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The carbon budget of South Asia

P. K. Patra[1], J. G. Canadell[2], R. A. Houghton[3], S. L. Piao[4], N.-H. Oh[5], P. Ciais[6], K. R. Manjunath[7], A. Chhabra[7], T. Wang[6], T. Bhattacharya[8], P. Bousquet[6], J. Hartman[9], A. Ito[10], E. Mayorga[11], Y. Niwa[12], P. Raymond[13], V. V. S. S. Sarma[14], and R. Lasco[15]

[1]Research Institute for Global Change, JAMSTEC, Yokohama 236 0001, Japan
[2]Global Carbon Project, CSIRO Marine and Atmospheric Research, Canberra, ACT 2601, Australia
[3]Woods Hole Research Center, 149 Woods Hole Road, Falmouth, MA 02540, USA
[4]Peeking University, Beijing 100871, China
[5]Seoul National University, 1 Gwanak-ro, Gwanak-gu, Seoul, South Korea
[6]IPSL – LSCE, CEA CNRS UVSQ, Centre d'Etudes Orme des Merisiers, 91191 Gif sur Yvette, France
[7]Space Application Centre, ISRO, Ahmedabad 380 015, India
[8]National Bureau of Soil Survey and Land use Planning (ICAR) Amravati Road, Nagpur 440 033, India
[9]Institute for Biogeochemistry and Marine Chemistry, 20146, Hamburg, Germany
[10]National Institute for Environmental Studies, Tsukuba, Ibaraki 305-8506, Japan
[11]Applied Physics Laboratory, University of Washington, Seattle, USA
[12]Meteorological Research Institute, Tsukuba, Japan
[13]Yale University, New Haven, CT 06511, USA

[14]National Institute of Oceanography, Visakhapatnam 530 017, India
[15]The World Agroforestry Centre (ICARF), Laguna 4031, Philippines

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Correspondence to: P. K. Patra (prabir@jamstec.go.jp)

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Abstract

The source and sinks of carbon dioxide (CO_2) and methane (CH_4) due to anthropogenic and natural biospheric activities were estimated for the South Asia region (Bangladesh, Bhutan, India, Nepal, Pakistan and Sri Lanka). Flux estimates were based on top-down methods that use inversions of atmospheric data, and bottom-up methods that use field observations, satellite data, and terrestrial ecosystem models. Based on atmospheric CO_2 inversions, the net biospheric CO_2 flux in South Asia (equivalent to the Net Biome Productivity, NBP) was a sink, estimated at $-104 \pm 150\,\mathrm{Tg\,C\,yr^{-1}}$ during 2007–2008. Based on the bottom-up approach, the net biospheric CO_2 flux is estimated to be $-191 \pm 193\,\mathrm{Tg\,C\,yr^{-1}}$ during the period of 2000–2009. This last net flux results from the following flux components: (1) the Net Ecosystem Productivity, NEP (net primary production minus heterotrophic respiration) of $-220 \pm 186\,\mathrm{Tg\,C\,yr^{-1}}$ (2) the annual net carbon flux from land-use change of $-14 \pm 50\,\mathrm{Tg\,C\,yr^{-1}}$, which resulted from a sink of $-16\,\mathrm{Tg\,C\,yr^{-1}}$ due to the establishment of tree plantations and wood harvest, and a source of $2\,\mathrm{Tg\,C\,yr^{-1}}$ due to the expansion of croplands; (3) the riverine export flux from terrestrial ecosystems to the coastal oceans of $+42.9\,\mathrm{Tg\,C\,yr^{-1}}$; and (4) the net CO_2 emission due to biomass burning of $+44.1 \pm 13.7\,\mathrm{Tg\,C\,yr^{-1}}$. Including the emissions from the combustion of fossil fuels of $444\,\mathrm{Tg\,C\,yr^{-1}}$ for the decades of 2000s, we estimate a net CO_2 land-to-atmosphere flux of $297\,\mathrm{Tg\,C\,yr^{-1}}$. In addition to CO_2, a fraction of the sequestered carbon in terrestrial ecosystems is released to the atmosphere as CH_4. Based on bottom-up and top-down estimates, and chemistry-transport modeling, we estimate that $37 \pm 3.7\,\mathrm{Tg\,C\text{-}CH_4\,yr^{-1}}$ were released to atmosphere from South Asia during the 2000s. Taking all CO_2 and CH_4 fluxes together, our best estimate of the net land-to-atmosphere CO_2-equivalent flux is a net source of $334\,\mathrm{Tg\,C\,yr^{-1}}$ for the South Asia region during the 2000s. If CH_4 emissions are weighted by radiative forcing of molecular CH_4, the total CO_2-equivalent flux increases to $1148\,\mathrm{Tg\,C\,yr^{-1}}$ suggesting there is great potential of reducing CH_4 emissions for stabilizing greenhouse gases concentrations.

1 Introduction

South Asia (Bangladesh, Bhutan, India, Nepal, Pakistan and Sri Lanka) is home to 1.6 billion people and covers an area of $4.5 \times 10^6\,\mathrm{km^2}$. These countries are largely self-sufficient in food production through wide range of natural resources, and agricultural and farming practices (FRA, 2010). However, due to rapid economic growth, fossil fuel emissions have increased from $213\,\mathrm{Tg\,C\,yr^{-1}}$ in 1990 to about $573\,\mathrm{Tg\,C\,yr^{-1}}$ in 2009 (Boden et al., 2011). A detailed budget of CO_2 exchange between the earth's surface and the atmosphere is not available for the South Asia region due to a sparse network of key carbon observations such as atmospheric CO_2, soil carbon stocks, woody biomass, and CO_2 uptake and release by managed and unmanaged ecosystems. Only recently, Patra et al. (2011a) estimated net CO_2 fluxes at seasonal time intervals by inverse modeling (also known as top-down approach), revealing strong carbon uptake of $149\,\mathrm{Tg\,C\,month^{-1}}$ during July–September following the summer monsoon rainfall.

The region is also very likely to be a strong source of CH_4 due to rice cultivation by an amount, which still remains controversial in the literature (Cicerone and Shetter, 1981; Fung et al., 1991; Yan et al., 2009; Manjunath et al., 2011), and large numbers of ruminants linked to religious and farming practices (Yamaji et al., 2003; Chhabra et al., 2009). Since the green revolution there has been an increase in CH_4 emissions owing to the introduction of high-yielding crop species, increased use of nitrogen and phosphorus fertilizers, and expansion of cropland areas to meet the food demands of a growing human population in countries of South Asia (Bouwman et al., 2002; Patra et al., 2012a).

South Asia has also undergone significant changes in the rates of land use change over the last 20 yr contributing to the net carbon exchange. India alone has increased the extent of forest plantations by 4.5 Mha (~ 7 % of 64 Mha) from 1990 to 2010 leading to a 26 % increase in the carbon stock in living forest biomass (FRA, 2010).

In this paper we establish for the first time the net carbon budget of South Asia, including CO_2 and CH_4, and its inter-annual variability for the period 1990–2009. We achieve this goal by synthesizing the results of multiple approaches that include (1) atmospheric inversions as so-called top-down methods, and (2) fossil fuel consumption, forest/soil inventories, riverine exports, remote sensing products and dynamic global vegetation models as bottom-up methods. The comparison of independent and partially independent estimates from these various methods help to define the uncertainty in our knowledge on the South Asia carbon budget. Finally, we attempt to separate the net carbon balance into its main contributing fluxes including fluxes from net primary production, heterotrophic respiration, land use change, fire, and riverine export to coastal oceans. This effort is consistent with and a contribution to the REgional Carbon Cycle Assessment and Processes (Canadell et al., 2011; Patra et al., 2012b).

2 Materials and methods

The South Asia region designated for this study is shown in Fig. 1, along with the basic ecosystem types (DeFries and Townshend, 1994). A large fraction of the area is cultivated croplands and grassland or wooded grassland ($1.3 \times 10^6\,\mathrm{km}^2$ and $1.5 \times 10^6\,\mathrm{km}^2$ or $0.89 \times 10^6\,\mathrm{km}^2$, respectively). The rest of the area is classified as bare soil, shrubs, broadleaf evergreen, broadleaf deciduous and mixed coniferous ($0.35 \times 10^6\,\mathrm{km}^2$, $0.22 \times 10^6\,\mathrm{km}^2$, $0.11 \times 10^6\,\mathrm{km}^2$, $0.10 \times 10^6\,\mathrm{km}^2$ and $0.05 \times 10^6\,\mathrm{km}^2$, respectively). The region is bounded by the Indian Ocean in the south and the Himalayan mountain range in the north. The meteorological conditions over the South Asia region are controlled primarily by the movement of the inter-tropical convergence zone (ITCZ). When the ITCZ is located over the Indian Ocean (between Equator to 5° S) during boreal autumn, winter and spring, the region is generally dry without much occurrence of rainfall. When the ITCZ is located north of the region, about 70 % of precipitations occur during the boreal summer (June–September). Some of these prevailing meteorological conditions are discussed in relations with CO_2 and CH_4 surface fluxes, and concentration variations in earlier studies (Patra et al., 2009, 2011a).

2.1 Emissions from the combustion of fossil fuels and cement production

Carbon dioxide emission statistics were taken from the CDIAC database of consumption of fossil fuels and cement production (Boden et al., 2011). CO_2 emissions were derived from energy statistics published by the United Nations (2010) and processed according to methods described in Marland and Rotty (1984). CO_2 emissions from the production of cement were based on data from the US Department of Interior's Geological Survey (USGS, 2010), and emissions from gas flaring were derived from data provided by the UN, US Department of Energy's Energy Information Administration (1994), Rotty (1974).

2.2 Emissions from land use and land use change

Emissions from land use change include the net flux of carbon between the terrestrial biosphere and the atmosphere resulting from deliberate changes in land cover and land use (Houghton, 2003). Flux estimates are based on a book keeping model that tracks living and dead carbon stocks including wood products for each hectare of land cultivated, harvested or reforested. Data on land use change was from the Global Forest Resource Assessment of the Food and Agriculture Organization (FAO, 2010). We also extracted information from national communication reports to the United Nations Framework Convention on Climate Change.

2.3 Fire emissions

Fire emissions for the region were obtained from the Global Fire Emissions Database version 3.1 (GFEDv3.1). GFED is based on a combination of satellite information on fire activity and vegetation productivity (van der Werf et al., 2006, 2010). The former is based on burned area, active fires, and fAPAR from various satellite sensors, and the latter is estimated with the satellite-driven Carnegie Ames Stanford Approach (CASA) model.

2.4 Transport of riverine carbon

To estimate the land to ocean carbon flux we used the six ocean coastline segments with their corresponding river catchments for South Asia as described by the COSCAT database (Meybeck et al., 2006). The lateral transport of carbon to the coast was estimated at the river basin scale using the Global Nutrient Export from WaterSheds (NEWS) model framework (Mayorga et al., 2010), including NEWS basin areas. The carbon species models are hybrid empirically and conceptually based models that include single and multiple linear regressions developed by the NEWS effort and Hartmann et al. (2009), and single-regression relationships assembled from the literature. Modeled dissolved and particulate organic carbon (DOC and POC) loads used here (from Mayorga et al., 2010) were generated largely using drivers corresponding to the year 2000, including observed hydro-climatological forcings, though some parameters and the observed loads are based on data spanning the previous two decade. Total suspended sediment (TSS) exports were also estimated by NEWS. Dissolved inorganic carbon (DIC) estimates correspond to weathering-derived bicarbonate exports and do not include CO_2 supersaturation; the statistical relationships developed by Hartmann et al. (2009) were adjusted in highly weathered tropical soils (ferralsols) to 25 % of the modeled values found in Hartmann et al. (2009) to account for overestimates relative to observed river exports (J. Hartmann and N. Moosdorf, unpublished); adjusted grid-cell scale exports were aggregated to the basin scale using NEWS basin definitions (Mayorga et al., 2010), then reduced by applying a NEWS-based, basin-scale consumptive water removal factor from irrigation withdrawals (Mayorga et al., 2010). DIC modeled estimates represent approximately 1970–2000. Overall, carbon loads may be characterized as representing general conditions for the period 1980–2000. Carbon, sediment and water exports were aggregated from the river basin scale to corresponding COSCAT regions.

2.5 Fluxes by terrestrial ecosystem models

We use the net primary productivity (NPP) and heterotrophic respiration (RH) simulated by ten ecosystem models: HyLand, Lund-Potsdam-Jena DGVM (LPJ), ORCHIDEE, Sheffield–DGVM, TRIFFID, LPJ_GUESS, NCAR_CLM4C, NCAR_CLM4CN, OCN and VEGAS. The models used the protocol as described by the carbon cycle model intercomparison project (TRENDY) (Sitch et al., 2012; Piao et al., 2012; dgvm.ceh.ac.uk/system/files/Trendy_protocol%20_Nov2011_0.pdf), where each model was run from its pre-industrial equilibrium (assumed at the beginning of the 1900s) to 2009. We present net ecosystem productivity (NEP = NPP – RH) from two simulation cases; S1: where models consider change in climate and rising atmospheric CO_2 concentration, and S2: where models consider change in atmospheric CO_2 concentration alone.

The historical changes in atmospheric CO_2 concentration for the period of 1901–2009 were derived from ice core records and NOAA atmospheric observations (Keeling and Whorf, 2005). For the climate forcing datasets, monthly climate data for the period of 1901–2009 from CRU-NCEP datasets with a spatial resolution $0.5^\circ \times 0.5^\circ$ (http://dods.extra.cea.fr/data/p529viov/cruncep/) were used. Information on land use change was derived from HYDE 3.1 land cover dataset (Goldewijk, 2001, fftp://ftp.pbl.nl/../../hyde/hyde31_final/). These models do not include lateral fluxes of C exported away from ecosystems (from soils to rivers, biomass harvested products) nor fluxes resulting from forest and agricultural management.

We performed correlation analyses between detrended net carbon flux and two climate drivers, annual temperature and annual precipitation, in order to diagnose the modeled interannual response of net carbon fluxes to these drivers (positive for carbon source, negative for carbon sink). The detrended fluxes were calculated by removing the 30-yr linear trend of each variable (net carbon flux, annual temperature and annual precipitation), in order to avoid the confounding effects of the simultaneous trends of temperature or rainfall, with those of other environmental drivers such as rising CO_2.

2.6 Atmospheric inverse models

The biospheric (non-fossil CO_2) CO_2 fluxes are available from state-of-the art atmospheric inversion models from the TransCom database at IPSL/LSCE (http://transcom.lsce.ipsl.fr; Peylin et al., 2012). Estimated fluxes from the following models are included in this analysis: C13_CCAM, C13_CCAM, Carbontracker_EU, Jena_s96_v3.2, JMA_2010, LSCE_an_v2.1, LSCE_var_v1.0, NICAM_MRI, RIGC_TDI64, TransCom-L3_mean. We also obtained regional specific inversion results for South Asia using the CARIBIC (Schuck et al., 2010) data in the upper troposphere over India and Pakistan, which is subsequently validated using the CONTRAIL (Machida et al., 2008) data of vertical profiles over Delhi and upper troposphere over Asia (Patra et al., 2011a). CONTRAIL observations are also used for inversion, with CARIBIC data for validation (Niwa et al., 2012). Measurements of atmospheric CO_2 in the South Asia region are limited to Cabo de Rama, India for the period of 1993–2002 (Bhattacharya et al., 2009). This site constrains the CO_2 fluxes from India during winter to spring seasons only. Thus the use of aircraft measurements is indispensible for top-down flux estimates over the full seasonal cycle.

2.7 Methane fluxes

Top-down estimates: global distributions of CH_4 emissions are prepared using site scale field measurements, inventories (in the case of fossil CH_4 emissions and livestock emissions) and their extrapolation using remote sensing of wetland distribution and terrestrial ecosystem models (e.g. Mathews and Fung, 1987; Olivier and Berdowski, 2001; Ito and Inatomi, 2012). Components of these bottom-up estimations are scaled and used as an input to chemistry-transport models and compared with atmospheric mixing ratio measurements, or are used as prior flux estimates for inverse modeling of surface CH_4 fluxes (Patra et al., 2011a; Bousquet at al., 2006 and references therein). Patra et al. (2011b) prepared 6 distinct CH_4 budgets; 5 of those being anthropogenic sources (EDGAR, 2010; version 3.2, 4.0) in combination with natural sources due to

wetlands (Ringeval et al., 2010; Ito and Inatomi, 2012), biomass burning (van der Werf et al., 2006), and those from Fung et al. (1991), and one being based on inversion of atmospheric concentrations (Bousquet et al., 2006).

Bottom-up estimates for India: methane fluxes for India were estimated using bottom-up inventory data which relied on SPOT Vegetation NDVI, Radarsat Scan SAR (SN2) and IRS AWiFS to map the different rice lands and generate the feed/fodder area for livestock consumption (Manjunath et al., 2011; Chhabra et al., 2009).

3 Results and discussion

3.1 Emissions from fossil fuels and cement production

Figure 2 shows the fossil fuel and cement CO_2 emissions trends over the South Asia region and member countries over the past two decades. Growth rates are calculated as the slope of a fitted linear function, normalized by the average emissions for the period of interest. The average regional total emissions are estimated to be 278 and 444 $\mathrm{Tg\,C\,yr^{-1}}$ for the periods of 1990s and 2000s, respectively. The regional total emissions have steadily increased from 213 $\mathrm{Tg\,C\,yr^{-1}}$ in 1990 to 573 $\mathrm{Tg\,C\,yr^{-1}}$ in 2009. About 90 % of emissions from South Asia are due to fossil fuel consumptions in India at a normalized growth rate of 4.7 $\%\,\mathrm{yr^{-1}}$ for the period of 1990–2009. The decadal growth rates do not show significant differences between the 1990s (5.5 $\%\,\mathrm{yr^{-1}}$) and 2000s (5.3 $\%\,\mathrm{yr^{-1}}$) for the whole region, while an increased rate of consumptions was observed after 2005 (6.8 $\%\,\mathrm{yr^{-1}}$). This acceleration (Fig. 2) in fossil fuel consumption is largely due to the growth of the Indian economy, where the gross domestic product (GDP) doubled, from 34 trillions of Indian Rupees in 2005 to 67 trillions of Indian Rupees in 2010 (http://en.wikipedia.org/wiki/Economy_of_India).

3.2 Emissions from land-use change (LUC)

The annual net flux of carbon from land-use change in South Asia was a small sink ($-11\,\mathrm{Tg\,C\,yr^{-1}}$ for the 1990s and $-14\,\mathrm{Tg\,C\,yr^{-1}}$ for the period 2000–2009) (Table 2). The average sink over the 20-yr period 1990–2009 was $-12.5\,\mathrm{Tg\,C\,yr^{-1}}$. Three activities drove this net sink: establishment of tree plantations ($-13\,\mathrm{Tg\,C\,yr^{-1}}$ in the most recent decade), wood harvest ($-3\,\mathrm{Tg\,C\,yr^{-1}}$), and the expansion of croplands ($2\,\mathrm{Tg\,C\,yr^{-1}}$). Wood harvest results in a net sink of carbon because both industrial wood and fuelwood harvesting have declined recently, while the forest ecosystem productivity remained constant.

Tree plantations (eucalyptus, acacia, rubber, teak, and pine) expanded by $0.2\times10^{6}\,\mathrm{ha\,yr^{-1}}$ in the 1990–1999 period and by $0.3\times10^{6}\,\mathrm{ha\,yr^{-1}}$ during 2000–2009 in the region (FRA, 2010). Uptake of carbon as a result of these new plantations, as well as those planted before 1990, averaged -11 and $-13\,\mathrm{Tg\,C\,yr^{-1}}$ in the two decades, respectively.

Industrial and fuelwood harvest (including the emissions from wood products and the sink in regrowing forests) was a net sink of -6 and $-3\,\mathrm{Tg\,C\,yr^{-1}}$ in the two decades, most of this sink from fuelwood harvest. The net sink attributable to logging suggests that rates of wood harvest have declined in recent decades, while the recovery of forests harvested in previous years drives a net sink in forests.

The carbon sink in expanding plantations and growth of logged forests was offset only partially by the C source from the expansion of croplands, which is estimated to have released $6\,\mathrm{Tg\,C\,yr^{-1}}$ and $2\,\mathrm{Tg\,C\,yr^{-1}}$ during the 1990s and the first decade of 2000, respectively.

The net change in forest area in South Asia was zero for the decade 1990–1999 and averaged $200\,000\,\mathrm{ha\,yr^{-1}}$ during 2000–2009 (FRA, 2010). Given the rates of plantation expansion during these decades ($200\,000\,\mathrm{ha\,yr^{-1}}$ in the 1990–1999 period and by $300\,000\,\mathrm{ha\,yr^{-1}}$ during 2000–2009), native forests were lost at rates of $200\,000\,\mathrm{ha\,yr^{-1}}$ and $100\,000\,\mathrm{ha\,yr^{-1}}$ in the two decades.

The large changes in forest area, both deforestation and afforestation, lead to gross emissions ($\sim120\,\mathrm{Tg\,C\,yr^{-1}}$) and a gross uptake ($\sim135\,\mathrm{Tg\,C\,yr^{-1}}$) that are large relative to the net flux of $14\,\mathrm{Tg\,C\,yr^{-1}}$. Thus, the uncertainty is greater than the net flux itself. The uncertainty is estimated to be $50\,\mathrm{Tg\,C\,yr^{-1}}$, a value is somewhat less than 50 % of the gross fluxes.

The net flux for South Asia was determined to a large extent by land-use change (the expansion of tree plantations) in India, which accounts for 72 % of the land area of South Asia, 85 % of the forest area, and >95 % of the annual increase in plantations. Although 11 estimates of the net carbon flux due to land use change for India published since 1980 have varied from a net source of $42.5\,\mathrm{Tg\,C\,yr^{-1}}$ to a net sink of $-5.0\,\mathrm{Tg\,C\,yr^{-1}}$. The recent estimates by Kaul et al. (2009) for the late 1990s and up to 2009 suggest a declining source/increasing sink (Table 2), consistent with the findings reported here for all of South Asia.

Because India represents the largest contribution to land-use change in South Asia, and because there have been a number of analyses carried out for India, the discussion below focuses on India. A major theme of carbon budgets for India's forests has been the roles of tree plantations versus native forests. The 2009 Forest Survey of India (FSI) reported a 5 % increase in India's forest area over the previous decade. This is a net change, however, masking the loss rate of native forests (0.8 % to 3.5 % per year) and a large increase in plantations (eucalyptus, acacia, rubber, teak, or pine trees) ($\sim5700\,\mathrm{km^2}$ to $\sim18\,000\,\mathrm{km^2}$ per year) (Puyravaud et al., 2010).

The same theme is evident in the earlier carbon budgets for India's forests. Ravindranath and Hall (1994) noted that, nationally, forest area declined slightly (0.04 %, or 23 750 ha annually) between 1982 and 1990. At the state level, however, adding up only those states that had lost forests (still an underestimate of gross deforestation), the loss of forest area was $497\,800\,\mathrm{ha\,yr^{-1}}$ between 1982 and 1986, and $266\,700\,\mathrm{ha\,yr^{-1}}$ between 1986 and 1988. These losses were obviously offset by "gross" increases in forest area in other states.

Similarly, Chhabra et al. (2002) found a net decrease ~ 0.6 Mha in total forest cover for India 1988–1994, while district-level changes indicated a gross increase of 1.07 Mha and a gross decrease of 1.65 Mha. These changes in area translated into a decrease of 77.8 Tg C in districts losing forests and an increase of 81 Tg C in districts gaining forests (plantations) during the same period. It seems odd, though not impossible, that carbon accumulated during this period while forest area declined. Clearly, the uncertainties are high.

This analysis did not include shifting cultivation in South Asia, but Lele and Joshi (2008) attributed much of the deforestation in northeast India to shifting cultivation. Houghton (2007) also omitted the conversion of forests to waste lands, while Kaul et al. (2009) attribute the largest fluxes of carbon to conversion of forests to croplands and wastelands. It seems unlikely that forests are deliberately converted to wastelands. Rather, wastelands probably result either from degradation of croplands (which are then replaced with new deforestation) or from over-harvesting of wood.

Fuelwood harvest, and its associated degradation of carbon stocks, and even deforestation, seems another primary driver of carbon emissions in South Asia. For example, Tahir et al. (2010) report that the use of fuelwood in brick kilns contributed to deforestation in Pakistan, where 14.7 % of the forest cover was lost between 1990 and 2005.

In Nepal, Upadhyay et al. (2005) attribute the loss of carbon through land-use change to fuelwood consumption and soil erosion, and Awasthi et al. (2003) suggest that fuelwood harvest at high elevations of Himalayan India may not be sustainable. On the other hand, Unni et al. (2000) found that fuelwood harvest within a 100-km radius of two cities showed both conversion of natural ecosystems to managed ones and the reverse, with no obvious net reduction in biomass. They inferred that the demand for fuelwood on forest and non-forest biomass was not great enough to degrade biomass.

The net sink estimated for South Asia in this study may have underestimated the emissions from forest degradation; logged forests were assumed to recover unless they were converted to another use. If wood removals exceed the rate of wood growth, carbon stocks will decline (forest degradation) and may ultimately be lost entirely (deforestation).

3.3 Emissions from fires

South Asia is not a large source of CO_2 emission due to biomass burning as per the GFED3.1 (Global Fire Emission Database, version 3.1; van der Werf et al., 2006, 2010). Out of about global total emissions of 2,013 ± 384 Tg C yr^{-1} due open fires as detected by the various satellites sensors, 47 ± 30 Tg C yr^{-1} (2.3 % of the total) only are emitted in the South Asian countries. The average and 1σ standard deviations are calculated from the annual mean emissions in the period 1997–2009. The total emission is reduced to 44 ± 13 Tg C yr^{-1} if the period of 2000–2009 is considered. The total fire emissions can be attributed to agriculture waste burning (14 ± 4 Tg C yr^{-1}), deforestation fires (21 ± 11 Tg C yr^{-1}), forest fires (2.6 ± 1.5 Tg C yr^{-1}), savanna burning (4.8 ± 1.9 Tg C yr^{-1}) and woodland fires (1.8 ± 1.0 Tg C yr^{-1}) for the period of 2000–2009. The seasonal variation of CO_2 emissions due to fires is discussed in Sect. 3.7.

Fire emissions due to agricultural activities will be largely recovered through the annual cropping cycles, and emissions from wildfires in natural ecosystems will be also largely recovered through regrowth over multiple decades (unless there is a fire regime change for which we have no evidence). For these reasons, carbon emissions from fires from the GFED product will not be used to estimate the regional carbon budget, given that fire emissions associated with deforestation are already included in the land use change flux presented in this study. GFED fire fluxes are use to interpreted interannual variability.

3.4 Riverine carbon flux

The total carbon export from South Asian rivers was 42.9 Tg C yr^{-1}, with COSCAT exports ranging from 0.01 to 33.4 Tg C yr^{-1} for the period of 1980–2000 (Table 4). Considering that about 611 Tg C yr^{-1} is estimated to be released from global river systems

(Cole et al., 2007; Batin et al., 2009), rivers in the South Asia region contribute about 7 % of global riverine carbon export, which is more than twice the world average rate (the South Asia has about 3 % of the global land area). The largest riverine carbon export was observed from the Bengal Gulf COSCAT, which is dominated by the combined Ganges-Brahmaputra discharge. The riverine carbon exports from the other five remaining COSCAT basins were lower by up to two orders of magnitude, ranging from only 0.01 to 4.4 Tg C yr^{-1} (Table 4).

Because large riverine carbon loads can be due to large basin area, we also provide the basin carbon yield (riverine carbon load per unit area, excluding PIC). Basin carbon yields varied by a few orders of magnitude, ranging from 0.04 to 18.4 g C m^{-2} yr^{-1}. The largest basin carbon yield was again from the Bengal Gulf COSCAT. However, Laccadive Basin COSCAT and West Deccan Coast COSCAT also released 9.5 and 8.2 g C m^{-2} yr^{-1}, respectively. The global mean terrestrial carbon yield can be calculated by dividing the global riverine carbon export of 611 Tg C yr^{-1} (Aufdenkampe et al., 2011; Battin et al., 2009) by the total land area of 149 million km^{2}, providing a global mean yield of 4.1 g C m^{-2} yr^{-1}. Therefore, the three COSCAT regions in South Asia released more carbon per unit area than the global average. Considering that riverine carbon export is heavily dependent on discharge, this is not surprising since the three COSCAT regions have annual discharge values 40 to 120 % larger than the global average discharge to the oceans of 340 mm yr^{-1} (Mayorga et al., 2010).

The three COSCAT regions with the largest basin carbon yields (Bengal Gulf, Laccadive Basin, and West Deccan Coast) also corresponded to the area of highest NPP of the South Asia (Kucharik et al., 2000), consistent with areas of cultivated crops and forested regions (Fig. 1). This suggests that terrestrial inputs of carbon to the river system of the region can be a significant factor next to the riverine discharge.

The relative contribution of DIC (Dissolved Inorganic Carbon), DOC (Dissolved Organic Carbon), and POC (Particulate Organic Carbon) to the total riverine carbon exports varied depending on the region. The Bengal Gulf COSCAT exported riverine DIC, DOC, and POC of 9.3, 7.0, and 17.1 Tg C yr^{-1}, respectively, demonstrating the strong

POC contribution (Table 4). Riverine TSS (Total Suspended Sediment) loads and basin yields were also the largest from the Bengal Gulf COSCAT, indicating the strong correlation between POC and TSS.

The carbon emitted by soils to rivers headstreams can be degassed to atmosphere as CO$_2$ or deposited into sediment during the riverine transport from terrestrial ecosystem to oceanic ecosystem (Aufdenkampe et al., 2011; Cole et al., 2007). The estimated carbon release to the atmosphere from Indian (inner) estuaries (1.9 Tg C yr^{-1}; Sarma et al., 2012) is relatively small compared to the total river flux of South Asia region. The mosoonal discharge through these estuaries have a short residence time of OC, which helps the OC matters to be transported relatively unprocessed to the open/deeper ocean. The average residence time during the monsoonal discharge period is less than a day, as observed over the period of 1986–2010, with longest residence time of 7 days for the years of low discharge rate (Acharyya et al., 2012). On an average the processing rate of OC in estuaries is estimated to be 30 % in the Ganga-Brahmaputra river system in Bangladesh, and the remaining 70 % are stored in the deep water of Bay of Bengal (Galy et al., 2007).

3.5 Modeled long-term mean ecosystem fluxes from biosphere models

Bottom-up estimates from all ten ecosystem models, forced by rising atmospheric CO$_2$ concentration and changes in climate (S2 simulation), agree that terrestrial ecosystems of South Asia acted as a net carbon sink during 1980–2009. The average magnitude of the sink (NEP) estimated by the ten models is -210 ± 164 Tg C yr^{-1}, ranging from -80 Tg C yr^{-1} to -651 Tg C yr^{-1}. Rising atmospheric CO$_2$ alone (S1 simulation) accounts for 89 %-110 % of the carbon sink estimated in the CO$_2$ + Climate simulations (S2), suggesting a dominant role of the CO$_2$ fertilization effect in driving the regional sink. The decadal average NEPs are -193 ± 136, -217 ± 174 and -220 ± 186 Tg C yr^{-1}, respectively, for the 1980s, 1990s and 2000s. The net primary productivity (NPP) for the same decades are 2117 ± 372, 2160 ± 372 and 2213 ± 358 Tg C yr^{-1}, respectively.

Five of the eight models providing CO_2 + Climate simulations (S2) show that climate change alone led to a carbon source of 0.1 $Tg\,C\,yr^{-1}$ to 63 $Tg\,C\,yr^{-1}$ over the last three decades (the difference between simulation S2 and S1); the three other models (OCN, ORC and TRI) show that climate change enhanced the carbon sink by −14, −6 and −4 $Tg\,C\,yr^{-1}$. Such model discrepancies result in average net carbon flux driven by climate change is near neutral (10 ± 22 $Tg\,C\,yr^{-1}$).

3.6 Modeled long-term mean ecosystem fluxes from inversions

Top-down estimates of land–atmosphere CO_2 biospheric fluxes (i.e. without fossil fuel emissions, and inclusive of LUC flux and Riverine export) are estimated by using atmospheric CO_2 concentrations and chemistry-transport models. Results are available from 11 atmospheric inverse models participating in the TransCom intercomparison project with varying time period between 1988–2008 (Peylin et al., 2012). The inversions were run without any observational data over the South Asia region for most part of the 2000s. Therefore, we place a very low confidence in the TransCom inversion results, and a medium confidence in the results of two additional regional inversions using aircraft measurements over the region. The estimated net land–atmosphere CO_2 biospheric fluxes from the two regional inversions are −317 and −88.3 $Tg\,C\,yr^{-1}$ (Patra et al., 2011a; Niwa et al., 2012). The range of biospheric CO_2 fluxes estimated by the 11 TransCom inversions is −158 to 507 $Tg\,C\,yr^{-1}$, with a median value being a sink of −35.4 $Tg\,C\,yr^{-1}$ with a 1-σ standard deviation 182 $Tg\,C\,yr^{-1}$. The median of the TransCom inversions is chosen for filtering the effect of outliers values. In summary, for this RECCAP carbon budget, we propose as a synthesis of the inversion approach the mean value of the two "best" inversions using region-specific CO_2 data and the median of TransCom models (-147 ± 150 $Tg\,C\,yr^{-1}$). For comparison, the NBP is calculated as -104 ± 150 $Tg\,C\,yr^{-1}$ (Top-down biospheric flux – Riverine export; further details of NBP calculation in Sect. 3.10.1).

3.7 Seasonal variability of CO_2 fluxes

Figure 3 shows the comparisons of carbon fluxes as estimated by the terrestrial ecosystem models (NEP), atmospheric-CO_2 inverse models (NBP) and fire emissions as estimated from satellite products and modeling. According to the ecosystem and inversion models, the peak carbon release is around April–May, while the peak of CO_2 uptake is between July and October. The dynamics as seen by the TransCom (global) inversion models is quite unconstrained due to the lack of atmospheric measurements in the region. A recent study (Patra et al., 2011a) shows that the peak CO_2 uptake rather occurs in the month of August when inversion is constrained by regional measurements from commercial aircrafts. The months of peak carbon uptake are consistent with regional climate seasonality, i.e., the observed maximum rainfall during June–August months. This predominantly tropical biosphere is likely to be limited by water availability as the average daytime temperatures over this region are always above 20 °C and rainfall is very seasonal.

The peak-to-trough seasonal cycle amplitudes of NEP simulated by the ecosystem models are of similar magnitude (∼ 300 $Tg\,C\,yr^{-1}$) compared to those estimated by one of the inversion constrained by aircraft data (Patra et al., 2011a). The other regional inversion using atmospheric observations within the region estimated a seasonal cycle amplitude about 50 % greater, mainly due to large CO_2 release in the months of May and June (Niwa et al., 2012). A denser observational data network and field studies are required for narrowing the gaps between different source/sink estimations.

3.8 Interannual variability of carbon fluxes

Because aircraft CO_2 observations over South Asia region are limited to only two years (2007 and 2008), we will exclude inverse model estimates from the discussions on interannual variability.

All ten terrestrial ecosystem models agree that there is no significant trend in the net carbon flux (positive values mean carbon source, negative values mean carbon sink) over South Asia from 1980 to 2009 (Fig. 4). The estimated net carbon flux (simulation scenario S2) over South Asia exhibits relatively large year-to-year change among the two simulation scenarios. The interannual variation of the 30-yr net carbon flux estimated by the average of the ten models is 63 Tg C yr^{-1} measured by standard deviation, or 30 % measured by coefficient of variation (CV). In fact, the CV of the 30-yr net carbon flux estimated by different models show a large range from 14 % to 166 %, and only two models show a CV of larger than 100 %.

The model ensemble unanimously show that interannual variations in simulated net carbon flux is driven by the interannual variability in gross primary productivity (GPP) rather than that in terrestrial heterotrophic respiration (H_R), suggesting that variations in vegetation productivity play a key role in regulating variations of the net carbon flux. Similar results were also found in other regions such as Africa (Ciais et al., 2009).

To study the effect of climate change on net carbon flux variations, we performed correlation analyses between detrended anomalies of the modeled net carbon flux and detrended anomalies of climate (annual temperature and annual precipitation) over the last three decades (see Methods section). All models predict that carbon uptake decrease or reversed into net carbon source responding to increasing temperature, with two models (LPJ_GUESS and VEGAS) showing this positive correlation between temperature and net carbon flux statistically significant ($r > 0.4$, $P < 0.05$). Regarding the response to precipitation change, eight of the ten models predict more carbon uptake in wetter years, particularly for LPJ; TRIFFID shows a statistically significant ($P < 0.05$) negative correlation between precipitation and net carbon flux. Thus, warm and dry years, such as 1988 and 2002, tend to have positive net carbon flux anomalies (less carbon uptake or net carbon release). This further implies that the warming trend and the and non-significant trend in precipitation (Fig. 4) during the last three decades over South Asia might not benefit carbon uptake by terrestrial ecosystems, although models do not fully agree on the dominant climate driver of interannual variability in the net carbon flux. Six of the models (NCAR_CLM4CN, HyLand, LPJ, OCN, ORCHIDEE and TRIFFID) show interannual variability in net carbon flux closely associated with

variability in precipitation rather than in temperature. The precipitation is also found to be the main driver of seasonal variation in South Asian CO_2 flux (Patra et al., 2011a).

3.9 Methane emissions

3.9.1 Top-down and bottom-up South Asian CH_4 emissions

The South Asian CH_4 emissions are calculated from 6 scenarios prepared for the TransCom-CH_4 experiment (Patra et al., 2011b). Five of the emission scenarios are constructed by combining inventories of various anthropogenic/natural emissions and wetland emission simulated by terrestrial ecosystem model (bottom-up), and one is from atmospheric-CH_4 inversion (top-down). The estimated CH_4 emissions are in the range of 33.2 and 43.7 Tg C-CH_4 yr^{-1} for the period of 2000–2009, with an average value of 37.2 ± 3.7 (1σ of 6 emission scenarios) Tg C-CH_4 yr^{-1}.

3.9.2 Bottom-up CH_4 emissions from agriculture in India – implications for South Asian budget

Livestock production and rice crop cultivation are the two major sources of CH_4 emission from the agriculture sector. The reported emissions due to enteric fermentation and rice cultivation were 6.6 Tg C-CH_4 yr^{-1} and 3.1 Tg C-CH_4 yr^{-1}, respectively, using emission factors appropriate for the region (NATCOM, 2004). India is a major rice-growing country with a very diverse rice growing environment: continuously or intermittently flooded, with or without drainage, irrigated or rain fed and drought prone. The average emission coefficient derived from all categories weighted for the Indian rice crop is 74.1 ± 43.3 kg C-CH_4 ha^{-1} (Manjunath et al., 2011). The total mean emission (revised estimate) from the rice lands of India was estimated at 2.5 Tg C-CH_4 yr^{-1}. The wet season contributes about 2.3 Tg C-CH_4 yr^{-1} amounting to 88 % of the emissions. The emissions from drought-prone and flood-prone regions are 42 % and 18 % of the wet season emissions, respectively.

India has the world's largest total livestock population with 485 million in 2003, which accounts for ~57 % and 16 % of the world's buffalo and cattle populations, respectively. Methane emissions from livestock have two components: emission from "enteric fermentation" and "manure management". Results showed that the total CH_4 emission from Indian livestock, including enteric fermentation and manure management, was 11.8 Tg CH_4 for the year 2003. Enteric fermentation itself accounts for 8.0 Tg C-CH_4 yr^{-1} (~91 %). Dairy buffalo and indigenous dairy cattle together contribute 60 % of the total CH_4 emission. The three states with high live stock CH_4 emission are Uttar Pradesh (14.9 %), Rajasthan (9.1 %) and Madhya Pradesh (8.5 %). The average CH_4 flux from Indian livestock was estimated at 55.8 kg C-CH_4 ha^{-1} feed/fodder area (Chhabra et al., 2009). The milching livestock constituting 21.3 % of the total livestock contribute 2.4 Tg C-CH_4 yr^{-1} of emission. Thus, the CH_4 emission per kg milk produced amounts to 26.9 g C-CH_4 kg^{-1} milk (Chhabra et al., 2009b).

These CH_4 emission estimations of 8.8 Tg C yr^{-1} from livestocks are in good agreement with those of 8.8 (enteric fermentation + manure management) Tg C yr^{-1} in the Regional Emission inventory in Asia (REAS) for the year 2000 (Yamaji et al., 2003; Ohara et al., 2007), while emissions from rice cultivation of 2.5 Tg C yr^{-1} is about half of 4.6 Tg C yr^{-1}, estimated by Yan et al. (2009).

The REAS estimated total CH_4 emissions due to anthropogenic sources (waste management and combustion, rice cultivation, livestock) from South Asia is 25 Tg C yr^{-1} for the year 2000, with 6.5, 11.3 and 7.2 Tg C yr^{-1} are emitted due to rice cultivation, livestock and waste management. To match the range of the total flux from South Asia suggested by bottom-up inventories and atmospheric inversions (33.2–43.7 TgC/yr), the remaining CH_4 sources (mostly natural wetlands and biomass burning) for balancing total emissions from South Asia is in the range of 8–19 TgC yr^{-1}. The combination of bottom-up estimations of all CH_4 sources types from all the member nations with top-down estimates can help closing the methane budget in South Asia.

3.10 The carbon budget

3.10.1 Mean annual CO_2 budget

Figure 5 and Table 5 show the estimates of regional total CO_2-carbon emissions from different source types as discussed above. A fraction of the CO_2 emissions from fossil fuel burning (444 Tg C yr^{-1}, averaged over 2000–2009) is taken up by the ecosystem within the region as suggested by the net biome productivity (NBP) estimated at -191 ± 193 Tg C yr^{-1} by bottom-up methods, and at -104 ± 150 Tg C yr^{-1} estimated by top-down methods. The bottom-up NBP is estimated as the sum of terrestrial ecosystem simulated net ecosystem production (NEP), uptake and emissions due to land use change (LUC), and carbon export through the river system. The estimated CO_2 release due to fires (44 Tg C yr^{-1}) is of similar magnitude than the flux transported out of the land to the coastal oceans by riverine discharge (42.9 Tg C yr^{-1}), but fire emissions are not included in the budget because are largely taken into account in the LUC component. Considering the net balance of these source types (including all biospheric and fossil fuel fluxes of CO_2), the South Asia subcontinent is a net source of CO_2, with a magnitude in the range of 340 (top-down) to 253 (bottom-up) Tg C yr^{-1} in the period 2000–2009. We choose the mean value of 297 ± 244 Tg C yr^{-1} from the two estimates as our best estimate for the net land-to-atmosphere CO_2 flux for the South Asia region.

3.10.2 The mean annual carbon ($CO_2 + CH_4$) budget

Table 6 shows the emission and sinks of CO_2 and CH_4 for the South Asia region. The best estimate of the total carbon or CO_2-equivalent (CO_2-eq = $CO_2 + CH_4$) flux is 334 Tg C yr^{-1}, calculated with the average CH_4 emissions of 37 Tg C yr^{-1} and best estimate of CO_2 emissions of 297 Tg C yr^{-1}. For this CO_2-eq flux, we assumed all CH_4 is oxidized to CO_2 in the atmosphere within about 10 yr (Patra et al., 2011b). However, it is well known that CH_4 exerts 23 times more radiative forcing (RF) than CO_2 over a 100-yr period (IPCC, 2001). For estimating the role of South Asia in global warming, the region contributes RF-weighted CO_2-eq emission of 1148 (297+37 × 23) $\mathrm{Tg\,C\,yr^{-1}}$. The net RF-weight CH_4 emission from the South Asia region is more than double of that released as CO_2 from fossil fuel emissions. This result suggests that mitigation of CH_4 emission should be given high priority for policy implementation. The effectiveness of CH_4 emission mitigation is also greater due to shorter atmospheric lifetime compared to CO_2.

4 Future research directions

The top-down and bottom-up estimations of carbon fluxes showed good agreements within their respective uncertainties, because we are able to account for the major flow of carbon in to and out of the South Asia regions. However, there are clearly some missing flux components those require immediate attention. The fluxes estimated and not estimated in this work are schematically depicted in Fig. 6. Most notably the soil carbon pool and fluxes have not been incorporated in this analysis. The soil organic carbon (SOC) sequestration potential of the South Asia region is estimated to be in the range of 25 to 50 $\mathrm{Tg\,C\,yr^{-1}}$ by restoring degraded soil and changing cropland management practices (Lal, 2004). The carbon fluxes associated with international trade (e.g. wood and food products) are likely to be minor contributor to the total budget of South Asia, as the region is not a major exporter/importer of these products (FRA, 2010). The region is a major importer of coal and gas for supporting the energy supply (UN, 2010). These flux components, along with several others identified in Fig. 6, will be addressed in the working group of South and Southeast Asian Greenhouse Gases Budget during a 3-yr project of the Asia-Pacific Network (2011–2014).

5 Conclusions

We have estimated all major natural and anthropogenic carbon (CO_2 and CH_4) sources and sinks in the South Asia region using bottom-up and top-down methodologies.

Excluding fossil fuel emissions and by accounting for the riverine carbon export, we estimated a top-down CO_2 sink for the 2000s (equal to the Net Biome Productivity) of -104 ± 150 $\mathrm{Tg\,C\,yr^{-1}}$ based on recent inverse model simulations using aircraft measurement and median of multi-model estimate. The flux is in fairly good agreement with the bottom-up CO_2 flux estimate of -191 ± 186 $\mathrm{Tg\,C\,yr^{-1}}$ based on the net balance of the following fluxes: net ecosystem productivity, land use change, fire, and river export. These results show the existence of a globally modest biospheric sink, but a quite significant regionally and per area sink driven by the net growth and expansion of vegetation. In a longer time frame, the South Asia sink is also benefiting from the CO_2 fertilization effect on vegetation growth.

Including fossil fuel emissions, our best estimate of the net CO_2 land-to-atmosphere flux is a source of 297 ± 244 $\mathrm{Tg\,C\,yr^{-1}}$ from the average of top-down and bottom-up estimates, and a net CO_2-equivalent, including both CO_2 and CH_4, land-to-atmosphere flux of 334 $\mathrm{Tg\,C\,yr^{-1}}$ for the 2000s. We calculate that the RF-weighted total CH_4 emission is 851 $\mathrm{Tg\,C\,yr^{-1}}$ from the South Asia region. In terms of CO_2-equivalent flux, methane is largely dominating the budget, at a 100-yr horizon, because of its larger warming potential compared to CO_2. This indicates that a mitigation policy for CH_4 emission is preferred over fossil fuel CO_2 emission control or carbon sequestration in forested land.

Further constraints in the carbon budget of South Asia to reduce current differences between the bottom-up and top-down estimates will require the expansion of atmospheric observations including key isotopes of greenhouse gases and the continuous development of inverse modeling systems that can use a diverse set of data streams including remote sensing data. In addition, terrestrial ecosystem models will need to properly represent the crops given the large role of agriculture in the region, better constrain the role of wetlands in the methane budget, and expand observations on riverine carbon transport and its ultimate fate in the coastal and open oceans.

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Table 1. Average fossil fuel CO_2 emissions and annual growth rates (%) for the decade of 1990s, 2000s, and the full RECCAP period (1990–2009).

Country/ Region	Average Emissions ($\mathrm{Tg\,C\,yr^{-1}}$) 1990–2009	Growth rate ($\%\,\mathrm{yr^{-1}}$) 1990–2009	Average Emissions ($\mathrm{Tg\,C\,yr^{-1}}$) 1990–1999	Growth Rate ($\%\,\mathrm{yr^{-1}}$) 1990–1999	Average Emissions ($\mathrm{Tg\,C\,yr^{-1}}$) 2000–2009	Growth Rate ($\%\,\mathrm{yr^{-1}}$) 2000–2009
Bangladesh	8.207	6.2	5.638	6.0	10.775	6.1
Bhutan	0.113	7.8	0.072	11.4	0.154	8.5
India	319.81	4.7	247.44	5.6	392.18	5.3
Nepal	0.702	5.6	0.514	13.8	0.889	2.3
Pakistan	29.986	4.1	23.019	4.7	36.932	5.7
Sri Lanka	2.368	5.8	1.629	8.9	3.107	2.2
South Asia	361	5.7	278	8.4	444	5.0

Table 2. Net emissions (+) and accumulations (−) of carbon ($\mathrm{Tg\,C\,yr^{-1}}$) attributed to different types of land use in South Asia.

Assessment Period	Crops	Plantation	Industrial harvest	Fuelwood harvest	Shifting Cultivation	Total
1980–1989	5	−5	2	−4	0	−2
1990–1999	6	−11	−1	−5	0	−11
2000–2010	2	−13	0	−3	0	−14

Table 3. Estimates of carbon emissions (+) and removals (−) from land-use change in India (from Kaul et al., 2009).

Assessment period	Net C release ($\mathrm{Tg\,C\,yr^{-1}}$)	Deforestation ($\mathrm{Mha\,yr^{-1}}$)	Reference
1980	−3.98	–	Hall and Uhlig (1991)
1985	42.52	0.05	Mitra (1992)
1986	−5.00	0.49	Ravindranath et al. (1997)
1987	38.21	1.50	WRI (1990)
1990	0.40	0.06	ALGAS (1998)
1991	5.73	0.34	WRI (1994)
1994	12.8	–	Haripriya (2003)
1985–1996	9.0	–	Chhabra and Dadhwal (2004)
1994	3.86	–	NATCOM (2004)
1982–1992	5.65	0.22	Kaul et al. (2009)
1992–2002	−1.09	0.07	Kaul et al. (2009)
1980–1989	−2	–	This study
1990–1999	−11	–	This study
2000–2009	−14	–	This study

Table 4. Riverine carbon exports from the COSCAT regions in South Asia as estimated by Global NEWS (TSS: Total Suspended Sediment; DIC: Dissolved Inorganic Carbon; DOC: Dissolved Organic Carbon; POC: Particulate Organic Carbon; TC: Total Carbon (= DIC + DOC + POC)).

COSCAT number	COSCAT ID	Basin area	Discharge	Discharge	TSS load	DIC load	DOC load	POC load	TC
Unit		$10^6\,\mathrm{km^2}$	$\mathrm{km^3\,yr^{-1}}$	$\mathrm{mm\,yr^{-1}}$	$\mathrm{Tg\,yr^{-1}}$	$\mathrm{Tg\,yr^{-1}}$	$\mathrm{Tg\,yr^{-1}}$	$\mathrm{Tg\,yr^{-1}}$	$\mathrm{Tg\,yr^{-1}}$
1336	Bengal Gulf	1815	1370	755	3411.7	9.3	7.0	17.07	33.4
1337	East Deccan Coast	1118	270	241	153.7	1.8	1.2	1.33	4.4
1338	Laccadive Basin	0.121	79	645	47.0	0.4	0.3	0.42	1.2
1339	West Deccan Coast	0.337	160	475	136.4	1.2	0.7	0.85	2.8
1340	Indus Delta Coast	1389	55	39	13.0	0.8	0.3	0.10	1.2
1341	Oman Gulf	0.264	1	2	0.7	0.0	0.0	0.01	0.01
Sum		5046	1933	381	37617	13.6	9.5	19.8	42.9

Table 5. Decadal average CO_2 fluxes from the South Asia region using bottom-up estimations, top-down estimations and terrestrial ecosystem models. The range of estimate is given as maximum and minimum, and 1-σ standard deviations as the estimated uncertainty or from interannual variability (IAV).

Flux category	Flux ($Tg\,C\,yr^{-1}$)	Assessment period	Source
Fossil fuel	+444 (range: +364 to +573)	2000–2009	Boden et al. (2011)
Land use change	−14 ± 50	2000–2009	This study based on Houghton et al. (2007)
Open fires	+44.1 ± 13.7 (IAV)	2000–2009	GFEDv3.1
Riverine discharge (DIC + DOC + POC)	−42.9	1980–2000	This study based on Global NEWS, (Mayorga et al., 2010)
Atmospheric-CO_2 inverse model	−35.4 (model range: −158 to +507)	1997–2006	TransCom (Peylin et al., 2012)
Region-specific CO_2 inversion	−317 to −88.3	2007–2008	Patra et al. (2011), Niwa et al. (2012)
Ecosystem models (NEP)	−220 ± 186	2000–2009	Multiple models

Table 6. Annual fluxes of CO_2 and CH_4 ($Tg\,C\,yr^{-1}$). The best-estimate net flux is computed using the mean of top-down and bottom-up estimates.

Gas	Average fluxes		Best estimate	RF-weighted CO_2-eq
species	Bottom-up	Top-down		(100 yr horizon)
CO_2	−191 ± 186	−104 ± 150	−147 ± 239 (NBP) +444 (fossil fuel)	297
CH_4	37.9 ± 3.6	33.2–43.7	37 (total emission)	851
Total			334	1148

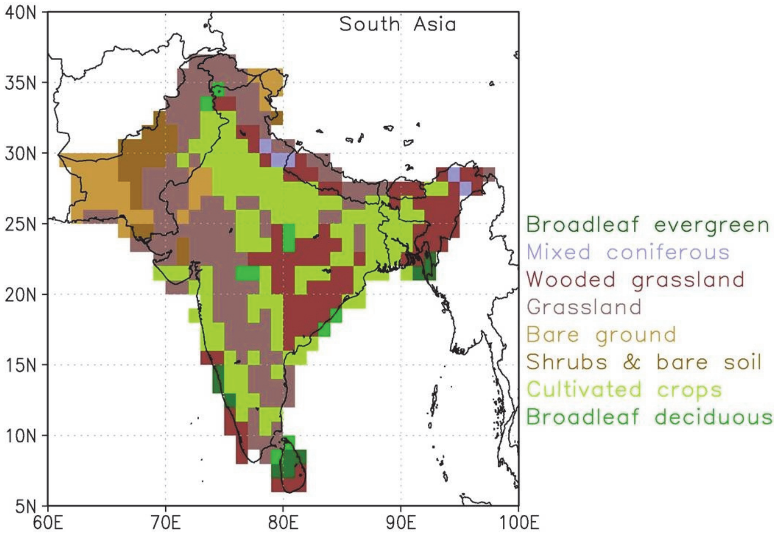


Fig. 1. Landmass selected for the RECCAP South Asia region following the definition of the United Nations and by accounting for the similarities in vegetation types.

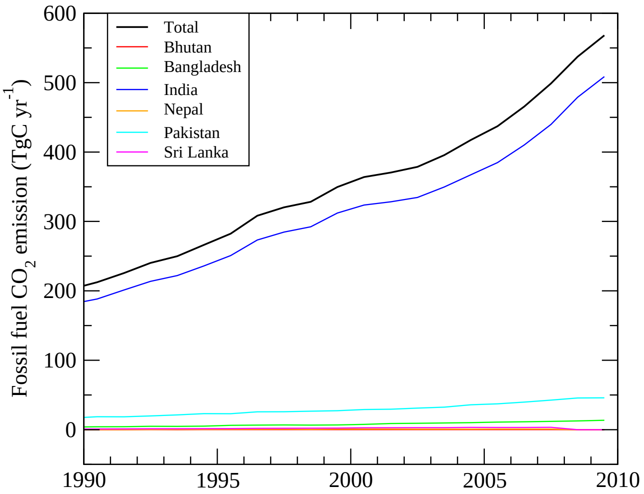


Fig. 2. Time series of CO$_2$ emissions due to fossil fuel consumption and cement production from the South Asia region during the period of 1990–2009.

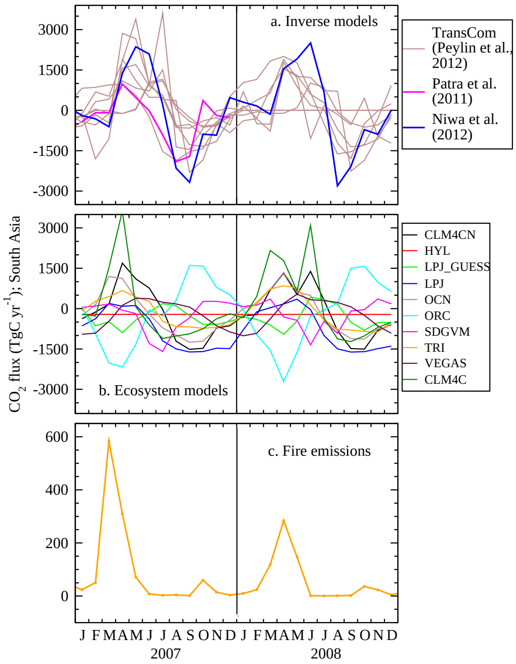


Fig. 3. Seasonal cycles of South Asian fluxes (Tg C yr^{-1}) as simulated by atmospheric inversions (**a**, top panel), terrestrial ecosystem models (**b**, middle panel) and fire emissions modeling (**c**, bottom panel).

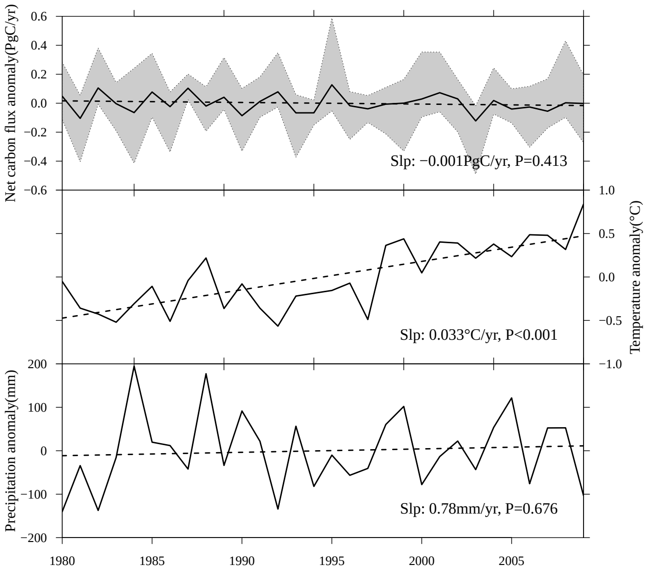
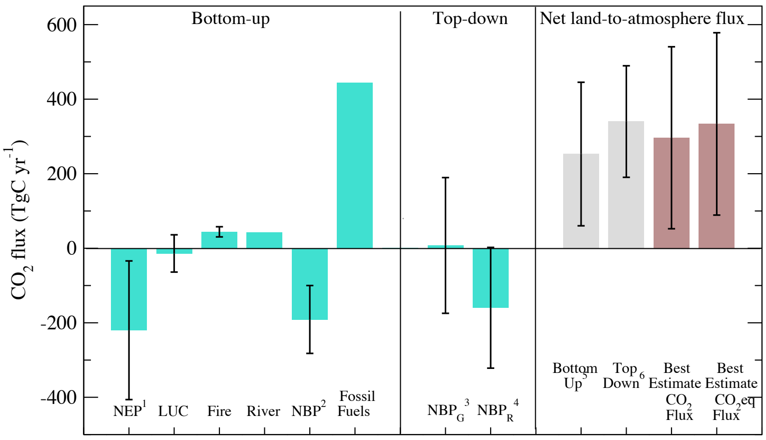


Fig. 4. Interannual variations in net carbon flux (top panel), annual temperature (middle panel) and annual precipitation (bottom panel) over South Asia from 1980 to 2009. Dashed lines show the least squared linear fit with statistics shown in text. Grey area in the top panel shows the range of net carbon flux anomalies estimated by the eleven ecosystem models.



(1) Net Ecosystem Productivity = NPP – heterotrophic respiration
(2) Net Biome Productivity = Sum of NEP, LUC, Fire, River (NBP = NEP – disturbances and lateral transport)
(3) Equivalent to NBP based on global CO$_2$ atmospheric inversions
(4) Equivalent to NBP based on region-specific CO$_2$ atmospheric inversions
(5) NBP^2 + Fossil Fuel emissions
(6) Weighted mean of NBP$_G$^{3} and NBP$_R$^{4} + Fossil Fuel emissions
(7) Best estimate for CO$_2$ (mean of bottom-up^5 and top-down^6 estimates)
(8) Best estimate for CO$_2$-equivalent that includes CO$_2$ and CH$_4$ fluxes

Fig. 5. Decadal mean CO$_2$ fluxes from various estimates and flux components. The period of estimations defer for source types (ref. Tables 5 and 6 for details).

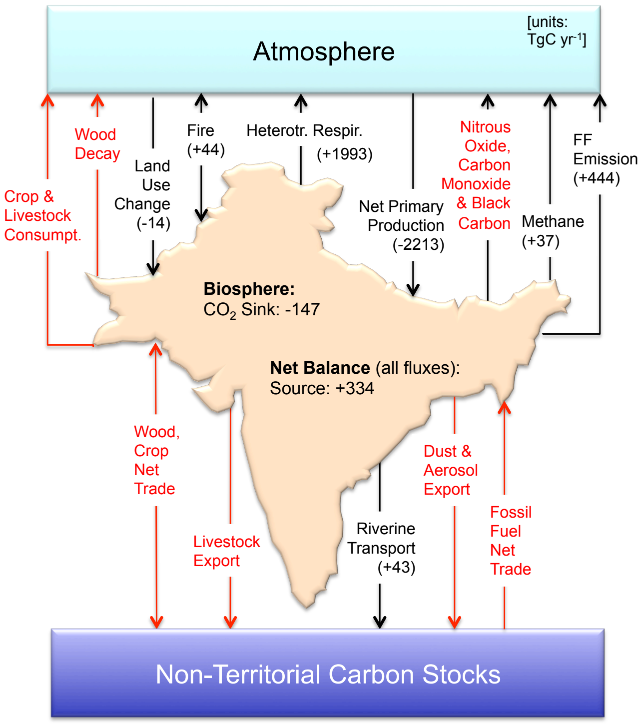


Fig. 6. Schematic diagram of major fluxes of CO$_2$, CH$_4$ nitrous oxide (N$_2$O) and related species in South Asia region. The flux components written in black ink are discussed in this work, and those marked in red ink requires attention for further strengthening our knowledge of regional GHGs budget. Direction of net carbon flow has not been determined well for some of the fluxes, which are represented by lines with arrowheads on both sides.