Biogeosciences Discuss., 10, 17469–17509, 2013
www.biogeosciences-discuss.net/10/17469/2013/
doi:10.5194/bgd-10-17469-2013

Biogeosciences
Discussions
Open Access

Impacts of droughts on carbon sequestration by China's terrestrial ecosystems from 2000 to 2011

Y. B. Liu[1,2,3], Y. L. Zhou[1,4], W. M. Ju[1,2], S. Q. Wang[5], X. C. Wu[1,2], and M. Z. He[1,2]

[1]Jiangsu Provincial Key Laboratory of Geographic Information Science and Technology, Nanjing University, Nanjing, 210023, China
[2]International Institute for Earth System Sciences, Nanjing University, Nanjing, 210023, China
[3]Jiangsu Key Laboratory of Agricultural Meteorology, College of Applied Meteorology, Nanjing University of Information Science and Technology, Nanjing, 210044, China
[4]School of Geographic and Oceanographic Sciences, Nanjing University, Nanjing, 210023, China
[5]Key Laboratory of Ecosystem Network Observation and Modeling, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, 100101, China

Received: 23 October 2013 – Accepted: 23 October 2013 – Published: 6 November 2013

Correspondence to: Y. B. Liu (yiboliu2012@163.com) and W. M. Ju (juweimin@nju.edu.cn)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

In recent years, droughts have frequently hit China's terrestrial ecosystems. How these droughts affected carbon sequestration by China's terrestrial ecosystems is still unclear. In this study, the process-based Boreal Ecosystem Productivity Simulator (BEPS) model, driven by remotely sensed vegetation parameters, was employed to assess the effects of droughts on net ecosystem productivity (NEP) of terrestrial ecosystems in China for the period from 2000 to 2011. Different categories of droughts, as indicated by a standard precipitation index (SPI), extensively hit terrestrial ecosystems in China, particularly in 2001, 2006, 2009 and 2011. The national total NEP exhibited a slight decline of $-11.3\,\mathrm{Tg\,C\,yr^{-2}}$ during the study period, mainly due to large reductions of NEP in typical drought-hit years 2001, 2006, 2009 and 2011, ranging from $61.1\,\mathrm{Tg\,C\,yr^{-1}}$ to $168.8\,\mathrm{Tg\,C\,yr^{-1}}$. National and regional total NEP anomalies were correlated with corresponding annual mean SPI, especially in Northwest China, North China, Central China, and Southwest China. In drought years, the reductions of NEP might be caused by a larger decrease in gross primary productivity (GPP) than in respiration (RE) (2001 and 2011), a decrease in GPP and an increase in RE (2009), or a larger increase in RE than in GPP (2006). Droughts had lagged effects of up to 3–6 months on NEP due to different reactions of GPP and RE to droughts. In east humid and warm parts of China, droughts have predominant and short-term lagged influences on NEP. In western cold and arid regions, the effects of droughts on NEP were relatively weaker and might last for a longer period of time.

1 Introduction

The exchange of CO_2 between land and the atmosphere is an important pathway in the global carbon cycle (Arnone et al., 2008; Schwalm et al., 2010). Carbon sequestration by terrestrial ecosystems is affected by a number of factors, including climate, atmospheric CO_2 concentration, nitrogen deposition, land cover types, and land use change. Extreme climate events, such as drought, could substantially affect ecosystem carbon fluxes and lead to significant inter-annual variability in regional and even global terrestrial carbon budget (Running, 2008; Xiao et al., 2011). In contrast to the gradual climate change, drought might intensively impact carbon sequestration by terrestrial ecosystems in a relatively short period through strong influences on both gross primary productivity (GPP) and respiration (RE), which releases carbon to the atmosphere (Baldocchi, 2005; Meir et al., 2008; Schwalm et al., 2010; van der Molen et al., 2011).

More frequent and severe droughts were projected to occur under future climate change, characterized by decreasing precipitation and increasing temperature, especially in the middle and high latitudes (IPCC, 2007; Dai, 2013). Owing to strong coupling between the carbon and water cycles (Law et al., 2002), the effects of drought events on terrestrial carbon sequestration have been intensively investigated in recent years (Cox et al., 2000; Zeng et al., 2004; Ciais et al., 2005; Wu and Chen, 2013). Models and remote sensing have been acted as effective tools for assessing the response of terrestrial carbon cycle to drought at regional and global scales (Chen et al., 2012a). Several modeling studies have been recently conducted to assess the impacts of drought on the productivity and carbon budget of terrestrial ecosystems for western North America (Schwalm et al., 2012), the southern United States (Chen et al., 2012a), Europe (Ciais et al., 2005; Reichstein et al., 2007; Vetter et al., 2008), Amazonia (Phillips et al., 2009; Potter et al., 2011; Nunes et al., 2012), East Asia (Saigusa et al., 2010; Xiao et al., 2009), the Northern Hemisphere mid-latitudes (Zeng et al., 2005), and the globe (Zhao and Running, 2010; Chen et al., 2013). All studies indicated that droughts significantly influenced the terrestrial carbon cycle and might even cause regional and global terrestrial ecosystems to shift from carbon sinks to carbon sources (Chen et al., 2013; Ponce Campos et al., 2013; Piao et al., 2013).

China has the third largest land area in the world, with diverse climates and biomes (Cao et al., 2003). Terrestrial ecosystems in China play an important role in the global terrestrial carbon sink. Quantifying the spatial and temporal variations of the terrestrial carbon budget in China is of great significance for studying past, current and future roles of terrestrial ecosystems in retarding the increase of atmospheric CO_2 concentration and climate change (Mu et al., 2008; Piao et al., 2009a; Tian et al., 2011b). The ability of terrestrial ecosystems in China to absorb carbon is limited by water availability, especially in vast arid and semiarid regions (Hu et al., 2010; Yi et al., 2010; Yu et al., 2013). Many severe drought episodes have occurred in China since the 1950s (Zou et al., 2005; Zhai et al., 2010), and especially in the first 10 yr of this century (Piao et al., 2009b; Qin et al., 2010; Lu et al., 2011; Wang et al., 2011; Wu et al., 2011). These droughts significantly influenced terrestrial carbon cycle at regional and national scales (Xiao et al., 2009).

Several studies have been devoted to investigate the impacts of droughts on regional or national terrestrial carbon budget in China. Working with tree-ring width chronologies and the Terrestrial Ecosystem Model (TEM), Xiao et al. (2009) discovered that severe and extended droughts during the 20th century substantially reduced ecosystem carbon sequestration, or even switched terrestrial ecosystems from carbon sinks to carbon sources. Using the Carnegie–Ames–Stanford approach (CASA) model, Pei et al. (2013) declared that some droughts in China during the period from 2001 to 2010 substantially reduced the countrywide net primary productivity (NPP), whereas others did not. Utilizing the MODIS GPP and NPP products, Zhang et al. (2012c) reported that the 2010 spring drought caused detectable reductions of GPP and NPP in southwestern China. Using three light use efficiency models (CASA, MODIS-GPP and EC-LUE (Eddy Covariance Light Use Efficiency) and one dynamic vegetation model (Integrated Biosphere Simulator, IBIS), Yuan et al. (2013) found that the carbon sink over North China declined 0.011 $\mathrm{Pg\,C\,yr^{-1}}$ during the 1999–2011 drought period. However, these studies mainly focused on the influences of droughts on GPP or NPP. How the national total net exchange of carbon between the atmosphere and terrestrial ecosystems is affected by droughts has not been thoroughly explored.

This study is devoted to assessing the impact of droughts on net ecosystem productivity (NEP) of terrestrial ecosystems in China over the period from 2000 to 2011 with a process-based Boreal Ecosystem Productivity Simulator (BEPS) model, which is driven by remotely sensed vegetation parameters. The objectives of this paper are to: (1) characterize the spatial and temporal variations of droughts during the period from 2000 to 2011 based on standard precipitation index (SPI); (2) evaluate the response of NEP to droughts for whole country and different regions of China; (3) assess the accumulative and lag effects of drought on carbon sequestration.

2 Data and methods

2.1 BEPS model description

The tool used in this study is the BEPS model (Liu et al., 1997), which originally stemmed from the FOREST biogeochemical cycles (FOREST-BGC) model (Running and Coughlan, 1988). This model includes photosynthesis, energy balance, hydrological, and soil biogeochemical modules (Ju et al., 2010b). It stratifies whole canopies into sunlit and shaded leaves to calculate daily carbon fixation using Farquhar's instantaneous leaf biochemical model (Farquhar et al., 1980) with a new temporal and spatial scaling scheme (Chen et al., 1999). Although initially developed to simulate NPP in boreal ecosystems in Canada, it has been improved in many ways and widely applied to estimate regional terrestrial carbon and water fluxes in China (Sun et al., 2004; Wang et al., 2005; Feng et al., 2007; Zhou et al., 2009; Ju et al., 2010a; Liu et al., 2013), North America (Liu et al., 1999; Ju et al., 2006; Sonnentag et al., 2008; Sprintsin et al., 2012; Zhang et al., 2012a), Europe (Wang et al., 2004), East Asia (Matsushita and Tamura, 2002; Zhang et al., 2010, 2012b), and globe (Chen et al., 2012b).

Details about the BEPS model have been fully described elsewhere (Liu et al., 1997, 2003; Chen et al., 1999, 2005; Ju et al., 2006). Only some major methodologies related to the calculation of NEP are briefly summarized here.

2.1.1 NEP calculation

NEP is calculated as the difference between photosynthesis and respiration:

$$\mathrm{NEP} = \mathrm{GPP} - R_\mathrm{m} - R_\mathrm{g} - R_\mathrm{h} \tag{1}$$

where R_h is the heterotrophic respiration, and maintenance respiration, R_m, and growth respiration, R_g, are the components of the autotrophic respiration. R_g is assumed to be 25 % of GPP and R_m is calculated as a function of biomass, temperature, and reference respiratory rate at 25 °C (Ju et al., 2006; Mo et al., 2008):

$$R_\mathrm{m} = \sum_{i=1}^{4} R_{\mathrm{m},i} = \sum_{i=1}^{4} M_i r_{\mathrm{m},i} Q_{10}^{(T-T_\mathrm{b})/10} \tag{2}$$

where M_i is the biomass carbon content (kg m^{-2}); subscript i denotes leaf, stem, coarse root, and fine root carbon pools, respectively; $r_{\mathrm{m},i}$ is the respiration rate at a base temperature T_b, set as 15 °C; T is the temperature.

The BEPS model simulates the dynamics of soil carbon using the methodology borrowed from the Century model (Parton et al., 1993). R_h is the total of carbon released from five litter carbon pools: surface structural, surface metabolic, soil structural, soil metabolic, and coarse woody and from four soil carbon pools: surface and soil microbes, slow, and passive (Ju et al., 2006; Mo et al., 2008):

$$R_\mathrm{h} = \sum_{j=1}^{9} \tau_j k_j C_j \tag{3}$$

where τ_j is the prescribed respiration coefficient of pool j; k_j the decomposition rate of pool j which equals the prescribed maximum decomposition rate down-scaled according to soil temperature, water content, texture, and lignin content; and C_j is the size of pool j, updated for each time step.

2.1.2 Regulation of stomatal conductance by soil water content

In the BEPS, the Jarvis model used to determine stomatal conductance of sunlit and shaded leaves (Jarvis, 1976) is regulated by temperature, atmospheric vapor pressure deficit, photosynthetic photon flux density, and soil water content. Assuming that vegetation is able to optimize the uptake of soil water, the soil water scalar, f_w, is determined from:

$$f_\mathrm{w} = \sum_{i=1}^{n} f_{\mathrm{w},i}\beta_i \tag{4}$$

where $f_{\mathrm{w},i}$ is the soil water stress factor in layer i, and β_i is the weight of layer i expressed as a function of soil water availability and root abundance (Ju et al., 2006):

$$\beta_i = \frac{r_i f_{\mathrm{w},i}}{\sum_{i=1}^{n} r_i f_{\mathrm{w},i}} \tag{5}$$

where r_i is the root fraction within layer i as determined from Zhang and Wegehenkel. (2006). The term $f_{\mathrm{w},i}$ in layer i is calculated as a function of volumetric soil water content, wilting point, field capacity, and porosity of soil layer i (Chen et al., 2005; Ju et al., 2010a).

2.2 Data used

The BEPS model is driven by both spatially variant and invariant datasets. Atmospheric $\mathrm{CO_2}$ concentration is assumed to be spatially homogenous. The spatially variant inputs into the BEPS include:

(1) Remote sensing data: these include yearly MODIS land cover datasets (MCD12Q1 V051) from 2001 to 2010 (Friedl et al., 2010) and 8 day leaf area index (LAI) from 2000 to 2011. The LAI dataset were inverted using the MODIS

reflectance product (MOD09A1 V05) and an algorithm based on a 4-scale geometric optical model (Deng et al., 2006; Liu et al., 2012). Previous studies proved that LAI inverted using this algorithm has superiority over the existing MODIS product (Pisek et al., 2007; Garrigues et al., 2008).

(2) Meteorological data: daily maximum and minimum air temperatures, precipitation, relative humidity, and incoming solar radiation required to force the BEPS model were interpolated from observations at 753 basic meteorological stations across China using the inverse distance weight method. In the interpolation of temperatures, a lapse rate of 6 °C per 1000 m was assumed. Incoming solar radiation is not observed at all meteorological stations, so it was estimated according to sunshine duration measurements at stations without solar radiation observations.

(3) Soil data: the volumetric fractions of clay, sand, and silt were interpolated from the soil texture maps developed by Shangguan et al. (2012) on the basis of the 1 : 1 000 000 scale soil map of China and 8595 soil profiles recorded in the second national soil survey dataset. The fractions of clay, sand and silt were used to estimate hydrological parameters, including the wilting point (water potential at 1500 kPa), field capacity (water potential at 33 kPa), porosity, saturated hydrological conductivity, and air entry water potential.

2.3 Drought assessment

A variety of indices have been developed to assess drought severity (Mishra and Singh, 2010; Dai, 2011). In this study, SPI was used as the indictor of drought severity, owing to its simplicity, temporal flexibility and spatial consistency (Hayes et al., 1999; Chen et al., 2012a). Recently, many studies have proved SPI to be effective at monitoring drought in China (Zhai et al., 2010; He et al., 2011; Pei et al., 2013; Zhang and Jia, 2013). The 1, 3, 6, 9 and 12 months SPIs for each month were calculated using monthly precipitation data over the period from 1970 to 2011. For a given month, the L ($L = 1$, 3, 6, 9, 12) months SPI is calculated using monthly precipitation data in the current and previous ($L-1$) months. Following McKee et al. (1993) and the classification standard of meteorological drought issued by the China Meteorological Administration (Zhang et al., 2011), precipitation deficit in a given year was classified into 9 categories according to the 12 month SPIs through the end of December (Table 1).

2.4 Assessment of carbon flux anomaly

The NEP anomaly caused by drought was assessed using a standardized anomaly index (SAI) that has been used by others (Peters et al., 2002; Lotsch et al., 2005; Xu et al., 2012; Pei et al., 2013):

$$\mathrm{NEP_{SAI}}(i) = [\mathrm{NEP}(i) - \mathrm{Mean(NEP)}]/\mathrm{Std(NEP)} \tag{6}$$

where $\mathrm{NEP_{SAI}}(i)$ is the NEP anomaly for year i, $\mathrm{NEP}(i)$ is the NEP in year i; Mean(NEP) and Std(NEP) are respectively the mean and standard deviation of the annual NEP during 2000–2011. The anomalies of GPP ($\mathrm{GPP_{SAI}}$) and RE ($\mathrm{RE_{SAI}}$) are assessed in the same way.

The carbon flux anomalies were classified into 5 categories: near normal ($|\mathrm{SAI}| \le 0.5$), slightly anomalous ($0.5 < |\mathrm{SAI}| \le 1$), moderately anomalous ($1 < |\mathrm{SAI}| \le 1.5$), severely anomalous ($1.5 < |\mathrm{SAI}| \le 2$), and extremely anomalous ($|\mathrm{SAI}| > 2$).

2.5 Assessment of accumulative lagged effects of drought on carbon sequestration

The accumulative lagged effects of drought on carbon sequestration was assessed on the basis of the correlations between monthly $\mathrm{NEP_{SAI}}$ values and monthly SPI. For each pixel, the correlation coefficient can be calculated as follows:

$$R(m,L) = \frac{\sum_{n=1}^{12}\left[\mathrm{NEP_{SAI}}(m,n) - \overline{\mathrm{NEP_{SAI}}(m)}\right]\left[\mathrm{SPI}(m,L,n) - \overline{\mathrm{SPI}(m,L)}\right]}{\sqrt{\sum_{n=1}^{12}\left[\mathrm{NEP_{SAI}}(m,n) - \overline{\mathrm{NEP_{SAI}}(m)}\right]^2}\sqrt{\sum_{n=1}^{12}\left[\mathrm{SPI}(m,L,n) - \overline{\mathrm{SPI}(m,L)}\right]^2}} \tag{7}$$

where $R(m,L)$ is the correlation coefficient between $\mathrm{NEP_{SAI}}$ and SPI in month m at a given L value ($L = 1, 3, 6, 9, 12$) for a specific pixel, $\mathrm{NEP_{SAI}}(m,n)$ is the $\mathrm{NEP_{SAI}}$ value in month m of year n, $\overline{\mathrm{NEP_{SAI}}(m)}$ is the average of $\mathrm{NEP_{SAI}}(m,n)$ over 12 yr, $\mathrm{SPI}(m,L,n)$ is the SPI value for a given L in month m of year n, $\overline{\mathrm{SPI}(m,L)}$ is the average of $\mathrm{SPI}(m,L)$ values over 12 yr. A value of L producing the largest $R(m,L)$ indicates that drought has accumulative lagged effects up to L months on NEP.

For better analysis of spatial and temporal patterns of drought events and of the terrestrial carbon cycle responses, China was divided into nine climatic zones (Piao et al., 2009a), which are displayed in Fig. 1.

3 Results

3.1 Spatial and temporal variations of drought in China during 2000–2011

Figure 2 shows the national means of annual SPI (the 12 month SPIs through the end of December) in China for the period from 1970 to 2011, indicating more droughts occurred in China from 2000 to 2011, in comparison with previous three decades. The national annual mean SPI was below zero in 2000, 2001, 2004, 2006, 2009 and 2011. It was even smaller than −0.20 in 2001, 2006, 2009 and 2011, indicating that China was widely hit by severe droughts in these four years. In 2001 and 2009, areas hit by different degrees of droughts accounted for 46.9 % and 48.8 % of the national total, respectively. Droughts in 2001 and 2011 were more serious, with above 20 % of the national total area affected by moderate, severe, and extreme droughts (Fig. 3).

In 2001, 2006, 2009 and 2011, the differences in the severity and areas of drought were distinguishable. In 2001, drought occurred in all regions but the Tibetan Plateau, South and Southwest China (Fig. 4). Areas affected by moderate and severe droughts were mainly located in Northeast China, Inner Mongolia, North China, and Central China. The drought in 2011 was recognized as the most serious one in the recent 60 yr (Sun and Yang, 2012). Vast areas of Southwest, Central, South and Southeast China were hit by moderate to extreme droughts, and those in Yunnan, Guizhou and Hunan Provinces were extremely serious.

Drought also occurred widely over China in 2009. However, the severity of drought was mostly mild to moderate (Gao and Yang, 2009; Lu et al., 2011; Barriopedro et al., 2012). Moderate drought mainly occurred in the south parts of both Southwest China and the Tibetan Plateau. In 2006, drought was mostly mild (Fig. 3). Moderate drought only occurred in areas around Chongqing (Wang et al., 2011; Wu et al., 2011).

3.2 Response of carbon sequestration to droughts

Figure 5 shows the annual departures of national total NEP from the multiyear mean over the period from 2000 to 2011. During the past 12 yr, the national total of NEP exhibited a slightly decreasing trend, at an average rate of $-11.3\,\mathrm{Tg\,C\,yr^{-2}}$. This decline of national NEP was mainly caused by a significant decrease of NEP in 2001, 2006, 2009 and 2011. In these four typical drought years, the national totals of NEP respectively decreased by 62.9, 88.0, 168.8 and $61.1\,\mathrm{Tg\,C\,yr^{-1}}$. The annual anomalies of national total NEP were correlated with national means of annual SPI ($r = 0.54$, $p = 0.06$). The main drivers for NEP reductions differed in different years. Annual total GPP and RE both decreased in 2001 and 2011 in comparison to 12 yr means. The larger decrease of GPP than RE resulted in sizeable reductions of annual total NEP in these two years. In 2006, national total GPP increased slightly while national total RE increased at a larger magnitude, causing notable decrease in the national NEP. The drought in 2009 caused a decrease in national total GPP and an increase in national total RE, resulting in the largest decrease of national total NEP in the study period.

In 2001, the decrease of simulated NEP mainly occurred in regions north of the Yangtze River (the blue and cyan colored areas in Fig. 6), including most of North China, the north parts of Southeast and Central China, and the east of Northwest China (Fig. 6). In drought affected regions, both annual GPP and RE decreased owing to low water availability. The reduction of GPP was larger than that of RE in most areas, resulting in decreases of NEP, which were significant in North and Northwest China. The SAI values of total NEP in these two regions were below −1.5 (Fig. 7).

The decrease of NEP in 2006 mainly occurred in the central areas of China (the blue and cyan colored areas in Fig. 6), such as the north parts of Southwest and Central China, the north and middle parts of Southeast China, and the east of Tibetan Plateau. The reduction of carbon sequestration in drought affected areas was mainly caused by the slight decrease of GPP and slight to severe increase of RE. The SAI values of regional total NEP in Southwest and Central China were −1.25 and −1.26, respectively (Figs. 6 and 7), indicating moderate reductions of regional total NEP here.

NEP decreased in most regions of China in 2009 with the exception of Northeast China, most of the Tibetan Plateau, and the western part of Northwest China (Fig. 6). The decrease of NEP was mostly caused by slight to moderate decreases of GPP and slight to severe increases in RE. Regional NEP totals decreased extremely in south China ($NEP_{SAI} = -2.23$), severely in the Tibetan Plateau ($NEP_{SAI} = -1.50$) and Southwest China ($NEP_{SAI} = -1.80$), and moderately in Central ($NEP_{SAI} = -1.42$) and Southeast China ($NEP_{SAI} = -1.08$) (Fig. 7).

In 2011, moderate to extreme droughts hit regions south of the Yangtze River (Fig. 4), resulting in detectable decreases in GPP. Meanwhile, RE also decreased to some extent due to the reduction of heterotrophic respiration caused by low soil water availability. As a consequence, the decrease of NEP was smaller in 2011 than that in 2009. The decrease of NEP mainly occurred in Central China, the eastern part of Southwest China, and adjacent areas of North and Southeast China (Fig. 6).

Figure 7 shows the anomalies of annual total GPP, RE and NEP, along with annual mean SPI in different regions of China. The anomalies of annual total NEP were positively correlated with annual mean SPI at the 0.01 significance level in Northwest, North, Central, and Southwest China. However, the linkages of NEP anomalies with annual mean SPI were not significant in Northeast China, Inner Mongolia, and the Tibetan Plateau, where temperature is the dominant factor controlling carbon sequestration. It should be kept in mind that most areas of Inner Mongolia are arid and semiarid, so vegetation activity is mainly controlled by water availability. However, in the northeastern part of Inner Mongolia, the climate is humid and water availability does not act as the crucial limiting factor of vegetation activity. The large fraction of total carbon sequestration capacity in Inner Mongolia is contributed by terrestrial ecosystems in the northeast part. Therefore, total carbon sequestration capacity in Inner Mongolia is not sensitive to precipitation anomalies. In humid Southeast and South China, the total NEP anomaly is also not significantly correlated with annual mean SPI. In these regions, temperature and water availability are normally suitable for vegetation growth. Radiation is a key factor driving the interannual variability of productivity (Nemani et al., 2003). Precipitation increase is normally associated with the decrease of radiation, possibly causing NEP decrease to some extent.

The simulations indicated that drought events in China during the past 12 yr generally caused detectable reductions of GPP and NEP in strongly drought-affected areas (Figs. 6 and 7). Similar negative effects of drought on carbon sequestration were also reported in some previous studies conducted in Europe (Ciais et al., 2005; Vetter et al., 2008) and America (Xiao et al., 2011; Chen et al., 2012a; Schwalm et al., 2012).

3.3 The accumulative lagged effect of drought on NEP

Figure 8 shows the maximum correlation coefficient between SPI and monthly $\mathrm{NEP}_{\mathrm{SAI}}$ for the period 2000–2011 and the SPI time-scales at which the maximum correlation between SPI and $\mathrm{NEP}_{\mathrm{SAI}}$ is found. $\mathrm{NEP}_{\mathrm{SAI}}$ is correlated with SPI at the 0.05 significance level over 82 % of the vegetated land areas (Fig. 8a), especially in Southwest, Southeast, and Northeast China. The SPI time-scales, at which correlation between SPI and $\mathrm{NEP}_{\mathrm{SAI}}$ maximizes, exhibit distinguishable spatial patterns (Fig. 8b). Drought had relatively shorter time-scales accumulative lagged effect on NEP in the southern regions of China (e.g., 1–3 month). In cropland regions, NEP responded to drought at middle time-scales (about 6 months). Drought might impact on NEP at longer time scales in cold grassland areas than in other regions.

4 Discussion

4.1 The impact of drought on the national terrestrial carbon budget

Many studies indicated that terrestrial ecosystems had been acting as a carbon sink in recent decades, although estimates are still inconsistent (Cao et al., 2003; Houghton and Hackler, 2003; Pan et al., 2004; Fang et al., 2007; Piao et al., 2009a; Tian et al., 2011a). Piao et al. (2009a) suggested that terrestrial carbon sinks amounted to 0.19–0.26 Pg C during the 1980s and 1990s, accounting for 28–37 % of concurrent CO_2 emissions in China. In recent years, anthropogenic carbon emissions increased very quickly in China (Wang et al., 2012a), implying the increasing importance of maintaining terrestrial carbon sinks. Our simulation indicates that the national total NEP of China slightly declined during the period from 2000 to 2011 ($-11.3\,\mathrm{Tg\,C\,yr^{-2}}$), mainly due to considerable reductions of NEP caused by widely distributed severe droughts in 2001, 2006, 2009 and 2011. In these four years, the decreases of national total NEP ranged from $61.1\,\mathrm{Tg\,C\,yr^{-1}}$ to $168.8\,\mathrm{Tg\,C\,yr^{-1}}$, approximately 30 % to 94 % of the average carbon sink strength of forest during 1999–2008 estimated based on forest inventory data (Pan et al., 2011; Guo et al., 2013; Zhang et al., 2013). Therefore, drought is a dangerous threat to the terrestrial carbon sink in China. With possible increases in drought frequency and severity in future (IPCC, 2007; Dai, 2013), the role of China's terrestrial ecosystems in offsetting fossil fuel emission might be weakened.

4.2 The lagged effect of drought on carbon sequestration by terrestrial ecosystems

It was found here that drought has lagged effects on NEP. The time-scales, at which NEP most significantly respond to drought, spatially differ, rapid in eastern warm humid regions and slow in northern and western cold semiarid grassland regions. Similar findings have also been reported in other studies, which used greenness index, chronologies of ring width, and NPP as vegetation growth indictors for assessing the influences of drought on vegetation. The lag time of drought affecting growth indicators is related to vegetation types, and local conditions. Ji and Peters (2003) found out that the 3 months SPI was most strongly correlated with the growing-season NDVI in American Great Plains. Based on the analysis of NDVI-SPI co-variability over different temporal-scales, Lotsch et al. (2003) suggested that 5-month SPI be used to assess the response of terrestrial ecosystems to drought. Jain et al. (2010) found that the NDVI has the highest correlation with 1-month, 3-month, and 9-month SPI in different regions of India. In Texas of US, the growing-season vegetation condition index (NDVI-based) was found to be most strongly correlated with the 6-month and 9-month SPI (Quiring and Ganesh, 2010). The correlation between chronologies of ring width and different time scales SPI for eight tree species in north-eastern Spain indicated that the tree growth most significantly responded to 9–11 months SPI for xeric sites and to shorter than 5 months SPI for mesic sites, respectively (Pasho et al., 2011). Recent studies on the effects of drought on NPP in China found out that correlations between drought intensity and NPP anomalies were the strongest during or after the drought intensity peaked (Chen et al., 2013; Pei et al., 2013). With vegetation indices from satellite imagery, tree-ring growth series, and aboveground net primary production records, Vicente-Serrano et al. (2013) recently reported the responses of global biomes to drought, both arid and humid biomes respond to drought at short time-scales while semiarid and subhumid biomes respond to drought at long time-scales. This is similar to our findings in this study. Based on in situ eddy covariance flux data and meteorological observation data at Qianyanzhou station, southern China, Huang et al. (2013) found drought exerted an approximate one month negatively lagged effect on potential productivity.

NEP is the balance between GPP and RE. The response of NEP to drought depends on how GPP and RE react to drought. At the initiation stage of drought, surface soil becomes dry but deep soil is still wet, so plants are able to take in water from deep soils to maintain normal stomata functional and carbon assimilation. Meanwhile, heterotrophic respiration is limited by low water availability in surface soil. Consequently, NEP would not decrease or would even increase. With the continuation of drought, water in deep soil layers will diminish and large decreases of GPP will occur, resulting in a reduction of NEP (Ju et al., 2006; Barr et al., 2007). These phenomena have been confirmed by eddy covariance measurements (Granier et al., 2007; Kljun et al., 2007). Krishnan et al. (2006) reported that after experiencing a 3 yr long drought, a boreal aspen stand in central Saskatchewan, Canada, declined in both growth and leaf area index even 2 yr after the drought. Pereira et al. (2007) demonstrated that the GPP, RE, and NEP of a Eucalyptus plantation located in southern Portugal, decreased during the drought years, the largest absolute decrease occurring in the second drought year.

4.3 Uncertainties and remaining issues

In this study, the response of terrestrial carbon fluxes in China to droughts was explored with the BEPS model, driven by remote sensing data. It should be kept in mind that there might be some uncertainties. Explicit soil water content dynamics is pivotal to understanding the impacts of drought on carbon sequestration by terrestrial ecosystems (Reichstein et al., 2002; Samanta et al., 2011). Similarly to most of other ecological models, the BEPS model used here does not account for the horizontal movement of soil water. This simplification would definitely over or underestimate the impact of drought on carbon sequestration in low or upper slopes areas. Irrigation is popularly practiced for most croplands in China, and was not included in the BEPS model. Consequently, the negative effects of drought on carbon sequestration by croplands might be overestimated.

The LAI is a key input to the BEPS model. In this study, the LAI was inverted using the MODIS reflectance data. Although the advantages of this LAI inversion algorithm have been proved in a series of previous studies, the inverted LAI still contain some uncertainties. The quality of the LAI depends largely on the quality of MODIS reflectance data, which is not guaranteed in many areas of China, especially in summer. A locally adjusted cubic-spline capping (LACC) method (Chen et al., 2006) was employed here to remove unrealistic fluctuations of LAI caused by residual cloud contamination and atmospheric noise. However, it is impossible to remove noise using the LACC method if good quality MODIS data are not available for a length period. The uncertainty in LAI would be propagated into estimated NEP.

NEP is affected by a number of factors, such as climate, disturbances and land cover change. Here the focused is only on the influence of extensively severe droughts on the terrestrial NEP cycle in China. Droughts might invoke other disturbances, such as fire, disease, insects, mortality or re-growth (Allen et al., 2010; Peng et al., 2011; van der Molen et al., 2011; Ma et al., 2012). These indirect effects of droughts on terrestrial carbon sequestration were not explored here. Land cover and land use change could also significantly modify the terrestrial carbon cycle (Piao et al., 2007; Xiao et al., 2009). During the study period, both the dramatic urbanization (Wang et al., 2012b) and large-scale forest plantation programs have concurrently occurred in China (Piao et al., 2012), thus impacting terrestrial carbon cycles at regional and national scales. These effects were not explicitly quantified here and require future research.

5 Conclusions

In this study, the influences of drought on carbon sequestration by terrestrial ecosystems during the period from 2000 to 2011 were assessed by model simulation and remote sensing data. The main conclusions are:

(1) Drought, as indicated by the SPI, occurred extensively and frequently in China during the period from 2000 to 2011, especially in 2001, 2006, 2009 and 2011. The spatial patterns of the droughts differed in these four years.

(2) The national total NEP slightly declined by $-11.3\,\mathrm{Tg\,C\,yr^{-2}}$ during the period from 2000 to 2011, mainly due to the large reductions of NEP in 2001, 2006, 2009 and 2011. Anomalies of national total NEP were correlated with annual SPI ($r = 0.54$, $p = 0.06$). The regional totals of annual NEP were sensitive to precipitation

anomalies in Northwest, North, Central, and Southwest China, and not sensitive to precipitation anomalies in other regions.

(3) The drivers of national total NEP reductions differed among years. In 2001 and 2011, droughts caused both national totals of GPP and RE to decrease. The former decreased to a large degree, resulting in decreases of national total NEP. In 2006, droughts were mostly mild or moderate, and the decrease of NEP was caused by a smaller increase of GPP compared with RE. In 2009, the largest decreases of national total NEP during the study period was caused by the decrease of GPP and increase of RE.

(4) The drought has accumulative lagged effects on carbon sequestration. The speed and degree, at which NEP responds to drought, varies spatially, rapidly and significantly in east humid and warm regions of China. In contrast, NEP responds to drought relatively slowly and less significantly in northern and western cold arid and semiarid regions.

Acknowledgements. This study is funded by the National Basic Research Program of China (973 Program) (2010CB950702 and 2010CB833503). We would greatly thank Scott Munro, University of Toronto for editing this manuscript. We gratefully acknowledge the constructive suggestions by reviewers, which helped to improve the quality of manuscript greatly.

References

Allen, C. D., Macalady, A. K., Chenchouni, H., Bachelet, D., McDowell, N., Vennetier, M., Kitzberger, T., Rigling, A., Breshears, D. D., Hogg, E. H., Gonzalez, P., Fensham, R., Zhang, Z., Castro, J., Demidova, N., Lim, J. H., Allard, G., Running, S. W., Semerci, A., and Cobb, N.: A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests, Forest Ecol. Manag., 259, 660–684, 2010.

Arnone III, J. A., Verburg, P. S. J., Johnson, D. W., Larsen, J. D., Jasoni, R. L., Lucchesi, A. J., Batts, C. M., von Nagy, C., Coulombe, W. G., Schorran, D. E., Buck, P. E., Braswell, B. H., Coleman, J. S., Sherry, R. A., Wallace, L. L., Luo, Y., and Schimel, D. S.: Prolonged suppression of ecosystem carbon dioxide uptake after an anomalously warm year, Nature, 455, 383–386, doi:10.1038/nature07296, 2008.

Baldocchi, D.: Environmental science: the carbon cycle under stress, Nature, 437, 483–484, 2005.

Barr, A. G., Black, T. A., Hogg, E. H., Griffis, T. J., Morgenstern, K., Kljun, N., Theede, A., and Nesic, Z.: Climatic controls on the carbon and water balances of a boreal aspen forest, 1994–2003, Glob. Change Biol., 13, 561–576, 2007.

Barriopedro, D., Gouveia, C. M., Trigo, R. M., and Wang, L.: The 2009/10 drought in China: possible causes and impacts on vegetation, J. Hydrometeorol., 13, 1251–1267, doi:10.1175/jhm-d-11-074.1, 2012.

Cao, M. K., Prince, S. D., Li, K. R., Tao, B., Small, J., and Shao, X. M.: Response of terrestrial carbon uptake to climate interannual variability in China, Glob. Change Biol., 9, 536–546, 2003.

Chen, G., Tian, H., Zhang, C., Liu, M., Ren, W., Zhu, W., Chappelka, A. H., Prior, S. A., and Lockaby, G. B.: Drought in the Southern United States over the 20th century: variability and its impacts on terrestrial ecosystem productivity and carbon storage, Clim. Change, 114, 379–397, doi:10.1007/s10584-012-0410-z, 2012a.

Chen, J. M., Liu, J., Cihlar, J., and Goulden, M. L.: Daily canopy photosynthesis model through temporal and spatial scaling for remote sensing applications, Ecol. Model., 124, 99–119, 1999.

Chen, J. M., Chen, X. Y., Ju, W. M., and Geng, X. Y.: Distributed hydrological model for mapping evapotranspiration using remote sensing inputs, J. Hydrol., 305, 15–39, 2005.

Chen, J. M., Deng, F., and Chen, M. Z.: Locally adjusted cubic-spline capping for reconstructing seasonal trajectories of a satellite-derived surface parameter, IEEE T. Geosci. Remote, 44, 2230–2238, 2006.

Chen, J. M., Mo, G., Pisek, J., Liu, J., Deng, F., Ishizawa, M., and Chan, D.: Effects of foliage clumping on the estimation of global terrestrial gross primary productivity, Global Biogeochem. Cy., 26, GB1019, doi:10.1029/2010gb003996, 2012b.

Chen, T., Werf, G. R., Jeu, R. A. M., Wang, G., and Dolman, A. J.: A global analysis of the impact of drought on net primary productivity, Hydrol. Earth Syst. Sci., 17, 3885–3894, doi:10.5194/hess-17-3885-2013, 2013.

Ciais, P., Reichstein, M., Viovy, N., Granier, A., Ogee, J., Allard, V., Aubinet, M., Buchmann, N., Bernhofer, C., Carrara, A., Chevallier, F., De Noblet, N., Friend, A. D., Friedlingstein, P., Grunwald, T., Heinesch, B., Keronen, P., Knohl, A., Krinner, G., Loustau, D., Manca, G., Matteucci, G., Miglietta, F., Ourcival, J. M., Papale, D., Pilegaard, K., Rambal, S., Seufert, G., Soussana, J. F., Sanz, M. J., Schulze, E. D., Vesala, T., and Valentini, R.: Europe-wide reduction in primary productivity caused by the heat and drought in 2003, Nature, 437, 529–533, doi:10.1038/nature03972, 2005.

Cox, P. M., Betts, R. A., Jones, C. D., Spall, S. A., and Totterdell, I. J.: Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model, Nature, 408, 184–187, doi:10.1038/35041539, 2000.

Dai, A.: Increasing drought under global warming in observations and models, Nat. Clim. Change, 3, 171–171, 2013.

Dai, A. G.: Drought under global warming: a review, Wires Clim. Change, 2, 45–65, 2011.

Deng, F., Chen, J. M., Plummer, S., Chen, M. Z., and Pisek, J.: Algorithm for global leaf area index retrieval using satellite imagery, IEEE T. Geosci. Remote, 44, 2219–2229, doi:10.1109/tgrs.2006.872100, 2006.

Fang, J. Y., Guo, Z. D., Piao, S. L., and Chen, A. P.: Terrestrial vegetation carbon sinks in China, 1981–2000, Sci. China Ser. D, 50, 1341–1350, 2007.

Farquhar, G. D., Caemmerer, S. V., and Berry, J. A.: A biochemical-model of photosynthetic CO_2 assimilation in leaves of C_3 species, Planta, 149, 78–90, 1980.

Feng, X., Liu, G., Chen, J. M., Chen, M., Liu, J., Ju, W. M., Sun, R., and Zhou, W.: Net primary productivity of China's terrestrial ecosystems from a process model driven by remote sensing, J. Environ. Manage., 85, 563–573, doi:10.1016/j.jenvman.2006.09.021, 2007.

Friedl, M. A., Sulla-Menashe, D., Tan, B., Schneider, A., Ramankutty, N., Sibley, A., and Huang, X.: MODIS Collection 5 global land cover: algorithm refinements and characterization of new datasets, Remote Sens. Environ., 114, 168–182, doi:10.1016/j.rse.2009.08.016, 2010.

Gao, H. and Yang, S.: A severe drought event in northern China in winter 2008–2009 and the possible influences of La Nina and Tibetan Plateau, J. Geophys. Res.-Atmos., 114, D24104, doi:10.1029/2009JD012430, 2009.

Garrigues, S., Lacaze, R., Baret, F., Morisette, J. T., Weiss, M., Nickeson, J. E., Fernandes, R., Plummer, S., Shabanov, N. V., Myneni, R. B., Knyazikhin, Y., and Yang, W.: Validation and intercomparison of global Leaf Area Index products derived from remote sensing data, J. Geophys. Res.-Biogeo., 113, 20, doi:10.1029/2007jg000635, 2008.

Granier, A., Reichstein, M., Breda, N., Janssens, I. A., Falge, E., Ciais, P., Grunwald, T., Aubinet, M., Berbigier, P., Bernhofer, C., Buchmann, N., Facini, O., Grassi, G., Heinesch, B., Ilvesniemi, H., Keronen, P., Knohl, A., Kostner, B., Lagergren, F., Lindroth, A., Longdoz, B., Loustau, D., Mateus, J., Montagnani, L., Nys, C., Moors, E., Papale, D., Peiffer, M., Pilegaard, K., Pita, G., Pumpanen, J., Rambal, S., Rebmann, C., Rodrigues, A., Seufert, G., Tenhunen, J., Vesala, I., and Wang, Q.: Evidence for soil water control on carbon and water dynamics in European forests during the extremely dry year: 2003, Agr. Forest Meteorol., 143, 123–145, 2007.

Guo, Z. D., Hu, H. F., Li, P., Li, N. Y., and Fang, J. Y.: Spatio-temporal changes in biomass carbon sinks in China's forests from 1977 to 2008, Sci. China Life Sci., 56, 661–671, doi:10.1007/s11427-013-4492-2, 2013.

Hayes, M. J., Svoboda, M. D., Wilhite, D. A., and Vanyarkho, O. V.: Monitoring the 1996 drought using the standardized precipitation index, B. Am. Meteorol. Soc., 80, 429–438, doi:10.1175/1520-0477(1999)080<0429:mtduts>2.0.co;2, 1999.

He, B., Lu, A. F., Wu, J. J., Zhao, L., and Liu, M.: Drought hazard assessment and spatial characteristics analysis in China, J. Geograph. Sci., 21, 235–249, 2011.

Houghton, R. A. and Hackler, J. L.: Sources and sinks of carbon from land-use change in China, Global Biogeochem. Cy., 17, 1034, doi:10.1029/2002gb001970, 2003.

Hu, Z., Yu, G., Fan, J., Zhong, H., Wang, S., and Li, S.: Precipitation-use efficiency along a 4500 km grassland transect, Global. Ecol. Biogeogr., 19, 842–851, doi:10.1111/j.1466-8238.2010.00564.x, 2010.

Huang, K., Wang, S., Zhou, L., Wang, H., Liu, Y., and Yang, F.: Effects of drought and ice rain on potential productivity of a subtropical coniferous plantation from 2003 to 2010 based on eddy covariance flux observation, Environ. Res. Lett., 8, 035021, doi:10.1088/1748-9326/8/3/035021, 2013.

IPCC: Climate Change 2007: the Physical Science Basis: Working Group I Contribution to the Fourth Assessment Report of the IPCC, edited by: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., and Miller, H. L., Cambridge University Press, 2007.

Jain, S. K., Keshri, R., Goswami, A., and Sarkar, A.: Application of meteorological and vegetation indices for evaluation of drought impact: a case study for Rajasthan, India, Nat. Hazards, 54, 643–656, doi:10.1007/s11069-009-9493-x, 2010.

Jarvis, P. G.: The interpretation of variations in leaf water potential and stomatal conductance found in canopies in field, Philos. T. Roy. Soc. B, 273, 593–610, 1976.

Ji, L. and Peters, A. J.: Assessing vegetation response to drought in the northern Great Plains using vegetation and drought indices, Remote Sens. Environ., 87, 85–98, 2003.

Ju, W. M., Chen, J. M., Black, T. A., Barr, A. G., Liu, J., and Chen, B. Z.: Modelling multi-year coupled carbon and water fluxes in a boreal aspen forest, Agr. Forest Meteorol., 140, 136–151, 2006.

Ju, W. M., Gao, P., Wang, J., Zhou, Y. L., and Zhang, X. H.: Combining an ecological model with remote sensing and GIS techniques to monitor soil water content of croplands with a monsoon climate, Agr. Water Manage., 97, 1221–1231, 2010a.

Ju, W. M., Gao, P., Zhou, Y. L., Chen, J. M., Chen, S., and Li, X. F.: Prediction of summer grain crop yield with a process-based ecosystem model and remote sensing data for the northern area of the Jiangsu Province, China, Int. J. Remote Sens., 31, 1573–1587, doi:10.1080/01431160903475357, 2010b.

Kljun, N., Black, T. A., Griffis, T. J., Barr, A. G., Gaumont-Guay, D., Morgenstern, K., McCaughey, J. H., and Nesic, Z.: Response of net ecosystem productivity of three boreal forest stands to drought, Ecosystems, 10, 1039–1055, 2007.

Krishnan, P., Black, T. A., Grant, N. J., Barr, A. G., Hogg, E. T. H., Jassal, R. S., and Morgenstern, K.: Impact of changing soil moisture distribution on net ecosystem productivity of a boreal aspen forest during and following drought, Agr. Forest Meteorol., 139, 208–223, 2006.

Law, B. E., Falge, E., Gu, L., Baldocchi, D. D., Bakwin, P., Berbigier, P., Davis, K., Dolman, A. J., Falk, M., Fuentes, J. D., Goldstein, A., Granier, A., Grelle, A., Hollinger, D., Janssens, I. A., Jarvis, P., Jensen, N. O., Katul, G., Mahli, Y., Matteucci, G., Meyers, T., Monson, R., Munger, W., Oechel, W., Olson, R., Pilegaard, K., Paw, K. T., Thorgeirsson, H., Valentini, R., Verma, S., Vesala, T., Wilson, K., and Wofsy, S.: Environmental controls over carbon dioxide and water vapor exchange of terrestrial vegetation, Agr. Forest Meteorol., 113, 97–120, 2002.

Liu, J., Chen, J. M., Cihlar, J., and Park, W. M.: A process-based boreal ecosystem productivity simulator using remote sensing inputs, Remote Sens. Environ., 62, 158–175, 1997.

Liu, J., Chen, J. M., Cihlar, J., and Chen, W.: Net primary productivity distribution in the BOREAS region from a process model using satellite and surface data, J. Geophys. Res.-Atmos., 104, 27735–27754, 1999.

Liu, J., Chen, J. M., and Cihlar, J.: Mapping evapotranspiration based on remote sensing: an application to Canada's landmass, Water Resour. Res., 39, 1189, doi:10.1029/2002WR001680, 2003.

Liu, Y., Ju, W., Chen, J., Zhu, G., Xing, B., Zhu, J., and He, M.: Spatial and temporal variations of forest LAI in China during 2000–2010, Chinese Sci. Bull., 57, 2846–2856, doi:10.1007/s11434-012-5064-8, 2012.

Liu, Y., Ju, W., He, H., Wang, S., Sun, R., and Zhang, Y.: Changes of net primary productivity in China during recent 11 yr detected using an ecological model driven by MODIS data, Front. Earth Sci., 7, 112–127, doi:10.1007/s11707-012-0348-5, 2013.

Lotsch, A., Friedl, M. A., Anderson, B. T., and Tucker, C. J.: Coupled vegetation–precipitation variability observed from satellite and climate records, Geophys. Res. Lett., 30, 1774, doi:10.1029/2003gl017506, 2003.

Lotsch, A., Friedl, M. A., Anderson, B. T., and Tucker, C. J.: Response of terrestrial ecosystems to recent Northern Hemispheric drought, Geophys. Res. Lett., 32, L06705, doi:10.1029/2004gl022043, 2005.

Lu, E., Luo, Y., Zhang, R., Wu, Q., and Liu, L.: Regional atmospheric anomalies responsible for the 2009–2010 severe drought in China, J. Geophys. Res.-Atmos., 116, D21114, doi:10.1029/2011jd015706, 2011.

Ma, Z., Peng, C., Zhu, Q., Chen, H., Yu, G., Li, W., Zhou, X., Wang, W., and Zhang, W.: Regional drought-induced reduction in the biomass carbon sink of Canada's boreal forests, P. Natl. Acad. Sci. USA, 109, 2423–2427, 2012.

Matsushita, B. and Tamura, M.: Integrating remotely sensed data with an ecosystem model to estimate net primary productivity in East Asia, Remote Sens. Environ., 81, 58–66, 2002.

McKee, T. B., Doesken, N. J., and Kleist, J.: The relationship of drought frequency and duration to time scales, 8th Conference on Applied Climatology, 179–184, 1993.

Meir, P., Metcalfe, D. B., Costa, A. C. L., and Fisher, R. A.: The fate of assimilated carbon during drought: impacts on respiration in Amazon rainforests, Philos. T. Roy. Soc. B, 363, 1849–1855, 2008.

Mishra, A. K. and Singh, V. P.: A review of drought concepts, J. Hydrol., 391, 204–216, 2010.

Mo, X. G., Chen, J. M., Ju, W. M., and Black, T. A.: Optimization of ecosystem model parameters through assimilating eddy covariance flux data with an ensemble Kalman filter, Ecol. Model., 217, 157–173, 2008.

Mu, Q., Zhao, M., Running, S. W., Liu, M., and Tian, H.: Contribution of increasing CO_2 and climate change to the carbon cycle in China's ecosystems, J. Geophys. Res.-Biogeo., 113, G01018, doi:10.1029/2006jg000316, 2008.

Nemani, R. R., Keeling, C. D., Hashimoto, H., Jolly, W. M., Piper, S. C., Tucker, C. J., Myneni, R. B., and Running, S. W.: Climate-driven increases in global terrestrial net primary production from 1982 to 1999, Science, 300, 1560–1563, 2003.

Nunes, E. L., Costa, M. H., Malhado, A. C. M., Dias, L. C. P., Vieira, S. A., Pinto, L. B., and Ladle, R. J.: Monitoring carbon assimilation in South America's tropical forests: model specification and application to the Amazonian droughts of 2005 and 2010, Remote Sens. Environ., 117, 449–463, doi:10.1016/j.rse.2011.10.022, 2012.

Pan, Y. D., Luo, T. X., Birdsey, R., Hom, J., and Melillo, J.: New estimates of carbon storage and sequestration in China's forests: effects of age-class and method on inventory-based carbon estimation, Clim. Change, 67, 211–236, doi:10.1007/s10584-004-2799-5, 2004.

Pan, Y. D., Birdsey, R. A., Fang, J. Y., Houghton, R., Kauppi, P. E., Kurz, W. A., Phillips, O. L., Shvidenko, A., Lewis, S. L., Canadell, J. G., Ciais, P., Jackson, R. B., Pacala, S. W., McGuire, A. D., Piao, S. L., Rautiainen, A., Sitch, S., and Hayes, D.: A large and persistent carbon sink in the world's forests, Science, 333, 988–993, doi:10.1126/science.1201609, 2011.

Parton, W. J., Scurlock, J. M. O., Ojima, D. S., Gilmanov, T. G., Scholes, R. J., Schimel, D. S., Kirchner, T., Menaut, J. C., Seastedt, T., Moya, E. G., Kamnalrut, A., and Kinyamario, J. I.: Observations and modeling of biomass and soil organic-matter dynamics for the grassland biome worldwide, Global Biogeochem. Cy., 7, 785–809, 1993.

Pasho, E., Julio Camarero, J., de Luis, M., and Vicente-Serrano, S. M.: Impacts of drought at different time scales on forest growth across a wide climatic gradient in north-eastern Spain, Agr. Forest Meteorol., 151, 1800–1811, doi:10.1016/j.agrformet.2011.07.018, 2011.

Pei, F., Li, X., Liu, X., and Lao, C.: Assessing the impacts of droughts on net primary productivity in China, J. Environ. Manage., 114, 362–371, doi:10.1016/j.jenvman.2012.10.031, 2013.

Peng, C., Ma, Z., Lei, X., Zhu, Q., Chen, H., Wang, W., Liu, S., Li, W., Fang, X., and Zhou, X.: A drought-induced pervasive increase in tree mortality across Canada's boreal forests, Nat. Clim. Change, 1, 467–471, doi:10.1038/nclimate1293, 2011.

Pereira, J. S., Mateus, J. A., Aires, L. M., Pita, G., Pio, C., David, J. S., Andrade, V., Banza, J., David, T. S., Paço, T. A., and Rodrigues, A.: Net ecosystem carbon exchange in three contrasting Mediterranean ecosystems – the effect of drought, Biogeosciences, 4, 791–802, doi:10.5194/bg-4-791-2007, 2007.

Peters, A. J., Walter-Shea, E. A., Ji, L., Vina, A., Hayes, M., and Svoboda, M. D.: Drought monitoring with NDVI-based standardized vegetation index, Photogramm. Eng. Rem. S., 68, 71–75, 2002.

Phillips, O. L., Aragao, L., Lewis, S. L., Fisher, J. B., Lloyd, J., Lopez-Gonzalez, G., Malhi, Y., Monteagudo, A., Peacock, J., Quesada, C. A., van der Heijden, G., Almeida, S., Amaral, I., Arroyo, L., Aymard, G., Baker, T. R., Banki, O., Blanc, L., Bonal, D., Brando, P., Chave, J., de Oliveira, A. C. A., Cardozo, N. D., Czimczik, C. I., Feldpausch, T. R., Freitas, M. A., Gloor, E., Higuchi, N., Jimenez, E., Lloyd, G., Meir, P., Mendoza, C., Morel, A., Neill, D. A., Nepstad, D., Patino, S., Penuela, M. C., Prieto, A., Ramirez, F., Schwarz, M., Silva, J., Silveira, M., Thomas, A. S., ter Steege, H., Stropp, J., Vasquez, R., Zelazowski, P., Davila, E. A., Andelman, S., Andrade, A., Chao, K. J., Erwin, T., Di Fiore, A., Honorio, E., Keeling, H., Killeen, T. J., Laurance, W. F., Cruz, A. P., Pitman, N. C. A., Vargas, P. N., Ramirez-Angulo, H., Rudas, A., Salamao, R., Silva, N., Terborgh, J., and Torres-Lezama, A.: Drought sensitivity of the Amazon rainforest, Science, 323, 1344–1347, doi:10.1126/science.1164033, 2009.

Piao, S., Sitch, S., Ciais, P., Friedlingstein, P., Peylin, P., Wang, X., Ahlström, A., Anav, A., Canadell, J. G., Cong, N., Huntingford, C., Jung, M., Levis, S., Levy, P. E., Li, J., Lin, X., Lomas, M. R., Lu, M., Luo, Y., Ma, Y., Myneni, R. B., Poulter, B., Sun, Z., Wang, T., Viovy, N., Zaehle, S., and Zeng, N.: Evaluation of terrestrial carbon cycle models for their response to climate variability and to CO_2 trends, Glob. Change Biol., 19, 2117–2132, doi:10.1111/gcb.12187, 2013.

Piao, S. L., Fang, J. Y., Zhou, L. M., Tan, K., and Tao, S.: Changes in biomass carbon stocks in China's grasslands between 1982 and 1999, Global Biogeochem. Cy., 21, GB2002, doi:10.1029/2005GB002634, 2007.

Piao, S. L., Fang, J. Y., Ciais, P., Peylin, P., Huang, Y., Sitch, S., and Wang, T.: The carbon balance of terrestrial ecosystems in China, Nature, 458, 1009–1082, doi:10.1038/nature07944, 2009a.

Piao, S. L., Yin, L., Wang, X. H., Ciais, P., Peng, S. S., Shen, Z. H., and Seneviratne, S. I.: Summer soil moisture regulated by precipitation frequency in China, Environ. Res. Lett., 4, 044012, doi:10.1088/1748-9326/4/4/044012, 2009b.

Piao, S. L., Ito, A., Li, S. G., Huang, Y., Ciais, P., Wang, X. H., Peng, S. S., Nan, H. J., Zhao, C., Ahlström, A., Andres, R. J., Chevallier, F., Fang, J. Y., Hartmann, J., Huntingford, C., Jeong, S., Levis, S., Levy, P. E., Li, J. S., Lomas, M. R., Mao, J. F., Mayorga, E., Mohammat, A., Muraoka, H., Peng, C. H., Peylin, P., Poulter, B., Shen, Z. H., Shi, X., Sitch, S., Tao, S., Tian, H. Q., Wu, X. P., Xu, M., Yu, G. R., Viovy, N., Zaehle, S., Zeng, N., and Zhu, B.: The carbon budget of terrestrial ecosystems in East Asia over the last two decades, Biogeosciences, 9, 3571–3586, doi:10.5194/bg-9-3571-2012, 2012.

Pisek, J., Chen, J. M., and Deng, F.: Assessment of a global leaf area index product from SPOT-4 VEGETATION data over selected sites in Canada, Can. J. Remote Sens., 33, 341–356, 2007.

Ponce Campos, G. E., Moran, M. S., Huete, A., Zhang, Y., Bresloff, C., Huxman, T. E., Eamus, D., Bosch, D. D., Buda, A. R., Gunter, S. A., Scalley, T. H., Kitchen, S. G., McClaran, M. P., McNab, W. H., Montoya, D. S., Morgan, J. A., Peters, D. P. C., Sadler, E. J., Seyfried, M. S., and Starks, P. J.: Ecosystem resilience despite large-scale altered hydroclimatic conditions, Nature, 494, 349–352, doi:10.1038/nature11836, 2013.

Potter, C., Klooster, S., Hiatt, C., Genovese, V., and Castilla-Rubio, J. C.: Changes in the carbon cycle of Amazon ecosystems during the 2010 drought, Environ. Res. Lett., 6, 034024, doi:10.1088/1748-9326/6/3/034024, 2011.

Qin, N., Chen, X., Fu, G., Zhai, J., and Xue, X.: Precipitation and temperature trends for the Southwest China: 1960–2007, Hydrol. Process., 24, 3733–3744, doi:10.1002/hyp.7792, 2010.

Quiring, S. M. and Ganesh, S.: Evaluating the utility of the Vegetation Condition Index (VCI) for monitoring meteorological drought in Texas, Agr. Forest Meteorol., 150, 330–339, doi:10.1016/j.agrformet.2009.11.015, 2010.

Reichstein, M., Tenhunen, J. D., Roupsard, O., Ourcival, J. M., Rambal, S., Miglietta, F., Peressotti, A., Pecchiari, M., Tirone, G., and Valentini, R.: Severe drought effects on ecosystem CO_2 and H_2O fluxes at three Mediterranean evergreen sites: revision of current hypotheses?, Glob. Change Biol., 8, 999–1017, 2002.

Reichstein, M., Ciais, P., Papale, D., Valentini, R., Running, S., Viovy, N., Cramer, W., Granier, A., Ogee, J., Allard, V., Aubinet, M., Bernhofer, C., Buchmann, N., Carrara, A., Grunwald, T., Heimann, M., Heinesch, B., Knohl, A., Kutsch, W., Loustau, D., Manca, G., Matteucci, G., Miglietta, F., Ourcival, J. M., Pilegaard, K., Pumpanen, J., Rambal, S., Schaphoff, S., Seufert, G., Soussana, J. F., Sanz, M. J., Vesala, T., and Zhao, M.: Reduction of ecosystem productivity and respiration during the European summer 2003 climate anomaly: a joint flux tower, remote sensing and modelling analysis, Glob. Change Biol., 13, 634–651, 2007.

Running, S. W. and Coughlan, J. C.: A general model of forest ecosystem processes for regional applications, 1. hydrologic balance, canopy gas exchange and primary production processes, Ecol. Model., 42, 125–154, 1988.

Running, S. W.: Climate change – ecosystem disturbance, carbon, and climate, Science, 321, 652–653, doi:10.1126/science.1159607, 2008.

Saigusa, N., Ichii, K., Murakami, H., Hirata, R., Asanuma, J., Den, H., Han, S.-J., Ide, R., Li, S.-G., Ohta, T., Sasai, T., Wang, S.-Q., and Yu, G.-R.: Impact of meteorological anomalies in the 2003 summer on Gross Primary Productivity in East Asia, Biogeosciences, 7, 641–655, doi:10.5194/bg-7-641-2010, 2010.

Samanta, A., Costa, M. H., Nunes, E. L., Vieira, S. A., Xu, L., and Myneni, R. B.: Comment on "Drought-Induced Reduction in Global Terrestrial Net Primary Production from 2000 Through 2009", Science, 333, 1093, doi:10.1126/science.1199048, 2011.

Schwalm, C. R., Williams, C. A., Schaefer, K., Arneth, A., Bonal, D., Buchmann, N., Chen, J. Q., Law, B. E., Lindroth, A., Luyssaert, S., Reichstein, M., and Richardson, A. D.: Assimilation exceeds respiration sensitivity to drought: a FLUXNET synthesis, Glob. Change Biol., 16, 657–670, 2010.

Schwalm, C. R., Williams, C. A., Schaefer, K., Baldocchi, D., Black, T. A., Goldstein, A. H., Law, B. E., Oechel, W. C., Paw U, K. T., and Scott, R. L.: Reduction in carbon uptake during turn of the century drought in western North America, Nat. Geosci., 5, 551–556, doi:10.1038/NGEO1529, 2012.

Shangguan, W., Dai, Y., Liu, B., Ye, A., and Yuan, H.: A soil particle-size distribution dataset for regional land and climate modelling in China, Geoderma, 171–172, 85–91, doi:10.1016/j.geoderma.2011.01.013, 2012.

Sonnentag, O., Chen, J. M., Roulet, N. T., Ju, W., and Govind, A.: Spatially explicit simulation of peatland hydrology and carbon dioxide exchange: influence of mesoscale topography, J. Geophys. Res.-Biogeo., 113, G02005, doi:10.1029/2007JG000605, 2008.

Sprintsin, M., Chen, J. M., Desai, A., and Gough, C. M.: Evaluation of leaf-to-canopy upscaling methodologies against carbon flux data in North America, J. Geophys. Res.-Biogeo., 117, G01023, doi:10.1029/2010jg001407, 2012.

Sun, C. and Yang, S.: Persistent severe drought in southern China during winter–spring 2011: large-scale circulation patterns and possible impacting factors, J. Geophys. Res.-Atmos., 117, D10112, doi:10.1029/2012jd017500, 2012.

Sun, R., Chen, J. M., Zhu, Q. J., Zhou, Y. Y., Liu, J., Li, J. T., Liu, S. H., Yan, G. J., and Tang, S. H.: Spatial distribution of net primary productivity and evapotranspiration in Changbaishan Natural Reserve, China, using Landsat ETM+ data, Can. J. Remote Sens., 30, 731–742, 2004.

Tian, H. Q., Melillo, J., Lu, C. Q., Kicklighter, D., Liu, M. L., Ren, W., Xu, X. F., Chen, G. S., Zhang, C., Pan, S. F., Liu, J. Y., and Running, S.: China's terrestrial carbon balance: contributions from multiple global change factors, Global Biogeochem. Cy., 25, GB1007, doi:10.1029/2010gb003838, 2011a.

Tian, H. Q., Xu, X. F., Lu, C. Q., Liu, M. L., Ren, W., Chen, G. S., Melillo, J., and Liu, J. Y.: Net exchanges of CO_2, CH_4, and N_2O between China's terrestrial ecosystems and the atmosphere and their contributions to global climate warming, J. Geophys. Res.-Biogeo., 116, G02011, doi:10.1029/2010jg001393, 2011b.

van der Molen, M. K., Dolman, A. J., Ciais, P., Eglin, T., Gobron, N., Law, B. E., Meir, P., Peters, W., Phillips, O. L., Reichstein, M., Chen, T., Dekker, S. C., Doubkova, M., Friedl, M. A., Jung, M., van den Hurk, B., de Jeu, R. A. M., Kruijt, B., Ohta, T., Rebel, K. T., Plummer, S., Seneviratne, S. I., Sitch, S., Teuling, A. J., van der Werf, G. R., and Wang, G.: Drought and ecosystem carbon cycling, Agr. Forest Meteorol., 151, 765–773, doi:10.1016/j.agrformet.2011.01.018, 2011.

Vetter, M., Churkina, G., Jung, M., Reichstein, M., Zaehle, S., Bondeau, A., Chen, Y., Ciais, P., Feser, F., Freibauer, A., Geyer, R., Jones, C., Papale, D., Tenhunen, J., Tomelleri, E., Trusilova, K., Viovy, N., and Heimann, M.: Analyzing the causes and spatial pattern of the European 2003 carbon flux anomaly using seven models, Biogeosciences, 5, 561–583, doi:10.5194/bg-5-561-2008, 2008.

Vicente-Serrano, S. M., Gouveia, C., Julio Camarero, J., Begueria, S., Trigo, R., Lopez-Moreno, J. I., Azorin-Molina, C., Pasho, E., Lorenzo-Lacruz, J., Revuelto, J., Moran-Tejeda, E., and Sanchez-Lorenzo, A.: Response of vegetation to drought time-scales across global land biomes, P. Natl. Acad. Sci. USA, 110, 52–57, doi:10.1073/pnas.1207068110, 2013.

Wang, A., Lettenmaier, D. P., and Sheffield, J.: Soil moisture drought in China, 1950–2006, J. Climate, 24, 3257–3271, doi:10.1175/2011jcli3733.1, 2011.

Wang, H., Zhang, R., Liu, M., and Bi, J.: The carbon emissions of Chinese cities, Atmos. Chem. Phys., 12, 6197–6206, doi:10.5194/acp-12-6197-2012, 2012.

Wang, L., Li, C., Ying, Q., Cheng, X., Wang, X., Li, X., Hu, L., Liang, L., Yu, L., Huang, H., and Gong, P.: China's urban expansion from 1990 to 2010 determined with satellite remote sensing, Chinese Sci. Bull., 57, 2802–2812, doi:10.1007/s11434-012-5235-7, 2012b.

Wang, Q., Tenhunen, J., Falge, E., Bernhofer, C., Granier, A., and Vesala, T.: Simulation and scaling of temporal variation in gross primary production for coniferous and deciduous temperate forests, Glob. Change Biol., 10, 37–51, 2004.

Wang, Q. F., Niu, D., Yu, G. R., Ren, C. Y., Wen, X. F., Chen, J. M., and Ju, W. M.: Simulating the exchanges of carbon dioxide, water vapor and heat over Changbai Mountains temperate broadleaved Korean pine mixed forest ecosystem, Sci. China Ser. D, 48, 148–159, doi:10.1360/05zd0015, 2005.

Wu, C. and Chen, J. M.: Diverse responses of vegetation production to interannual summer drought in North America, Int. J. Appl. Earth Obs., 21, 1–6, doi:10.1016/j.jag.2012.08.001, 2013.

Wu, Z. Y., Lu, G. H., Wen, L., and Lin, C. A.: Reconstructing and analyzing China's fifty-nine year (1951–2009) drought history using hydrological model simulation, Hydrol. Earth Syst. Sci., 15, 2881–2894, doi:10.5194/hess-15-2881-2011, 2011.

Xiao, J. F., Zhuang, Q. L., Liang, E. Y., McGuire, A. D., Moody, A., Kicklighter, D. W., Shao, X. M., and Melillo, J. M.: Twentieth-century droughts and their impacts on terrestrial carbon cycling in China, Earth Interact., 13, 10, doi:10.1175/2009ei275.1, 2009.

Xiao, J. F., Zhuang, Q. L., Law, B. E., Baldocchi, D. D., Chen, J. Q., Richardson, A. D., Melillo, J. M., Davis, K. J., Hollinger, D. Y., Wharton, S., Oren, R., Noormets, A., Fischer, M. L., Verma, S. B., Cook, D. R., Sun, G., McNulty, S., Wofsy, S. C., Bolstad, P. V., Burns, S. P., Curtis, P. S., Drake, B. G., Falk, M., Foster, D. R., Gu, L. H., Hadley, J. L., Katulk, G. G., Litvak, M., Ma, S. Y., Martinz, T. A., Matamala, R., Meyers, T. P., Monson, R. K., Munger, J. W., Oechel, W. C., Paw, U. K. T., Schmid, H. P., Scott, R. L., Starr, G., Suyker, A. E., and Torn, M. S.: Assessing net ecosystem carbon exchange of US terrestrial ecosystems by integrating eddy covariance flux measurements and satellite observations, Agr. Forest Meteorol., 151, 60–69, 2011.

Xu, X., Piao, S., Wang, X., Chen, A., Ciais, P., and Myneni, R. B.: Spatio-temporal patterns of the area experiencing negative vegetation growth anomalies in China over the last three decades, Environ. Res. Lett., 7, 035701, doi:10.1088/1748-9326/7/3/035701, 2012.

Yi, C. X., Ricciuto, D., Li, R., Wolbeck, J., Xu, X. Y., Nilsson, M., Aires, L., Albertson, J. D., Ammann, C., Arain, M. A., de Araujo, A. C., Aubinet, M., Aurela, M., Barcza, Z., Barr, A., Berbigier, P., Beringer, J., Bernhofer, C., Black, A. T., Bolstad, P. V., Bosveld, F. C., Broadmeadow, M. S. J., Buchmann, N., Burns, S. P., Cellier, P., Chen, J. M., Chen, J. Q., Ciais, P., Clement, R., Cook, B. D., Curtis, P. S., Dail, D. B., Dellwik, E., Delpierre, N., Desai, A. R., Dore, S., Dragoni, D., Drake, B. G., Dufrene, E., Dunn, A., Elbers, J., Eugster, W., Falk, M., Feigenwinter, C., Flanagan, L. B., Foken, T., Frank, J., Fuhrer, J., Gianelle, D., Goldstein, A., Goulden, M., Granier, A., Grunwald, T., Gu, L., Guo, H. Q., Hammerle, A., Han, S. J., Hanan, N. P., Haszpra, L., Heinesch, B., Helfter, C., Hendriks, D., Hutley, L. B., Ibrom, A., Jacobs, C., Johansson, T., Jongen, M., Katul, G., Kiely, G., Klumpp, K., Knohl, A., Kolb, T., Kutsch, W. L., Lafleur, P., Laurila, T., Leuning, R., Lindroth, A., Liu, H. P., Loubet, B., Manca, G., Marek, M., Margolis, H. A., Martin, T. A., Massman, W. J., Matamala, R., Matteucci, G., McCaughey, H., Merbold, L., Meyers, T., Migliavacca, M., Miglietta, F., Misson, L., Moelder, M., Moncrieff, J., Monson, R. K., Montagnani, L., Montes-Helu, M., Moors, E., Moureaux, C., Mukelabai, M. M., Munger, J. W., Myklebust, M., Nagy, Z., Noormets, A., Oechel, W., Oren, R., Pallardy, S. G., Kyaw, T. P. U., Pereira, J. S., Pilegaard, K., Pinter, K., Pio, C., Pita, G., Powell, T. L., Rambal, S., Randerson, J. T., von Randow, C., Rebmann, C., Rinne, J., Rossi, F., Roulet, N., Ryel, R. J., Sagerfors, J., Saigusa, N., Sanz, M. J., Mugnozza, G. S., Schmid, H. P., Seufert, G., Siqueira, M., Soussana, J. F., Starr, G., Sutton, M. A., Tenhunen, J., Tuba, Z., Tuovinen, J. P., Valentini, R., Vogel, C. S., Wang, J. X., Wang, S. Q., Wang, W. G., Welp, L. R., Wen, X. F., Wharton, S., Wilkinson, M., Williams, C. A., Wohlfahrt, G., Yamamoto, S., Yu, G. R., Zampedri, R., Zhao, B., and Zhao, X. Q.: Climate control of terrestrial carbon exchange across biomes and continents, Environ. Res. Lett., 5, 034007, doi:10.1088/1748-9326/5/3/034007, 2010.

Yu, G. R., Zhu, X. J., Fu, Y. L., He, H. L., Wang, Q. F., Wen, X. F., Li, X. R., Zhang, L. M., Zhang, L., Su, W., Li, S. G., Sun, X. M., Zhang, Y. P., Zhang, J. H., Yan, J. H., Wang, H. M., Zhou, G. S., Jia, B. R., Xiang, W. H., Li, Y. N., Zhao, L., Wang, Y. F., Shi, P. L., Chen, S. P., Xin, X. P., Zhao, F. H., Wang, Y. Y., and Tong, C. L.: Spatial patterns and climate drivers of carbon fluxes in terrestrial ecosystems of China, Glob. Change Biol., 19, 798–810, doi:10.1111/gcb.12079, 2013.

Yuan, W. P., Liu, D., Dong, W. J., Liu, S. G., Zhou, G. S., Yu, G. R., Zhao, T. B., Feng, J. M., Ma, Z. G., Chen, J. Q., Chen, Y., Chen, S. P., Han, S. J., Huang, J. P., Li, L. H., Liu, H. Z., Liu, S. M., Ma, M. G., Wang, Y. F., Xia, J. Z., Xu, W. F., Zhang, Q., Zhao, X. Q., and Zhao, L.:

Multiyear precipitation reduction strongly decrease carbon uptake over North China, Biogeosciences Discuss., 10, 1605–1634, doi:10.5194/bgd-10-1605-2013, 2013.

Zeng, N., Qian, H. F., Munoz, E., and Iacono, R.: How strong is carbon cycle-climate feedback under global warming?, Geophys. Res. Lett., 31, L20203 doi:10.1029/2004gl020904, 2004.

Zeng, N., Qian, H. F., Roedenbeck, C., and Heimann, M.: Impact of 1998–2002 midlatitude drought and warming on terrestrial ecosystem and the global carbon cycle, Geophys. Res. Lett., 32, L22709 doi:10.1029/2005gl024607, 2005.

Zhai, J., Su, B., Krysanova, V., Vetter, T., Gao, C., and Jiang, T.: Spatial variation and trends in PDSI and SPI indices and their relation to streamflow in 10 large regions of China, J. Climate, 23, 649–663, doi:10.1175/2009jcli2968.1, 2010.

Zhang, A. and Jia, G.: Monitoring meteorological drought in semiarid regions using multi-sensor microwave remote sensing data, Remote Sens. Environ., 134, 12–23, doi:10.1016/j.rse.2013.02.023, 2013.

Zhang, C., Ju, W., Chen, J. M., Zan, M., Li, D., Zhou, Y., and Wang, X.: China's forest biomass carbon sink based on seven inventories from 1973 to 2008, Clim. Change, 118, 933–948, doi:10.1007/s10584-012-0666-3, 2013.

Zhang, F., Ju, W., Chen, J., Wang, S., Yu, G., Li, Y., Han, S., and J, A.: Study on evapotranspiration in East Asia using the BEPS ecological model, J. Nat. Resour., 25, 1596–1606, 2010.

Zhang, F., Chen, J. M., Chen, J., Gough, C. M., Martin, T. A., and Dragoni, D.: Evaluating spatial and temporal patterns of MODIS GPP over the conterminous US against flux measurements and a process model, Remote Sens. Environ., 124, 717–729, doi:10.1016/j.rse.2012.06.023, 2012a.

Zhang, F., Ju, W., Shen, S., Wang, S., Yu, G., and Han, S.: Variations of terrestrial net primary productivity in East Asia, Terr. Atmos. Ocean Sci., 23, 425–437, doi:10.3319/tao.2012.03.28.01(a), 2012b.

Zhang, L., Xiao, J., Li, J., Wang, K., Lei, L., and Guo, H.: The 2010 spring drought reduced primary productivity in southwestern China, Environ. Res. Lett., 6, 045706, doi:10.1088/1748-9326/6/4/045508, 2012c.

Zhang, Y. Q. and Wegehenkel, M.: Integration of MODIS data into a simple model for the spatial distributed simulation of soil water content and evapotranspiration, Remote Sens. Environ., 104, 393–408, 2006.

Zhao, M. and Running, S. W.: Drought-induced reduction in global terrestrial net primary production from 2000 through 2009, Science, 329, 940–943, doi:10.1126/science.1192666, 2010.

Zhou, L., Wang, S., Chen, J., Feng, X., Ju, W., and Wu, W.: The spatial-temporal characteristics of evapotranspiration of China's terrestrial ecosystems during 1991–2000, Resour. Sci., 31, 962–972, 2009.

Zou, X. K., Zhai, P. M., and Zhang, Q.: Variations in droughts over China: 1951–2003, Geophys. Res. Lett., 32, L04707, doi:10.1029/2004gl021853, 2005.

Table 1. Drought classification based on SPI values.

SPI values	Drought category
≥ 2.00	Extreme wet
1.50 to 1.99	Severe wet
1.00 to 1.49	Moderate wet
0.49 to 0.99	Mild wet
−0.49 to 0.49	Near normal
−0.99 to −0.49	Mild drought
−1.49 to −1.00	Moderate drought
−1.99 to −1.50	Severe drought
≤ -2.0	Extreme drought

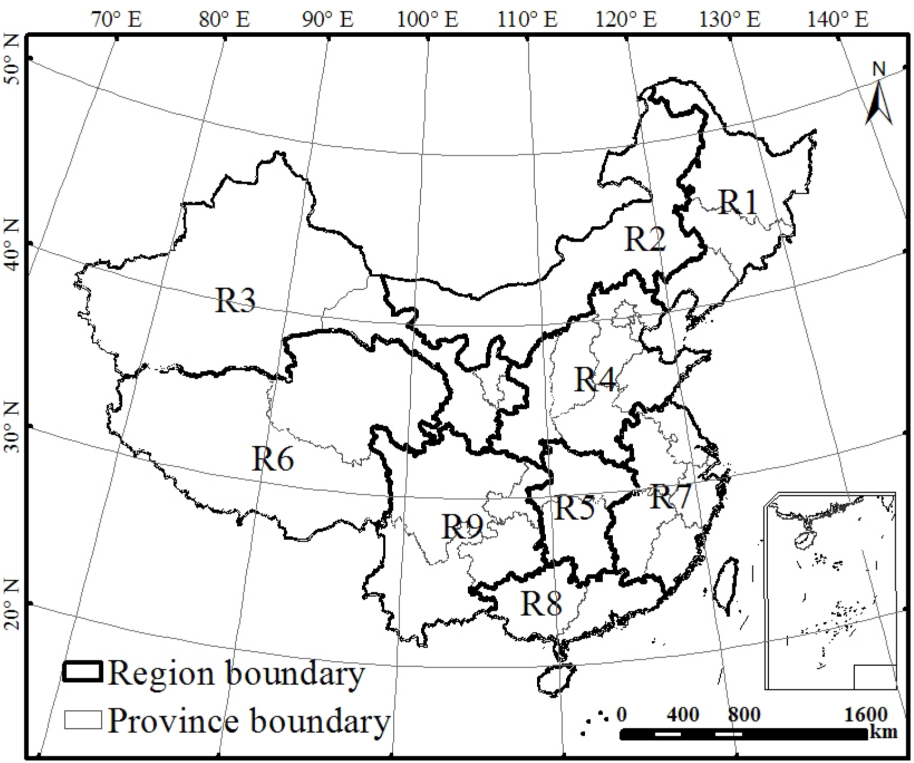

Fig. 1. Spatial distribution of the nine sub-regions in China. Northeast China (R1) (Heilongjiang, Jilin, Liaoning), Inner Mongolia (R2), Northwest China (R3) (Gansu, Ningxia, Xinjiang), North China (R4) (Beijing, Hebei, Henan, Shandong, Shanxi, Shaanxi, Tianjin), Central China (R5) (Hubei, Hunan), Tibetan Plateau (R6) (Qinghai, Tibet), Southeast China (R7) (Anhui, Fujian, Jiangsu, Jiangxi, Shanghai, Taiwan, Zhejiang), South China (R8) (Guangdong, Guangxi, Hainan, Hongkong, Macao), and Southwest China (R9) (Guizhou, Sichuan, Yunnan, Chongqing).

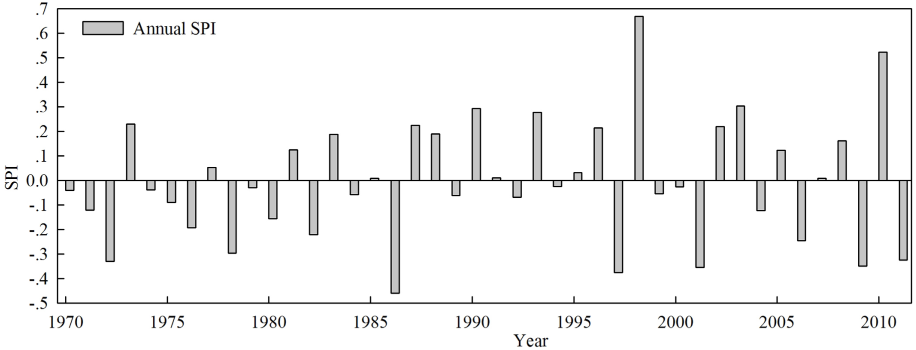

Fig. 2. National mean of annual SPI in China from 1970 to 2011.

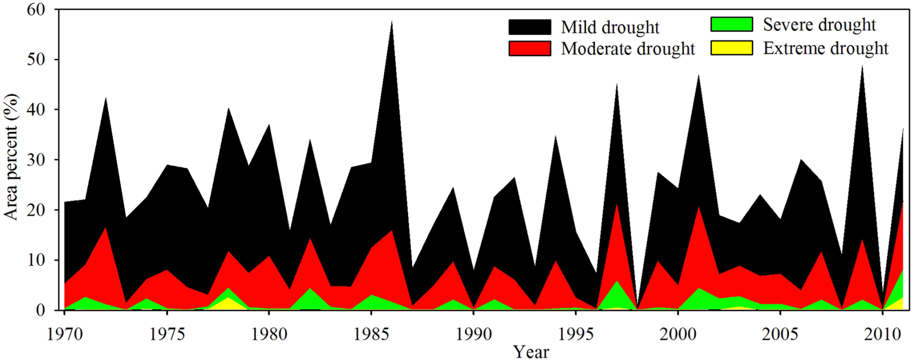

Fig. 3. Percentages of areas hit by different categories of droughts from 1970 to 2011.

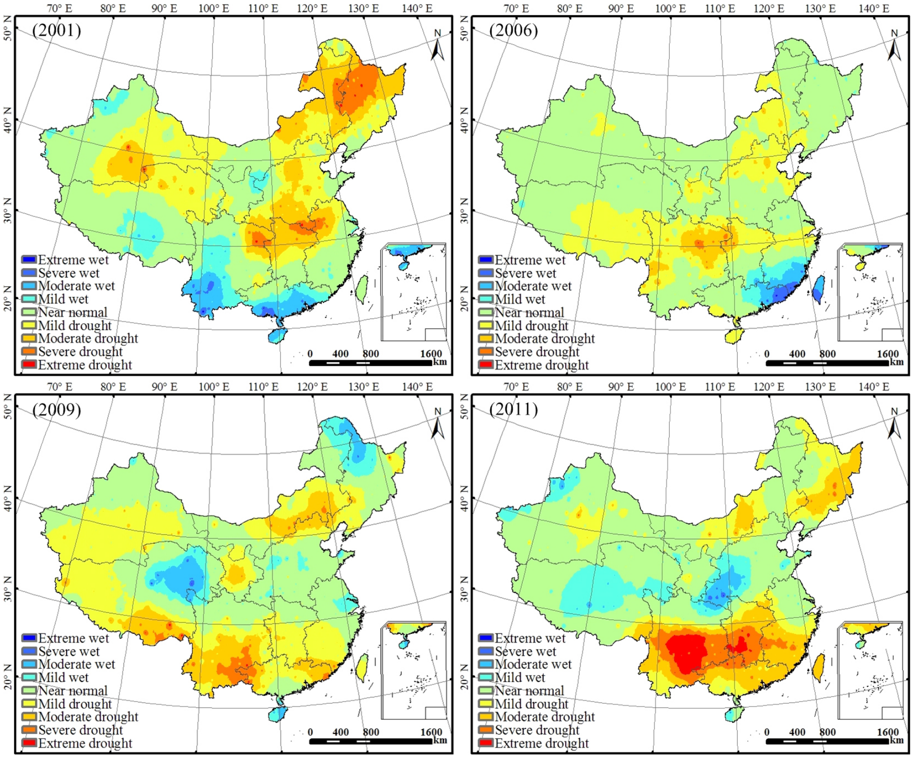

Fig. 4. Areas hit by different categories of droughts in 2001, 2006, 2009 and 2011.

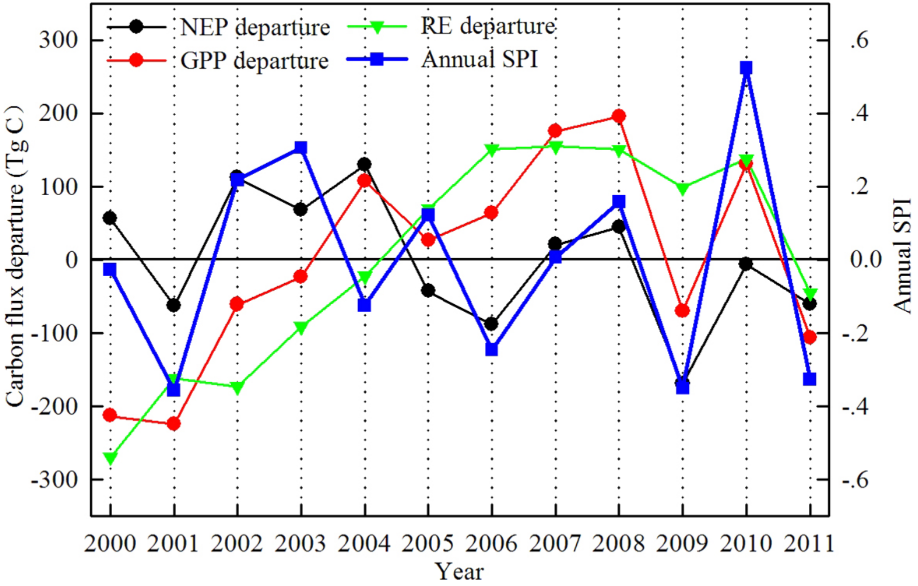

Fig. 5. Departures of annual national total NEP, GPP, and RE from multiyear means and annual mean SPI in China from 2000 to 2011. Annual SPI presented here is mean of the 12 months SPI through the end of December for all pixels over China.

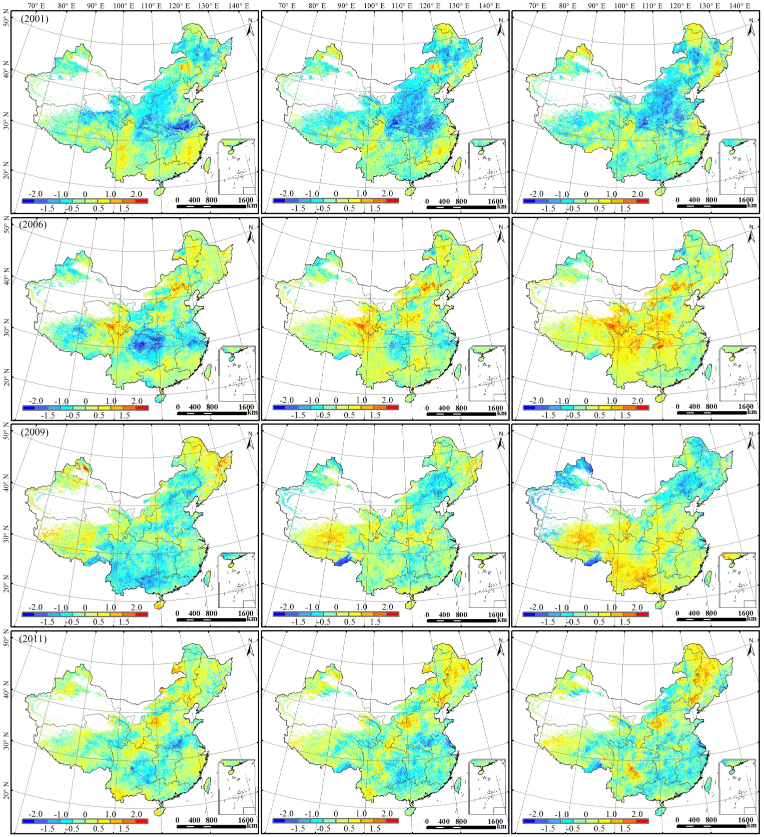

Fig. 6. The spatial distributions of SAI values of annual NEP (left panels), GPP (central panels), and RE (right panels) in 2001, 2006, 2009 and 2011, respectively. SAI values were calculated using Eq. (6). Negative values (the blue and cyan colored areas) represent annual GPP, RE, and NEP smaller than 12 yr means, vice versa.

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
◀I
▶I
◀
▶
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

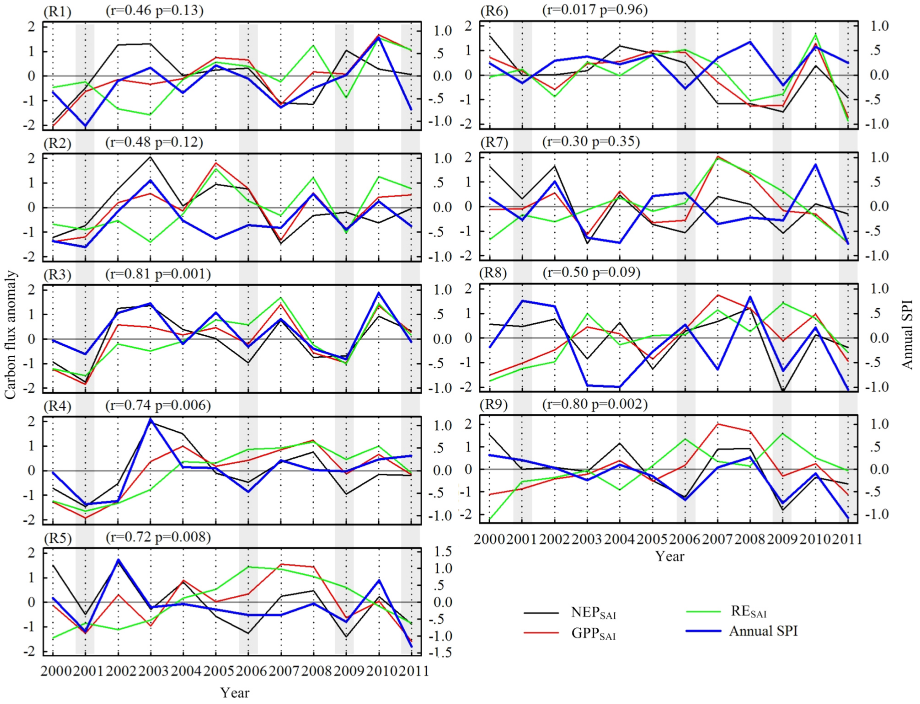

Fig. 7. Anomalies of annual total NEP, GPP and RE, along with annual mean SPI in nine regions of China from 2000 to 2011. SPI presented here is the mean of 12 month SPI through the end of December for all pixels in a specific region of China. R1: Northeast China; R2: Inner Mongolia; R3: Northwest China; R4: North China; R5: Central China; R6: Tibetan Plateau; R7: Southeast China; R8: South China; R9: Southwest China.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

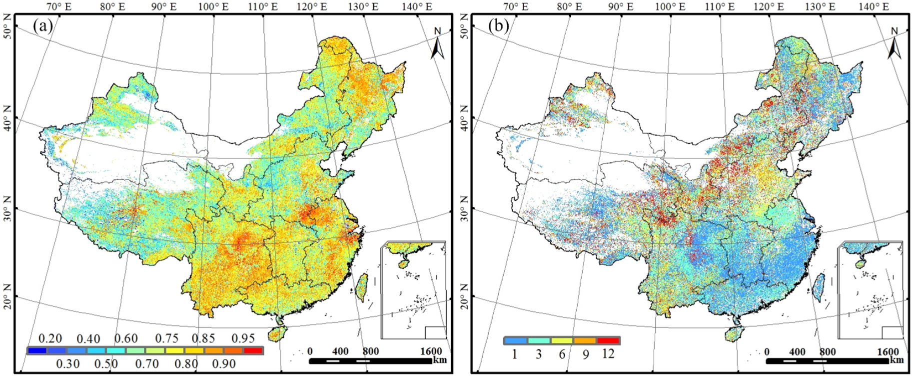

Fig. 8. Spatial distribution of **(a)** the correlations between SPI and monthly NEP_{SAI} for the period 2000–2011 The values represent the maximum correlation recorded for each pixel, independently of the month of the year and the SPI time-scale. **(b)** SPI time-scales at which the maximum correlation between SPI and NEP_{SAI} is found. Areas with no significant correlations ($p < 0.05$) are indicated in white. Desert and ice areas are masked and not included in the analyses.