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Assessing the characteristics of net primary production due to future climate change and CO_2 under RCP4.5 in China

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ABSTRACT

In this study, the maximal extent of future net primary production (NPP) uncertainties are explored by employing the conditional nonlinear optimal perturbation related to parameters (CNOP-P) approach and the Lund-Potsdam-Jena (LPJ) model based on future climate change assessments, which are provided by 10 general circulation models (GCMs) of the Coupled Model Intercomparison Project 5 (CMIP5) under the Representative Concentration Pathway (RCP) 4.5 scenario at the North-South Transect of Eastern China (NSTEC). The CNOP-P approach produces a scenario of climate change within the feasible bounds that could cause maximal uncertainty of NPP. We find that the future NPP will increase due to changes in climate and atmospheric CO_2; however, there is a difference in the extent of the variation resulting from the 10 GCMs and the CNOP-P approach. Future NPPs are estimated from 3.89 Gt C (MRI-CGCM3 model) to 4.51 Gt C (bcc-csm1-1 model) using the LPJ model driven by the outputs of 10 GCMs. The estimates of NPP with two CNOP-P-type climate change scenarios are 4.74 Gt C and 5.31 Gt C and are larger than estimates of NPP by the outputs of the 10 GCMs. The above results imply that the terrestrial ecosystem supplies possible conditions for future carbon sinks for all climate change scenarios, especially for the CNOP-P-type climate change scenarios, although the estimates remain uncertain. Stimulative photosynthesis due to high precipitation and restrained autotrophic respiration due to low temperatures may play important roles in the carbon sink due to the CNOP-P-type climate change and CO_2 in all climate change scenarios. In addition, it is found that the combination of climate change and increasing CO_2 is the main driver of the increase of NPP.

1. Introduction

The net primary production (NPP), which quantifies the amount of atmospheric carbon fixed by plants and accumulated as biomass, is considered an important regulating factor in the global carbon cycle (Fang et al., 2001; Nemani et al., 2003; Gonsamo et al., 2013; Ni, 2013; Walker et al., 2015). Therefore, the spatial and temporal characteristics of the global and regional NPP have been paid attention due to concerns about the current and future behavior of the terrestrial carbon cycle (Woodward and Lomas, 2004; Doughty et al., 2015). Therefore, accurate estimates or predictions of the variation of the NPP are studied and discussed.

Despite observation data and numerical models, uncertainties in NPP are still not adequately estimated and predicted (Chen et al., 2000; Wang and Barrett, 2003; Zhou et al., 2013; Zhu and Zhuang, 2015). For example, Shao et al. (2016) employed a literature-based data set with 54 NPP estimates from 33 studies and found that the NPP in China's terrestrial ecosystems was 3.35 ± 1.25 Pg C yr^{-1} (mean $\pm$ SD) during 1901–2005 (most estimates were during 1981–2001), which was very close to the value from the outputs of the Multi-scale synthesis and terrestrial model intercomparison project (MsTMIP) conducted during 1981–2000 (3.36 ± 0.63 PgC yr^{-1}). Moreover, some of the sources of uncertainty (e.g., the spatiotemporal scales and land cover conditions) were also detected using the approach of classification and regression tree (CART) analysis. Gao and Liu (2008) employed five terrestrial ecosystem models to estimate the NPP. They found that the average NPP of different models was 2.864 Gt C in China; however, the NPP estimated by the five models ranged from 2.421 to 3.341 Gt C. The study implies that model error is a key

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factor in the calculation of NPP. In addition, the uncertainties of the feedback between vegetation and the atmosphere are also a main source of uncertainty in the estimates of NPP from the atmospheric general circulation model (AGCM) coupled with the terrestrial ecosystem model. Among all factors leading to uncertainties of the NPP using the terrestrial ecosystem models, the uncertainty of climate change is one of the key input factors for calculating the future NPP. Arora and Matthews (2009) calculated the NPP simulated by the box model equivalents of the Canadian Terrestrial Ecosystem Model (CTEM) and Top-down Representation of Interactive Foliage and Flora Including Dynamics (TRIFFID), forced with emissions from A2, A1B, and B1 IPCC SRES scenarios for the 2001–2100 period. Gang et al. (2015) utilized the modified Comprehensive Sequential Classification System (CSCS) model and 25 global climate models under the Representative Concentration Pathway 2.6 (RCP2.6) scenario to clarify the decadal variations of the NPP. All of the above studies found uncertainties of estimation of NPP in different climate change scenarios. Moreover, the response of NPP to climate change (temperature and precipitation) is nonlinear, further hindering exact calculations of NPP. Due to nonlinearity and relations between the terrestrial ecosystem and the atmosphere, current estimates of the NPP remain uncertain. Thus, the estimation of the range of the NPP under a reasonable climate change scenario is an interesting problem.

In this study, to reasonably estimate the variation of the NPP in future climate change scenarios and elucidate nonlinear relations between the NPP and climate change, the conditional nonlinear optimal perturbation related to parameters (CNOP-P) approach (Mu et al., 2010) is employed to estimate the maximal uncertainties of the NPP. CNOP-P represents a new climate change scenario, which is reasonably constrained by climate projections from 10 general circulation models (GCMs) of the Coupled Model Intercomparison Project 5 (CMIP5) under the Representative Concentration Pathway (RCP) 4.5 scenario. The CNOP-P approach has been widely applied to examine the uncertainties and predictability of atmosphere, ocean, and land processes, including the predictability of El Niño-Southern Oscillation (ENSO), typhoons, the Kuroshio large meander (KLM) state, grassland ecosystems (Duan and Zhang, 2010; Qin and Mu, 2011; Sun and Mu, 2011, 2014; Wang et al., 2012; Zheng et al., 2012), and terrestrial ecosystems. Moreover, Sun and Mu (2013) employed the CNOP-P approach to evaluate the variations of the NPP in response to increases of 2 °C in temperature and 20% in precipitation, with changes in the variability and variances of temperature and precipitation. In their studies, these authors attempted to determine the maximal uncertainty of the models of the NPP. However, their climate change scenario was restricted to only an increase in temperature and precipitation by 2 °C and 20%, respectively, which may be statistical results from the GCMs. Future projections from GCMs do not yield consistent extents of variation in temperature and precipitation. Under the climate change scenarios provided by GCMs, the maximal uncertainty of the NPP in China remains unknown. Therefore, the maximal uncertainty of estimates of the NPP was explored based on the multiple GCMs.

2. Study region, model, and methods

2.1. Study region

There is notable spatial heterogeneity in the distribution of the NPP in China. The NPP is low in Northwestern and Southwestern China and high in Northern and Southern China. The sensitive regions of impact of climate change on the NPP are located in Northern and Southern China. Thus, the area of the North-South Transect of Eastern China (NSTEC) was chosen as the region for our study. This region extends from Hainan Island to the northern border of China, ranging from longitude 108° to 118° E at latitudes less than 40° N and from longitude 118° to 128° E at latitudes equal to or greater than 40° N (Li et al., 2004; Sheng et al., 2011; Lu et al., 2013; Zhan et al., 2014). Because this region is located in the Monsoon Asia region, climate change and its influence on NPP are intense (Mu et al., 2008). Thus, it is necessary to demonstrate the response of the NPP on climate change in NSTEC.

Table 1
Ten GCMs from CMIP5.

Model Name	Model ID	Country of origin	Resolution (Lat. × Long.)
ACCESS1-0	M01	Australia	1.875° × 1.25°
CCSM4	M02	USA	1.25° × 0.9°
CNRM-CM5	M03	France	~1.4° × 1.4°
Fgoals-s2	M04	China	~2.81° × 1.66°
HadGEM2-AO	M05	Korea	1.875° × 1.25°
HadGEM2-CC	M06	United Kingdom	1.875° × 1.25°
IPSL-CM5A-MR	M07	France	2.5° × 1.25°
MIROC5	M08	Japan	~1.4° × 1.4°
MPI-ESM-LR	M09	Germany	1.875° × 1.875°
MRI-CGCM3	M10	Japan	1.125° × 1.125°

2.2. LPJ model and input data

The LPJ dynamical global vegetation model ("LPJ version 1") is employed in our study. The LPJ model can provide a representation of terrestrial vegetation dynamics and biogeochemical cycling using process-based coding (Sitch et al., 2003). The model includes ten plant functional types (PFTs) used to distinguish different photosynthetic (C3 vs. C4), phenological (deciduous vs. evergreen), and physiognomic (tree vs. grass) features. It employs the Farquhar-Collatz photosynthesis scheme to simulate realistic gross primary production (GPP) and plant respiration. Subtracting plant respiration from GPP gives the net primary production (NPP). The LPJ-DGVM used in this study has been intensively applied to explore the impact of climate change on the regional terrestrial ecosystem (Wu et al., 2014; Wang, 2014; Zhao and Wu, 2014). In addition, the LPJ model has been developed as an inversion method for the models LPJ-GUESS (Lund-Potsdam-Jena General Ecosystem Simulator), LPJ-Why (LPJ Wetland Hydrology), and LPJ-WHyMe (LPJ Wetland Hydrology and Methane) (Wania et al., 2009, 2010) to assess the terrestrial carbon cycle in different regions (Wolf et al., 2012; Manusch et al., 2014; Allen et al., 2016). Additionally, the LPJ model has also been coupled with climate change to evaluate the interaction between the terrestrial carbon cycle and the atmosphere (Yurova and Volodin, 2011; Willeit et al., 2014).

To evaluate the future variation of the NPP and its uncertainty, the data (precipitation, temperature, cloud cover, and wet day frequency) driving the LPJ model under the Representative Concentration Pathway (RCP) 4.5 scenario are shown in Table 1. These results were employed to drive the LPJ model during 2011–2100. Each of these models is a fully coupled atmosphere-ocean model operating at geographical grid resolutions between 2° and 6° and resolving vertical processes between 10 and 20 layers of both the atmosphere and the ocean. The outputs from the ten models were spatially interpolated to a 0.5° resolution and bias-corrected (based on 1961–1990 bias) with CRU TS2.1 climate data set (Mitchell and Jones, 2005). Additionally, a data set of atmospheric CO_2 concentrations from RCP4.5 during 2011–2100 was also essential (IPCC, 2013). Soil texture data were based on the Food and Agriculture Organization (FAO) soil data set (Zobler, 1986).

2.3. Conditional nonlinear optimal perturbation related to parameter (CNOP-P) approach

Not only was the future uncertainty of the NPP evaluated, but the possible maximal uncertainty of the NPP was also explored