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Implications of overestimated anthropogenic CO_2 emissions on East Asian and global land CO_2 flux inversion

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Abstract

Measurement and modelling of regional or country-level carbon dioxide (CO_2) fluxes are becoming critical for verification of the greenhouse gases emission control. One of the commonly adopted approaches is inverse modelling, where CO_2 fluxes (emission: positive flux, sink: negative flux) from the terrestrial ecosystems are estimated by combining atmospheric CO_2 measurements with atmospheric transport models. The inverse models assume anthropogenic emissions are known, and thus the uncertainties in the emissions introduce systematic bias in estimation of the terrestrial (residual) fluxes by inverse modelling. Here we show that the CO_2 sink increase, estimated by the inverse model, over East Asia (China, Japan, Korea and Mongolia), by about 0.26 PgC year^{-1} (1 Pg = 10^{12} g) during 2001–2010, is likely to be an artifact of the anthropogenic CO_2 emissions increasing too quickly in China by 1.41 PgC year^{-1}. Independent results from methane (CH_4) inversion suggested about 41% lower rate of East Asian CH_4 emission increase during 2002–2012. We apply a scaling factor of 0.59, based on CH_4 inversion, to the rate of anthropogenic CO_2 emission increase since the anthropogenic emissions of both CO_2 and CH_4 increase linearly in the emission inventory. We find no systematic increase in land CO_2 uptake over East Asia during 1993–2010 or 2000–2009 when scaled anthropogenic CO_2 emissions are used, and that there is a need of higher emission increase rate for 2010–2012 compared to those calculated by the inventory methods. High bias in anthropogenic CO_2 emissions leads to stronger land sinks in global land–ocean flux partitioning in our inverse model. The corrected anthropogenic CO_2 emissions also produce measurable reductions in the rate of global land CO_2 sink increase post-2002, leading to a better agreement with the terrestrial biospheric model simulations that include CO_2-fertilization and climate effects.

Keywords: East Asian carbon budget, Fossil fuel emission, Terrestrial biospheric uptake, Emission monitoring and verification

Background

In order to combat global and regional climate change, efforts are being continued by the United Nations Framework Convention on Climate Change (UNFCCC) since the Kyoto Protocol (1996). The Paris Agreement (2015) during the 21st conference of parties (COP21; www.un.org/sustainabledevelopment/cop21), called for Intended Nationally Determined Contributions (INDCs) to greenhouse gases emission reduction to limit global warming below 2 °C and as close to 1.5 °C as possible. However, the measure of INDCs varies by country, e.g. China, the largest emitter of anthropogenic CO_2 by fossil fuel consumption and cement production (FFC), targets to achieve ambitious 33.8% lower CO_2 emissions per unit of gross domestic product (GDP) in 2014 than the 2005 level, and the CO_2 emissions per GDP will be at 60% of the 2005 level by 2030 (http://unfccc.int/focus/indc_portal/items/8766.php). On the other hand, developed nations declare straightforward reduction targets in total greenhouse gases (GHGs) emissions, e.g. the United States commits to a reduction of total GHG emission of 26–28% in 2025 compared to the 2005 levels, and Japan aims to reduce total GHG emissions by about 26%

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by 2030 compared to a base level of 2005–2013. To the best of our knowledge, no independent emission tracking system with sufficient accuracy exists today that can be employed for monitoring, reporting and verification (MRV) of the claimed emission reductions.

These committed emission reduction targets and their reference years demand for country-specific MRV systems that is supported by the national statistics and independent methods. The independent methods, such as the inverse modelling, suffer from lack of spatially and temporally uniform measurements, and from uncertainties in transport models (Gurney et al. 2002; Patra et al. 2006; Peylin et al. 2013). The other issue in inverse modelling is the separation of sources and sinks into component fluxes. Because the inversion system is ill-constrained by observations, only one component of the anthropogenic or terrestrial CO_2 fluxes can be optimized in state-of-the-art inverse models. The inverse models traditionally assume the anthropogenic CO_2 emission as a known quantity, which is calculated from better known industrial indicators, e.g. the GDP, FFC and energy intensity—energy consumed per unit of GDP. The terrestrial CO_2 exchange is lesser known compared to emissions due to FFC because of sparse inventories from forestry, unpredictable human intervention on land-use change, poor knowledge of environmental impacts on biospheric health, etc. If inverse modelling is adopted as one of the MRV systems for evaluating the progress of the Paris Agreement and INDCs, no assumption on the uncertainties in anthropogenic CO_2 emissions would be permitted.

Over the years, we have found it difficult to quantify uncertainties in FFC CO_2 emissions (Andres et al. 2012; Olivier et al. 2014), and the inverse modelling community is well informed about some of the interference on flux inversions (Gurney et al. 2005; Peylin et al. 2011). Clearly the maximum uncertainty in FFC CO_2 emissions is found for China (Guan et al. 2012; Liu et al. 2015; Korsbakken et al. 2016). A biased higher or lower FFC CO_2 emission will lead to artificially stronger (weaker) biospheric CO_2 sink over a given land region. In the recent times, the inverse model results are post-processed by applying a FFC CO_2 emission correction term (Peylin et al. 2013; Thompson et al. 2016). This method is a good approximation when biases in assumed FFC CO_2 emission only influence land CO_2 flux of the same region, but this is probably not the case because our regional fluxes are poorly constrained by observational data (Saeki et al. 2017; Thompson et al. 2016). However, the effect of high/low bias in the rate of FFC CO_2 emission increase on the decadal variations of inversion estimated terrestrial CO_2 uptake has not been discussed in detail (Patra et al. 2016a). Because the model transport biases do not vary significantly from year to year, our inversion systems can better constrain the interannual/decadal variation in land fluxes compared to their magnitude, provided an accurate estimation of FFC CO_2 emissions is available.

Any wrong assumption on the growth rate of a priori FFC CO_2 emission is compensated by the land source or sink in such a way that detection of bias in a priori emission remained thus far elusive by validation approaches using independent aircraft CO_2 observations. This situation is different for species with predominantly terrestrial source, e.g. CH_4, because the total emission can be well estimated by inverse model (atmospheric sink is parameterized separately and do not affect regional source inversion for the species with lifetime of several years). Patra et al. 2016b have used aircraft measurements over Sendai, Japan, to validate CH_4 emissions and emission increase rates for the East Asia region, and suggested that the rate of anthropogenic CH_4 emission increase should be only at 59% of that is estimated for 2002–2010 by the Emission Database for Global Atmospheric Research (EDGAR42FT; Olivier et al. 2014). About 75% of FFC CO_2 emissions and up to 40% of anthropogenic CH_4 emissions are caused due to the coal/oil industry (mining and burning), which have produced 82 and 72% of the increase in their emissions, respectively, in the period 2002–2010 (EDGAR42FT; http://edgar.jrc.ec.europa.eu/overview.php?v=42FT2010). Since the increase rate of CH_4 emissions over China is closely related to that of CO_2 emissions, we apply the CH_4 emission increase rate for correcting CO_2 emission increase rate.

In this study, we have used results from three inversion cases, simulated using varied FFC CO_2 emissions, to illustrate the impacts of assumptions on a priori emissions on the estimated land CO_2 fluxes. The rate of a priori FFC CO_2 emission increase is then scaled by the reduced emission increase rate determined by CH_4 inversion. We show that the application of revised rate of FFC CO_2 emission increase leads to (1) no significant increase in CO_2 sink over the East Asia region after 2002, and (2) global land CO_2 sink increase agree better with that simulated by the global dynamic vegetation models (DGVMs). Implications of correct magnitude of FFC CO_2 emissions on land–ocean partitioning of global CO_2 sinks are also discussed.

Methods

We have used FFC CO_2 emission maps from the (1) CDIAC: emissions of top-20 countries from CDIAC (Boden et al. 2016) distributed using EDGAR4 emission maps (2010 emission maps repeated for the latter years), (2) CARBONES: a project of the European Union (I. van der Laan-Luijkx, personal communication, 2015; as in Thompson et al. 2016; see also www.carbones.eu/wcmqs/project/ccdas/#Fossil%20Fuel), and (3) CARBONES emission maps, but scaled with the IEA (International Energy Agency) emissions for South Asia, East Asia, Southeast Asia and rest of the world (as in Thompson et al. 2016; referred to as IEA). The global total FFC CO_2 emissions were 6.9, 6.8 and 6.6 PgC $year^{-1}$ in 2002, and 9.4, 9.1 and 8.5 PgC $year^{-1}$ in 2011, respectively, for the CDIAC, CARBONES and IEA inventories. CO_2 inversions are performed for 2001–2012 to optimize fluxes from 84 regions of the globe using the JAMSTEC's atmospheric chemistry-transport model (ACTM) and CO_2 observations from 66 sites taken from GLOBALVIEW-CO_2 (2013) data products (Ref. Saeki et al. 2017 for more details; Thompson et al. 2016). The region divisions of 84-region inverse model and location of CO_2 measurement sites are depicted in Fig. 1. Apart from the FFC CO_2 emissions, the net ecosystem exchange (NEE) of terrestrial biosphere is taken from Carnegie-Ames-Stanford Approach (CASA) terrestrial biosphere model (Randerson et al. 1997), and oceanic exchanges are taken from Takahashi et al. (2009). ACTM inversion results for 2002–2011 are presented here after discarding the first and last year of inversions as spin-up and spin-down, respectively.

Similarly, CH_4 inversions are performed for 53-land regions only, using ACTM forward simulations and atmospheric data from 37 sites (see Patra et al. 2016b for details). The regional CH_4 emissions for the East Asia region are taken as the mean of their five ensemble cases, which have passed the post-inversion validation test using independent aircraft measurements by Tohoku Univ (Umezawa et al. 2014). The inversion ensemble members are based on different a priori emission scenarios. The EDGAR42FT inventory, used as a priori, suggested an increase of 23.4 Tg-CH_4 emissions from East Asia, which is contributed entirely by the anthropogenic emission increase rate in China. The validation exercise using independent aircraft measurement over Sendai by Tohoku University permitted an increase of about 16.1 Tg-CH_4 during the period of 2002–2012. For a robust estimation of a posteriori to a priori emissions scaling factor, we applied linear fits to the data (Fig. 2a). Here we will apply a scaling factor of 0.59 (=1.53/2.61; slopes of the linear fits for a posteriori and a priori emissions in Fig. 2a) to FFC CO_2 emission "increase rate" for the period 2003–2014, relative to the emissions for 2002 from CDIAC inventory, using the slopes of the fitted lines to

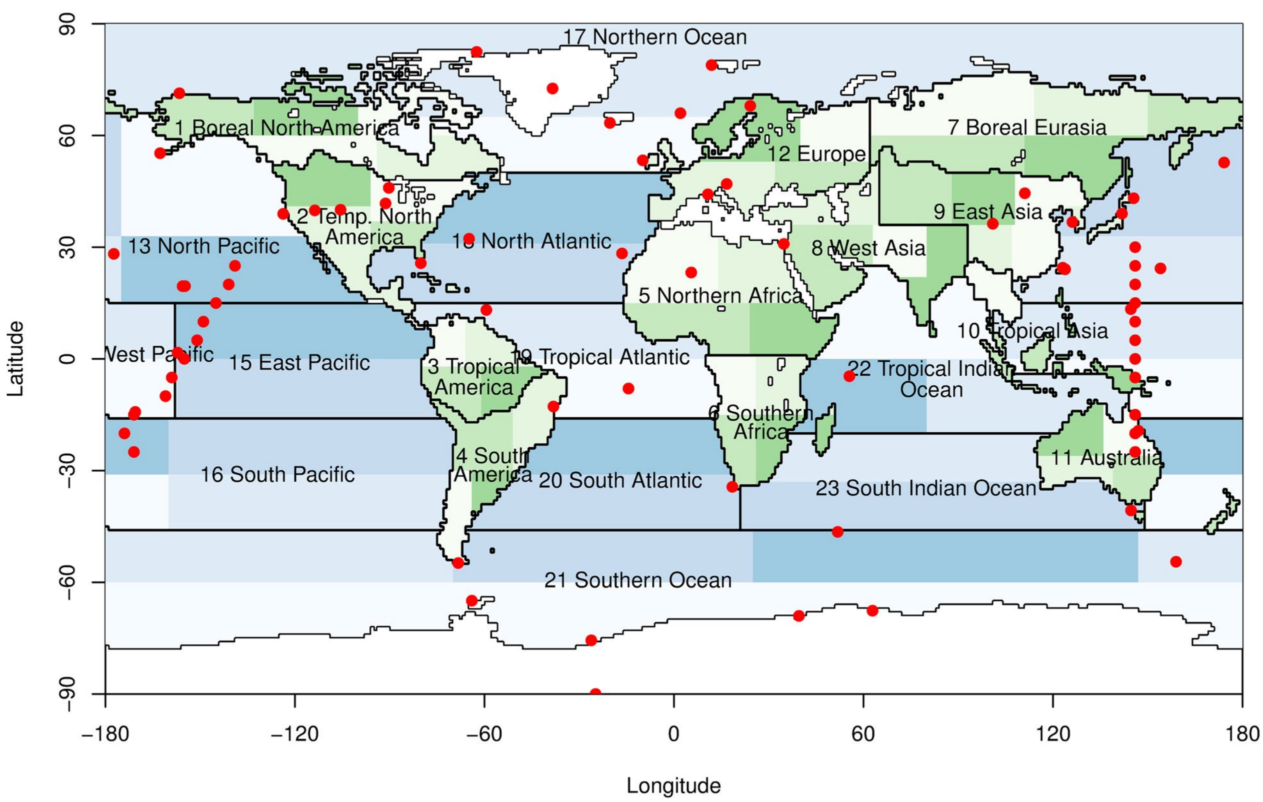

Fig. 1 Maps of CO_2 inversion regions (54 land and 30 ocean; *shaded*) and atmospheric observation network (*circle*) with mostly surface sites, except for the Japan AirLines (JAL) flight track between Tokyo and Sydney/Brisbane. The snow-covered (zero flux) Antarctica and Greenland are not optimized by the inversion system. The CH_4 inverse model solves for emissions from 53 land only regions (1 region less in the Southeast Asia; ref. Patra et al. 2016b)

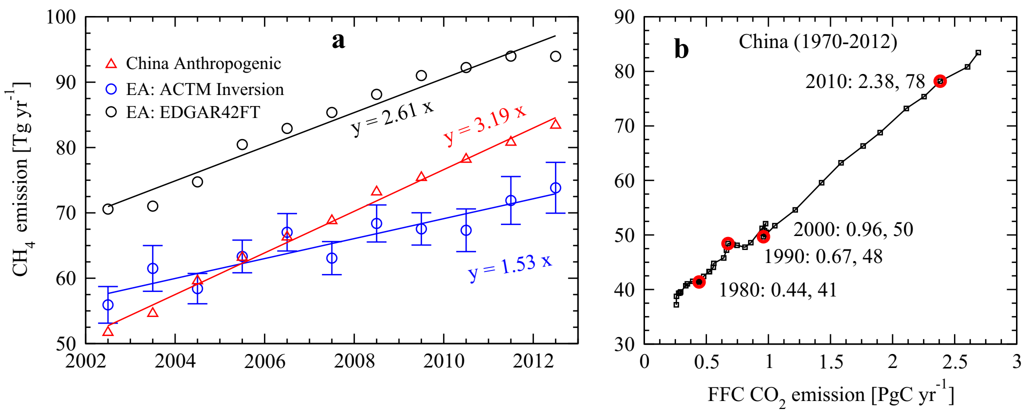

Fig. 2 **a** Comparisons of CH_4 inversion results (*black*: a priori; *blue*: a posteriori) for the East Asia (EA) region with the EDGAR42FT estimated anthropogenic emissions for China. The linear fits to the annual mean values are shown as *lines*, with slopes the fits marked. **b** Linear relationship of anthropogenic CO_2 and CH_4 emissions for China over the period of 1970–2012 (Olivier et al. 2014). The inter-decadal values are marked by *text* and *red circles*

the East Asian CH_4 emission time series. A comparison of East Asian total CH_4 emissions with the anthropogenic CH_4 emissions from China suggests the dominating role of China for recent emission increases over the East Asia region. The application of this CH_4-inversion-derived scaling factor to the CO_2 emission increase rate assumes constant CH_4/CO_2 emission ratio over the periods of our analyses, and is deemed valid as per the linearity maintained in anthropogenic emission inventories of CO_2 and CH_4 over the period of 1970–2012 (EDGAR4; Fig. 2b).

We have used DGVM model simulated CO_2 fluxes from the Trends and drivers of the regional-scale sources and sinks of carbon dioxide (TRENDY) project, covering the period of 1990–2012. The DGVMs account for the effect of CO_2 fertilization and climate variations (simulation case S2; Sitch et al. 2015). Inverse model estimated ensemble mean CO_2 fluxes for East Asia for the period of 1993–2012 are taken from Thompson et al. (2016).

Results and discussion

This topic of discussion is most relevant for the East Asia region because the global FFC CO_2 emission increase rate in the 2000s is mainly driven by the industrial CO_2 emission from China (about 65% of 2.17 PgC year^{-1} increase in global emission during 2001–2010). Because our inverse model does not well constrain CO_2 fluxes from China alone, due to lack of measurement sites within the source regions (Fig. 1), we aggregated six inverse model regions to discuss the change in fluxes over East Asia in this study over the past 2 decades.

Figure 3 shows the effect of different FFC CO_2 emission a priori on the estimation of residual land CO_2 fluxes estimated by the 84-region inverse model for the East Asia region. We find the FFC CO_2 emissions as per the CDIAC inventory method are always higher compared to the CARBONES and IEA inventories, varying from 0.49 PgC in 2002 to a maximum of 0.76 in 2009 for CDIAC–IEA. The CDIAC–CARBONES differences decrease from a maximum of 0.47 in 2003 to 0.12 PgC in 2011 (Fig. 3a). A fairly compensatory land CO_2 fluxes are estimated for the East Asia region with the interannual variations (IAVs) being opposite in phase. The mean (± $^{1-}\sigma$ standard deviations for the IAVs) differences of 0.59 ± 0.08 and 0.37 ± 0.12 PgC in FFC CO_2 emissions lead to a mean uptake bias over the East Asia by −0.40 ± 0.10 and −0.21 ± 0.08 PgC, respectively, for the 2002–2011 period. This suggests about 60–67% of the FFC CO_2 emission bias is transferred to land uptake increase for the East Asia region, and the rest of 33–40% of FFC CO_2 bias affects inverse model results for other regions.

It would have been ideal to validate the a posteriori land CO_2 fluxes using aircraft (independent) observations that are not used in the inversion system, as in the case of inverted CH_4 emissions using vertical profiles over Sendai, Japan (Patra et al. 2016b). Such validation has also been attempted in Thompson et al. (2016), but large model–model differences in annual mean land fluxes for the East Asia region could not be separated using aircraft observations over Korea and Japan. Both the ACTM and MACC models with East Asian land fluxes of −0.94 and −0.44 PgC year^{-1}, respectively, for 2008–2011 well-simulated the CO_2 concentration within the planetary boundary layer and vertical gradients between 1 and 4 km (Thompson et al. 2016; their Fig. 2). Unlike CH_4, which has sources predominantly on the Earth's surface

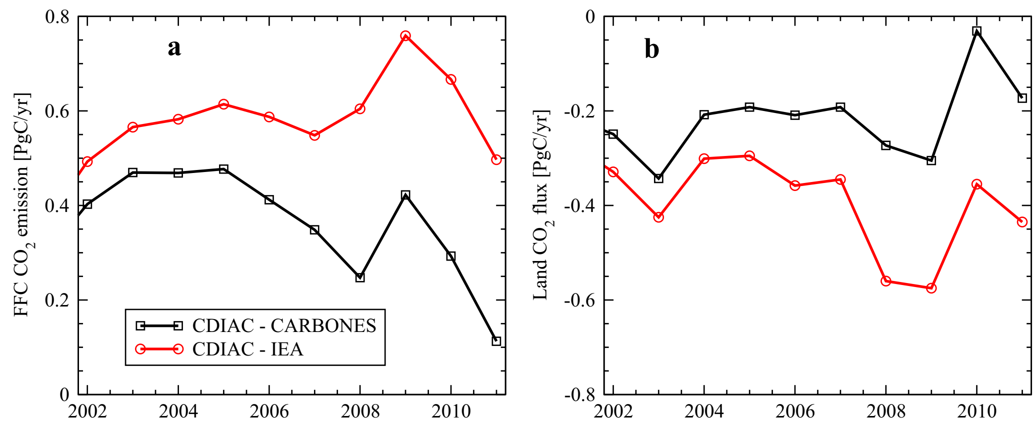

Fig. 3 Time series of differences in FFC CO_2 emission cases (CARBONES and IEA) relative to the CDIAC case (**a**), and the resulting differences in land CO_2 sinks estimated by 84-region inverse model (**b**) for East Asia (*black line*: CDIAC–CARBONES; *red line*: CDIAC–IEA)

(a global surface sink of ~27 Tg-CH_4 year^{-1}, compared to ~550 Tg-CH_4 year^{-1} of emission), CO_2 has very strong source-sink variations over the land regions (Fig. 4). The annual mean biases for FFC CO_2 emissions or land fluxes are much smaller than the seasonal variations in land CO_2 exchange. In addition, our inversion system optimizes land-CO_2 fluxes for a given FFC CO_2 emission, where the inverted land fluxes can compensate for biases in an a priori FFC CO_2 emission. Such a compensatory effect helps to simulate observed CO_2 concentrations from aircrafts for very different source (FFC) and sink (land biosphere) combinations.

Figure 5 shows the quickest FFC CO_2 emission increase in China is seen during 2003–2006 coincides well with the worsening emission intensity (CO_2 emission per GDP produced), as used in preparation of EDGAR emission inventories (Olivier et al. 2014). The FFC CO_2 emissions increase from China alone explains about 62% (1.72 out of 2.62 PgC year^{-1}) global FFC emission increase in the period of 2002–2011 (Fig. 5a, b). In 2002–2003, the rate of FFC CO_2 emission increase (~20% year^{-1}) from China was twice its GDP growth rate (10% year^{-1}). The CO_2 emission increase is caused by a combined effect of fuel consumption and worsening emission intensity, from 216 kgC per thousand US$ in 2002 to 250 kgC per thousand US$ in 2005 (Fig. 5c). Note also that the emission intensity of China was about three and two times higher in 2002 and 2012, respectively, compared to those of India, Japan or USA. Given the available historical information, it is probably difficult to revise the inventory emissions retrospectively for the first half of the 2000s. Therefore we apply a CH_4 emission scaling factor of 0.59 to the rate of anthropogenic CO_2 emission increase for China (Ref. Fig. 2a and associated text). By talking into account the sequestered CO_2 in carbonating cement materials (Xi et al. 2016), the FFC CO_2 emission increase would be moderated by 0.09 PgC in the period 2002–2012, which is about 12% of the mismatch in FFC CO_2 emissions between CDIAC/GCP and this study in 2012 (Fig. 5).

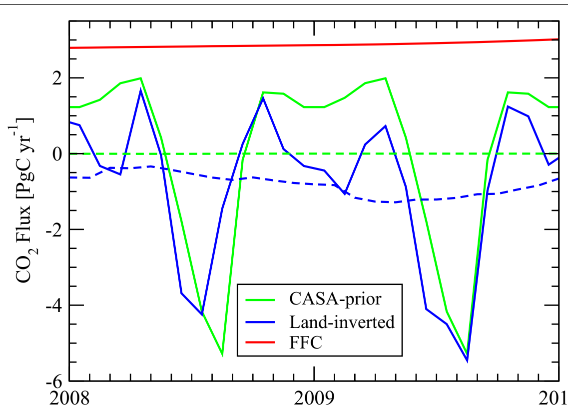

Fig. 4 Monthly time variations of FFC CO_2 emissions and land CO_2 fluxes as simulated by the a priori model (CASA; annually balanced to no net fluxes) and that estimated by the inverse model for East Asia. *Broken lines* are for 12-month running mean CASA (*green*) and inversion (*blue*) fluxes

The FFC CO_2 emissions, before and after CH_4 emission scaling, are compared with a scenario when the emissions are assumed to increase as per the GDP increase rate of China. This suggest that until about 2009, the FFC CO_2 emission increase was faster than the GDP increase since 2003, while the scaled emission increase is still higher than that due to the GDP increase but until about 2006. The emission intensity probably improved at a faster rate leading to the Beijing Olympic in 2008 and the years that followed (ref. EDGAR42FT). Thus, the net FFC CO_2 emission increase during 2003–2014 at the rate of GDP increase is in apparent violation of the

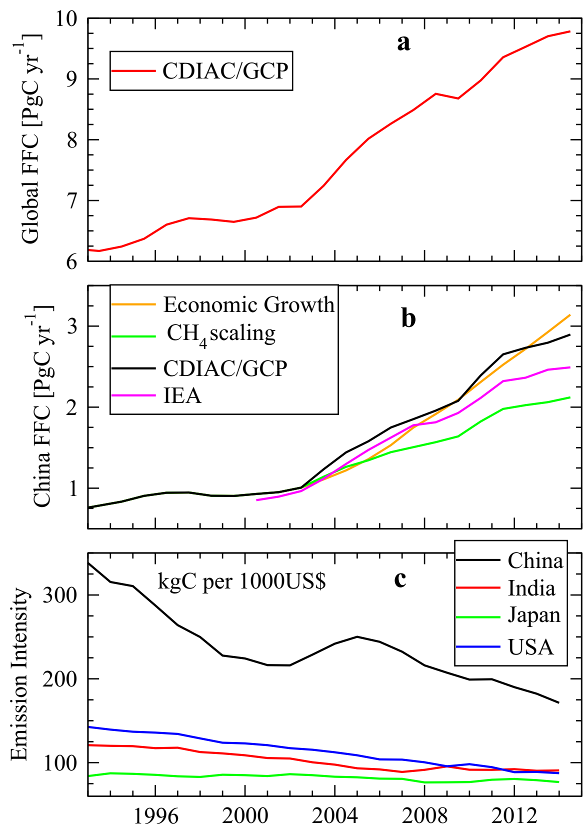

Fig. 5 Time series of global total FFC CO_2 emissions (**a**) and FFC CO_2 emission scenarios for China (**b**). Three scenarios based on a scaling factor from CH_4 inversion results for East Asia and as per the economic growth are shown in comparison with that estimated by CDIAC and IEA emission inventories. The annual emission estimates of Liu et al. (2015) agree within ±4% with those estimated by IEA for individual years. **c** The emission intensity of China in comparison with India, Japan and USA

common development mechanism of industrialization (Kaya Identity; Kaya and Yokoburi 1997). Emissions per unit of GDP should decrease with time as the industries strive to improve productivity, and more energy is produced through green technology investments (Raupach et al. 2007). About 20.3% of total energy generated in China (4.994 PWh) has been by renewable energy in 2012 compared to that of 17.6% (of 1.654 PWh) in 2002 (IEA, International Energy Agency 2016; www.iea.org/statistics/statisticssearch/). About 79 and 83% of China's energy is generated from coal and crude oil in 2002 and 2012, respectively, which constitute about 89 and 87% of its total CO_2 emissions (IEA 2016; Boden et al. 2016).

Choosing different time periods, we find that the rate of FFC CO_2 emission increase (1.04 PgC as per CDIAC) is about 75% of Chinese GDP increase during 2007–2014, and our revised emissions are about 64% of the economic growth for another time period of 2002—2011. As a sensitivity case, we have checked the calculation for an arbitrary scaling factor of 0.69, and that produced an FFC CO_2 emission of 2.19 PgC year^{-1} in 2012 compared to the case presented here with 2.02 PgC year^{-1}. This maximum difference of 0.17 PgC year^{-1} in East Asian CO_2 flux during the period of 2010–2012 (Fig. 8) does not affect most of the conclusions of this work, and the difference is much smaller than that derived using CDIAC FFC emissions (0.71 PgC year^{-1}). Our revised FFC CO_2 emissions show better agreement, compared to CDIAC, with a consumption-based emission inventory for China (Fig. 5b; IEA 2016). The difference between IEA and our revised FFC CO_2 emissions has developed during the period of 2003–2007, when the emission intensity worsened for China, and only a systematic bias is seen for the later 5 years.

This correction to Chinese FFC CO_2 emission increase after 2003 has large consequences for the global and regional CO_2 budgets. Figure 6 shows the 84-region inverse model estimated global CO_2 fluxes using three cases of FFC CO_2 emissions as described in "Methods". The FFC CO_2 emissions are balanced well by the residual/inverted land sink estimation for simulating the global atmospheric burden increase, which is seen as the greatest and smallest global total sinks for CDIAC and IEA, respectively (further details in Saeki et al. 2017). More interesting is to note that the CO_2 land sink is greater by 1.18 PgC year^{-1} for CDIAC case compared to IEA emission case, and that is at the expenses of a large reduction in oceanic CO_2 sink by 0.51 PgC year^{-1}. This is because the FFC CO_2 biases are located over the land region, and thus the compensatory sink biases in inverse model occur over the land regions when constrained by observations. Some leakage of FFC CO_2 is expected, e.g. 33–40% for the East Asia region, as most of the FFC CO_2 emission signals are not strongly constrained by measurements within the region. The bias in global total CO_2 fluxes for the CARBONES and IEA inversion cases arises from the land total alone, with the ocean total sinks being similar. Our results clearly suggest that the land–ocean partitioning of CO_2 sinks is affected greatly by the uncertainties in FFC CO_2 a priori emissions, which was more often linked to transport model uncertainties (Gurney et al. 2002; Peylin et al. 2013).

Further, the land CO_2 sink bias due to uncertainties in FFC CO_2 emission should influence our understanding of the global and regional carbon budgets. Figure 7 shows sectorial CO_2 sources/sinks budget obtained from the Global Carbon Project (GCP; Le Quéré et al. 2015). The GCP estimated global land CO_2 sink depends on the FFC CO_2 inventory, model of land-use change emissions

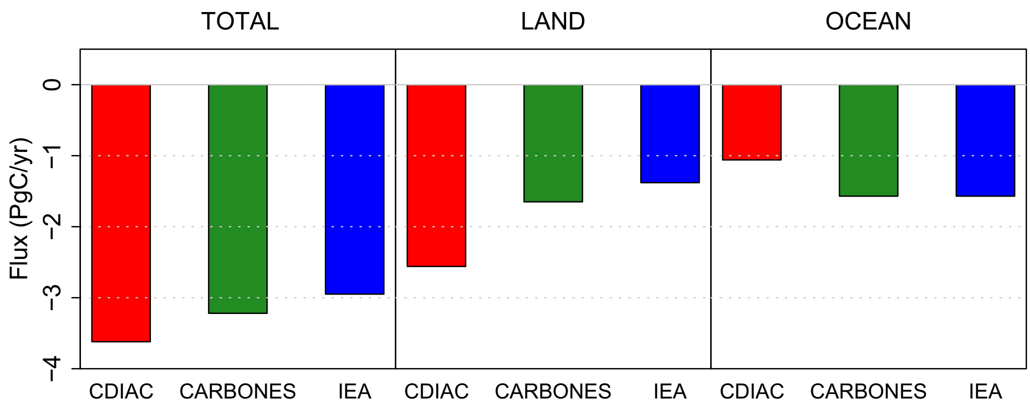

Fig. 6 Bar plot of global total, land and ocean sinks by inverse modelling for three different anthropogenic emission inventories, averaged over 2002–2011. The mean FFC CO_2 emissions were 8.23 ± 0.78, 7.96 ± 0.76 and 7.61 ± 0.59 PgC $year^{-1}$, respectively, for CDIAC, CARBONES and IEA inventories

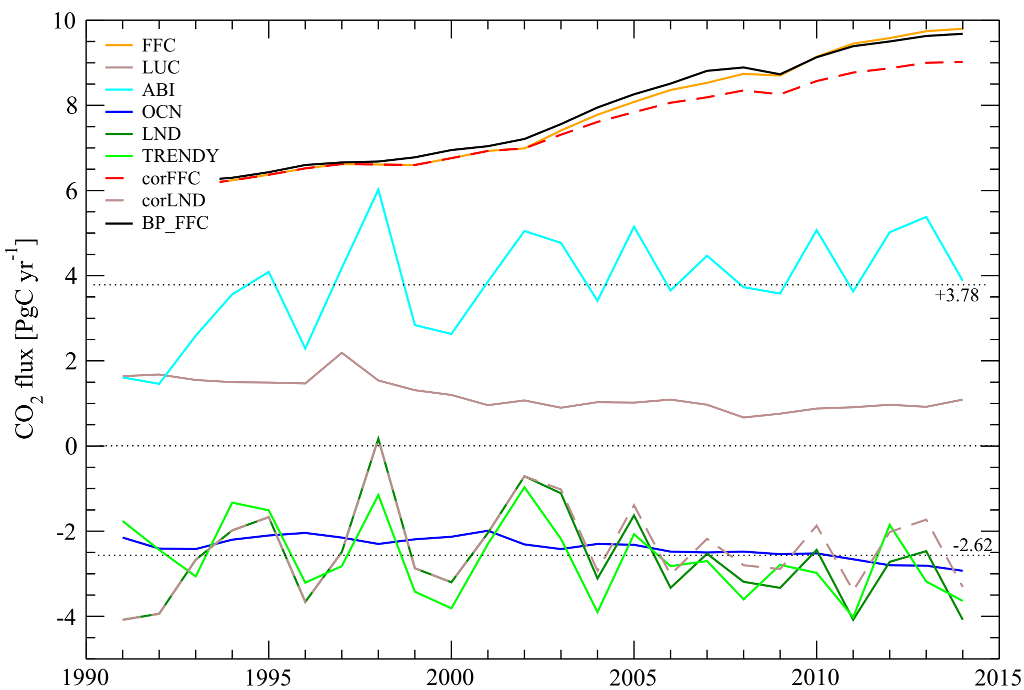

Fig. 7 Time series of CO_2 fluxes as estimated by the Global Carbon Project for fossil fuel and cement (FFC), land-use change (LUC), atmospheric burden increase (ABI), oceanic exchange (OCN), residual land biosphere (LND = FFC + LUC − ABI − OCN), ensemble mean land fluxes simulated by the global dynamic vegetation models (from TRENDY project). FFC corrected by CH_4 inversion scaling (corFFC) are also shown in comparison with recent update of British Petroleum (BP) emission inventory of global totals. Corrected land fluxes (corLND) is based on residuals calculated using corFFC emissions. *Three horizontal dotted-lines* at −2.62, 0 and 3.78 PgC are marked for easy reference to the flux variabilities

and atmospheric burden increase from measured CO_2 concentration. We corrected the global FFC CO_2 emission using scaled emissions for China only (broken red line; =Global − CDIAC China + CH_4-Scaled China), and correspondingly calculated the corrected land CO_2 sink (broken brown line; Fig. 7). Apparently, the recent release of CO_2 emission inventory by the British Petroleum (BP 2016) also suggested a slower emission increase during 2007–2014, compared to the CDIAC inventory, and is comparable to our corrected FFC CO_2 emission.

However, the rate of BP emission increase is still slightly faster than CDIAC inventory and much faster than our corrected FFC emission for the problematic time period of 2002–2007. The higher emissions during the late 1990s in the latest BP emission inventory, compared to CDIAC, agree better with Francey et al. (2013), who suggested no stabilization of emissions during the period 1996–1999.

The corrected FFC CO_2 emissions may also help resolve one the mismatches in the GCP's residual land CO_2 sink budget and ensemble mean of the TRENDY DGVM simulations. A comparison suggests the GCP land sink increased by 2.04 PgC during the period 2001–2014, while that increased by only 1.34 PgC in the case of the TRENDY S2 simulation. The revised GCP land sink, using corrected FFC CO_2 emissions, is calculated to be 1.27 PgC, which is in closer agreement with the TRENDY simulation (Fig. 7). The assessment of the CO_2 sink simulation, by the DGVMs, has large implications for future prediction of carbon–climate feedback.

The policymaking of emission mitigation or verifying the success of INDCs, towards reduction of global levels of GHGs concentration, rely on our ability to estimate the time evolution of regional sources and sinks. However, estimations of FFC CO_2 emissions and the land sink in China has been one of most discussed issues in recent times (Liu et al. 2015; Thompson et al. 2016; Jiang et al. 2016). Jiang et al. (2016) estimated a large sink in China's terrestrial biosphere, in the range of 0.39–0.51 PgC year^{-1} for the period 2006–2009, which agrees well with the ensemble mean CO_2 sink of 0.46 PgC year^{-1} estimated by Thompson et al. (2016). Strong regional CO_2 sink over a short period of time is in no apparent contradiction with our state-of-the-art knowledge, when all the component fluxes have uncertainties. However, we are unable to propose a simple biospheric mechanism for increasing CO_2 uptake systematically by 0.26 PgC within a decade in East Asia, from a mean flux of −0.20 PgC year^{-1} in 2000–2002 to −0.46 PgC year^{-1} in 2009–2011. The CO_2 uptake increase of similar amount is also calculated over a longer time period, from 0.08 ± 0.14 (mean ± $^{1-}\sigma$ for IAVs) PgC year^{-1} during 1993–2002 to 0.36 ± 0.14 PgC year^{-1} during 2003–2012. The corrected CO_2 uptakes for the same periods are calculated as 0.08 ± 0.14 and 0.03 ± 0.16 PgC year^{-1}, respectively, using the CH_4-scaled FFC CO_2 emissions.

The TRENDY S2 simulation, including CO_2 fertilization and climate effects, produced CO_2 uptakes of 0.09 ± 0.11 and 0.13 ± 0.10, respectively, for the periods 1993–2002 and 2003–2012 (Fig. 8). The TRENDY simulations showed excellent agreement with inversion results for a slower rate of FFC CO_2 emission increase for both the interannual variations and sink magnitudes, except for magnitudes during 2010–2012. These CO_2 uptakes are also in good agreement with the average biomass carbon sink of 0.17 PgC year^{-1} during 1999–2008, estimated based on forest stands inventory in China (Zhang et al. 2013), or the net carbon sink in the range of 0.19–0.26 PgC year^{-1} using inventory, biogeochemical models and inverse models (Piao et al. 2009).

The anomalously high East Asian emission of ~0.2 PgC year^{-1} during 2010–2012 is likely to arise from an underestimation of the rate of FFC CO_2 emission increase. Although the Chinese economic growth showed no sign of slowing down, the CDIAC estimated FFC CO_2 emission showed sharp decrease in the rate of emission increase since 2011 (Fig. 5). As per the Chinese economic growth, a proportional increase in FFC CO_2 emission would raise the emission by 0.3 PgC in the period 2009–2012. The proposed emission increase is consistent with one of the scenarios in Korsbakken et al. (2016), i.e. the National apparent consumption (pre-third National Economic Census, NEC) and that of the IEA. The a posteriori CH_4 emissions also show continued increase during the years 2010–2012 (Fig. 2a, blue line). The use of FFC CO_2 emissions from IEA show excellent agreement between corrected land sinks and the TRENDY simulation for the period 2010–2012, but produced a too strong sink increase during 2005–2009 (Fig. 8). Resolving the rate of increase in FFC CO_2 emission from China for different time segments is beyond the scope of this work. We believe large investment is required to develop independent MRV system involving atmospheric measurement and model for tracking CO_2 emissions from industrial and biospheric activities.

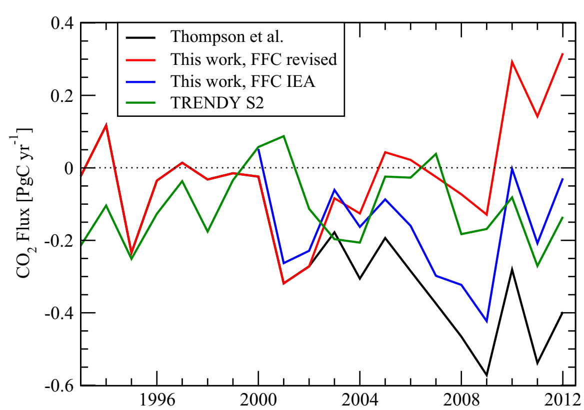

Fig. 8 Effect of FFC CO_2 emission increase rate on regional carbon budget of East Asia. The mean inversion flux of East Asia (from Thompson et al. 2016) is corrected a posteriori for revised China FFC CO_2 emissions using scaling from CH_4 inversion (This work, FFC revised) and that from the IEA (This work, FFC IEA). The mean CO_2 exchange simulated by TRENDY DGVMs (S2 simulation) are also shown

Conclusions

We have shown that the large land CO_2 uptake increase by 0.26 PgC year^{-1} during 2001–2010, estimated for the East Asia by recent inverse modelling studies, is likely to be caused by a possible overestimation of increase rate in 'assumed' anthropogenic CO_2 emissions. Unfortunately, the FFC CO_2 emission and land sink dipole remained unresolved by validation experiments using independent CO_2 data. However, the CH_4 inversion results (predominantly source) showed an overestimation of anthropogenic emissions from East Asia, mainly China (Patra et al. 2016b). The strong correlation in anthropogenic emissions of CO_2 and CH_4 for the period 1970–2012 (Olivier et al. 2014) provides evidence for a reduction in the rate of FFC CO_2 emission increase by a factor of 0.59 for the period of 2002-2012. These results have large implications for carbon emission mitigation target, and development of MRV systems (e.g. for the INDCs). One fixed scaling factor of 0.59 for anthropogenic CO_2 emission for the period 2002–2012 is found to be inappropriate in this study. The flattening of FFC CO_2 emission after about 2009 in our revised case (Fig. 2a, black circle) is apparently inconsistent with the consumption-based emission inventories, and implies that CO_2 emission continued to increase at similar rates between 2009 and 2012, which is consistent with China's national apparent consumption of coal and IEA emissions. The continued increase in anthropogenic emissions for 2010–2012 is also suggested by the CH_4 inversion results. We need to evaluate applications of any such factor using different chemical tracers, probably at every 3–5 year time intervals.

The accuracy of net terrestrial CO_2 uptake should be established in relation with the a priori FFC CO_2 emissions. Currently, the FFC CO_2 emission inventories are largely unconstrained by independent observations. We show that a significant bias in a priori FFC emissions leads to an abrupt carbon uptake increase in the regional and global terrestrial ecosystem mainly, and partly affects the oceanic carbon uptake estimations. High biased FFC CO_2 emissions produced stronger land sinks in global land–ocean flux partitioning because the emission bias occurs mostly over the land and affect the residual sink estimation within the same region. In particular, a reduced rate of FFC CO_2 emission increase is suggested to produce an overall consistency between the inverse model estimated East Asian and global land uptake increases with those simulated by the terrestrial vegetation models for the time periods after 2002.

Authors' contributions

TS and PKP designed the model experiments, TS performed CO_2 inversions and major part of the analyses, PKP and TS wrote the paper. Both authors read and approved the final manuscript

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Competing interests

The authors declare that they have no competing interests.

Availability of data and materials

CO_2 measurements are available for scientific use at http://ds.data.jma.go.jp/gmd/wdcgg; http://www.esrl.noaa.gov/gmd/dv/ftpdata.html; http://caos.sakura.ne.jp/tgr/. All the model results and analysis tools are available unconditionally from the ACTM group by contacting the lead authors.

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