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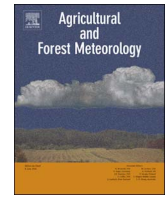

Climate-driven uncertainties in modeling terrestrial ecosystem net primary productivity in China

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ABSTRACT

Evaluating the uncertainties in regional/global carbon flux estimates is essential for better understanding of terrestrial carbon dynamics. At the regional scale, climate input data is an important source of model simulation uncertainty. In this study, a process-based ecosystem model, CEVSA, was run driven by four climate input datasets during 1980–2004, i.e., climate input datasets interpolated from 756 (756s) and 2400 weather stations (2400s), the NCEP/NCAR and Princeton reanalysis datasets. We used the 2400s dataset as the reference because it was derived from high density weather station interpolation. The simulated Net Primary Productivity (NPP) based on interpolated climate data from the 756s and the two reanalysis datasets were compared with that from the 2400s dataset. Then, we quantified the uncertainty of model simulations at regional-scale caused by climate input data, and evaluated the performance of different climate datasets across different eco-regions. Our results suggest that the 756s, Princeton and NCEP/NCAR reanalysis datasets overestimated the 25-year mean annual temperature by 7.66%–12.25% and the precipitation by 2.83%–8.43%, respectively; accordingly, the simulated NPP ranged from 3.53 to 3.96 Pg C, 6% to 12% higher than the reference over the entire China. The 756s and the two reanalysis datasets captured well the trend and interannual variations of annual NPP during the study period, but showed systematic errors in the total amount of NPP compared with the 2400s dataset. To increase the station density in the eco-regions with a station density greater than 1.0 station per 10^4 km^2 (1.0 s/10^4 km^2) would not decrease the uncertainty for model simulation at a 0.1° spatial resolution. The NCEP/NCAR and Princeton reanalysis datasets showed larger uncertainties in most eco-regions compared with the interpolated datasets. Our results also suggest that the accuracy of the NCEP/NCAR reanalysis data should be further improved in most eco-regions. On Qinghai-Tibet Plateau and in northwestern China, all four climate input datasets had relatively lower accuracy due to the limited observation data available. Future work should further evaluate the simulated NPP against observations and quantify the accuracy of driving climate data to decrease the uncertainty of model simulations at the regional scale.

1. Introduction

Terrestrial ecosystems play an important role in offsetting climate warming and increases in atmospheric CO_2 concentration (Schimel et al., 2001; Xiao et al., 2014). The terrestrial carbon sink, its responses to climate change and the quantification of the associated uncertainties have been given priority in global climate change research. The fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC and Climate Change, 2007) has acknowledged the importance of the quantification of uncertainty. Cao et al. (2005) noted that the still existed uncertainties associated with estimating the magnitude and variations of the terrestrial carbon sink would influence the prediction of climate change effects and effective implementation of the Kyoto Protocol.

Net primary productivity (NPP) is a key component of carbon fluxes of terrestrial ecosystems (Ito, 2011). Estimating the NPP and evaluating its response to climate change are fundamental to our understanding of the carbon absorption capacity of terrestrial ecosystems and the

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associated biogeochemical processes. NPP could not be measured directly (Lauenroth et al., 2006), and it was calculated based on variables measured directly, such as tree height, diameter at breast height, biomass, and statistical grain yield, etc. Ecosystem models are the most important tool used to estimate NPP and other carbon fluxes at regional and global scales (Melillo et al., 1993; Cox et al., 2000; Cramer et al., 2001; Nemani et al., 2003; Xiao et al., 2009). However, few studies have been paid attention to the uncertainties of modeled carbon fluxes, including NPP, at the regional scale (Quaife et al., 2008; Xiao et al., 2011). Identifying the uncertainty is important for evaluating the performance of models (Sheffield et al., 2006) and helps to identify future research areas for ecosystem processes and mechanisms. Furthermore, although it is impossible to remove all uncertainties from model simulations, uncertainties can be reduced by acknowledging the sources of uncertainty and through the development of assessment models (Yao et al., 2011).

Uncertainties of ecosystem models came from three sources: (1) uncertainties in model parameters; (2) uncertainties in model structure; and (3) uncertainties in input data. Much research has focused on the uncertainties derived from model parameters (Jørgensen, 1994). Eddy covariance observations and model-data assimilation techniques were used to assess the uncertainty of model parameters and the associated uncertainty of modeled carbon fluxes at a single site for a given plant function type (Knorr and Kattge, 2005; Xu et al., 2006; Mahadevan et al., 2008; Luo et al., 2009; Mitchell et al., 2009; Peng et al., 2011; Xiao et al., 2011; Zhang et al., 2012). The uncertainty of model predictions caused by model structure and input data have also aroused concerns (Matsushita et al., 2004; Sacks et al., 2006; Melboune-Thomas et al., 2011). Process-based ecosystem models can differ widely in their structures, which leads to substantial uncertainties among their predictions (Franks et al., 1997; Schulz et al., 2001; Raupach et al., 2005). However, it is difficult to quantify the uncertainty caused by model structure. The intercomparison of different ecosystem models provides a method to evaluate the effect of model structure on the uncertainty of model predictions (Friedlingstein et al., 2006; Wang et al., 2011; Huntzinger et al., 2011). Although intercomparison between models cannot decrease the uncertainty, it helps the development of the ecosystem models and decision-making associated with climate change and ecosystem management (Xing and Guo, 2006; Ascough et al., 2008; Xiao et al., 2014 Ascough et al., 2008; Xiao et al., 2014).

The uncertainty of regional or global carbon flux estimates has rarely been quantified, although evaluating this uncertainty is essential to improving our understanding of terrestrial carbon dynamics (Xiao et al., 2014). At the regional scale, the uncertainty associated with input variables, such as land cover and climate data, is an important source of the uncertainties of regional model predictions (Matsushita et al., 2004; Xiao et al., 2014). Few previous studies have assessed the contribution of the uncertainties inherent in land cover maps to the uncertainty of modeled carbon fluxes at the regional scale (Quaife et al., 2008; Xiao et al., 2011). Climate data are the most important input variables for ecosystem models, especially at regional or global scales. Previous research in environmental and hydrological modeling has assessed the uncertainty associated with input variables. Researchers using the distributed hydrological models found that the amount and distribution of precipitation observation sites in a watershed influences the modeled runoff (Lope, 1996; Nandakumar and Mein, 1997; Liao et al., 2014). Overall, the uncertainties derived from the climate data had a large influence on the simulations (Matsushita et al., 2004; Liao et al., 2014). However, no study has assessed climate data uncertainty and the associated uncertainty in regional carbon flux estimation using process-based ecosystem models, particularly over a large region with complex topography, varied climate regimes, and highly diverse ecosystems.

Developing reliable, high-resolution historical meteorological data is difficult, especially in regions such as the Qinghai–Tibet Plateau, northwestern China, and high mountains, where observational data are scarce. At the regional scale, the amount and spatial distribution of meteorological observation stations, data processes, and interpolation methods add a large amount of uncertainty to the gridded climate variables used as input data for regional simulations (Zhang et al., 2012). Most existing estimations of NPP in Chinese terrestrial ecosystems that used process-based ecosystem models (Tao et al., 2003; Cao et al., 2003; Huang, 2006; Liang and Xie, 2006; He et al., 2007; Ji et al., 2008) used the gridded climate dataset based on interpolation data from 756 national reference climatological stations by ANUSPLINE (Hutchinson, 1983). A second dataset, which included over 2400 observation stations across China, including the national reference climatological stations, basic synoptic stations, and general weather stations, has a higher density of weather observation sites, especially in eastern China and at low elevations. At the global scale, reanalysis datasets have been used for long-term, large-scale modeling (Sheffield et al., 2006) and climate change research (Xu et al., 2001). Currently, the most popular reanalysis datasets include those from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR; Kalnay et al., 1996; Kistler et al., 2001), European Centre for Medium-Range Weather Forecasts (ERA-40 and ERA-15; Gibson et al., 1997), the Japan Meteorological Agency (JRA-25 and JRA-55; Onogi et al., 2007; Ebita et al., 2011; Kobayashi and Iwasaki, 2016), and the National Aeronautics and Space Administration Data Assimilation Office (NASA DAO; Schubert et al., 1993). A new global, high temporal and spatial resolution reanalysis dataset (Princeton) was constructed by combining new global observation datasets with NCEP/NCAR reanalysis data (Sheffield et al., 2006). In this study, we used two interpolated gridded dataset based on the 756 (756s) and 2400 stations (2400s) described above, as well as two reanalysis datasets, NCEP/NCAR and Princeton, as input climate variables to simulate the tempo-spatial pattern of Chinese terrestrial ecosystem NPP from 1980 to 2004, using the process-based ecosystem model, CEVSA. Typically, the number of weather stations significantly affects the accuracy of interpolation, with the more stations used for interpolation, the greater the accuracy and precision of the interpolated data. Therefore, the simulation based on the 2400s dataset was used as the reference. By comparing the other three simulations with the reference simulation, our research objectives were to assess (1) the uncertainty in climate input data and associated uncertainty in NPP estimation of Chinese terrestrial ecosystems by a process-based ecosystem model; (2) the effect of weather station density and spatial distribution on the uncertainty associated with interpolation data and the modeled NPP for different regions; and (3) the performance of reanalysis datasets on modeled NPP and the spatial pattern of their uncertainties.

2. Material and methods

2.1. Model description

The CEVSA model is a process-based ecosystem model that simulates energy transfers, water and carbon cycles based on eco-physiological processes. The model is composed of three submodels: a biophysical submodel, a vegetation submodel, and a biogeochemical submodel (Cao and Woodward, 1998a,b). The biological and ecological principles, equations, and parameters used in the CEVSA model were obtained from numerous laboratory and field experiments and observations.

NPP is the result of plant photosynthesis minus autotrophic respiration (R_a). Plant photosynthesis depends on the CO_2 utilization efficiency of photosynthetic biochemical processes (A_b) and CO_2 supply by diffusion through stomata into leaf intercellular spaces (A_d). The rate of plant CO_2 assimilation implied by biochemical processes (A_b) is

$$A_b = \min\{W_c, W_j, W_p\}(1 - 0.5P_o/\tau P_c) - R_d \quad (1)$$

where Wc represents the efficiency of photosynthetic enzyme system, specifically the carboxylating enzyme Rubisco, and is related with foliar nitrogen content. Wj is the limitation of electron transport to