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Discussions

Carbon balance of China constrained by CONTRAIL aircraft CO_2 measurements

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Abstract

Terrestrial CO_2 flux estimates in China using atmospheric inversion method are beset with considerable uncertainties because very few atmospheric CO_2 concentration measurements are available. In order to improve these estimates, nested atmospheric CO_2 inversion during 2002–2008 is performed in this study using passenger aircraft-based CO_2 measurements over Eurasia from the Comprehensive Observation Network for Trace gases by Airliner (CONTRAIL) project. The inversion system includes 43 regions with a focus on China, and is based on the Bayesian synthesis approach and the TM5 transport model. The terrestrial ecosystem carbon flux modeled by the BEPS model and the ocean exchange simulated by the OPA-PISCES-T model are considered as the prior fluxes. The impacts of CONTRAIL CO_2 data on inverted China terrestrial carbon fluxes are quantified, the improvement of the inverted fluxes after adding CONTRAIL CO_2 data are rationed against climate factors and evaluated by comparing the simulated atmospheric CO_2 concentrations with three independent surface CO_2 measurements in China. Results show that with the addition of CONTRAIL CO_2 data, the inverted carbon sink in China increases while those in South and Southeast Asia decrease. Meanwhile, the posterior uncertainties over these regions are all reduced. CONTRAIL CO_2 data also have a large effect on the inter-annual variation of carbon sinks in China, leading to a better correlation between the carbon sink and the annual mean climate factors. Evaluations against the CO_2 measurements at three sites in China also show that the CONTRAIL CO_2 measurements have improved the inversion results.

1 Introduction

Carbon dioxide (CO_2) and other greenhouse gases emitted from human activities are the main cause of global warming (IPCC, 2007). Terrestrial ecosystems play a very important role on regulating the atmospheric CO_2 concentration. According to the

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evidence from atmosphere observations, Le Quéré et al. (2009) estimated that the mean CO_2 uptake rate of the global terrestrial ecosystem is $2.6 \pm 0.7\,\mathrm{Pg\,C\,yr^{-1}}$ for 1990–2000, which offsets 40 % of the global fossil fuel carbon emissions. Pacala et al. (2001) found that North American terrestrial ecosystems sequestered 30–50 % of its industrial CO_2 emissions in the 1980s. China has a vast land area of 960×10^6 ha, and nearly 80 % of the land areas are covered with various types of vegetation, including forest (16.5 %), grass (34.8 %), shrubs (18.5 %), croplands (11.2 %), and other types (Fang et al., 2007). Using the methods of bottom-up (inventory survey and process-based ecosystem model) and top-down (atmospheric inversion) approaches, many studies have been conducted during the past decade to estimate China's terrestrial ecosystem carbon sinks (e.g., Cao et al., 2003; Fang et al., 2007; Piao et al., 2009; Tian et al., 2011; Jiang et al., 2013). Fang et al. (2007) estimated the land sinks in China could offset 20.0–26.8 % of its industrial carbon emissions. However, there are still large gaps of land sink derived using bottom-up and top-down methods (Piao et al., 2009). One of the main reasons may be attributed to the lack of enough CO_2 concentration observations, which lead to large uncertainties in the inversion results, because the atmospheric inversion is highly depended on the atmospheric CO_2 measurements. Jiang et al. (2013) pointed out that due to lack of sufficient observations, most regions of the country have a low uncertainty reduction percentage (< 10 %) by way of atmospheric inversion, especially for South and Southwest China, and the overall uncertainty reduction is relatively lower compared with North America and Europe.

The lack of surface measurements can partially be compensated for by aircraft measurements in the free troposphere. Many vertical profiles of CO_2 have been obtained over Europe and North America using research aircraft (Crevoisier et al., 2010; Xueref-Remy et al., 2011). Compared with research aircrafts, passenger aircraft CO_2 measurements are done at much lower cost, and could cover larger areas. Presently, there are two well-known CO_2 measurement projects using passenger aircrafts, the Civil Aircraft for the Regular Investigation of the atmosphere Based on an Instrument Container (CARIBIC) project (Brenninkmeijer et al., 2007; Schuck

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et al., 2009) and the Comprehensive Observation Network for Trace gases by Airliner (CONTRAIL) project (Machida et al., 2008; Matsueda et al., 2008). CARIBIC measures atmospheric CO_2 by flask sampling between Germany and destinations in Europe, Africa, North and South America and Asia four flights per month, while CONTRAIL measures CO_2 continuously between Japan and Europe, Australia, South and Southeast Asia, and North America. Patra et al. (2011) performed an inversion study based on CARIBIC data and evaluated the results against CONTRAIL data. With the CONTRAIL measurements, Niwa et al. (2012) conducted an inverse modeling study with a focus on tropical terrestrial regions. Their results showed that CONTRAIL data have a large impact on the inversion results.

In this study, a China-focused atmospheric inversion is conducted using CONTRAIL measurements over Eurasia. The inversion system and CONTRAIL data used are first described, followed by presentation and discussion of the impact of CONTRAL data on inverted carbon fluxes and posterior uncertainties in China and its surrounding areas.

2 Method and data

2.1 Inversion setting

In this study, a Bayesian synthesis inversion method (Rayner et al., 1999; Enting et al., 1989) is used to improve the estimations of CO_2 sources and sinks as well as their uncertainties. The global surface is separated into 43 regions based on the 22 TransCom large regions (e.g. Gurney et al., 2003; Baker et al., 2006), with 13 small regions in China (Fig. 2). A monthly transport operator for the 43 regions and forward transport simulations for carbon emissions from fossil fuel and biomass burning are calculated using a global two-way nested transport model TM5 (Krol et al., 2005). The fossil fuel inventory is from the Miller Carbon Tracker fossil fuel emission field (CarbonTraker 2010, 2011), which is constructed based on CDIAC 2007 (Boden et al., 2010) and EDGAR 4 databases (Olivier and Berdowski, 2001). The biomass-burning

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inventory is from the Global Fire Emissions Database version 3 (GFEDv3) (van der Werf et al., 2010). Hourly terrestrial ecosystem carbon exchanges simulated by the BEPS model (Chen et al., 1999; Ju et al., 2006) and daily carbon fluxes across the air–water interface calculated by the OPA-PISCES-T model (Buitenhuis et al., 2006) are considered as prior fluxes. The terrestrial ecosystem carbon fluxes of each grid are neutralized annually. It is assumed that there is an uncertainty of 2.0 $PgCyr^{-1}$ for global terrestrial fluxes (Deng and Chen, 2011), and an uncertainty of 0.88 $PgCyr^{-1}$ for global ocean fluxes (Baker et al., 2006). A total of 130 CO_2 observations from GLOBALVIEW-CO_2 2010 dataset (GLOBALVIEW-CO_2, 2010) are adopted, including 54 flask observations, 7 continuous measurements, 5 tower sites, 6 ship sites, and 58 aircraft sites. The locations of the GLOBALVIEW (GV) CO_2 observations could be found in Fig. 2. Further details of the inversion system are described in Jiang et al. (2013).

2.2 CONTRAIL aircraft CO_2 measurements

The CONTRAIL project measures CO_2 concentrations using continuous measurement equipment on passenger aircrafts (Machida et al., 2008; Matsueda et al., 2008). Calibrations and evaluations have shown that the accuracy of CONTRAIL data compares well with the GV CO_2 data (Machida et al., 2011). In this study, aircraft CO_2 measurements over Eurasia during November 2005–December 2009 are used. The measurements between Japan and Europe, Korea, Taiwan, South Asia and Southeast Asia are shown in Fig. 1a. In order to use the continuous observations in the inversion system, the measurements are divided into 87 sites, including 19 level flight sites (∼ 10 km, Fig. 1a) and 68 vertical sites. Following Niwa et al. (2012), each vertical measurement profile is divided into 5 layers: 0–1000 m, 1000–2000 m, 2000–4000 m, 4000–6000 m, and 6000–8000 m. The flight altitude higher than 8000 m is considered as level flight. For the level flight sites, first, we define 19 regions with each of size $10^\circ \times 10^\circ$ according to the flight routes (Fig. 1a); then, all the observation records with altitude higher than 8000 m located in one region are averaged to get the concentration

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of that site, and its location is determined by averaging the location of all observation records as well. Daily mean data for each site are smoothed (Fig. 1b) using the same technique as Masarie and Tans (1995), and then averaged to monthly mean value. In view of high pollution near the ground around airports by aircraft emissions, only data measured above 2000 m are used. And samples in each clustered site shorter than 6 months are also excluded. Consequently, 54 CONTRAIL CO_2 sites are used in this study (Fig. 2).

2.3 CO_2 measurements in China

In this study, CO_2 concentrations measured at three China observation sites, i.e., Longfengshan (LFS), Shangdianzi (SDZ), and LinAn (LAN) are used to evaluate forward simulation results. LFS, SDZ and LAN are three regional background stations established by Chinese Academy of Meteorological Sciences (CAMS), China Meteorological Administration (CMA), which are located in Northeast China, North China, and East China, respectively (Fig. 3). The weekly flask measurements of these stations are sampled and analyzed using the recommended methods of the Global Atmosphere Watch programme of World Meteorological Organization (WMO/GAW), and the results are comparable to that of the Earth System Research Laboratory in National Oceanic and Atmospheric Administration (NOAA/ESRL). For more detailed information about these observations, please refer to Liu et al. (2009).

3 Results and discussions

3.1 Impact on inter-annual variations

Two inversion experiments are conducted from 2000 to 2009, the first (Case GV) run with only GLOBALVIEW CO_2 included, the second run with CONTRAIL CO_2 data added (Case GVCT). For each experiment, the first two years are considered to be the spin-up period, and the last year is the spin-down time. Therefore, the analysis period

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in this study is from 2002 to 2008. Figure 4 shows the inter-annual variations (IAVs) of the inverted land sinks (excluding biomass burning emissions, the same thereafter) and the posterior uncertainties of the two experiments in China. When only GV CO_2 is used, the IAVs show a less negative trend, with strongest land sink occurring in 2002, and weakest sink in 2008. When CONTRAIL CO_2 is added after December 2005, significant changes occur after 2005, with large changes in 2007, compared to Case GV. The CONTRAIL CO_2 also has an obvious impact on the posterior uncertainties from 2005 to 2008, especially in 2007 and 2008. The posterior uncertainties in 2008 and 2009 are reduced from around 0.195 to 0.183 $PgCyr^{-1}$ ($\sim 6\%$). Overall, when the CONTRAIL CO_2 data are added, the inverted carbon sink in China increases by 0.05 $PgCyr^{-1}$ (30 %), the posterior uncertainty is reduced by 0.0043 $PgCyr^{-1}$ (2.2 %), and the mean carbon sink in China is -0.25 ± 0.19 $PgCyr^{-1}$ for 2002–2008.

Temperature, precipitation and radiation are three key climate factors those affect plant growth. Zhu et al. (2007) investigated the impact of climatic changes on net primary productivity (NPP) of terrestrial vegetation in China by analyzing 18 years' (1982–1999) climatic data and satellite observations of vegetation activity, and showed that plant growth is temperature-limited in northern China, and is radiation-limited in southern China. Hence, in order to study whether the impact of CONTRAIL data is reasonable, it should be useful to check the relationship between inter-annual variations of climate factors and land sink in different regions of China. Because the changes of posterior fluxes mainly occur in southern China and northern China (see Sect. 3.2), only these two regions are investigated. Monthly climate data of 484 stations obtained from China Meteorological Administration (CMA) during the study period are used for the analysis, in which 269 stations are located in southern China, and the others are located in northern China (Fig. 3). Figure 5a shows the relationship between solar radiation and land sink in southern China. It shows that during 2002–2006, there is a strong correlation between radiation and carbon sink for both Case GV and Case GVCT: high radiation is corresponding to strong carbon uptake, and vice versa. However, from 2006 to 2008, this relationship is not observed in the posterior

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fluxes for Case GV. The changes caused by CONTRAIL data lead to a better correlation between the fluxes and radiation. In northern China, correlation between temperature and land sink is illustrated in Fig. 5b. The changes caused by adding CONTRAIL data also make the fluxes better correlated with the temperature. In southern China, with moderate temperatures and plentiful rainfalls, the plant growth is usually limited by radiation. Higher radiation might benefit for the vegetation growth and subsequently increase the land carbon sink. In northern China, usually the summer has moderate temperatures while winter is very cold, and a warmer winter might lengthen the growing season. The temperature in the wintertime of 2006–2007 is much higher than normal years (figure not shown), probably accounting for much stronger carbon sink. These indicate that the IAVs of posterior fluxes in China by additional constraint of CONTRAIL CO_2 data could be more reasonable.

3.2 Impact on spatial pattern

As shown in Sect. 3.1, CONTRAIL CO_2 has large impacts on the inverted carbon fluxes and uncertainties during the 2006–2008 periods. Furthermore, the impacts of CONTRAIL CO_2 on the spatial patterns of the inverted global carbon fluxes and uncertainties for 2006 to 2008 are shown in Fig. 6. For Case GV, most of the land regions are found to be carbon sinks (Fig. 6a), with strong sinks ($> 50\,\mathrm{g\,C\,m^{-2}\,yr^{-1}}$) occurring in Boreal Asia, South and Southeast Asia, the eastern US and southern South America (S.A.), while Tropical America and Southern Africa appear as carbon sources. Most China regions appear as weak carbon sinks ($< 30\,\mathrm{g\,C\,m^{-2}\,yr^{-1}}$). Comparing Case GVCT with the Case GV, the carbon sinks decrease in South and Southeast Asia, tropical Africa, boreal and western temperate North America, and Southwest China, with the most significant decrease happening in Southeast Asia ($> 50\,\mathrm{g\,C\,m^{-2}\,yr^{-1}}$). The carbon sinks increase in Europe, boreal and western Asia, eastern temperate North America, eastern China, southern Africa and most of the Pacific, with the most notable increase in eastern China. It should be noted that though only CONTRAIL CO_2 data over Eurasia are used in this study, its impacts are

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global. Meanwhile, posterior uncertainties over most of the Northern Hemisphere and tropical regions are reduced, with the most significant reduction occuring in South and Southeast Asia (∼ 10 %). In China, the uncertainty reduction in all regions is smaller than 5 %, with largest reductions in East and Southwest China.

Compared with results from Niwa et al. (2012) for the same time period, the decrease of land sink in Southeast Asia, increases of land sinks in Europe, boreal Asia, eastern temperate North America, and southern Africa, and the reductions of posterior uncertainties in South and Southeast Asia are consistent. However, in South Asia and eastern China, although large effects of CONTRAIL CO_2 data on land sinks were also derived in Niwa et al. (2012), the impacts are opposite. Moreover, the magnitude of the effects on the inverted land fluxes and associated uncertainties are much smaller than those in Niwa et al. (2012). In order to gain insight on the causes of the differences between this study and Niwa et al. (2012), mean monthly prior and posterior fluxes of Case GV and Case GVCT in China, South Asia and Southeast Asia (including Indo-China Peninsula and tropical Asia) during 2006–2008 are compared in Fig. 7. In China, there are large differences in the prior fluxes. The seasonal amplitude of Niwa's fluxes (simulated using CASA model) is much larger than that (simulated using BEPS model) of this study. After being constrained by GV and CONTRAIL CO_2 data, the posterior fluxes from this study and Niwa et al. (2012) tend to be close to each other: the land sinks during growing season increase in this study, while those decrease in Niwa et al. (2012), and the strongest sinks are very similar in magnitude. However, the flux estimated in this study turns from source to sink in May, reaching the strongest in July, while that estimated in Niwa et al. (2012) turns from source to sink in July, reaching the strongest in August. This delay leads to a relatively large divergence in the inverted annual carbon sink (–0.29 vs. 0.25 $Pg\,C\,yr^{-1}$). In contrast, in South Asia, the seasonal amplitude of Niwa's prior fluxes is smaller than that of this study. When only being constrained with GV CO_2 data, the land sinks during the growing season obviously increase in this study, while little changes happen with Niwa's results. After CONTRAIL CO_2 data are added, the sinks during the growing season decrease, and the sources

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during non-growing season increase in this study, leading to a decrease in the annual land sink; while in Niwa et al. (2012), the land sources increase significantly during the non-growing season, and the land sinks during the growing increase remarkably as well. The annual land sinks in South Asia from these two studies are very close. In Southeast Asia, there are also significant differences in the prior fluxes: compared with Niwa's results, there are much higher carbon sinks from May to October, and higher sources from December to April in this study. When only being constrained with GV CO_2 data, except in October and November, more carbon is absorbed in all month in this study, especially in February and September; while in Niwa et al. (2012), the land sinks increase in March, September and October, and in the other months, the land sources increase. The annual land sink increases from 0.0 $PgCyr^{-1}$ to −0.68 $PgCyr^{-1}$ in this study, while little changes occur in Niwa et al. (2012). This difference may partly due to the use of Bukit Koto Tabang (BKT) station in Indonesia and the CONTRAIL-ASE observations between Australia and Japan included in GLOBALVIEW dataset in this study (Fig. 2), which were not used in Niwa et al. (2012). After the CONTRAIL CO_2 data are added, the carbon sinks decrease in all months in this study, and they decrease in most months in Niwa et al. (2012) as well. The monthly variations of the posterior fluxes between this study and Niwa et al. (2012) are similar to a certain extent, especially from September to December. However, from January to August, the carbon sources in Niwa et al. (2012) are significantly higher than that of this study, especially in January, February, June and July. Overall, the uses of different prior fluxes and amount of GV observations may result in these different effects of CONTRAIL CO_2 data. However, the posterior fluxes from these two studies tend to be close to each other after being constrained with CONTRAIL CO_2 data.

The statistics show that with the further constraint of CONTRAIL CO_2 data, the carbon sink in China increases from $-0.16 \pm 0.19\,PgCyr^{-1}$ to $-0.29 \pm 0.18\,PgCyr^{-1}$. At the same time, the land sinks of Southeast Asia and South Asia decrease from -0.68 ± 0.34 and $-0.28 \pm 0.32\,PgCyr^{-1}$ to -0.35 ± 0.30 and $-0.11 \pm 0.30\,PgCyr^{-1}$, respectively. When CONTRAIL data are added, the land sink in China is close to

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the inversion result of $-0.35\,\mathrm{Pg\,C\,yr^{-1}}$ stated in Jiang et al. (2013) for the same period, which was derived by adding three additional China CO_2 observation stations. The land sink obtained for South Asia, $-0.11 \pm 0.30\,\mathrm{Pg\,C\,yr^{-1}}$, agrees well with the $-0.104 \pm 0.15\,\mathrm{Pg\,C\,yr^{-1}}$ result of Patra et al. (2013) for 2007–2008 period. Southeast Asia is one of the most forested regions in the world. Its land sink should be dominated by forest. Pan et al. (2011) estimated that here the forest carbon flux from 2000 to 2007 was $-0.12\,\mathrm{Pg\,C\,yr^{-1}}$. Carbon emission from biomass burning is $0.30\,\mathrm{Pg\,C\,yr^{-1}}$ in this region from GFEDv3, so, the net carbon flux, excluding fossil fuel emissions, is $-0.05\,\mathrm{Pg\,C\,yr^{-1}}$ ($-0.35 + 0.30 = -0.05\,\mathrm{Pg\,C\,yr^{-1}}$) in this study, which is comparable to the results of Pan et al. (2011). The main reason of the significant changes in South and Southeast Asia is that there are very few CO_2 measurements in the GV dataset in these regions (Fig. 2), so there is an insufficient observational constraint, leading to large uncertainties in the inverted carbon fluxes. The addition of CONTRAIL data reduces uncertainty by markedly increasing observations in these regions. Despite the fact that most CONTRAIL CO_2 measurements are in the middle and upper troposphere, due to strong tropical convection, the resulting observational constraints are still relatively strong, thus decreasing land sinks in these regions. Niwa et al. (2012) have detailed the mechanisms of CONTRAIL CO_2 data impacts on the fluxes. The large changes in Eastern China could be explained with that there are many CONTRAIL CO_2 measurements over East China Sea, Korea and Japan, which are mostly downwind of China, so CONTRAIL CO_2 over these regions could directly sense carbon fluxes in eastern China to a certain extent. Figure 8 shows contributions from emissions in different regions of the globe at a current month (July 2007) and for the previous five months (1 Pg carbon emitted from each region at one month) to the CO_2 concentration in July 2007 at 2000–4000 m height over Taipei airport (TPE). There are strong contributions from the emissions of eastern China (South China, East China forest, and Yangtze plain) at the current month (July 2007). Therefore, CONTRAIL CO_2 data could significantly affect the inversion results in China.

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3.3 Evaluation against CO_2 measurements in China

We further use the CO_2 concentration measured at three China observation sites, i.e., LFS, SDZ, and LAN, to evaluate the forward simulation results using the TM5 model from the posterior fluxes. The weekly measurements are smoothed and extrapolated to obtain monthly values, using the same technique as GV-CO_2 dataset (Masarie and Tans, 1995). The simulations are conducted from 2000 to 2009, with initial concentration of 368 ppmv (Ed Dlugokencky and Pieter Tans, NOAA/ESRL, www.esrl.noaa.gov/gmd/ccgg/trends/). Since the impact of CONTRAIL CO_2 is the largest in 2007, the simulation results in 2007 are evaluated using the CO_2 concentration measurements (Fig. 9). Obviously, the simulated CO_2 concentrations using the posterior fluxes constrained by CONTRAIL data are much closer to the observations during the summertime at all three sites. The mean biases between the simulations and observations at LAN, LFS and SDZ are reduced from 2.13, 4.39, and 3.62 ppmv to 1.28, 3.40, and 2.74 ppmv, respectively. Moreover, the seasonal amplitude of CO_2 concentration between wintertime and summertime may better reflect the seasonal variations in land ecosystem sources and sinks in the upwind areas of the stations. Except at SDZ, simulated concentration amplitude using posterior fluxes constrained by CONTRAIL data is also much closer to the observations (Fig. 9) than those without the CONTRAIL constraint. Therefore, CONTRAIL data have helped improve the inversion results for China.

4 Summary and conclusions

In this study, CONTRAIL Aircraft CO_2 measurements over Eurasia are used to constrain the inversion besides GV CO_2 data in a nested atmospheric inversion system with the focus on China during 2002–2008. The CONTRAIL CO_2 measurements are grouped into 87 sites, and 54 of the sites are then added into the inversion system. The impact of the CONTRAL data on the inverted carbon fluxes and posterior

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uncertainties in China and its surrounding areas are quantified. Results show that when the CONTRAIL CO_2 data are added, the inverted carbon sink in China increases, and that in South and Southeast Asia decreases. The changes in South and Southeast Asia make the inverted carbon sinks more comparable with previous studies. CONTRAIL CO_2 data also make a large impact on the inverted inter-annual variation of carbon sinks in China, with the largest change in 2007. This change makes the carbon sink in northern China better correlated with the annual mean air temperature and that in southern China better correlated with the solar radiation. Moreover, we use the CO_2 data measured at three China observation sites to evaluate the forward simulation results using the TM5 model based on the posterior fluxes. Results show that the large change of the land sink in China in 2007 has made the simulated concentrations in better agreement with the observations at three sites that are not used in the inversion. Finally, it is interesting to note that more CO_2 measurements in or around China added to the inversion lead to an increase in the inverted sinks in China.

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References

Baker, D. F., Law, R. M., Gurney, K. R., Rayner, P., Peylin, P., Denning, A. S., Bousquet, P., Bruhwiler, L., Chen, Y. H., Ciais, P., Fung, I. Y., Heimann, M., John, J., Maki, T., Maksyutov, S., Masarie, K., Prather, M., Pak, B., Taguchi, S., and Zhu, Z.: TransCom 3 inversion intercomparison: impact of transport model errors on the interannual variability of regional CO_2 fluxes, 1988–2003, Global Biogeochem. Cy., 20, GB1002, doi:10.1029/2004GB002439, 2006.

Brenninkmeijer, C. A. M., Crutzen, P., Boumard, F., Dauer, T., Dix, B., Ebinghaus, R., Filippi, D., Fischer, H., Franke, H., Frieß, U., Heintzenberg, J., Helleis, F., Hermann, M., Kock, H. H., Koeppel, C., Lelieveld, J., Leuenberger, M., Martinsson, B. G., Miemczyk, S., Moret, H. P., Nguyen, H. N., Nyfeler, P., Oram, D., O'Sullivan, D., Penkett, S., Platt, U., Pupek, M., Ramonet, M., Randa, B., Reichelt, M., Rhee, T. S., Rohwer, J., Rosenfeld, K., Scharffe, D., Schlager, H., Schumann, U., Slemr, F., Sprung, D., Stock, P., Thaler, R., Valentino, F., van Velthoven, P., Waibel, A., Wandel, A., Waschitschek, K., Wiedensohler, A., Xueref-Remy, I., Zahn, A., Zech, U., and Ziereis, H.: Civil Aircraft for the regular investigation of the atmosphere based on an instrumented container: The new CARIBIC system, Atmos. Chem. Phys., 7, 4953–4976, doi:10.5194/acp-7-4953-2007, 2007.

Boden, T. A., Marland, G., and Andres, R. J.: Global, Regional, and National Fossil-Fuel CO_2 Emissions, Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., USA, doi:10.3334/CDIAC/00001_V2010, 2010.

Buitenhuis, E., Le Quéré, C., Aumont, O., Beaugrand, G., Bunker, A., Hirst, A., Ikeda, T., O'Brien, T., Piontkovski, S., and Straile, D.: Biogeochemical fluxes through mesozooplankton, Global Biogeochem. Cy., 20, GB2003, doi:10.1029/2005GB002511, 2006.

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.

CarbonTraker 2010: Fossil Fuel Module, available at: http://www.esrl.noaa.gov/gmd/ccgg/carbontracker/CT2010/documentation_ff.html#ct_doc, last access: 12 March 2014, 2011.

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.

Crevoisier, C., Sweeney, C., Gloor, M., Sarmiento, J. L., and Tans, P. P.: Regional US carbon sinks from three-dimensional atmospheric CO_2 sampling, P. Natl. Acad. Sci. USA, 107, 18348–18353, doi:10.1073/pnas.0900062107, 2010.

Deng, F. and Chen, J. M.: Recent global CO_2 flux inferred from atmospheric CO_2 observations and its regional analyses, Biogeosciences, 8, 3263–3281, doi:10.5194/bg-8-3263-2011, 2011.

Enting, I. G. and Mansbridge, J. V.: Seasonal sources and sinks of atmospheric CO_2: direct inversion of filtered data, Tellus B, 41, 111–126, 1989.

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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.

GLOBALVIEW-CO2: Cooperative Atmospheric Data Integration Project – Carbon Dioxide, NOAA ESRL, Boulder, Colorado, available at: http://www.esrl.noaa.gov/gmd/ccgg/globalview/, last access: 12 March 2014, 2010.

Gurney, K. R., Law, R. M., Denning, A. S., Rayner, P. J., Baker, D., Bousquet, P., Bruhwiler, L.,Chen, Y. H., Ciais, P., Fan, S. M., Fung, I. Y., Gloor, M., Heimann, M., Higuchi, K., John, J., Kowalczyk, E., Maki, T., Maksyutov, S., Peylin, P., Prather, M., Pak, B. C., Sarmiento, J., Taguchi, S., Takahashi, T., and Yuen, C. W.: TransCom 3 CO_2 inversion intercomparison: 1. Annual mean control results and sensitivity to transport and prior flux information, Tellus B, 55, 555–579, 2003.

Intergovernmental Panel on Climate Change (IPCC), I. S. A.: The Physical Science Basis of Climate Change: Changes in Atmospheric Constituents and in Radiative Forcing, Cambridge University Press, New York, 2007.

Jiang, F., Wang, H. W., Chen, J. M., Zhou, L. X., Ju, W. M., Ding, A. J., Liu, L. X., and Peters, W.: Nested atmospheric inversion for the terrestrial carbon sources and sinks in China, Biogeosciences, 10, 5311–5324, doi:10.5194/bg-10-5311-2013, 2013.

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.

Krol, M., Houweling, S., Bregman, B., van den Broek, M., Segers, A., van Velthoven, P., Peters, W., Dentener, F., and Bergamaschi, P.: The two-way nested global chemistry-transport zoom model TM5: algorithm and applications, Atmos. Chem. Phys., 5, 417–432, doi:10.5194/acp-5-417-2005, 2005.

Le Quéré, C., Raupach, M. R., Canadell, J. G., Marland, G., Bopp, L., Ciais, P., Conway, T. J., Doney, S. C., Feely, R., Foster, P., Friedlingstein, P., Gurney, K., Houghton, R. A., House, J. I., Huntingford, C., Levy, P. E., Lomas, M. R., Majkut, J., Metzl, N., Ometto, J. P., Peters, G. P., Prentice, I. C., Randerson, J. T., Running, S. W., Sarmiento, J. L., Schuster, U., Sitch, S., Takahashi, T., Viovy, N., van der Werf, G. R., and Woodward, F. I.: Trends in the sources and sinks of carbon dioxide, Nat. Geosci., 2, 831–836, doi:10.1038/ngeo689, 2009.

Liu, L. X., Zhou, L. X., Zhang, X. C., Wen, M., Zhang, F., Yao, B., and Fang, S. X.: The characteristics of atmospheric CO_2 concentration variation of four national background stations in China, Sci. China Ser. D, 52, 1857–1863, doi:10.1007/s11430-009-0143-7, 2009.

Machida, T., Matsueda, H., Sawa, Y., Nakagawa, Y., Hirotani, K., Kondo, N., Goto, K., Nakazawa, T., Ishikawa, K., and Ogawa, T.: Worldwide measurements of atmospheric CO_2 and other trace gas species using commercial airlines, J. Atmos. Ocean. Tech., 25, 1744–1754, doi:10.1175/2008JTECHA1082.1, 2008.

Machida, T., Tohjima, Y., Katsumata, K., and Mukai, H.: A new CO_2 calibration scale based on gravimetric one-step dilution cylinders in National Institute for Environmental Studies – NIES 09 CO_2 scale, GAW Rep. 194, 114–119, World Meteorol. Organ., Geneva, Switzerland, 2011.

Masarie, K. A. and Tans, P. P.: Extension and integration of atmospheric carbon dioxide data into a globally consistent measurement record, J. Geophys. Res., 100, 11593–11610, doi:10.1029/95JD00859, 1995.

Matsueda, H., Machida, T., Sawa, Y., Nakagawa, Y., Hirotani, K., Ikeda, H., Kondo, N., and Goto, K.: Evaluation of atmospheric CO_2 measurements from new flask air sampling of JAL airliner observations, Pap. Meteorol. Geophys., 59, 1–17, doi:10.2467/mripapers.59.1, 2008.

Niwa, Y., Machida, T., Sawa, Y., Matsueda, H., Schuck, T. J., Brenninkmeijer, C. A. M., Imasu, R., and Satoh, M.: Imposing strong constraints on tropical terrestrial CO_2 fluxes using passenger aircraft based measurements, J. Geophys. Res., 117, D11303, doi:10.1029/2012JD017474, 2012.

Olivier, J. G. J. and Berdowski, J. J. M.: Global emissions sources and sinks, in: The Climate System, edited by: Berdowski, J., Guicherit, R., and Heij, B. J., A. A. Balkema Publishers/Swets & Zeitlinger Publishers, Lisse, the Netherlands, 33–78, 2001.

Pacala, S. W., Hurtt, G. C., Baker, D., Peylin, P., Houghton, R. A., Birdsey, R. A., Heath, L., Sundquist, E. T., Stallard, R. F., Ciais, P., Moorcroft, P., Caspersen, J. P., Shevliakova, E., Moore, B., Kohlmaier, G., Holland, E., Gloor, M., Harmon, M. E., Fan, S.-M., Sarmiento, J. L., Goodale, C. L., Schimel, D., and Field, C. B.: Consistent land- and atmosphere-based US carbon sink estimates, Science, 292, 2316–2320, 2001.

Pan, Y., Birdsey, R. A., Fang, J., 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., McGuire, A. D., Piao, S., 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.

Patra, P. K., Niwa, Y., Schuck, T. J., Brenninkmeijer, C. A. M., Machida, T., Matsueda, H., and Sawa, Y.: Carbon balance of South Asia constrained by passenger aircraft CO_2

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14, 7683–7709, 2014

Carbon balance of China constrained by CONTRAIL aircraft CO_2 measurements

F. Jiang et al.

measurements, Atmos. Chem. Phys., 11, 4163–4175, 2011, http://www.atmos-chem-phys.net/11/4163/2011/.

Patra, P. K., Canadell, J. G., Houghton, R. A., Piao, S. L., Oh, N.-H., Ciais, P., Manjunath, K. R., Chhabra, A., Wang, T., Bhattacharya, T., Bousquet, P., Hartman, J., Ito, A., Mayorga, E., Niwa, Y., Raymond, P. A., Sarma, V. V. S. S., and Lasco, R.: The carbon budget of South Asia, Biogeosciences, 10, 513–527, doi:10.5194/bg-10-513-2013, 2013.

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, 1009–1013, doi:10.1038/nature07944, 2009.

Rayner, N. A., Parker, D. E., Horton, E. B., Folland, C. K., Alexander, L. V., Rowell, D. P., Kent, E. C., Kaplan, A.: Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century, J. Geophys. Res., 108, 4407, doi:10.1029/2002JD002670, 2003.

Rayner, P. J., Enting, I. G., Francey, R. J., and Langenfelds, R.: Reconstructing the recent carbon cycle from atmospheric CO_2, ^{13}C and O_2/N_2 observations, Tellus B, 51, 213–232, 1999.

Schuck, T. J., Brenninkmeijer, C. A. M., Slemr, F., Xueref-Remy, I., and Zahn, A.: Greenhouse gas analysis of air samples collected onboard the CARIBIC passenger aircraft, Atmos. Meas. Tech., 2, 449–464, doi:10.5194/amt-2-449-2009, 2009.

Tian, H., 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, 2011.

van der Werf, G. R., Randerson, J. T., Giglio, L., Collatz, G. J., Mu, M., Kasibhatla, P. S., Morton, D. C., DeFries, R. S., Jin, Y., and van Leeuwen, T. T.: Global fire emissions and the contribution of deforestation, savanna, forest, agricultural, and peat fires (1997–2009), Atmos. Chem. Phys., 10, 11707–11735, doi:10.5194/acp-10-11707-2010, 2010.

Xueref-Remy, I., Messager, C., Filippi, D., Pastel, M., Nedelec, P., Ramonet, M., Paris, J. D., and Ciais, P.: Variability and budget of CO_2 in Europe: analysis of the CAATER airborne campaigns – Part 1: Observed variability, Atmos. Chem. Phys., 11, 5655–5672, doi:10.5194/acp-11-5655-2011, 2011.

ACPD

14, 7683–7709, 2014

Carbon balance of China constrained by CONTRAIL aircraft CO_2 measurements

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Zhu, W. Q., Pan, Y. Z., Yang, X. Q., and Song, G. B.: Comprehensive analysis of the impact of climatic changes on Chinese terrestrial net primary productivity, Chinese Sci. Bull., 52, 3253–3260, 2007.
Zou, X. K., Ren, G. Y., and Zhang, Q.: Droughts variations in China based on a compound index of meteorological drought, Climatic and Environmental Research, 15, 371–378, 2010 (in Chinese).

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14, 7683–7709, 2014

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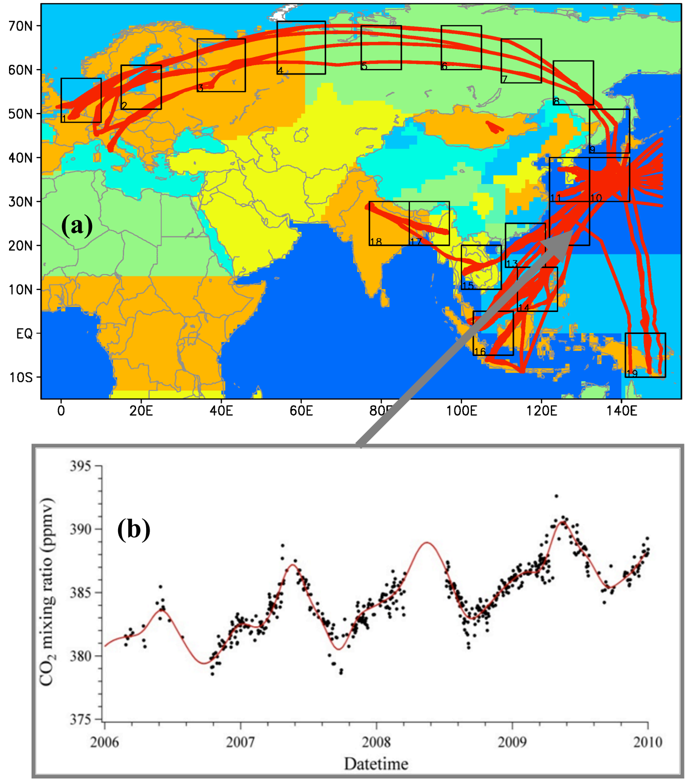

Fig. 1. A map of CONTRAIL measurements; **(a)** the CONTRAIL measurement locations (red dots), black rectangles represent the area partitions of the measurements of level flights, shaded represent different inversion regions over Eurasia; **(b)** Time series of the measurements over East China Sea, black line indicates a curve fitted to the daily CO_2.

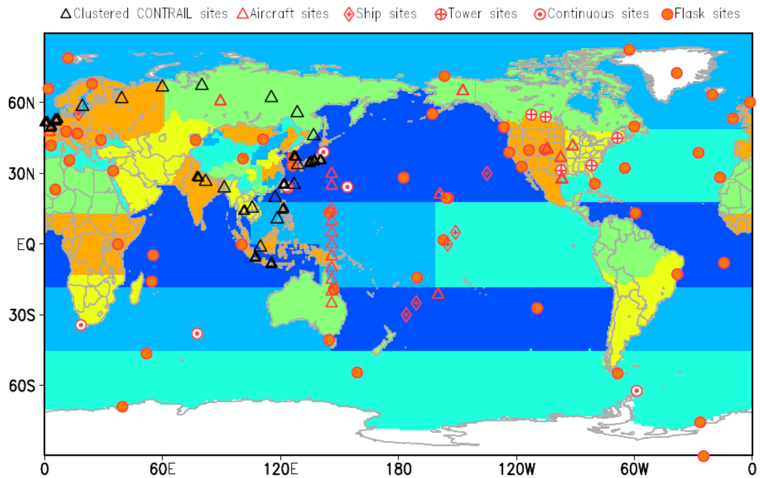

Fig. 2. An inversion scheme: 21 regions in Asia (13 regions in China) and 22 regions for the rest of the globe. Locations of 184 CO_2 observational sites are also indicated, including 130 sites from GV dataset (54 flask sites, 7 continuous sites, 5 tower sites, 6 ship sites, 58 aircraft sites) and 54 sites from CONTRAIL aircraft measurements (bold ones include 3 vertical sites at 2000–4000, 4000–6000, 6000–8000 m for ascending and descending flights data and thin ones include 1 sites at 8000–12 000 m for level flights data).

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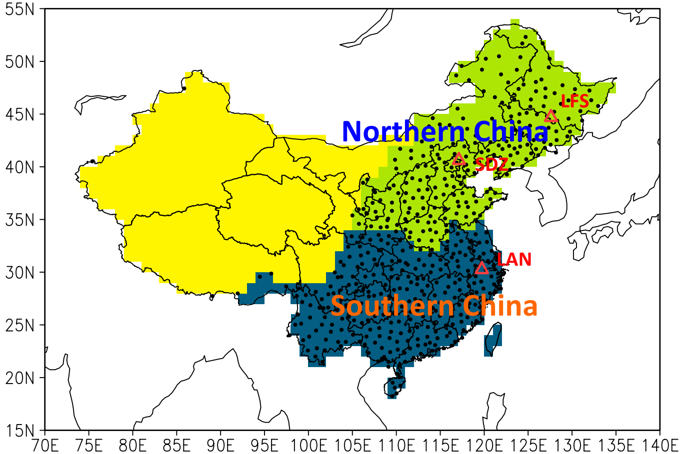

Fig. 3. Locations of observations (black point: meteorological data locations; red triangle: CO_2 observation sites in China, which are used for evaluation in this study).

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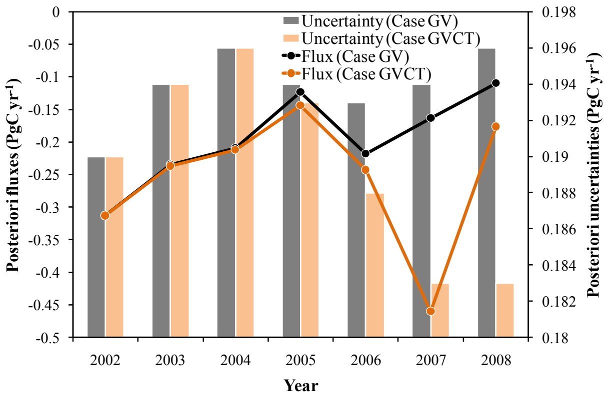

Fig. 4. Impact on inter-annual variations of inverted carbon flux and posterior uncertainty in China.

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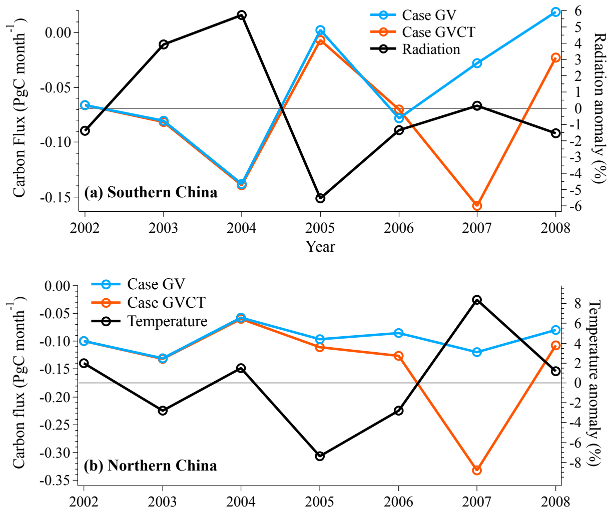

Fig. 5. Inter-annual variations of the posterior fluxes and climate factors in southern China **(a)** and northern China **(b)**.

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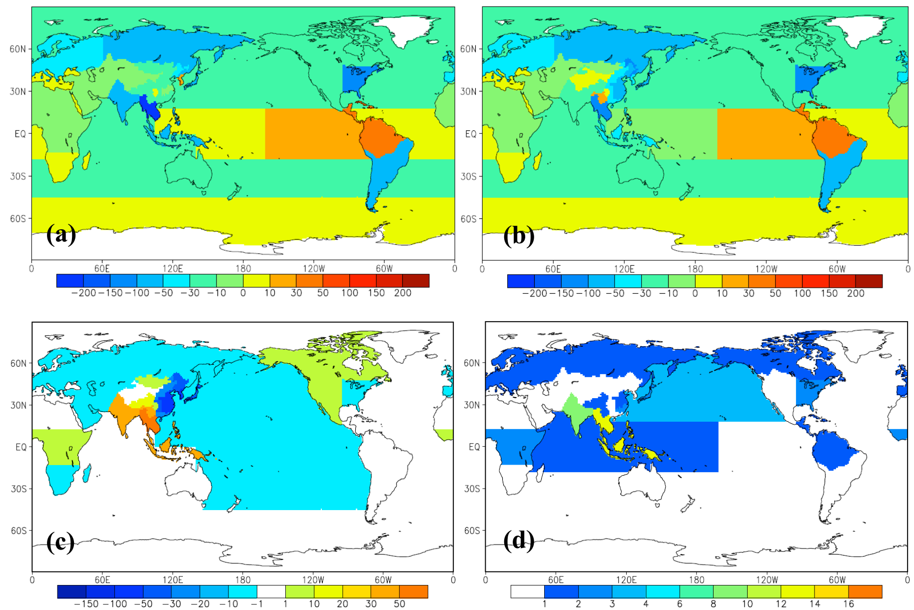

Fig. 6. Inverted global carbon flux for **(a)** Case GV; **(b)** Case GVCT; and impact of CONTRAIL CO_2 on **(c)** the inverted carbon fluxes and **(d)** posterior uncertainties (averaged for 2006 to 2008, $g\,C\,m^{-2}\,yr^{-1}$).

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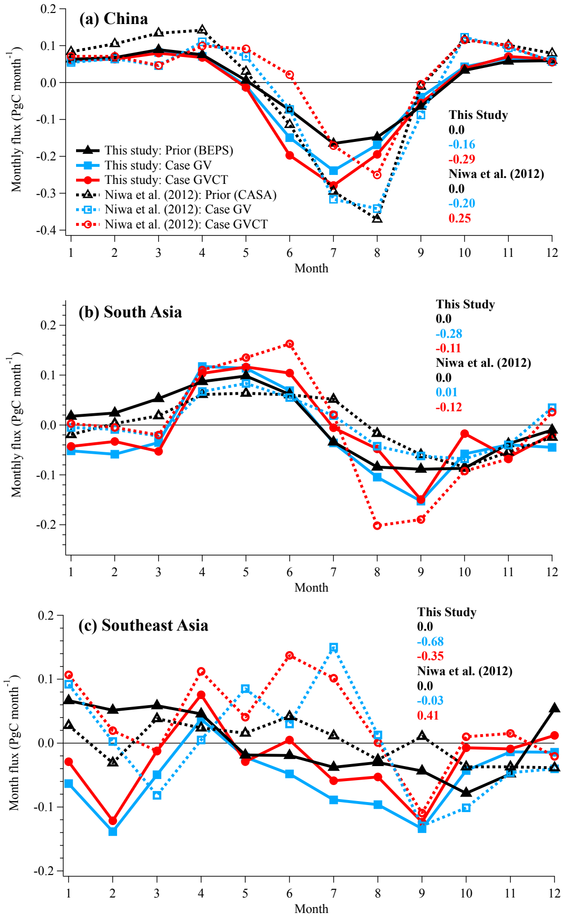

Fig. 7. Mean monthly fluxes in **(a)** China, **(b)** South Asia and **(c)** Southeast Asia during 2006–2008 (case GV: only constrained by GV CO_2; case GVCT: constrained by both GV CO_2 and CONTRAIL CO_2).

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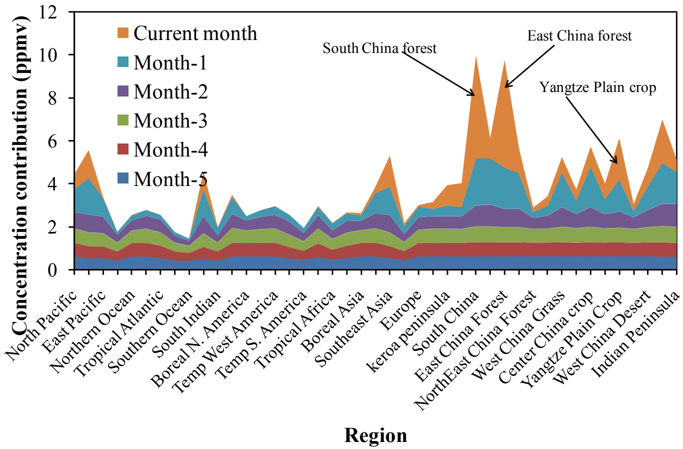

Fig. 8. Contributions from emissions of different regions in July 2007 and the previous five months (1 Pg C month^{-1} region^{-1}) to the CO_2 concentration in July 2007 at 2000–4000 m over Taipei airport (TPE).

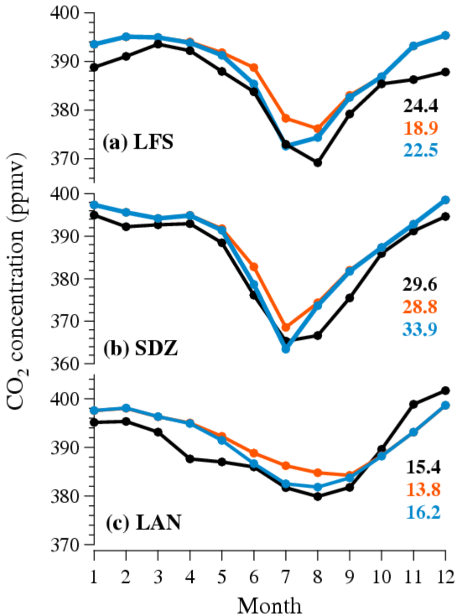

Fig. 9. Simulated and observed monthly CO_2 concentrations at three China stations, the black lines represent the observations, the orange lines represent the simulations from the land fluxes constrained with GV CO_2 only, the blue lines represent the simulations from the land fluxes constrained by additional CONTRAIL CO_2, and the numbers represent the concentration amplitude between wintertime and summertime.