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Contribution of climate change and rising CO_2 to terrestrial carbon balance in East Asia: A multi-model analysis

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ABSTRACT

In this study, we use three process-based terrestrial ecosystem models (Lund-Potsdam-Jena Dynamic Global Vegetation Model — LPJ-DGVM; ORganizing Carbon and Hydrology In Dynamic Ecosystems – ORCHIDEE; Sheffield model – SDGVM) to investigate the historical response of ecosystem Net Primary Productivity (NPP) and Net Ecosystem Productivity (NEP) over East Asia to climate change and rising atmospheric CO_2. The results suggest that between 1901 and 2002, the modeled NPP has significantly increased by 5.5–8.5 Tg C yr^{-1} (15–20% growth). Such increase in NPP has caused an increased cumulated terrestrial C storage by about 5–11 Pg C. About 50–70% fraction of this total C sink is located in vegetation biomass. Our modeling results also suggest that 40–60% of the accumulate C uptake of the 20th century is credited to the period of 1980–2002. Although all models tend to agree at the continental scale that East Asia played a role of net C sink (0.14–0.18 Pg C yr^{-1}) during 1980s and 1990s, the trends of NEP are different among the models. Both LPJ and ORCHIDEE estimate a slight but insignificant NEP decrease from 1980 to 2002 ($P>0.05$), while SDGVM estimates a statistically significant increase in NEP at a rate of 0.005 Pg C yr^{-2} ($P<0.05$). Also, there is no consensus among models on the dominant driving factors controlling interannual variation in NPP and NEP at the continental scale, implying that more efforts are needed to investigate the vulnerability of the East Asian terrestrial carbon cycle.

1. Introduction

In the past two decades, inversion models of atmospheric CO_2 concentration have provided evidence that terrestrial ecosystems of the Northern Hemisphere are a large carbon sink (Gurney et al., 2002; Peylin et al., 2005; Stephens et al., 2007). The strength of that sink shows high year-to-year variation in response to climate variation (Bousquet et al., 2000; Piao et al., 2008). Most of the focus has been given so far to the North American and European continents (Schimel et al., 2000; Pacala et al., 2001; Janssens et al., 2003; Ciais et al., 2008). For example, Schimel et al. (2000) used three ecosystem models to estimate that rising atmospheric CO_2 and climate change stimulated net carbon (C) accumulation by about 0.08 Pg C yr^{-1} in the conterminous United States. Vetter et al. (2008) investigated the variability of the European C balance using seven models, and estimated that the total carbon flux anomaly during the European heatwave in 2003 ranged between −0.02 and −0.27 Pg C relative to the net carbon flux in 1998–2002. However, substantial uncertainties remain for the spatial distribution of the carbon source/sink and its underlying causes (IPCC, 2007).

East Asia (including China, Japan, Korea, and Mongolia) covers a vast area of $12*10^6$ km^2. Regional climate is dominated by the Asian monsoon, with diverse climate types ranging from tropical to cold-temperate and from humid to extremely dry. Due to the large climate variance, the vegetation of East Asian includes a broad range of tropical, temperate, and boreal forests, grassland, and desert (Fang et al., 2001). On the other hand, East Asia is maybe one of the most critical and sensitive regions in the global climate system (Fu et al., 2006; Piao et al., 2010). During the past two decades, mean annual temperature over China increased by more than 0.6 °C/decade, a much faster rate than the global land mean temperature trend (~0.27 °C/decade; IPCC, 2007). Associated with this warming, a significant change in seasonal precipitation pattern has been also observed (Piao et al., 2005). Such

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rapid shifts in temperature and precipitation certainly impact the regional carbon balance between productivity and decomposition rates. Better quantification and understanding of the carbon cycle of East Asian ecosystems, and of its perturbation by past and current climate change, is a high priority where research is needed (IPCC, 2007).

Ecosystem models have established as useful tools for understanding and predicting terrestrial carbon cycle at local, regional, continental and global scales (Ciais et al., 2005; Piao et al., 2008; Sitch et al., 2008; Peng et al., 2009), in synergy with observations. Modeling the effects of climate on the terrestrial carbon cycle of East Asia has been tackled for instance by Piao et al. (2005) and Mu et al. (2008). Using a biogeochemical model, Piao et al. (2005) concluded that vegetation productivity in China has increased significantly due to climate change and rising atmospheric CO_2. More recently, after analyzing interannual variations in the terrestrial C budget of China, Mu et al. (2008) found an increasing C sink for China from 1960 to 2000, with C being mainly packed away in the vegetation biomass. Although these modeling studies helped to improve our understanding of the response of ecosystem C fluxes to climate and CO_2, their conclusions depend to an unknown extent on the model parameterizations. To assess the uncertainties due to model structure and parameter choices, it is necessary to perform simulation analysis with an ensemble of independent models (Cramer et al., 2001; Friedlingstein et al., 2006; Sitch et al., 2008). Although in a current study Piao et al. (2009a,b) have presented China's C budget estimate using five different biogeochemical models, the linkage between climate change and terrestrial ecosystem C balance of these regions was not fully investigated because the study focused mainly on the magnitude of current C budget at national scale.

In this work, three independently developed process-based models, Lund-Potsdam-Jena (LPJ) model (Sitch et al., 2003), ORganizing Carbon and Hydrology In Dynamic Ecosystems (ORCHIDEE) model (Krinner et al., 2005), and Sheffield (SDGVM) model (Woodward and Lomas, 2004) are used to estimate the impact of climate change on the East Asian terrestrial carbon budget and make comparison. The simulation period covers the last century to incorporate a long-term dynamics that affects the ecosystem carbon cycle. The primary objective of this study is to investigate uncertainties of historical variation in vegetation net primary productivity (NPP) and net ecosystem productivity (NEP) driven by climate change and by rising atmospheric CO_2.

2. Methods

2.1. Ecosystem models

We applied three process-based ecosystem models to simulate the terrestrial biogeochemical processes from 1901 to 2002. The three models are: Lund-Potsdam-Jena Dynamic Global Vegetation Model (LPJ-DGVM) (Sitch et al., 2003); ORganizing Carbon and Hydrology In Dynamic Ecosystems (ORCHIDEE) model (Krinner et al., 2005); and Sheffield model (Woodward and Lomas, 2004). The main features of the three models are summarized in Table 1. These models have been extensively validated against measured carbon fluxes at particular sites around the world (Krinner et al., 2005; Sitch et al., 2003); they also realistically simulate observed historical change in leaf area index (LAI) and transient responses of carbon fluxes to climate variability (Lutch et al., 2002; Ciais et al., 2005; Piao et al., 2006, 2008). Tao and Zhang (2010) have also validated LPJ derived NPP and carbon storage against observation in China. Terrestrial NEP fluxes from ORCHIDEE have also been successfully validated against measured carbon fluxes at particular sites in China (Tan et al., 2009; Peng et al., in prepare).

The LPJ-DGVM is a coupled dynamic biogeography-biogeochemistry model which explicitly considers key ecosystem processes such as photosynthesis, carbon allocation, mortality, resource competition, fire disturbance and soil heterotrophic respiration. To account for the variety of structure and functioning among plants, 10 plant functional types (PFTs) are distinguished. Gross primary production is calculated following Farquhar et al. (1980) using an inner-leaf CO_2 concentration that is dependent on the canopy conductance. Canopy conductance is constrained by photosynthesis and soil water supply. The effect of soil water availability on LAI is taken into account. LPJ's sub-model of light use efficiency assumes no limitation of nitrogen uptake (Haxeltine and Prentice, 1996). The dynamic vegetation carbon pools for leaves, sapwood, heartwood, and fine roots determine plant functioning, e.g. NPP and soil water uptake. Three soil carbon pools with different turnover rates are used to calculate temperature and moisture dependent heterotrophic respiration. The depth of soil in LPJ is 1 m.

The ORCHIDEE model (Krinner et al., 2005) is a dynamic global vegetation model to simulate the global carbon and water cycles. ORCHIDEE consists of five vegetation carbon reservoirs, four litter reservoirs, and three soil reservoirs. The vegetation assimilation in ORCHIDEE is based on Farquhar et al. (1980) for C3 photosynthesis and Collatz et al. (1991) for C4 photosynthesis, and the carbon allocation among leaves, stem and roots is according to the allocation scheme of Friedlingstein et al. (1998). Maintenance respiration is a function of each living biomass pool and temperature (Ruimy et al., 1996). Heterotrophic respiration parameterization is taken from the CENTURY model (Parton et al., 1993). The depth of soil in ORCHIDEE is 2 m.

The SDGVM model was developed to simulate both functional variables (e.g., primary productivity) and structural variables (e.g., leaf area index). Plant CO_2 assimilation is based on work by Farquhar et al. (1980). Stomatal conductance is taken from Jarvis (1976) and

Table 1
Characteristics of the biogeochemical models.

Process	LPJ	ORCHIDEE (ORC)	SDGVM (SHE)
Photosynthesis	Farquhar et al. (1980)/Collatz et al. (1991)	Farquhar et al. (1980)/Collatz et al. (1991)	Farquhar et al. (1980)/Collatz et al. (1991)
Stomatal conductance	Haxeltine and Prentice(1996)	Ball et al. (1987)	Leuning (1995)
Sapwood respiration	Dependent on sapwood mass and C:N ratio (Lloyd and Taylor, 1994)	Dependent on temperature, sapwood mass and C:N ratio	Annual sapwood increment, C:N f(T)
Fine root respiration	f(T,C_{root})	f(T,C_{root})	f(T,C_{root})
Evapotranspiration	Total evapotranspiration (Monteith, 1995)	Transpiration, interception loss, bare ground evaporation and snow sublimation are computed using Monteith-type formulations (Ducoudré et al., 1993)	Penman-Monteith transpiration (Monteith, 1981) + interception + evaporation from soil surface
Soil water balance	2 soil layers Modified bucket model from Neilson (Neilson, 1993)	2 soil layers (deep bucket layer and upper layer of variable depth)	3 soil + 1 litter layer Modif. Bucket model
Litter fall	Annual litter carbon balance	Daily litter carbon balance	Monthly litter carbon balance
Hetetrophic respiration	f(T,θ_{top},tissue type)	Based on Parton et al. (1988)	Similar to CENTURY (Parton et al., 1993)
C allocation	Annual allometric relationship for individuals	Based on resource optimization (Friedlingstein et al., 1998)	Daily allocation by demand in order of priority LAI>roots>wood
N uptake			f (soil C, N, T, and moisture)
N allocation	Implicit, dependent on demand	Fixed C:N	Variable N with light