{\circ}\text{S}$, which corresponds to the simulated low MME NPP of $35^{\circ}\text{--}30^{\circ}\text{S}$. Generally, the simulated MME NPP in the northern hemisphere compares better with IGBP NPP than in the southern hemisphere.

3.2 Relationship between climate and terrestrial ecosystem NPP

Many studies have indicated that the terrestrial ecosystem has a strong relationship with climate (Melillo *et al.* 1993; Ito and Oikawa 2000; Bala *et al.* 2013). Figure 2 presents the spatial patterns of correlation coefficients between MME NPP and Pr, Tas, and Rsd. Figure 2(a) shows that NPP has a positive correlation with Pr almost everywhere except in a number of small locations. The highest correlation coefficients, with a greater statistical significance of 99.9%, mainly appear in the north of Russia, Alaska, and Sahel. The correlation

Figure 2. Correlation between annual averaged MME NPP and climate variables MME (a) Pr, (b) Tas and (c) Rds (green line indicates the correlation coefficients corresponding to the 99% significance level) during 1976–2005 over global land.

coefficients of NPP with Tas are positive in the northern hemisphere, but in most areas of southern hemisphere, they are negative. The highest positive correlation coefficients appear in the north of Russia and Europe, in the north of America, Sahel area, east of Tibet Plateau, and northeast of China, while the highest negative correlation coefficients appear in the Amazon, west of Brazil, and south of Australia. The correlation coefficients of NPP with Rds are negative almost everywhere, except in the north of Europe, northwest of Russia and east coast of America. The highest correlation coefficient appears in the east of Russia, south of India, Sahel and north of South America,

which is related to the regional climate. For example, in the Sahel region and south of India, the precipitation and temperature are very suitable for plant growth, and the third variable of Rds is the limiting factor, and so we can get the highest correlation coefficient.

In order to obtain the real relationship between climate and terrestrial ecosystem NPP, we separated the interannual variability from the effects of trends, and subtracted the linear trend and mean from the time series of annual Pr, Tas, Rds, and NPP. The results still show that NPP has positive correlations with Pr almost everywhere (figure 3a). The correlation coefficients of NPP with Tas are positive in the high latitudes of the northern hemisphere and east Asia, while in most areas of southern hemisphere, they are negative. The

Figure 3. Same as figure 2, but with mean and trend removed.

correlation coefficients of NPP with Rsds are negative almost everywhere, except the north of Europe, which is very similar with the results presented in figure 2(c).

Comparing figures 2 and 3, one can see some obvious differences. The level of correlation is less in figure 3 than in figure 2, because the trend and mean were removed. In figure 2, Pr mainly has a positive correlation coefficient with NPP, and Tas and Rsds mainly have a negative correlation coefficient with NPP. The patterns of correlation coefficient between Pr, Rsds, and NPP (figure 3a, c) are similar to figure 2(a and c), but the pattern of correlation coefficient between Tas and NPP (figure 3b) is different from figure 2(b), which is because Tas has an obvious increasing trend. The correlation coefficients between global average NPP and Pr, Tas, and Rsds are 0.64, 0.86 and -0.01 , respectively. This means that the terrestrial ecosystem NPP has a similar change with Tas and Pr or NPP is mainly related to Tas and Pr.

3.3 Trends in NPP

During the past 100 years, earth has experienced dramatic environmental changes: the global average temperature has risen; CO_2 concentrations have continued to rise; global warming will heat the lower atmosphere and enable it to hold more moisture, thus global water cycle has speeded up; and terrestrial ecosystem also has changed (Melillo et al. 1993; Brönnimann et al. 2008; Jones et al. 2009).

Figure 4 shows the spatial pattern of the linear trend in terrestrial ecosystem NPP between 1976 and 2005, which has an obvious increasing temporal trend almost globally except in some locations of South Africa, Australia, Mexico, and

South America. The largest increasing trend appears in the Sahel area, South Asia, and South America, mainly focused on the equatorial zone ($>5 \text{ gCm}^{-2} \bullet 100 \text{ yr}^{-2}$). In most areas of Eurasia and North America, there is also an increase of $1\text{--}3 \text{ gCm}^{-2} \bullet 100 \text{ yr}^{-2}$.

Table 4 shows the area-averaged trend of NPP on global and regional scale. For the global scale, the trend of MME NPP is $3.901 \text{ gCm}^{-2} \bullet 100 \text{ yr}^{-2}$. The largest trend appears over $60^\circ\text{--}90^\circ\text{N}$, which is larger than $4.784 \text{ gCm}^{-2} \bullet 100 \text{ yr}^{-2}$, because the Tas is increasing rapidly in this zone, which is favourable for plant growth. Generally, the trend in the northern hemisphere is larger than in the southern hemisphere, and this may be because the climate changes (such as Pr and Tas) in the northern hemisphere is stronger than in the southern hemisphere (Friedman et al. 2013).

The global IGBP NPP is 55.05 PgCyr^{-1} , and the simulated MME NPP is 50.6 PgCyr^{-1} . For each model of our research, the simulated NPP varies from 21.46 to 74.40 PgCyr^{-1} (not shown figures), and the difference is from -33.59 to 19.35 PgCyr^{-1} comparing the proxy data. NorESM1-M simulates the lowest NPP, which is almost 30% of the highest NPP from IPSL-CM5A-LR. Many studies have indicated that the global NPP ranges from 39.9 to 80.5 PgCyr^{-1} (Cramer et al. 1999; Dan et al. 2007), which demonstrates that there is great uncertainty in simulated terrestrial ecosystem NPP. However, because of the deficiency of long term global NPP data, the modelling NPP validation is not implemented fully and maturely at global and region scales comparing the validations of climatic simulations. Maybe this means that we need to improve understanding the factors that govern the variability of NPP model estimation (Ahl et al. 2005).

Figure 4. Trend of MME NPP, with unit of $\text{gCm}^{-2} \bullet 100 \text{ yr}^{-1}$ during 1976–2005 over global land.

Table 4. Area-averaged trend of MME NPP, with unit of $\text{gCm}^{-2} \bullet 100 \text{ yr}^{-2}$.

MME NPP trend	Global	60°–30°S	30°S–0	0–30°N	30°–60°N	60°–90°N
	3.901	2.624	3.777	4.119	3.674	4.784

Figure 5. Long term anomaly changes of climate and terrestrial ecosystem NPP during 1860–2005 over global land, units are $\text{gCm}^{-2}\text{yr}^{-1}$ mmday^{-1} , $^{\circ}\text{C}$ and $\text{Wm}^{-2}\text{s}^{-1}$ for NPP, Pr*10, Tas*100 and Rsds*10, respectively.

3.4 Long term changes of climate and terrestrial ecosystem NPP

Figure 5 shows the interannual variation of global land MME NPP and climatic factors (Pr, Tas and Rsds) from 1860 to 2005. It is very clear that NPP has shown an increasing temporal trend in the past 150 years, and the trend from 1960 to 2005 is larger than the trend from 1860 to 1960, which is related to the trends of climate factors. Pr shows fluctuant variation from 1860 to 1955, without an increasing trend or decreasing trend, while from 1955 to 1965, there is a decreasing trend, and from 1965 to 2005, there is an increasing trend. Tas shows an increasing trend throughout, while Rsds always shows a decreasing trend. All the changes in the climatic factors are favourable for the changes in NPP, and it can be inferred that the terrestrial ecosystem has shown a positive response to climate change in the past 150 years. Figure 5 shows another characteristic that the Rsds is very sensitive to volcanic eruptions, and then Tas and Pr, this is consistent with other researches (Garrison 1995; Gu and Adler 2010). Volcanic eruptions have a complex and regional effect on NPP; they enhance or diminish NPP (Krakauer and Randerson 2003); for the global annual average, the effect is limited and indirect.

4. Conclusions

In the present study, we first used IGBP NPP data to validate and compare the simulated global MME NPP in historical scenarios of 10 CMIP5 models. By comparing the spatial pattern at global scale,

we found general consistency between MME NPP and IGBP NPP data, albeit with some differences among values.

Terrestrial ecosystem NPP is strongly related to climatic factors. Based on the present research, terrestrial ecosystem NPP has a strong correlation coefficient with Tas and Pr. For global land between 1976 and 2005, the correlation coefficients between global average NPP and Pr, Tas and Rsds are 0.64, 0.86, and -0.01 , respectively, and Pr shows a slight increase, Tas shows an obvious increase, and NPP shows an obvious increasing temporal trend.

During the past 150 years, MME NPP has increased 3.647 PgC during historical period, which shows an increasing temporal trend of $3.9 \text{ gCm}^{-2} \bullet 100 \text{ yr}^{-2}$, and the terrestrial ecosystem has responded positively to climate change. The global IGBP NPP is 55.05 PgCyr^{-1} , and the simulated global MME NPP is 50.6 PgCyr^{-1} . The simulated NPP has huge uncertainty.

In reality, the terrestrial ecosystem is a complex variable, which can be effected by many factors, such as climate, CO_2 , human activity, and so on. It must be said that the CO_2 fertilization effect is important in photosynthesis and carbon cycle calculation. In the 21st century, the land carbon storage is expected to be enhanced by the CO_2 increase but dampened by climate change (Friedlingstein *et al.* 2006; Shao *et al.* 2013). Note that CO_2 concentration is prescribed for the historical simulations of CMIP5 and there is no feedback. In the present paper, we have only discussed climatic effects. However, the terrestrial ecosystem is also related strongly with vegetation type, but the

problem is we are unable to get vegetation maps for all the models, which causes some limitations on our research.

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