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SPECIAL FEATURE: ORIGINAL ARTICLE

Lessons learned from CarboEastAsia: Carbon and water cycles in East Asian terrestrial ecosystems

Site-level model–data synthesis of terrestrial carbon fluxes in the CarboEastAsia eddy-covariance observation network: toward future modeling efforts

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Abstract Based on the model–data comparison at the eddy-covariance observation sites from CarboEastAsia datasets, we report the current status of the terrestrial carbon cycle modeling in monsoon Asia. In order to assess the modeling performance and discuss future requirements for both modeling and observation efforts in Asia, we ran eight terrestrial biosphere models at 24 sites from 1901 to 2010. By analyzing the modeled carbon fluxes against the CarboEastAsia datasets, the strengths and weaknesses of terrestrial biosphere modeling over Asia were evaluated. In terms of pattern and magnitude, the carbon fluxes (i.e., gross primary productivity, ecosystem respiration, and net ecosystem exchange) at the temperate and boreal forest sites were simulated best, whereas the simulation results from the tropical forest, cropland, and disturbed sites were poor. The multi-model ensemble mean values showed lower root mean square errors and higher correlations, suggesting that composition of multiple terrestrial biosphere models would be preferable for terrestrial carbon budget assessments in Asia. These results indicate that the

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current model-based estimation of terrestrial carbon budget has large uncertainties, and future research should further refine the models to permit re-evaluation of the terrestrial carbon budget.

Keywords Carbon fluxes · East Asia · Eddy covariance measurement · Model comparison · Terrestrial biosphere model

Introduction

Terrestrial ecosystems in monsoon Asia, which account for ~16 % of the global terrestrial net primary productivity and biomass (Oikawa and Ito 2001), play an important role in global terrestrial carbon cycles. Large interannual variations in the terrestrial carbon budget have been reported in Asian ecosystems by both terrestrial biosphere models (Mu et al. 2008) and atmospheric inversion studies (Patra et al. 2005). The dynamics of the terrestrial carbon budget are influenced by various environmental effects such as El Niño/La Nina (Tian et al. 2003) and Asian monsoons (Kwon et al. 2010; Hong and Kim 2011).

Terrestrial biosphere models are important tools for estimating the terrestrial carbon budget and understanding the causes of spatiotemporal variations. Due to the critical importance of monsoon Asia in the global carbon budget, many studies have conducted carbon budget simulation over Asia. Piao et al. (2009) estimated the terrestrial carbon budget in China using terrestrial biosphere models, remote sensing data, and inventory data. Ito (2008) and Sasai et al. (2011) estimated the terrestrial carbon budget in East Asia using the Vegetation Integrative SImulator for Trace gases (VISIT) and Biosphere model integrating Eco-physiological And Mechanistic approaches using Satellite data (BEAMS) models, respectively. Ichii et al. (2010) estimated the terrestrial carbon budget of Japan using nine terrestrial biosphere models. Piao et al. (2011) estimated the spatiotemporal patterns of the terrestrial carbon budget in East Asia using four terrestrial biosphere models. However, different model simulations yielded significantly different estimates of terrestrial carbon budgets.

The model-by-model differences have been analyzed through model intercomparison activities. On the global scale, the simulated net primary productivity (NPP) differs greatly among 17 terrestrial biosphere models (Cramer et al. 1999). Cramer et al. (2001) also reported that six different dynamic global vegetation models (DGVMs) produced large discrepancy in the future carbon budget estimates. Recently, many multi-model analyses have been conducted at regional to continental scales to characterize the models' ability to simulate the terrestrial carbon budget. Schwalm et al. (2010) applied multiple terrestrial biosphere models to North America and found poor agreement between the model and the observation. Jung et al. (2007) conducted a multi model–data comparison over Europe, and reported a root means square error (RMSE) of about 30 % in European forest sites. Ichii et al. (2010) conducted a model–data comparison over Japan, in which model calibration using the observation decreased the differences in spatial carbon fluxes.

The previous studies of the model–data synthesis focusing on Asia were conducted using small numbers of the observation sites due to the limited data availability. Recent development of AsiaFlux, however, enables accumulation and provision of the eddy-covariance data from various ecosystems (http://asiaflux.net). For example, the CarboEastAsia dataset is a collection of eddy-covariance measurements covering a wide spatial range from Siberia to Southeast Asia and from humid coastal areas to semiarid inland regions (Saigusa et al. 2012; http://www.carboeastasia.org). This dataset provides a unique opportunity to evaluate the terrestrial biosphere models over Asia.

The purposes of this study are to evaluate the terrestrial biosphere models using the CarboEastAsia dataset and to summarize the current status and future perspectives on terrestrial biosphere modeling in Asia. We used eight terrestrial biosphere models for 24 eddy-covariance measurement sites and evaluated the models' outputs comparing against the CarboEastAsia dataset. Then, we described the current issues inherent in the applications of

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terrestrial biosphere models to Asia, its future perspectives, and the contributions of this site-level model–data synthesis to the CarboEastAsia program.

Materials and methods

We used the CarboEastAsia dataset (Saigusa et al. 2012) collected from 24 sites in Asia that provided carbon flux data [i.e., gross primary productivity (GPP), ecosystem respiration (RE), and net ecosystem exchange (NEE)] as well as meteorological data (Table S1). The carbon fluxes by eddy-covariance observations were processed, gap-filled and flux-partitioned under the CarboEastAsia program (Saigusa et al. 2012). The 24 sites used in this study dealt with a wide gradient of temperature and precipitation covering from tropical to boreal forest ecosystems and humid to semi-arid ecosystems. They also included several sites affected by human management (e.g., cropland and rice paddy). The details of the dataset were described in Saigusa et al. (2012).

Eight terrestrial biosphere models, which fell into the categories of diagnostic, prognostic, and dynamic models, were used in this study. As the diagnostic models, we used the BEAMS (Sasai et al. 2005) and Carnegie-CASA (Field et al. 1995) models that utilize satellite-based vegetation parameters such as leaf area index (LAI). Biome-BGC (Thornton et al. 2002), CLM3.5-CN (Oleson et al. 2008), PnET-CN (Aber et al. 1997), and VISIT (Ito 2008) models are prognostic models and use climate data only as time-variable inputs with constant vegetation type. As dynamic models, LPJ-DGVM (Sitch et al. 2003; Gerten et al. 2004) and MOSES2/TRIFFID (Cox 2001) models were used. Although these dynamic models calculate the temporal changes in the distribution of vegetation types in addition to carbon cycles, the vegetation type was fixed using site information in this study. Therefore, no competition among vegetation and successional change was considered. The details of the models are given in Table S2.

The model inputs consist of time-variable data (e.g., climate and satellite data) and static data (e.g., location, vegetation type, and soil information). Climate data at each site were generated from 1901 to 2010 based on the global climate data with adjustments based on the meteorological observations at each site. For example, air temperature data were based on CRU TS3.1 data (Mitchell and Jones 2005), NCEP reanalysis data (Kalnay et al. 1996), and site observations. The daily and 6-hourly variations of air temperature are based on NCEP reanalysis data, and the monthly averages are adjusted to fit the CRU TS3.1 data by adding offset. Since NCEP reanalysis data are not available for the period of 1901–1947, the reanalysis data for 1948 were used instead. Next, the derived air temperature time-series were adjusted by the site-observed air temperature on monthly time scales based on linear regression. Similarly, precipitation and solar radiation data were generated by merging NCEP reanalysis data, CRU TS3.1 precipitation data (Mitchell and Jones 2005), ISCCP-FD solar radiation data (Zhang et al. 2004), and site observations. For other climate inputs such as longwave radiation, wind speed, and relative humidity, NCEP reanalysis data were used. Satellite-based time-series data were taken from Terra/MODIS products. The vegetation index (MOD13Q1) (Huete et al. 2002) and LAI/FPAR (MOD15A2) (Myneni et al. 2002) products were used after screening of the data quality check. Because Terra/MODIS data became available from 2000, the data prior to 2000 were used for the period from 1901 to 1999. Static data were provided from the site information, if available. Otherwise, global data (Harmonized World Soil Database for soil texture and depth; FAO/IIASA/ISRIC/ISSCAS/JRC 2012) were used.

Generally, a consistent protocol was applied to all models. The model spin-up was first performed and then the models were executed using time-variable inputs from 1901 to 2010. For most of the models, the spin-up was conducted using the 1901–1930 climate data repeatedly until the soil carbon reached an equilibrium. For the models that are not intended to use multiple years of data for spin-up (BEAMS; used 1901 climate data repeatedly for the spin-up) or adopt different spin-up strategy (VISIT; used 1901–2010 climate data repeatedly for the spin-up), other pertinent approaches for the spin-up were used. Due to different temporal scales (i.e., from hourly to monthly) of the model outputs, we have chosen a monthly scale to analyze the model outputs compared to the observations.

The Taylor diagram (Taylor 2001) is known as a useful tool in the studies of model–data intercomparison for its effective visual framework (e.g., Schwalm 2010). We presented the results of model performance by plotting the standard deviation (σ) of the model outputs, RMSE, and correlation coefficient (R) together in one plot. Model performance is indicated by proximity to the benchmark. For the carbon fluxes (i.e., GPP, RE, and NEE), monthly averages for each site were used for the Taylor diagrams. The observed monthly carbon fluxes were normalized by the observed σ and this was used as a benchmark. Both the σ of the modeled monthly carbon fluxes and the RMSE between the observed and the modeled were also normalized by the observed σ.

We performed the following two analyses. First, to determine how well the current terrestrial biosphere models simulate carbon fluxes at each site and identify the sites showing an obvious disparity between the model simulation and the observations, the site-by-site differences in the model performance were evaluated using the differences between the model ensemble mean and the observation at each site. Second, to assess the performance and characteristic of each model, the model-by-model differences in model performance were estimated using the modeled and observed carbon fluxes across all sites. In addition to Taylor diagrams, the mean monthly variations of the modeled and observed GPP, RE, and NEE were shown in Figs. S2, S3, and S4, respectively.

Results

Site-by-site differences in model performance

The terrestrial biosphere models underestimate the σ of monthly carbon fluxes at most sites (Fig. 1), and the model simulations of GPP and RE are better than those of NEE (Fig. 1). For example, the models show smaller normalized σ of the monthly GPP and RE variations at many sites (i.e., normalized $\sigma < 0.8$ at 12 and 10 sites for GPP and RE, respectively) (Fig. 1a, b). The majority of the sites exhibit high R (i.e., $R > 0.95$ at 13 and 12 sites for GPP and RE, respectively) and low normalized RMSE values (i.e., RMSE $<0.5\sigma$ at 13 and 12 sites for GPP and RE, respectively) (Fig. 1a, b). The site-by-site model performance for NEE shows that the model simulations of NEE is inferior to those of GPP and RE. The R values of NEE is lower than those of GPP and RE, and no sites exhibit $R > 0.95$ (Fig. 1c). The normalized RMSE values of NEE is also greater than those of GPP and RE with only two sites (MMF and QHB) exhibiting RMSE $<0.5\sigma$. The lower R and higher normalized RMSE values in NEE suggest that NEE is more difficult to predict than GPP and RE because NEE represents a delicate difference of two large quantities (GPP and RE), and uncertainties in simulated GPP and RE are propagated into the NEE estimation. In addition, the models underestimate normalized σ of NEE at most sites (22 sites).

The models performed poorly at the following sites (Fig. 1; Table 1): tropical forests (BNS, MKL, PDF, and SKR; the mean values of normalized σ, normalized RMSE and R over 4 sites are 0.38, 0.92 and 0.46 for GPP, and

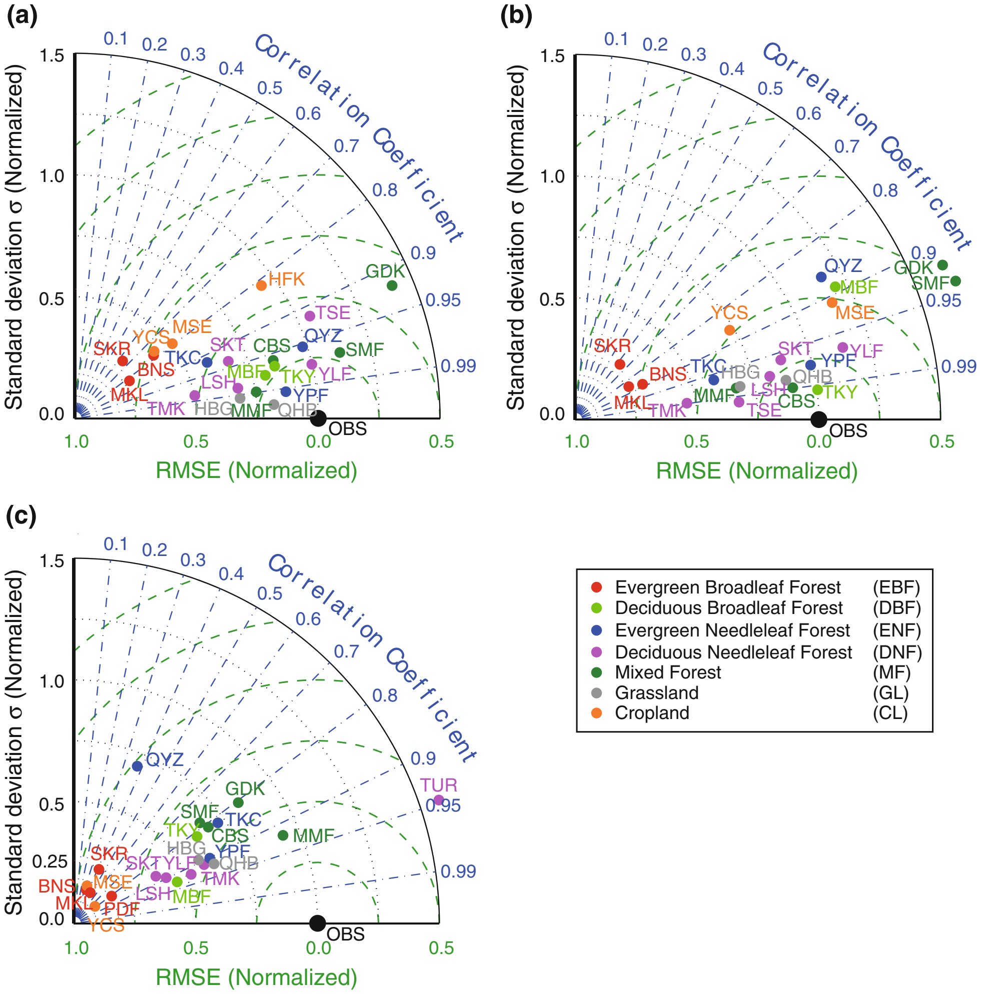

Fig. 1 Taylor diagram of the model performances for each site: **a** GPP, **b** RE, and **c** NEE. *Filled black circles* represent the mean model ensemble for each site. Benchmarks (shown as *OBS*) correspond to the observed monthly carbon fluxes normalized by the standard deviation of observed monthly carbon fluxes. The standard deviations and RMSEs are normalized by the standard deviations of the observed monthly data. The sites not shown in the figure have the following statistics: **a** TUR (normalized $\sigma = 3.0$, normalized RMSE $= 2.1$, $R = 0.98$) and PDF (normalized $\sigma = 0.53$, normalized RMSE $= 1.3$, $R = -0.42$), **b** TUR (normalized $\sigma = 4.5$, normalized RMSE $= 3.5$, $R = 0.95$), HFK (normalized $\sigma = 2.1$, normalized RMSE $= 1.2$, $R = 0.93$) and PDF (normalized $\sigma = 0.51$, normalized RMSE $= 1.4$, $R = -0.58$), and **c** TSE (normalized $\sigma = 1.6$, normalized RMSE $= 2.5$, $R = -0.81$) and HFK (normalized $\sigma = 0.25$, normalized RMSE $= 1.1$, $R = -0.23$)

Table 1 Statistics (normalized σ, normalized RMSE, and *R*) of model–data comparison in each ecosystem type

	GPP			RE			NEE		
	σ	RMSE	*R*	σ	RMSE	*R*	σ	RMSE	*R*
EBF	0.38	0.93	0.46	0.34	0.93	0.45	0.18	0.92	0.49
DBF	0.83	0.28	0.97	1.10	0.34	0.94	0.54	0.61	0.87
ENF	0.82	0.33	0.96	0.92	0.42	0.93	0.68	0.69	0.70
DNF	1.16	0.67	0.96	1.41	0.88	0.97	0.85	0.94	0.62
MF	1.04	0.37	0.96	1.22	0.54	0.96	0.78	0.55	0.83
GL	0.75	0.26	0.99	0.79	0.28	0.98	0.60	0.52	0.91
CL	0.62	0.66	0.79	1.32	0.73	0.90	0.18	0.99	0.29

Each number is the mean of each ecosystem type

DNF deciduous coniferous forest, *ENF* evergreen needleleaf forest, *MF* mixed forest, *DBF* deciduous broadleaf forest, *EBF* evergreen broadleaf forest, *GL* grassland, *CL* cropland

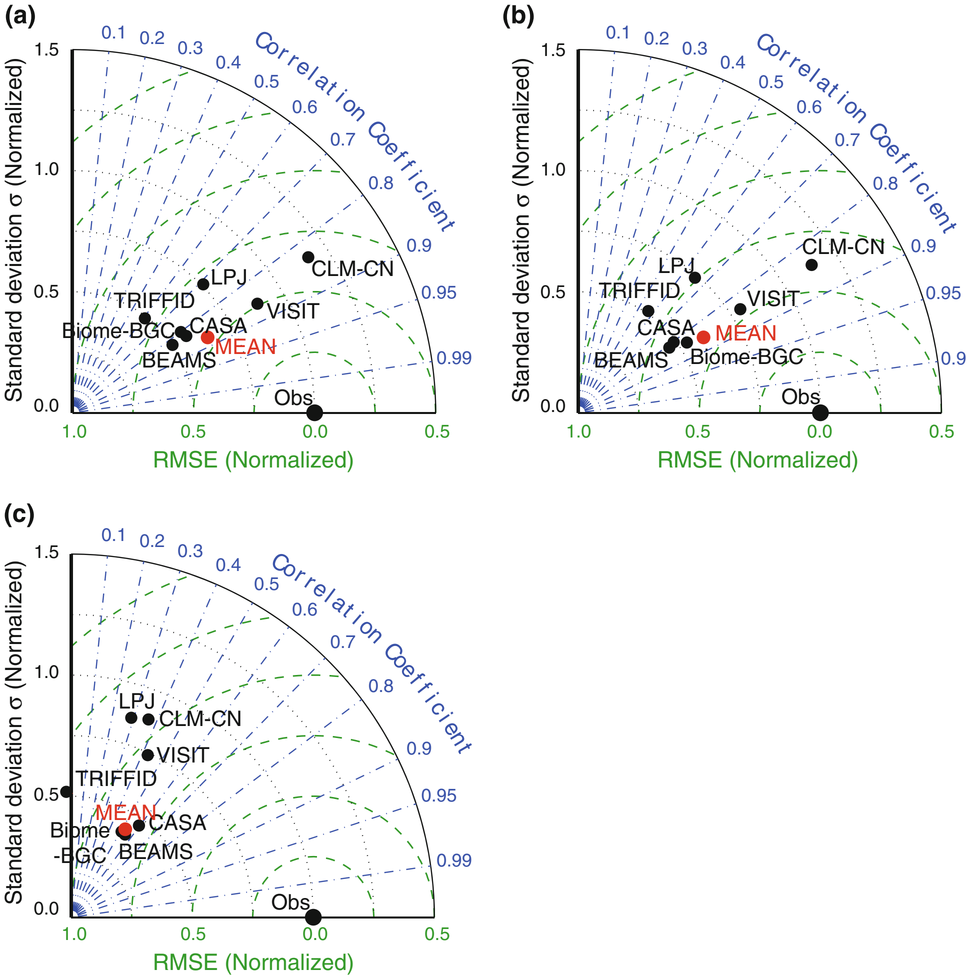

Fig. 2 Taylor diagram of the mean model performances across all sites: **a** GPP, **b** RE, and **c** NEE. *Filled black* and *red circles* correspond to individual models and ensemble mean performances across all sites, respectively. Benchmarks (shown as *OBS*) correspond to the observed monthly carbon fluxes normalized by the observed standard deviation. The standard deviations and RMSEs are normalized by the standard deviations of the observed monthly data (color figure online)

0.18, 0.92 and 0.49 for NEE); cropland (HFK, MSE, and YCN; the respective mean values of normalized σ, normalized RMSE and *R* are 0.62, 0.66 and 0.79 for GPP, and 0.18, 0.99 and 0.29 for NEE); severely disturbed sites (PDF with human-induced drain and TSE with clear-cut); and sites with anomalous decreases in GPP in the middle of the growing season due to light or water limitations (GDK, QYZ, and TKC).

Model-by-model differences in model performance

The analysis clearly indicates that the model-by-model differences in carbon fluxes estimates are mainly due to the differences in σ (Fig. 2). The seven model outputs exhibit generally similar R (0.6–0.9) and normalized RMSE (0.6–0.8) values, whereas they show different normalized σ (0.5–1.2) values for both GPP and RE (Fig. 2a, b). The CLM3.5-CN model had higher values of normalized σ ($\sim$1.2 of normalized σ) for both GPP and RE compared to the those of normalized σ from the other models (Fig. 2a, b). As shown in the site-by-site evaluation above, NEE exhibits inferior statistics compared to those of GPP and RE in the model-by-model evaluation. The model-by-model differences are explained by all three statistical measures: R (-0.05 to 0.6), normalized σ (0.4–0.9), and normalized RMSE (0.8–1.2) (Fig. 2c). The use of an ensemble mean value results in the best estimates of the observed findings among all single models for GPP and RE except for GPP by VISIT model, which shows the smallest normalized RMSE and highest R values.

Discussion and future perspectives

According to the analysis of the site-by-site differences, the terrestrial biosphere models had a poor predictability at tropical forest sites, cropland sites, disturbed sites, and the sites showing an anomalous decrease in GPP. First, tropical forest sites generally have the lowest values of R and normalized σ, and the highest values of normalized RMSE. Despite the recent attempts to apply various models to tropical forest ecosystems to analyze the controlling factors of the seasonal carbon cycles (e.g., Ichii et al. 2007; Verbeeck et al. 2011), an improvement of the modeling application to Asian tropical forests remains an important research need. Second, the simulated carbon cycles of cropland sites were poor, because some models that have cropland as an ecosystem type used the default settings for cropland phenology (when available), and others used grassland parameterization instead. Third, the sites with strong disturbance histories (i.e., TSE with clear-cut and PDF with human-induced drain) had poor model predictions because no model can yet account for these effects. Fourth, the observed anomalous decrease in GPP in the middle of the growing season was primarily caused by the intensive and extensive rainy season during the monsoons (at GDK and TKC sites) and a severe dry season (at QYZ site). These results indicate that the terrestrial biosphere models need to be improved in terms of model parameterization for the interplay between carbon and water dynamics for ecosystems in monsoon Asia.

The multi-model evaluation using the 24 CarboEastAsia sites demonstrated that the eight terrestrial biosphere models tend to underestimate the standard deviations of monthly variations (i.e., seasonal amplitude) in GPP, RE, and NEE. As a result, the underestimation of standard deviations can be propagated into errors and uncertainties in the estimation of model-based carbon budget especially for their seasonal maximum, at regional to continental scales. These site-level problems have commonly been reported in other model–observation comparison studies. For example, the tendency of the model underestimation compared to the observation has been reported in studies from North America (Schwalm 2010), Europe (Jung et al. 2007), and Japan (Ichii et al. 2010). Large discrepancies from the model-by-model comparisons have also been reported from North America (Schwalm 2010) and Japan (Ichii et al. 2010). Thus, further model refinements are necessary to reduce potential uncertainties in continental-scale carbon budget estimation using terrestrial biosphere models.

To further improve the terrestrial biosphere models, (1) treatment of the specific land covers (e.g., rice paddy, Li et al. 2004, and larch forests, Ueyama et al. 2010) unique to Asia, must be improved, and (2) natural disturbances such as monsoons (e.g., Kwon et al. 2010; Hong and Kim 2011), typhoons (Ito 2010), and human-induced disturbances (e.g., Ueyama et al. 2011) must be incorporated into the models. Such improvements may require a new framework in ecosystem modeling (e.g., resilience and thermodynamic approaches) to deal with self-organizing possibilities of ecosystems with disturbances and to bridge ecological and societal systems (e.g., Jorgensen et al. 2007).

Use of more model constraints and criteria of model evaluation is also important. For example, more observed parameters such as biomass and soil carbon (e.g., Richardson et al. 2010), and soil respiration (e.g., Liang et al. 2010; Tamai 2010) should be used in future model evaluation. In addition, other model evaluation criteria should be applied such as the use of the frequency domain (e.g., Mahecha et al. 2010; Hong and Kim 2011) and underlying interactions in ecosystem processes in terms of process network (Ruddel and Kumar 2009). Application of model–data integration schemes such as parameter optimization and assimilation is also important (e.g., Ichii et al. 2009; Ju et al. 2010) to eliminate the freedom of parameter tuning by hand. Model testing with long-term observations, including anomalous climate years, is required to test the sensitivities of the models to climate anomalies. Examples of climate anomalies in recent years include the widespread negative anomalies in temperature and radiation in the summer of 2003 (e.g., Saigusa et al. 2010), severe freezing in China in the winter of 2008 (e.g., Zhou et al. 2011), and the heatwave in Russia and Asia in the summer of 2010 (NOAA National Climatic Data Center 2010).

Further studies beyond model–data comparison are also required. This study demonstrated the large differences among the simulated carbon budgets; however, one of the major purposes of terrestrial biosphere modeling is to estimate more accurate carbon budget and to reduce uncertainties. Toward this objective, a more detailed model intercomparison focusing on specific processes is required. For example, Adams et al. (2004) compared the photosynthesis routine included in 18 terrestrial biosphere models, and evaluated their differences in sensitivity to climate variables. In addition, current terrestrial biosphere models have large uncertainties in the parameter tuning processes that are usually conducted manually. To reduce uncertainties caused by human factors, we need to set objective standards for the model evaluations such as the use of a common model parameter across models, the application of model parameter optimization routines, and the removal of outlying models. We also need to go beyond model intercomparison and identify the weakness of each model and develop better submodels for models as needed. The next step is to envision and develop an integrated next generation model based on the careful assessment of individual terrestrial biosphere models.

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