Nested atmospheric inversion for the terrestrial carbon sources and sinks in China

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Abstract. In this study, we establish a nested atmospheric inversion system with a focus on China using the Bayesian method. The global surface is separated into 43 regions based on the 22 TransCom large regions, with 13 small regions in China. Monthly CO2 concentrations from 130 GlobalView sites and 3 additional China sites are used in this system. The core component of this system is an atmospheric transport matrix, which is created using the TM5 model with a horizontal resolution of 3º × 2º. The net carbon fluxes over the 43 global land and ocean regions are inverted for the period from 2002 to 2008. The inverted global terrestrial carbon sinks mainly occur in boreal Asia, South and Southeast Asia, eastern America and southern South America. Most China areas appear to be carbon sinks, with strongest carbon sinks located in Northeast China. From 2002 to 2008, the global terrestrial carbon sink has an increasing trend, with the lowest carbon sink in 2002. The inter-annual variation (IAV) of the land sinks shows remarkable correlation with the El Niño Southern Oscillation (ENSO). The terrestrial carbon sinks in China also show an increasing trend. However, the IAV in China is not the same as that of the globe. There is relatively stronger land sink in 2002, lowest sink in 2006, and strongest sink in 2007 in China. This IAV could be reasonably explained with the IAVs of temperature and precipitation in China. The mean global and China terrestrial carbon sinks over the period 2002–2008 are −3.20 ± 0.63 and −0.28 ± 0.18 PgC yr−1, respectively. Considering the carbon emissions in the form of reactive biogenic volatile organic compounds (BVOCs) and from the import of wood and food, we further estimate that China’s land sink is about −0.31 PgC yr−1.

1 Introduction

Carbon dioxide (CO2) and other greenhouse gases emitted from human activities are the main cause of global warming (IPCC, 2007). In 2008, the carbon emissions from fossil fuel combustion, cement production and land use change reached 10 PgC yr−1. About 40 % of these CO2 were detained in the atmosphere, leading to the increase in atmospheric CO2 concentration at an unprecedented rate (about 1.8 ppm yr−1) (Le Quéré et al., 2009). At the present, China has become the largest CO2 emitter in the world, and will continue to increase in the near future due to population growth and economic development (Leggett, 2011).

Terrestrial ecosystems play a very important role on regulating the atmospheric CO2 concentration. In the 1990s and during 2000–2005, on average, terrestrial ecosystems absorbed −1.0 ± 0.6 and −0.9 ± 0.6 PgC yr−1 carbon from the atmosphere, accounting for about 16% and 13% of the emissions from fossil fuel combustion and cement production, respectively (IPCC, 2007). During 1980–2000, the carbon sinks of forests, grasslands, and shrubs in China were −0.075, −0.007, and −0.014 to −0.024 PgC yr−1, respectively, which in total offset 20.0–26.8 % of China’s industrial
carbon emissions (Fang et al., 2007). Based on the 1999–2003 national forest inventory, Wang et al. (2010) calculated the carbon sink of China’s forest to be $-0.21 \text{Pg C yr}^{-1}$. Using an ecosystem model, Wang et al. (2007) simulated the forest carbon sink to be $-0.18 \pm 0.05 \text{Pg C yr}^{-1}$ during 1988–2001, and Tian et al. (2011) simulated the China land sink to be $-0.21 \text{Pg C yr}^{-1}$ during 1961–2005, with a range from $-0.18–0.24 \text{Pg C yr}^{-1}$. However, since it is very difficult to obtain detailed inventories of soil carbon storage and forest resources, the carbon sink estimations based on inventories still have large uncertainties. Simulations using ecosystem models are highly dependent on model structure, model parameters and input data, and they also have large uncertainties.

Atmospheric inversion is a method that uses observed atmospheric CO$_2$ concentrations to optimize land and ocean carbon fluxes. For this purpose, an atmospheric transport model is used to simulate the atmospheric CO$_2$ concentration based on a prior estimate of the land and ocean fluxes. The optimization of the prior fluxes is made according to the difference between observed and simulated CO$_2$ concentrations. With this method, many studies have been conducted to estimate the global terrestrial carbon fluxes (e.g., Enting and Mansbridge, 1989; Rayner et al., 1999a; Claïs et al., 2000; Gurney et al., 2002; Law et al., 2003; Rödenbeck et al., 2005; Patra et al., 2005a; Rayner et al., 2008; Maki et al., 2010), and most of these studies focused on the spatial pattern of the carbon sources and sinks and the inter-annual variations. In recent years, one of the research directions of atmospheric inversion is to estimate fluxes in finer spatial resolutions (e.g., Gerbig et al., 2003; Peylin et al., 2005; Peters, et al., 2007; Schuh et al., 2010). Peters et al. (2007) developed the first global carbon assimilation system named Carbon Tracker with a focus on North America. Based on the Carbon Tracker, CarbonTracker-Europe was then developed (Peters et al., 2010), which is focused on Europe. Deng et al. (2007) developed a nested atmospheric inversion method in which the central region is divided into a number of cells, while large regions remain the same outside of the central region, and the inversion for large and small regions is done simultaneously. With this method, much more detailed carbon fluxes of the areas of concern could be inverted compared to the global large region scheme, and the uncertainty caused by setting boundary conditions in regional inversion could be reduced. Based on this method, Deng et al. (2007) successfully inverted carbon sources and sinks for North America in a relatively high resolution (30 small regions). In this paper, based on the nested method, we established a China-focused nested atmospheric inversion system. Using this system, we investigate the spatial distribution of terrestrial ecosystems carbon sources and sinks in China as well as their inter-annual variations during 2002–2008. The description of the inversion system is presented in Sect. 2, and the inverted spatial patterns of terrestrial carbon fluxes as well as their inter-annual variations are presented and discussed in Sect. 3.

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2 Inversion method

The observed CO$_2$ concentration at one time and one place is contributed by the transport of the fluxes from all global regions for a past period of time and the initial well-mixed CO$_2$ concentration. The transport contributions could be expressed as a transport operator multiplied by the fluxes. So, if we have enough CO$_2$ observations, the transport operator and the initial CO$_2$ concentration, the fluxes could be known. In this study, we use the time-dependent Bayesian synthesis method (Rayner et al., 1999a) to solve this inversion problem. Details about this method could be found in Deng et al. (2007). The key of this method is to minimize the following cost function (Enting et al., 1995; Rayner et al., 1999a).

$$J = \frac{1}{2}(M(s - c)^T R^{-1} (M(s - c) + \frac{1}{2} (s - s_p)^T Q^{-1} (s - s_p)$$

where $M$ is a matrix representing the transport operator; $c$ is the observations; $s$ is the unknown vector of the carbon fluxes of all regions at different times combined with the initial well-mixed atmospheric CO$_2$ concentration; $s_p$ is a priori estimation of $s$; and $R$ and $Q$ are the uncertainties of $c$ and $s_p$, respectively. By minimizing this cost function, the posterior fluxes $s_{post}$ and their uncertainties $Q_{post}$ could be obtained as

$$s_{post} = \left(M^T R^{-1} M + Q^{-1} \right)^{-1} \left(M^T R^{-1} c + Q^{-1} s_p \right).$$

$$Q_{post} = \left(Q^{-1} + M^T R^{-1} M \right)^{-1}.$$

2.1 Inversion regions

In this study, the global surface is separated into 43 regions based on the 22 TransCom large regions (e.g., Gurney et al., 2003), with 13 small regions in China (Fig. 1). The partition scheme in China is mainly based on land cover types (i.e., forest, crop, grass, and desert). MODIS land cover data for the year 2007 using the University of Maryland (UMD) classification scheme (Hansen et al., 1998) were used in this study, which were obtained from http://lpdaac.usgs.gov (LP DAAC, 2001). The forest in China is separated into 5 regions: South China (region 29), Southwest China (region 30), East China (region 31), central China (region 32), and Northeast China (region 33). The crop is separated into 4 regions: Sichuan Basin (region 37), North China crop region (mainly North China plain, region 38), Yangtze Plain (region 39) and Northeast China Plain (region 40). The grass is partitioned into 3 regions: North China grass region (region 34), Southwest China grass region (region 35) and Northwest China grass region (region 36). The rest of Asia is separated into 8 regions. They are Southeast Asia, Indo-China peninsula, Indian peninsula, Japan, Korean peninsula, Mongolia, West Asia, and boreal Asia. Temperate North America is separated...
into 2 regions due to the significant land cover difference between east and west temperate North America. In addition, Africa is partitioned into 3 regions in this study: northern Africa, tropical Africa, and southern Africa (see Fig. 2).

2.2 Transport modeling

Monthly transport operator M of ten years (January 2000 to December 2009) for the 43 regions is calculated using the global two-way nested transport model TM5 (Krol et al., 2005), which has been evaluated extensively and consistently and performs well on vertical and horizontal transport in ongoing intercomparisons (Stephens et al., 2007), and it has been widely used in global atmospheric chemistry studies (e.g., Houweling et al., 1998; Dentener et al., 2003; Peters et al., 2002) and atmospheric inversion research (e.g., Meirink et al., 2008; Krol et al., 2008; Peters, et al., 2007). TM5 is an off-line model that is driven by meteorological fields from the ECMWF model. In this study, TM5 is run at a horizontal resolution of $3^\circ \times 2^\circ$ around the world, and without nested domain. There are 25 vertical layers, with the model top at about 1 hPa. The ECMWF outputs with $1^\circ \times 1^\circ$ horizontal resolution, 60 vertical layers and a 3-hour interval (for most variables) were used to drive the model.

Firstly, TM5 is modified to tag the CO$_2$ concentrations contributed from the carbon fluxes of each region. Then, the contributions of each month and each region to the CO$_2$ concentrations at each observation are calculated. In total, TM5 is run 120 times, and each time the model is continuously run for three years, with 1 Pg carbon emitted from each region in the first month, and no emissions in the subsequent months. The distribution of the 1 Pg carbon emissions in each terrestrial region is according to the annual mean net primary production (NPP) pattern, which is calculated using the BEPS model (Chen et al., 1999; Ju et al., 2006); while no distribution was considered for the ocean region. However, we assume that no carbon exchanges happen when the sea surface is covered by ice. Monthly sea ice data from the HadISST dataset (Rayner, et al., 2003) are used in this study.

TM5 is also used in forward transport simulation from January 2000 to December 2009 for two types of fluxes in the same grid system with transport operator calculations. One type of flux is (i) the Miller Carbon Tracker fossil fuel emission field, which is constructed based on CDIAC 2007 (Boden et al., 2010) and EDGAR 4 databases (Olivier and Berdowski, 2001). The emissions in 2008 and 2009 are extrapolated from the 2007 CDIAC statistics using energy consumption statistics from the BP Statistical Review of World Energy 2010. More detailed descriptions can be found in the document of Carbon Tracker (http://carbontracker.noaa.gov). The other type is (ii) the monthly mean fire emission available from the Global Emissions Fire Database version 3 (GFEDv3) (van der Werf et al., 2010). As we assume that these two fluxes have been correctly estimated, the CO$_2$ concentrations from the contributions of these fluxes will be pre-subtracted in the inversion system. Hence, the matrix $c$ in Eq. (1) can be further expressed as

$$c = c_{\text{obs}} - c_{\text{ff}} - c_{\text{fire}},$$

where $c_{\text{obs}}$ is the observed monthly CO$_2$ concentration; $c_{\text{ff}}$ and $c_{\text{fire}}$ are simulated ones by the forward simulation from fluxes (i) and (ii), respectively.

2.3 Priori fluxes and their uncertainties

Hourly terrestrial ecosystem carbon exchanges and daily carbon fluxes across the air–sea interface are considered as prior fluxes. The former is simulated using the BEPS model, which is a process-based, remote sensing data driven, and mechanistic ecosystem model (Chen et al., 1999; Ju et al., 2006). In this study, BEPS is run at $1^\circ \times 1^\circ$ resolution for 7 land cover types (i.e., evergreen coniferous forest, deciduous coniferous forest, deciduous broadleaf forest, evergreen broadleaf forest, shrub, C4 plants and others), and it is driven by NCEP.
reanalyzed data, and remotely sensed leaf area index (LAI) (Deng et al., 2006). The annual fluxes at each grid are neutralized according to the work of Deng and Chen (2011). The ocean flux is modeled using the OPA–PISCES–T model, which is a state-of-the-art combined global ocean circulation (OPA) and biogeochemistry model (PISCES–T) (Buitenhuis et al., 2006), and it has been evaluated to have good performances on ocean carbon fluxes in the equatorial Pacific (Feely et al., 2006), North Pacific (McKinley et al., 2006) and Southern Ocean (Le Quéré et al., 2007). We have evaluated the annual global ocean fluxes calculated using OPA–PISCES–T model of $-2.3 \, \text{PgC} \, \text{yr}^{-1}$, which is close to the frequently used ocean fluxes in most inversions (e.g., Maksyutov et al., 2003; Houweling et al., 2004; Chevallier et al., 2010) of Takahashi et al. (2009) ($-2.0 \, \text{PgC} \, \text{yr}^{-1}$).

Using the same ocean fluxes and uncertainties, Deng and Chen (2011) have successfully inverted the global land and ocean fluxes.

There are many sources of uncertainty in these model simulations, including errors in the meteorological data, errors of model parameters, and errors caused by the model structure. So, estimating the uncertainties of the simulated carbon fluxes is extremely difficult. In this study, we use an uncertainty of $2.0 \, \text{PgC} \, \text{yr}^{-1}$ for the global land surface (Deng and Chen, 2011), and an uncertainty of $0.88 \, \text{PgC} \, \text{yr}^{-1}$ for the global ocean surface (Baker et al., 2006). The uncertainty on the land is spatially distributed based on the annual NPP distribution simulated by BEPS, while the one on the ocean is distributed according to the area of each ocean region. The prior uncertainties of each region are listed in Table 1. These prior uncertainties are also in the range of those used in previous studies (e.g., Rödenbeck et al., 2003; Gurney et al., 2004; Bruhwiler et al., 2007).

### 2.4 Observations and model–data mismatch errors

CO₂ observations from 133 sites are used in this study, in which 130 time series are from the GLOBALVIEW-CO₂ 2010 dataset (GLOBALVIEW-CO₂, 2010), including 54 flask observations, 7 continuous measurements, 5 tower sites, 6 ship sites, and 58 aircraft sites (aircraft at each flight level is considered as one site), and 3 additional China sites: Longfengshan (LFS), Shangdianzi (SDZ) and Lin’an (LAN) are obtained from Chinese Academy of Meteorological Sciences (CAMS), China Meteorological Administration (CMA). The Mt. Waliguan GAW baseline station in western China has been included in the GLOBALVIEW dataset. There are over 300 time series of observations in GLOBALVIEW-CO₂ 2010 dataset, which were measured by many different organizations. The dataset is a product of the observations, including smoothed values, and interpolated and extrapolated values. In this study, we select data according to the following principles: (1) only smoothed values are selected; (2) if there are many stations in one region, only the data from NOAA Earth System Research Laboratory (ESRL) are selected (e.g., North America), while if only few stations in one region, the data from other organizations are also considered (e.g., Asia); (3) we generally do not choose tower

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**Fig. 1.** Time series of the CO₂ measurements at Longfengshan (LFS) in Northeast China, black points indicate weekly flask observations; red line indicates a curve fitted to the measurements.

**Fig. 2.** An inversion scheme: 21 regions in Asia (13 regions in China) and 22 regions for the rest of the globe. Locations of 133 CO₂ observational sites are also indicated, including 57 flask sites, 7 continuous sites, 5 tower sites, 6 ship sites, and 58 aircraft sites.
observations unless there are very few observations in that area, and if one tower station is selected, only the top-level observations are used; and (4) stations near large cities or airports are mostly not used. For the continuous sites and two tower sites located in the US (ESRL, Fig. 2), the data observed during 12:00–16:00 LST are used, and for another three tower sites located in Canada (Environment Canada), the measurements between 15:00 and 17:00 LST are used. LFS, SDZ and LAN are three regional background stations established by CMA/CAMS, which are located in Northeast China, North China, and East China, respectively. The measurements of these stations were sampled and analyzed using the recommended methods of WMO/GAW, and the results are comparable with those of NOAA/ESRL. For more detailed information about these observations, please refer to Liu et al. (2009). Before monthly averaging, the weekly measurements are smoothed using the same technique as GLOBALVIEW-CO$_2$ dataset (Masarie and Tans, 1995), and Fig. 1 shows the weekly measurements and smoothed curve in LFS. The locations of the all sites are shown in Fig. 2.

The estimation of the model–data mismatch is very difficult (Bruhwiler et al., 2007), since the errors come from both the observations (instrument errors) and the simulations. Various methods (e.g., Rayner et al., 1999a; Gurney et al., 2004; Michalak et al., 2005) have been used to determine the model–data mismatch. In this study, the data–mismatch error is defined using the following function, which is similar to Peters et al. (2005) and Deng and Chen (2011).

\[ R = \sigma_{\text{const}}^2 + GV sd^2, \]  

(5)

where $GVsd$ reflects the observation error, which is the standard deviation of the residual distribution in the average monthly variability (var) file of GLOBALVIEW-CO$_2$ 2010, and the constant portion $\sigma_{\text{const}}$ reflects the simulation error, due to the different performances of the model on each observation station. This portion also varies with station. Except for some difficult stations, the observation sites are divided into 5 categories. The categories and respective value are as follows: Antarctic sites/oceanic flask and continuous sites (0.30), ship and tower sites (1.0), mountain sites (1.5), aircraft samples (0.5), and land flask/continuous sites (0.75). The value of 3.5 is used for the difficult sites (e.g., abp01D0, bkt01D0). In addition, it is noted that SDZ and LAN are treated as difficult sites in this study, because SDZ is near Beijing, and LAN is near Yangtze River delta.

### 3 Results and discussion

#### 3.1 Uncertainty reduction

The posterior flux uncertainties could be estimated based on formula Eq. (3) in Sect. 2. Table 1 shows the uncertainties

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### Table 1. Prior and posterior errors as well as the error reduction rates for each region.

| ID | Region                  | Prior error (PgC yr$^{-1}$) | Post. error (PgC yr$^{-1}$) | Error redu. rate (%) |
|----|-------------------------|-----------------------------|----------------------------|----------------------|
| 1  | North Pacific           | 0.28                        | 0.16                       | 41.2                 |
| 2  | West Pacific            | 0.20                        | 0.16                       | 22.3                 |
| 3  | East Pacific            | 0.22                        | 0.19                       | 13.2                 |
| 4  | South Pacific           | 0.38                        | 0.25                       | 33.4                 |
| 5  | Northern ocean          | 0.16                        | 0.08                       | 47.1                 |
| 6  | North Atlantic          | 0.18                        | 0.15                       | 19.4                 |
| 7  | Tropical Atlantic       | 0.18                        | 0.16                       | 11.0                 |
| 8  | South Atlantic          | 0.20                        | 0.18                       | 9.1                  |
| 9  | Southern Ocean          | 0.46                        | 0.14                       | 70.0                 |
| 10 | Tropical Indian         | 0.26                        | 0.20                       | 21.8                 |
| 11 | South Indian            | 0.21                        | 0.18                       | 14.1                 |
| 12 | Mediterranean           | 0.05                        | 0.05                       | 8.7                  |
| 13 | Boreal N. America       | 0.21                        | 0.13                       | 39.5                 |
| 14 | Temp east America       | 0.31                        | 0.18                       | 41.6                 |
| 15 | Temp west America       | 0.31                        | 0.13                       | 60.0                 |
| 16 | Tropical America        | 1.21                        | 0.62                       | 48.6                 |
| 17 | Temp. S. America        | 0.75                        | 0.54                       | 27.2                 |
| 18 | Northern Africa         | 0.06                        | 0.06                       | 3.3                  |
| 19 | Tropical Africa         | 0.30                        | 0.25                       | 17.6                 |
| 20 | Southern Africa         | 1.03                        | 0.60                       | 42.1                 |
| 21 | Australia               | 0.25                        | 0.12                       | 53.8                 |
| 22 | Europe                  | 0.47                        | 0.17                       | 63.9                 |
| 23 | Boreal Asia             | 0.38                        | 0.18                       | 51.3                 |
| 24 | West Asia               | 0.12                        | 0.10                       | 17.9                 |
| 25 | Southeast Asia          | 0.28                        | 0.19                       | 30.8                 |
| 26 | Indo-China              | 0.48                        | 0.34                       | 34.8                 |
| 27 | Indian peninsula        | 0.40                        | 0.33                       | 18.8                 |
| 28 | Mongolia                | 0.07                        | 0.06                       | 20.6                 |
| 29 | Japan                   | 0.06                        | 0.05                       | 13.9                 |
| 30 | South China forest      | 0.06                        | 0.06                       | 2.0                  |
| 31 | Southwest China forest  | 0.11                        | 0.11                       | 3.0                  |
| 32 | East China forest       | 0.06                        | 0.05                       | 11.2                 |
| 33 | Central China forest    | 0.06                        | 0.06                       | 2.6                  |
| 34 | Northeast China forest  | 0.07                        | 0.06                       | 5.8                  |
| 35 | North China grass       | 0.08                        | 0.07                       | 16.4                 |
| 36 | West China grass        | 0.12                        | 0.06                       | 47.2                 |
| 37 | Northwest China grass   | 0.02                        | 0.02                       | 0.8                  |
| 38 | Central China crop      | 0.02                        | 0.02                       | 0.2                  |
| 39 | North China crop        | 0.07                        | 0.07                       | 3.6                  |
| 40 | Yangtze Plain crop      | 0.06                        | 0.06                       | 11.7                 |
| 41 | Northeast China crop    | 0.07                        | 0.06                       | 21.0                 |
| 42 | South China forest      | 0.06                        | 0.06                       | 2.0                  |
| 43 | Indian peninsula        | 0.40                        | 0.33                       | 18.8                 |
| 44 | Southern China forest   | 0.12                        | 0.06                       | 47.2                 |
| 45 | Global total            | 2.27                        | 0.36                       | 84.1                 |
of prior and posterior fluxes as well as the uncertainty reduction rates of each region. For the global total, 84% of the prior flux uncertainty is reduced due to the constraint of the observations around the world. However, due to the uneven distribution of the observation sites, there are significant differences between different regions. For global land and ocean, the error reduction rates are 68.5% and 36.4%, respectively, since there are many more observation sites distributed over land than over ocean, especially for the surface observation sites (45 vs. 30). Over land, the uncertainties in northern land are reduced much more than those in tropical and southern land, with largest reduction rates happening in Europe (63.8%) and North America (56.5%). Due to lack of enough observations in China, most China regions are with low reduction rates (< 10%), especially for South and Southwest China. Overall, 29.6% of prior flux uncertainty is reduced in China, which is relatively lower compared to North America and Europe.

3.2 Inverted global carbon fluxes

3.2.1 Distribution of the carbon sinks

In this study, the inversions are conducted from 2000 to 2009. The first two years are considered as a spin-up period, and the last year is treated as a spin-down time. Hence, the inverted results from 2002 to 2008 are used for analysis. Figure 3 shows the inverted mean distribution of terrestrial (excluding biomass burning emissions, same as thereafter) and ocean carbon fluxes for 2002–2008. Most of the land regions are inverted as carbon sinks, with strong sinks occurring in boreal Asia, South and Southeast Asia, eastern America and southern South America, while tropical America and southern Africa are carbon sources to the atmosphere. This spatial pattern is quite consistent with the MODIS global NPP changes from 2000 through 2009 (Zhao and Running, 2010), especially in Africa, North America and Eurasia. However, the flux patterns in southern South America and Southeast Asia are inconsistent with the changes in MODIS NPP, and indicate that there may be large uncertainties that existed in these regions. As shown in Table 1, the posterior flux uncertainties of these two regions are 0.54 and 0.19 PgC yr⁻¹, with error reduction rates of 27% and 31%, respectively. In North America, our result (−0.81 ± 0.21 PgC yr⁻¹) is in the range of Carbon Tracker 2010 (CT2010, −0.66 PgC yr⁻¹, data downloaded from http://carbontracker.noaa.gov, same as thereafter) and Deng and Chen (2001) (−0.89 PgC yr⁻¹). In Europe, our result (−0.28 ± 0.17 PgC yr⁻¹) is close to CT2010 (−0.31 PgC yr⁻¹), but higher than CarbonTracker-Europe (−0.165 PgC yr⁻¹, Peters et al., 2010) and Deng and Chen (2011) (−0.22 PgC yr⁻¹). In South Asia, the inverted result is −0.30 ± 0.33 PgC yr⁻¹, which is higher than the results obtained based on bottom-up methods (−0.19 ± 0.19 PgC yr⁻¹, Patra et al., 2013). The estimated global terrestrial ecosystem carbon sink is −3.20 ± 0.63 PgC yr⁻¹ (Table 2), which is slightly lower than the results of Deng and Chen (2011) (−3.63 ± 0.49 PgC yr⁻¹) and CT2010 (−3.85 PgC yr⁻¹), but close to the value estimated by Le Quéré et al. (2009) (2000–2008, −3.0 ± 0.9 PgC yr⁻¹) using five global vegetation models.

3.2.2 Inter-annual variations

Figure 4 shows the inter-annual variation (IAV) of the inverted global land carbon sinks. For comparison, the IAVs from CT2010, Deng and Chen (2011) and Le Quéré et al. (2009) are also shown. The global IAV of land sinks is 3.13 PgC yr⁻¹, with a range from −1.41 PgC yr⁻¹ to −4.54 PgC yr⁻¹. From 2002 to 2008, the global terrestrial carbon sink has an increasing trend. It increases from 2002 to 2004, and decreases in 2005, then continuing to increase from 2005 to 2008. The land carbon sink is the lowest in 2002 and highest in 2008. The IAVs of the land sinks show remarkable correlation with the El Niño Southern Oscillation.
Table 2. Comparison of the inverted carbon sinks in this study with previous studies during 2002–2008 (PgC yr$^{-1}$).

| Region          | Global       | Land         | Ocean        | North America | Europe       | China        |
|-----------------|--------------|--------------|--------------|---------------|--------------|--------------|
| This study      | −5.75 ± 0.39 | −3.20 ± 0.63 | −2.55 ± 0.56 | −0.81 ± 0.21  | −0.28 ± 0.17 | −0.28 ± 0.18 |
| Deng and Chen, 2011$^a$ | −5.58        | −3.63 ± 0.49 | −1.95 ± 0.41 | −0.89 ± 0.18  | −0.22        | −            |
| CarbonTracker 2010 | −5.72        | −3.85        | −1.87        | −0.66         | −0.31        | −0.26        |
| Le Quéré et al., 2009$^b$ | −5.3         | −3.0 ± 0.9   | −2.3 ± 0.4   | −             | −            | −            |

$^a$ Mean from 2002 to 2007; $^b$ mean from 2000 to 2008.

(ENSO); the weaker land sinks in 2002, 2005, and 2007 correspond to the strong El Niño events in 2002–2003, 2004–2005, and 2006–2007, respectively, while the stronger land sink in 2008 corresponds to the La Niña event (http://www.esrl.noaa.gov/psd/enso/mei/). That is because the IAVs are dominated by the tropical land fluxes in this study, and the IAVs of tropical land fluxes have been studied to have strong relationship with the ENSO cycle (Rayner et al., 1999b; Rödenbeck, et al., 2003; Patra et al., 2005b; Gurney et al., 2012).

The increasing trend in the terrestrial sink in this study agrees well with the other studies (Fig. 4). During 2002–2008, our results are weaker than Deng and Chen (2011) and CT2010, which are caused by the partition of carbon sinks between land and ocean, since the carbon sink of ocean ($−2.55 \pm 0.56$ PgC yr$^{-1}$) inverted in this study is larger than that ($−1.95$ Pg C yr$^{-1}$) obtained by Deng and Chen (2011) and CT2010. The differences between this study and Deng and Chen (2011) are mainly due to the selection in observation sites, as the selection of CO$_2$ data in this study is much stricter than Deng’s work. Many more CO$_2$ data were used in Deng and Chen (2011), especially over continental region. The differences with CT2010 may be related to the inversion approach, the observations and the prior fluxes, as CT2010 uses the method of ensemble Kalman filter, the observations at the sampling time, and CASA model outputs and Takahashi ocean fluxes (Takahashi et al., 2009) as prior fluxes. Le Quéré et al. (2009) showed the land sinks of global land carbon sinks estimated using five global vegetation models. During 2002–2005, our results show stronger IAVs than those of Le Quéré et al. (2009), while after 2006, our results are lower than those of Le Quéré et al. (2009). Figure 5 shows a further comparison with previous inversion studies (Chevallier et al., 2010; Rödenbeck, 2005; Peters et al., 2007; Deng and Chen, 2011) as well as Le Quéré et al. (2009) focusing on global net carbon fluxes (Fig. 5a) and terrestrial ecosystem carbon fluxes (land sinks + biomass burning emissions) (Fig. 5b). The global net carbon exchange shows considerable agreement. Our result is in the range of previous studies. However, the ecosystem fluxes inverted in this study are weaker than the previous inversion studies for all the years, but close to Le Quéré et al. (2009) during 2002–2005. These indicate that the land sink may be a little underestimated and the ocean sink may be overestimated in this study.

3.3 Inverted China carbon fluxes

3.3.1 Distribution of the carbon sinks

As shown in Fig. 3, most China areas appear to be carbon sinks, with strongest carbon sinks located in Northeast China (greater than $−50$ gC m$^{-2}$ yr$^{-1}$). Large carbon sinks (greater than $−30$ gC m$^{-2}$ yr$^{-1}$) also occur in the North China crop region, Southeast China forest region and Southwest China grass region. South and Southwest China are inverted to be weak sinks or sources. During 2002–2008, the inverted carbon sink in China is $−0.28 \pm 0.18$ PgC yr$^{-1}$, in which 36% of the carbon is absorbed in Northeast China (including region 33 and 40), 30% of the carbon is captured in North and Northwest China grass regions (including region 34 and 35), and 24% of the uptake is located in eastern China (including region 31, 38 and 39). The carbon sink in China derived in this study is very close to that in Europe ($−0.28 \pm 0.17$ PgC yr$^{-1}$). Basically, this spatial pattern agrees well with the NPP changes derived by Zhao and Running (2010). Compared with previous studies, the inverted carbon sinks in this study are close to the result of CT2010 ($−0.26$ PgC yr$^{-1}$) for the same period, but lower than the inversion ensemble result ($−0.35 \pm 0.33$ PgC yr$^{-1}$) over the period of 1996–2005, which is derived by Piao.
et al. (2009). When we distinguish different ecosystem regions, the forest, grass, and crop regions capture carbon of $-0.097 \pm 0.16$ PgC yr$^{-1}$ (35 %), $-0.084 \pm 0.09$ PgC yr$^{-1}$ (30 %) and $-0.093 \pm 0.11$ PgC yr$^{-1}$ (34 %), respectively. The inverted carbon sinks of forest and grass regions are comparable with Carbon Tracker’s results, while the carbon sink in crop regions is stronger than CT2010, which may be attributed to the three China observation stations added in this study, since these three sites are located in or close to crop regions.

### 3.3.2 Inter-annual variations

Figure 6 shows the IAVs of the carbon sinks of terrestrial ecosystems in China. The IAV of China land sinks is 0.30 PgC yr$^{-1}$, with a range from $-0.12$ PgC yr$^{-1}$ to $-0.42$ PgC yr$^{-1}$. From 2002 to 2005, the carbon sink decreases year by year, and then there is an increasing trend. During 2002 to 2008, the carbon sink is lowest in 2005, and highest in 2007. Overall, there is an increasing trend for the land sinks in China. For comparison, the IAVs of land sinks in China inverted by CT2010 are also shown in Fig. 6. The IAVs of CT2010 also show an increasing trend. However, it could be found that the IAVs between this study and CT2010 are different: in 2003, there is a lowest land sink in CT2010, while the land sink estimated in this study is moderate; in 2004, the land sink of CT2010 is much stronger than that in 2003, while in this study it is slightly weaker than that in 2003; in CT2010, the highest land sink occurs in 2006, while in this study, the highest occurs in 2007. Temperature, precipitation and solar radiation are three key climate factors that impact the photosynthesis of plants. Generally, high temperature, plenty of rainfall and solar radiation are beneficial to plant growth and result in stronger carbon sinks. Figure 7 shows the anomalies of land sinks and the anomalous percentages of the three climate factors during 2002–2008 in China. Monthly climate data of 658 stations in China during the study period are used for analysis, which were obtained from China Meteorological Administration (CMA). In 2002, there are positive anomalies of all three climate factors, especially for annual precipitation (greater than 8 %), corresponding to the negative anomaly of land sink in this study (increasing sink). In 2003, the anomalies of all three factors are negative, corresponding to the decrease of land sink. In 2004, though the solar radiation increases (3.5 %), the annual precipitation is the least, with an anomalous percentage of more than $-5$ %. Because of the reduced precipitation, drought was relatively severe in this year (Zou et al., 2010), corresponding to the further decrease of land sink. In 2005, the precipitation is close to normal years (anomalous percentage less than 2 %), but both solar radiation and temperature are lower than normal. Inspecting the spatial pattern for the anomalies of carbon sinks and annual mean temperature (Fig. 8a, b), we found that in 2005 the temperature decreases in most of the China region, with highest negative anomalous percentage occurring in Northeast China (greater than 10 %), and the land sinks decrease over the whole China region, with a significant decrease happening in Northeast China. In 2006, the temperature rises significantly from 2005 to be close to normal years, while the precipitation decreases ($-2.5$ %), leading to severe drought in this year (Zou et al., 2010), corresponding to a moderate land sink in this year. In 2007, the temperature is highest during this study period, with anomalous percentage greater than 5 %, and the solar radiation and rainfall are close to normal years, corresponding to the strongest land sink. Figure 8c and d show the spatial pattern for the anomalies of the carbon sinks and annual mean temperature in this year. It could be found that the temperature significantly increases in Northeast and eastern China region, correspondingly, and the land sinks increase in these regions. In 2008, the temperature and solar radiation are close to normal years, while the rainfall is more adequate than normal years, with anomalous percentage higher than 6 %. The climate factors in this year are similar to those in 2002; correspondingly, the land sink is also close to 2002. These indicate that the inverted IAVs of this study could be reasonably explained with variations in climate factors. In addition, since the prior land sinks are neutral in this study, these IAVs are fully constrained by the observations, indicating that the inversion is effective in this study.

The IAVs in China are not the same as those for the globe (Sect. 3.2.2). The main reason may be that the IAVs of global carbon sinks are dominated by tropical land fluxes, which are highly affected by ENSO (Sect. 3.2.2), but the impacts of ENSO on tropical zone and on China are different. Except in 2005, it seems that the IAVs of China land sinks have negative correlation with ENSO cycle: the increases of land sinks correspond to strong El Niño events, while the decrease of land sink corresponds to La Niña event. A similar relationship also found in temperate North America (Patra et al., 2005b). North Atlantic Oscillation (NAO) is another climate event impacting the global and regional climate. Patra
which may lengthen the growing seasons, causing much stronger carbon sinks.

### 3.3.3 Carbon budget in China

The inverted net carbon flux during 2002–2008 is 1.37 PgC yr\(^{-1}\) in China, with fossil fuel and biomass burning emissions of 1.64 and 0.014 PgC yr\(^{-1}\), and terrestrial land sink of \(-0.28 \pm 0.18\) PgC yr\(^{-1}\). However, another two carbon sources were not considered in this inversion study. First, carbon could be emitted from the consumption of wood and food imported from outside of China. Based on Food and Agriculture Organization of the United Nations (FAO) statistical databases, Piao et al. (2009) estimated that 0.008 PgC of wood and 0.004 PgC of food were imported into China every year. Second, Terrestrial ecosystems also emit carbon in the form of biogenic volatile organic compounds (BVOCs), and most of these BVOCs are oxidized to CO in the atmosphere (Naik et al., 2004), and then converted to CO\(_2\) after reacting with OH. Guenther (2002) noted that the predicted annual global reactive BVOC emissions of about 1.2 PgC could result in the annual production of approximately 1.0 PgC as CO\(_2\) per year (83%). Granier et al. (2000) estimated that about 80% of the reactive dominant BVOC (i.e., isoprene) got oxidized to CO\(_2\). Hence, BVOCs play an important role in the global carbon budget and cycling. Most reactive BVOCs have a short lifetime in the atmosphere (< 1 day), but the conversion from CO to CO\(_2\) is slow and usually takes 1–2 months. Hence, the observations of CO\(_2\) concentration in or around China have already included the contributions from the atmospheric oxidation of reactive BVOCs emitted around the globe. Therefore, without considering the full chemistry, we treat this indirect CO\(_2\) source implicitly from BVOC oxidation as the direct source of CO\(_2\) from the

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**Table 3.** Comparison of the terrestrial carbon sinks in China derived using different methods (PgC yr\(^{-1}\)).

| Reference       | Method              | Period    | Forest      | Grass       | Crop        | Total       |
|-----------------|---------------------|-----------|-------------|-------------|-------------|-------------|
| This study      | Inversion method    | 2002–2008 | −0.097 ± 0.16 | −0.084 ± 0.09 | −0.093 ± 0.11 | −0.28 ± 0.18 |
| This study\(^a\) | Assimilation system | 2002–2008 | −0.116      | −0.084      | −0.105      | −0.31       |
| CarbonTracker   | Process-based model | 1961–2005 | −0.115      | −0.045      | −0.049      | −0.21 ± 0.078 |
| Tian et al. (2011)\(^b\) | Process-based model | 1982–1999 | −0.101      | −0.037      | −0.033      | −0.18 ± 0.073 |
| Piao et al. (2009)\(^b\) | Process-based model | 1980–2002 | –           | –           | –           | –           |
| Pan et al. (2011) | Inversion study     | 1996–2005 | –           | –           | –           | –           |
|                 | Inventory-based method | 2000–2007 | −0.115      | –           | –           | –           |

\(^a\) The results after considering the carbon emissions in the form of reactive biogenic volatile organic compounds (BVOCs) and from the import of wood and food.

\(^b\) The carbon sinks of shrubland have been distributed to forest, grass and crop land according to the fractions of 36.8%, 38.8%, and 11.7%, respectively, since the shrubland in this study is included in the forest, grass and crop regions.
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Fig. 7. Inter-annual variations of the anomaly of terrestrial carbon sinks and anomalous percentages of climate factors in China (2002 - 2008).

Fig. 8. Anomaly of land sinks (a, c, gC m\(^{-2}\) yr\(^{-1}\), positive indicates sink decreases; negative indicates sink increases) and anomalous percentage of annual mean temperature (b, d, %, positive indicates temperature increases; negative indicates temperature decreases) in 2005 (a and b) and 2007 (c and d).

biosphere and hence overestimate the direct CO\(_2\) source from the biosphere or underestimate the biospheric CO\(_2\) sink. Because of the slow conversion from BVOCs to CO\(_2\) in the well-mixed atmosphere, we expect small regional differences in CO\(_2\) from the contributions of BVOCs. In our global-scale inversion, CO\(_2\) observations around the globe are used, and regional biases in the inverted net CO\(_2\) flux due to BVOC–CO–CO\(_2\) conversions are expected to be similar to those in other regions of the globe. As China’s land area is about 2% of the global surface area, we estimate that our inversion without considering the full chemistry underestimates the CO\(_2\) sink in China by 0.02 PgC yr\(^{-1}\) (i.e., 2% of the global value of 1.0 PgC yr\(^{-1}\)), which is also close to the value estimated from the emissions of reactive BVOCs (i.e., isoprene and monoterpenes, 24 TgC yr\(^{-1}\), Jiang et al., 2012) in China (24 TgC yr\(^{-1}\) \times 80% = 0.019 PgC yr\(^{-1}\)). Though this underestimation is very small, it may be important when we compare the inversion result with the process model results. Hence, we further estimate that China land CO\(_2\) sink is about \(-0.28 + (-0.012) + (-0.02) = -0.31\) PgC yr\(^{-1}\) (Fig. 9), which offsets 19% of the fossil fuel carbon emissions. This result is higher than the previous results obtained through process-based modeling (Tian et al., 2011; Piao et al., 2009) and inventories-based estimation (Piao et al., 2009) (Table 3).

Most reactive BVOCs are emitted from forest area (Jiang et al., 2012), while most imported food and wood are probably consumed in crop regions. Therefore, we estimate that the carbon sinks of forest, grass, and crop region are \(-0.116, -0.084,\) and \(-0.105\) PgC yr\(^{-1}\), respectively. Compared with previous studies, the carbon sink of forest land is comparable with the values of Tian et al. (2011), Piao et al. (2009) and Pan et al., (2011), while the carbon sinks of grassland and cropland are slightly stronger than the results of Tian et al. (2011) and Piao et al. (2009), and the reason may be attributed to the fact that the grass and crop regions in this
study include some forest covers. If we consider the contribution of small forests in grass and crop regions, the forest carbon sinks estimated in this study would be larger than the results of previous studies. Nevertheless, the estimations of the carbon sinks from different ecosystems are very rough, and in order to derive more accurate carbon sinks for different ecosystems, more detailed regional partition schemes and more CO$_2$ measurements in China are needed.

4 Summary and conclusions

A nested atmospheric inversion system with focus on China using the Bayesian approach is established in this study. The global surface is separated into 43 regions based on the 22 TransCom large regions, with 13 small regions in China. Monthly CO$_2$ concentrations from 130 GlobalView sites (Mt. Waliguan GAW baseline station in western China included) and the extra 3 China sites are used in this system. The TM5 model is used for calculating the monthly transport matrix, which is run in a horizontal resolution of $3^\circ \times 2^\circ$. The carbon fluxes of terrestrial ecosystems and the air-water interface are considered as prior fluxes, which are simulated using the BEPS model and the OPA–PISCES–T model, respectively.

Using this inversion system, we investigate the spatial and temporal characteristics of the global and China terrestrial ecosystem carbon fluxes during 2002–2008. The inverted global terrestrial carbon sinks mainly occur in boreal Asia, South and Southeast Asia, eastern US and Southern South America. Most China areas appear to be carbon sinks, with strongest carbon sinks located in Northeast China. From 2002 to 2008, the global terrestrial carbon sink has an increasing trend, with the lowest carbon sink in 2002. The land carbon sinks in China also display an increasing trend, with lowest sink in 2005 and highest sink in 2007. The interannual variations (IAVs) of the global land sinks show remarkable correlation with the El Niño Southern Oscillation (ENSO), while the IAVs in China show a strong relationship with temperature and precipitation. The mean global and China terrestrial carbon sinks over the period 2002–2008 are $-3.20 \pm 0.63$ and $-0.28 \pm 0.18$ PgC yr$^{-1}$, respectively. Considering the emissions of biogenic volatile organic compounds (BVOCs) and the import of wood and food, we estimate that the China terrestrial ecosystem carbon sink is about $-0.31$ PgC yr$^{-1}$ during 2002–2008.

Though large uncertainties still exist in this study, the uncertainty reduction in the Asian region is relatively low compared to Europe and North America, especially in South and Southwest China because of the lower density of CO$_2$ observation sites in Asia. In order to improve the inversion further, more CO$_2$ observations over these regions are needed. This study first gives the insight into the inter-annual variations of the terrestrial carbon sinks in China from the atmospheric perspective, which is helpful for understanding mechanisms influencing the regional carbon cycle.

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