ASIA-PACIFIC NETWORK FOR GLOBAL CHANGE RESEARCH

Project Reference Number:

ARCP2013-01CMY-Patra/Canadell

Greenhouse gas budgets of South and Southeast Asia

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Final Report Submitted to APN

Part One: Overview of Project Work and Outcomes

Non-Technical Summary

Within the United Nations Framework Convention on Climate Change, countries are continuing to negotiate emission reduction targets and exploring mitigation strategies best suited to their technical capabilities and regional biophysical characteristics. One of the largest impediments to advance on the latter is the lack of high quality estimates of greenhouse gas (GHG) fluxes in and out of natural and managed ecosystems. In this project, we have undertaken the most ambitious synthesis effort to date using global and regional datasets and model outputs to constrain the regional GHG budgets of South and Southeast Asia, where the source/sink balance of GHGs has large uncertainties.

Keywords

Greenhouse Gases, Regional Sources and Sinks, South and Southeast Asia

Objectives

The main goal of this proposal is to compile and synthesize information from multiple sources, essential to understand the role of climate-human systems in the production of greenhouse gas emissions. This will be achieved through cooperation between scientists from South and Southeast Asia, and experts from other parts of the world. Mean estimates of the GHGs balance at the regional level and attribution to flux components will be valuable information for climate policy development in the region, particularly of mitigation policies. Several workshops and personnel visits among the participating institutions are planned for improving exchange of observational data, training on numerical model, and analysis tools.

Amount Received and Number of Years Supported

The Grant awarded to this project was:

US$ 50,000 for Year 1:

US$ 50,000 for Year 2:

US$ 45,000 for Year 3:

Activity Undertaken

- The South Asian Carbon Budget
- The Southeast Asian Carbon Budget

Results

With this third year of reporting, we have now completed the three mains tasks we set up to do:

1. To estimate the source and sinks of carbon dioxide (CO_2) and methane (CH_4) due to anthropogenic and natural biospheric activities 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±150 TgC yr^{-1} during 2007-2008. Based on the bottom-up approach, the net biospheric CO_2 flux is estimated to be -191±193 TgC 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±186 TgC yr^{-1} (2) the annual net carbon flux from land-use change of -14±50 TgC yr^{-1}, which resulted from a sink of -16 TgC yr^{-1} due to the establishment of tree plantations and wood harvest, and a source of 2 TgC yr^{-1} due to the expansion of croplands; (3) the riverine export flux from terrestrial ecosystems to the coastal oceans of +42.9 TgC yr^{-1}; and (4) the net CO_2 emission due to biomass burning of +44.1±13.7 TgC yr^{-1}. Including the emissions from the combustion of fossil fuels of 444 TgC yr^{-1} for the decades of 2000s, we estimate a net CO_2 land-to-atmosphere flux of 297 TgC 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 modelling, we estimate that 37±3.7 TgC-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 TgC 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 TgC yr^{-1} suggesting there is great potential of reducing CH_4 emissions for stabilizing greenhouse gases concentrations (Patra et al., 2013)
2. To estimate the source and sinks of carbon dioxide and methane due to anthropogenic and natural biospheric activities for the Southeast Asia region (Brunei, Cambodia, Indonesia, Laos, Malaysia, Myanmar, the Philippines, Thailand, Timor-Leste, Papua New Guinea, Singapore, and Vietnam). The bottom-up biospheric carbon budget is +209 TgC yr^{-1}, and the total carbon budget including fossil fuel emissions is +463 TgC yr^{-1}. The top-down biospheric carbon budget is +365 TgC yr^{-1}. These results are will be detailed in an upcoming peer-reviewed publication (Canadell et al., in prep.).
3. To support the analysis of air-sea CO_2 exchange over the Indian Ocean, which is connecting the South and Southeast Asian region. The Indian Ocean (44^{o}S–30^{o}N) plays an important role in the global carbon cycle, yet it remains one of the most poorly sampled ocean regions. Several approaches have been used to estimate net sea–air CO_2 fluxes in this region: interpolated observations, ocean biogeochemical models, atmospheric and ocean inversions. As part of the RECCAP (REgional Carbon Cycle Assessment and Processes) project, we combine these different approaches to quantify and assess the magnitude and variability in Indian Ocean sea–air CO_2 fluxes between 1990 and 2009. Using all of the models and inversions, the median annual mean sea–air CO_2 uptake of −0.37±0.06 PgC yr^{-1} is consistent with the −0.24±0.12 PgC yr^{-1} calculated from observations. The fluxes from the

southern Indian Ocean (18–44°S; −0.43±0.07 PgC yr^{-1}) are similar in magnitude to the annual uptake for the entire Indian Ocean.

The results of these three activities and products were used in the 5^{th} assessment report of the Intergovernmental Panel on Climate Change (IPCC) for chapter 6 of Working Group 1, i.e., Carbon and Other Biogeochemical Cycles (Ciais et al., 2013). Dr. Canadell is a lead author and Dr. Patra is a contributory author to this chapter of the IPCC AR5.

We have also begun air sampling from Comilla, Bangladesh (23.45°N, 91.20°E), as a collaborative effort between JAMSTEC and National Institute for Environmental Studies (NIES) in Japan, and Dhaka University and Bangladesh Meteorological Department (BMD) in Bangladesh. This activity records concentrations of all major greenhouse gases (CO_2, CH_4, N_2O, CO, H_2, SF_6) since June 2012 at weekly time intervals.

Three international workshops on Asian greenhouse gases budget have been conducted to discuss and share information on the state of knowledge of various source sectors of CO_2, CH_4 and N_2O. These workshops have led to various peer reviewed research papers already published or shortly to be submitted. One training programme in Dhaka University for the master course students and young faculties was conducted. In each of these events about 50 people participated (details below).

Relevance to the APN Goals, Science Agenda and to Policy Processes

The main goal of this proposal is to compile and synthesize information from multiple sources, essential to understand the role of climate-human systems in the production of greenhouse gas emissions. This will be achieved through cooperation between scientists from South and Southeast Asia, and experts from other parts of the world. Mean estimates of the GHGs balance at the regional level and attribution to flux components will be valuable information for climate policy development in the region, particularly of mitigation policies. Several workshops and personnel visits among the participating institutions have been conducted for improving exchange of observational data, training on numerical model, and analysis tools.

Self-evaluation

Significant progress was made over the past one and half years towards the completion of the territorial budgets of CO_2, CH_4 , N_2O for South and Southeast Asia. The full carbon budgets for the two regions are now available. Most importantly, the project has been able to create an international network of collaborators who are now working together beyond the APN grant, and so leaving a long-term legacy of APN's investment in supporting the establishment of robust and comprehensive GHG budgets.

Potential for further work

A whole Asian greenhouse gases budget will be the obvious next step, where the East, South and Southeast Asia regions can be combined in an analysis for all the major gases, e.g., CO_2, CH_4 , N_2O, carbon monoxide (CO), and Black Carbon (BC).

Publications

Canadell, J. G., et al., The Southeast Asian Carbon Budget, in prep.

Patra, P. K., J. G. Canadell, and S. Lal, The rapidly changing greenhouse gas budget of Asia, EOS Trans. (AGU), 93, 237, doi: 10.1029/2012EO250006, June 2012.

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Ciais, P., C. Sabine, et al., Working group I, Contribution to the IPCC fifth assessment report (AR5), CLIMATE CHANGE 2013: THE PHYSICAL SCIENCE BASIS, Chapter 6: Carbon and Other Biogeochemical Cycles, Cambridge University Press, 2013.

Acknowledgments

This work is a contribution to the REgional Carbon Cycle Assessment and Processes (RECCAP), an activity of the Global Carbon Project. The work is partly supported by JSPS/MEXT (Japan) KAKENHI-A (grant#22241008) and Asia Pacific Network (grant#ARCP2011-11NMY-Patra/Canadell). Canadell is supported by the Australian Climate Change Science Program of CSIRO-BOM-DCCEE. The inverse model results of atmospheric CO_2 and terrestrial ecosystem model results are provided under TransCom (http://transcom.lsce.ipsl.fr) and TENDY (http://www-lscedods.cea.fr/invsat/RECCAP) projects, respectively, and we appreciate all the modelers' contribution by providing access to their databases. We thank all our collaborators for this project, especially, Lingxi Zhou/China (zhoulx@cams.cma.gov.cn); Shilong Piao/China (slpiao@pku.edu.cn); Al Hooijer/Singapore (aljosja.hooijer@deltares.nl); Rizaldi Boer/Indonesia (rizaldiboer@gmail.com); H. Simbolon/Indonesia (herbolon @indo.net.id); Manish Naja/India (manish@aries.res.in); Tapas Bhattacharya/India (tapas@nbsslup.ernet.in); Shuji Aoki/ Japan (aoki@m.tohoku.ac.jp); Akihiko Ito/Japan (itoh@nies.go.jp); Toshinonu Machida/Japan (tmachida@nies.go.jp); Yoshiki Yamagata/Japan (yamagata@nies.go.jp); Guido van der Werf/The Netherlands (guido.van.der.werf@falw.vu.nl); Richard A. Houghton/USA (rhoughton@whrc.org); Steven Sitch/UK (s.sitch@leeds.ac.uk); Kawser Ahmed/Bangladesh (kawser @univdhaka.edu); Monzul Hazarika/Thailand (manzul@ait.ac.th); Peter Rayner/Australia (prayner@unimelb.edu.au); Yosuke Niwa/Japan (niwa@mri-jma.go.jp), Kentaro Ishijima/Japan (ishijima@jamstec.go.jp), Chun-Ho Cho/Korea (choch0704@korea.kr)

Preface

The timing of this final report comes at a critical period of international negotiations in the United Nations Convention Framework on Climate Change. During this year nations will be pledging their voluntary mitigation commitments to the Intended Nationally Determined Contribution (INDC) database. This report and the associated publications bring the most up to date information on sources and sinks, trends and variability of greenhouse gases for nations in South Asia and Southeast Asia. This information is of strategic value to countries to determine those contributions including the possible role of land-based options as part of their mitigation portfolios.

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1. Introduction

South Asia (Bangladesh, Bhutan, India, Nepal, Pakistan and Sri Lanka) is home to 1.6 billion people and covers an area of 4.5×10^6 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 TgC yr^{-1} in 1990 to about 573 TgC 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 TgC $month^{-1}$ during July-September following the summer monsoon rainfall.

Southeast Asia (Brunei, Cambodia, Indonesia, Laos, Malaysia, Myanmar, the Philippines, Thailand, Timor-Leste, Papua New Guinea, Singapore, and Vietnam) is a complex geographical and geopolitical region. It has mainland and peninsular components dominated by tropical rainforest and cropland, and savanna woodlands in drier areas of the northeast. Forest cover constitutes 214 million hectares equal to 29 percent of the Asia-Pacific region's total forest area (FAO 2011). Most of the region is considered a biodiversity hotspot because it harbours a high number of endemic species largely threatened by forest loss (Myers et al. 2000; Sodhi et al. 2010). The region is also home to the most extensive tropical peatlands in the world with an estimated carbon pool of 68 PgC (Page et al. 2011), a quantity rapidly diminishing along with the loss of the remaining swamp forest due to deforestation and drainage (Hooijer et al. 2010; Miettinen et al. 2011).

The regions are 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), and large numbers of ruminants linked to religious and farming practices (Yamaji et al., 2003). 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 years 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). Over the last twenty years, Southeast Asia has undergone through some of the largest changes in land use due to (1) government policies to open up forest areas, particularly in Indonesia for the transmigration program during 1990s, and (2) the rapid expansion of oil-palm plantations for the domestic and international food and biodiesel markets, along with afforestation of fast growing Acacia plantations for the pulp and paper markets (Murdiyarso et al. 2011).

In this project we establish for the first time the net carbon budget of South and Southeast 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 and Southeast Asian 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. Methodology

The **South Asia** region designated for this study is shown in Figure 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 (1.3×10^6 km^2 and 1.5×10^6 km^2 or 0.89×10^6 km^2, respectively). The rest of the area is classified as bare soil, shrubs, broadleaf evergreen, broadleaf deciduous and mixed coniferous (0.35×10^6 km^2, 0.22×10^6 km^2, 0.11×10^6 km^2, 0.10×10^6 km^2 and 0.05×10^6 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^{o}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).

We define the boundaries of the **Southeast Asia** region based on a geographically consistent unit formed by Brunei, Cambodia, Indonesia, Lao People's Democratic Republic, Malaysia, Myanmar, the Philippines, Timor-Leste, Papua New Guinea, Singapore, and Vietnam (Figure 1). The total area of the region is about 4.5×10^6 km^2 of land with a population of 550×10^6 people in 2012 (World Bank 2012).

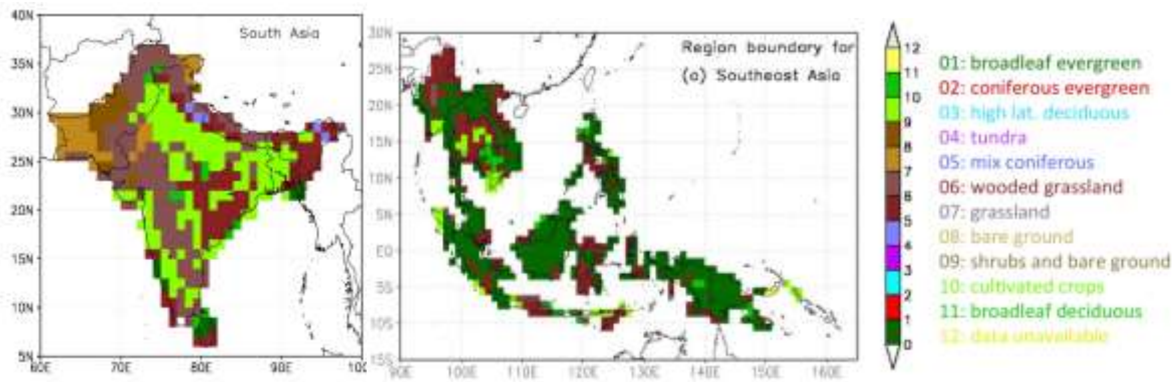


Figure 1: Landmass selected for the RECCAP South and Southeast Asia regions following the definition of the United Nations and by accounting for the similarities in vegetation types.

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 U.S. Department of Interior's Geological Survey (USGS 2010), and emissions from gas flaring were derived from data provided by the U.N., U.S. Department of Energy's Energy Information Administration (1994).

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. Modelled 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 modelled 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;

http://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°×0.5° (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, ftp://ftp.mnp.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 modelled 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-year 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., 2013). 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 & Discussion

3.1. Emissions from fossil fuels and cement production

3.1.1 South Asia

Table 1 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 TgC yr^{-1} for the periods of 1990s and 2000s, respectively. The regional total emissions have steadily increased from 213 TgC yr^{-1} in 1990 to 573 TgC 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% yr^{-1} for the period of 1990-2009. The decadal growth rates do not show significant differences between the 1990s (5.5% yr^{-1}) and 2000s (5.3% yr^{-1}) for the whole region, while an increased rate of consumptions was observed after 2005 (6.8% yr^{-1}). This acceleration (Table 1) 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).

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 (TgC yr^{-1}) 1990-2009	Growth rate (% yr^{-1}) 1990-2009	Average Emissions (TgC yr^{-1}) 1990-1999	Growth Rate (% yr^{-1}) 1990-1999	Average Emissions (TgC yr^{-1}) 2000-2009	Growth Rate (% 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

3.1.2. **Southeast Asia**

For the period of 1990-2009, Southeast Asia had cumulative emissions from the combustion of fossil fuel, gas flaring and cement production of 4,450 TgC, at an average of 174 TgC yr^{-1} during 1990-1999 and 271 TgC yr^{-1} during 2000-2009. The top three cumulative emitters during the 20-year period were Indonesia (1535 TgC), Thailand (1137 TgC), and Malaysia (725 TgC), accounting for 34%, 26% and 16% of the total regional emissions, respectively (Figure 2).

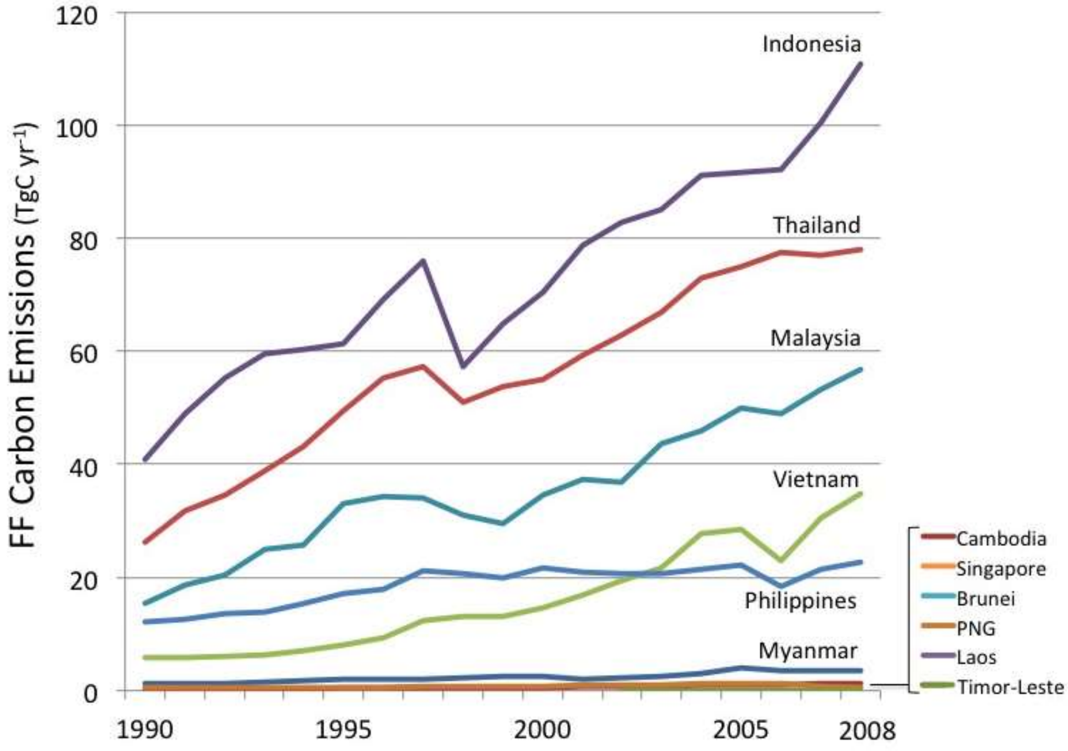


Figure 2: Carbon emissions from the combustion of fossil fuels from countries in Southeast Asia

3.2. Emissions from Land-use change (LUC)

3.2.1. South Asia

The annual net flux of carbon from land-use change in South Asia was a small sink (-11 TgC yr^{-1} for the 1990s and -14 TgC yr^{-1} for the period 2000-2009). The average sink over the 20-year period 1990-2009 was -12.5 TgC yr^{-1}. Three activities drove this net sink: establishment of tree plantations (-13 TgC yr^{-1} in the most recent decade), wood harvest (-3 TgC yr^{-1}), and the expansion of croplands (2 TgC 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 0.2×10^6 ha yr^{-1} in the 1990-1999 period and by 0.3×10^6 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 TgC 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 TgC 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 TgC yr^{-1} and 2 TgC 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 ha yr-1 during 2000-2009 (FRA, 2010). Given the rates of plantation expansion during these decades (200,000 ha yr^{-1} in the 1990-1999 period and by 300,000 ha yr^{-1} during 2000-2009), native forests were lost at rates of 200,000 ha yr^{-1} and 100,000 ha yr^{-1} in the two decades.

The large changes in forest area, both deforestation and afforestation, lead to gross emissions (~120 TgC yr^{-1}) and a gross uptake (~135 TgC yr^{-1}) that are large relative to the net flux of 14 TgC yr^{-1}. Thus, the uncertainty is greater than the net flux itself. The uncertainty is estimated to be 50 TgC 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 TgC yr^{-1} to a net sink of -5.0 TgC yr^{-1}. The recent estimates by Kaul et al. (2009) for the late 1990s and up to 2009 suggest a declining source/increasing sink, 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) (~5700 km2 to ~18,000 km2 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 ha yr^{-1} between 1982 and 1986, and 266,700 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 TgC in districts losing forests and an increase of 81 TgC 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).

3.2.2. Southeast Asia

Of the 11 countries included in Southeast Asia, Indonesia has the largest area of forest in 2010 (97,857,000 ha), approximately 3x greater than the country with the next largest forest (Myanmar and Papua New Guinea) (FAO, 2010).

Indonesia also has the highest rate of deforestation of native forests (3,275,000 ha yr^{-1}) (2000-2009) (FAO,2010), with Myanmar next (1,687,000 ha yr^{-1}), followed by Papua New Guinea (705,000 ha/yr), Malaysia (668,000 ha yr^{-1}), and Cambodia (632,000 ha yr^{-1}).

Thailand, Indonesia, and Vietnam have the largest areas of tree plantations in 2010 (3,986,000, 3,549,000, and 3,512,000 ha, respectively) (FAO, 2010).

The net flux of carbon from land-use change in Southeast Asia averaged 341 TgC yr^{-1} and 194 TgC yr^{-1} for the decades of 1990-1999 and 2000-2009, respectively (268 TgC yr^{-1} averaged over the period 1990-2009). The decline in emissions over the two decades is consistent with the reduced rates of deforestation reported by FAO (FAO, 2010) and Hansen et al. (2009). Nevertheless, high rates of deforestation (as high as 5% annually) continue at present in at least two locations, the eastern lowlands of Sumatra and the peatlands of Sarawak, Borneo (Miettinen et al., 2011).

The types of land use most important in the carbon budget are the conversion of forests to croplands and to shifting cultivation, with smaller net releases from logging. The net flux from logging includes both the emissions from wood products and the accumulations of carbon in regrowing forests.

The flux attributed to the expansion of croplands and shifting cultivation vary from decade to decade, and, because the approach used to assign deforestation to either croplands or shifting cultivation is subject to error, it is perhaps better to consider the two combined (i.e., 202, 276, and 184 TgC yr^{-1} for the agricultural expansion in the three decades, respectively).

It is important to note that the net flux of carbon from deforestation for croplands does not include the large emissions of carbon from the draining and burning of peatland forests, which alone contributed an estimated 300 TgC yr^{-1} to the net flux from Southeast Asia (Hooijer et al., 2010). It would probably be double-counting to add this 300 TgC yr^{-1} release to the estimates reported here, because the cultivation of upland soils is estimated here to have released 115 TgC yr^{-1}. A conservative estimate would be to add ~200 TgC yr^{-1} to the net flux reported here, yielding a net flux as high as 0.54 PgC yr^{-1} 1990-1999 and ~0.4 PgC yr^{-1} for 2000-2009.

Shifting cultivation is poorly documented at continental scales, but a recent analysis estimated the carbon emitted from fires associated with shifting cultivation in the tropics (Silva et al., 2011). For the countries of Southeast Asia (but lacking Papua New Guinea) their estimate was 48 TgC yr^{-1}. It is lower than the gross emissions of 155 and 100 TgC yr^{-1} (for the 1990s and 2000-2009, respectively) estimated here for gross emissions of carbon from fires for shifting cultivation.

Shifting cultivation is common in the region, and recent field studies have documented the recovery of forest in the fallows of shifting cultivation in Vietnam (Do et al., 2010) and in Sarawak, Malaysia (Jepsen, 2006).

Recent attention has focused on Indonesia and Papua New Guinea. The loss of forests in Sumatra and Kalimantan (Borneo), in particular, has been going on at least since the 1980s (Curran et al., 2004). That loss has continued to the present (Hansen et al., 2009; Broich et al., 2011) and seems likely to continue (Fuller et al., 2011). Rates of forest loss are highest at present in peat swamp forests (Langner et al., 2007; Miettinen et al., 2011) that are being drained and planted with oil palm plantations. The draining and burning releases large quantities of carbon to the atmosphere (Hooijer et al., 2010) and removes an important carbon sink from the landscape (Dommain et al., 2011). Coffee has also been important in driving deforestation in southwest Sumatra (Gaveau et al., 2008).

In Papua New Guinea population growth has led to deforestation for new agricultural lands (Ningal et al., 2007), but logging is also important. Bryan et al. (2009) estimate that 41% of the 53 TgC released from Papual New Guinea as a consequence of deforestation and degradation in 2001 resulted from logging. Selective logging damages and kills trees in addition to those harvested (Bryan et al., 2010), but in the absence of further disturbance, logged forests have the capacity to recover (Yosi et al., 2011).

In addition to the reduction of biomass that follows logging, forest fragmentation may also contribute to carbon emissions. Oil palm and rubber plantations were major contributors to forest fragmentation in Malaysia (Abdullah and Nakagoshi, 2007), oil palm being more important in wetlands and rubber plantations more important in forests.

3.3 Emissions from fires

3.3.1. South Asia.

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 TgC yr^{-1} due open fires as detected by the various satellites sensors, 47±30 TgC 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 TgC yr^{-1} if the period of 2000-2009 is considered. The total fire emissions can be attributed to agriculture waste burning (14±4 TgC yr^{-1}), deforestation fires (21±11 TgC yr^{-1}), forest fires (2.6±1.5 TgC yr^{-1}), savanna burning (4.8±1.9 TgC yr^{-1}) and woodland fires (1.8±1.0 TgC yr^{-1}) for the period of 2000-2009. The seasonal variation of CO_2 emissions due to fires is discussed in subsection 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 used to interpreted interannual variability.

3.3.2 Southeast Asia

Total carbon fire emissions (from CO_2) from Southeast Asia were 227 TgC yr^{-1} for the 1997-2011 period. The amount is comparable to 254 TgC yr^{-1} from fossil fuel carbon emissions during 2000-2008 although their long-term net contribution to radiative forcing in the atmosphere is different. Fire emissions are a gross flux that can partially be offset by vegetation regrowth following fire while fossil fuel emissions are a net flux to the atmosphere.

Of the total fire emissions for the period studied, emissions from deforestation and degradation fires are the single most dominant source accounting for 51%. Uniquely to Southeast Asia, peat fires are an important source of emissions as fires can last for months after the fires begin. They account for 33% of the total emissions, followed in decreasing order by fire emissions from savannas, forests, agriculture and woodlands.

Fire emissions are large contributors to inter-annual variability with larger fluxes during The Southern Oscillation/El Nino periods. The El Niño of 1997-1998 stands out from other periods with emissions due to peat fires seven times higher than the long-term mean (Figure 3). These results are consistent with bottom-up estimates based on field measurements (Page et al., 2002) and inverse modelling (Patra et al., 2005). The lower inter-annual variability in carbon emissions due to deforestation fires, compared to peat fires, could indicate greater control of natural climate variability on the extent of peat burning. It is well established, however, that all fires, small and big, are caused by human activity and that there I a close coupling between human activity and natural climate variability in determining fire emissions from the region ([Field and Shen, 2008].

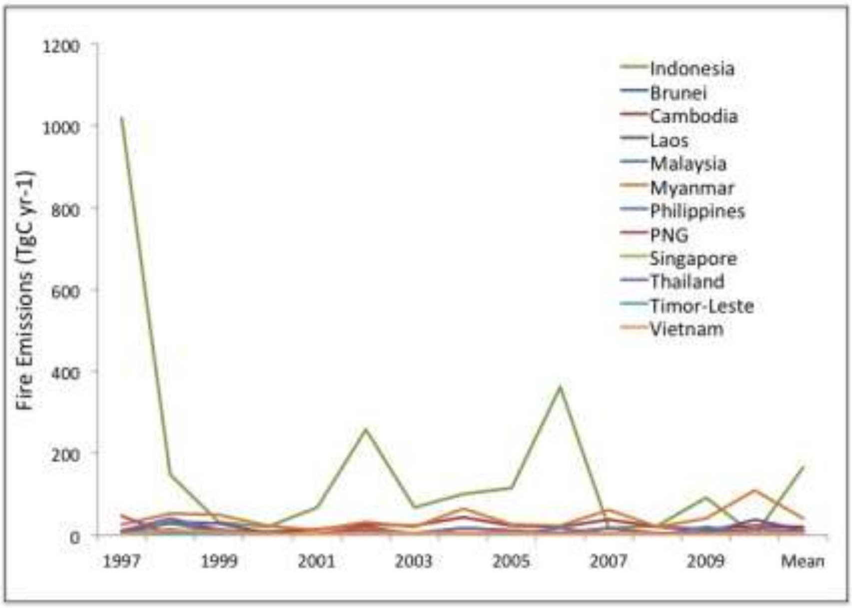


Figure 3: Inter-annual variability and mean of difference fire emission components for the Southeast Asia region.

3.4 Riverine Carbon Flux

3.4. South Asia

The total carbon export from South Asian rivers was 42.9 TgC yr^{-1}, with COSCAT exports ranging from 0.01 to 33.4 TgC yr^{-1} for the period of 1980-2000. Considering that about 611 TgC 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 TgC yr^{-1}.

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 gC 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 gC m-2 yr^{-1}, respectively. The global mean terrestrial carbon yield can be calculated by dividing the global riverine carbon export of 611 TgC yr^{-1} (Aufdenkampe et al. 2011, Battin et al. 2009) by the total land area of 149 million km2, providing a global mean yield of 4.1 gC 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 (Figure 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 TgC yr^{-1}, respectively, demonstrating the strong POC contribution. 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 TgC 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).

3.4.2 Southeast Asia

The total annual transport of carbon from land to the ocean through riverine transport is 119 TgC yr^{-1} in the form of DIC (60.6 TgC yr^{-1}), DOC (26.5 TgC yr^{-1}), and POC (32.3 TgC yr^{-1}). The 12 COSCAT regions Southeast Asia have a total riverine carbon export of 119.2 TgC yr^{-1}, ranging from 0.6 to 26.3 TgC yr^{-1} for individual regions. Considering an estimate of 0.9 PgC yr^{-1} released from global river systems [*Aufdenkampe et al.*, 2011; *Battin et al.*, 2009], rivers in Southeast Asia contribute 13% of global riverine carbon export. The area of the region is 5.72 million km^2, similar to the area of the neighboring South Asia (SA) (5.05 million km^2) (Patra et al. 2012), but riverine carbon export from the Southeast Asia region is about three times larger than that of South Asia.

3.5. Modeled long-term mean ecosystem fluxes from biosphere models

3.5.1 South Asia

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 TgC yr^{-1}, ranging from -80 TgC yr^{-1} to -651 TgC 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 TgC 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 TgC 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 TgC yr^{-1} to 63 TgC 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 TgC yr^{-1}. Such model discrepancies result in average net carbon flux driven by climate change is near neutral (10±22 TgC yr^{-1}).

3.5.2. Southeast Asia

The estimated average NPP from 10 models (CLM4C, CLM4CN, Hyland, LPJ, LPJ-GUESS, OCN, ORCHIDEE, SDGVM, TRIFFID, VEGAS) driven by climate change and rising atmospheric CO_2 concentration (simulation S2) is 5.1±0.8 PgC yr^{-1} (615.4±95.6 gC m^{-2} yr^{-1}) All models show a significant NPP increase at an average rate of 0.018±0.006 PgC yr^{-1} (0.3±0.1 % yr^{-1}) over the last three decades. Such a significant increase in NPP is mainly the result of the atmospheric CO_2 fertilization effect (0.015±0.005 Pg C yr^{-1}). We found that all models agreed that climate change plays a smaller role in driving the NPP trend as calculated by the difference between model estimated NPP in simulation S2 and that in simulation S1 (rising atmospheric CO_2 only). Temperature has a positive and significant trend with NPP (0.01°C yr^{-1}, P=0.03) and precipitation has a positive but marginally significant trend with NPP (7 mm yr^{-2}, P=0.06).

3.6. Modelled long-term mean ecosystem fluxes from inversions

3.6.1 South Asia

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 TgC 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 TgC yr^{-1}, with a median value being a sink of -35.4 TgC yr^{-1} with a 1-σ standard deviation 182 TgC 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 TgC yr^{-1}). For comparison, the NBP is calculated as -104±150 TgC yr^{-1} (Top-down biospheric flux – Riverine export; further details of NBP calculation in section 3.10.1).

3.6.2 Southeast Asia

The mean net biospheric CO_2 flux (excluding fossil fuel emissions) is estimated at 165 ± 378 TgC yr^{-1} based on 10 inverse models for the period of 2000-2008. The median value of 174 TgC yr^{-1} is not distinctly different from the mean value, indicating all the inversion results are spread widely around the mean. To this flux we add carbon exported out of the region through routes other than the atmosphere to complete the carbon budget. Thus, we add the riverine carbon export of 119 TgC yr^{-1} to estimate a mean of 284±378 TgC yr^{-1} as the net biospheric production of Southeast Asia (or carbon exported away from terrestrial ecosystems).

Flux anomalies are calculated by subtracting the long-term mean seasonal cycle from the original fluxes time series at monthly time intervals for each model (Figure 4). Although the net CO_2 flux estimated by inverse modeling greatly dependent on the selection of forward transport model, the flux anomalies, however, can be determined at greater consistency between the transport models. Thus we restrict detailed discussion to flux anomalies. Strong correlation of CO_2 flux anomalies is found with the ENSO Index at short to medium time scales, ranging from 3-months to several years (correlation coefficient = 0.57, 0.61 and 0.38 for the mean, mean+1σ and mean-1σ fluxes, respectively). Patra et al. (2005) have found correlation coefficients of 0.61, -0.63 and 0.41 for the ENSO Index, rainfall and temperature, respectively, at 2, 5 and 2 months time lag, with the CO_2 flux anomalies in the period of 1994-2001

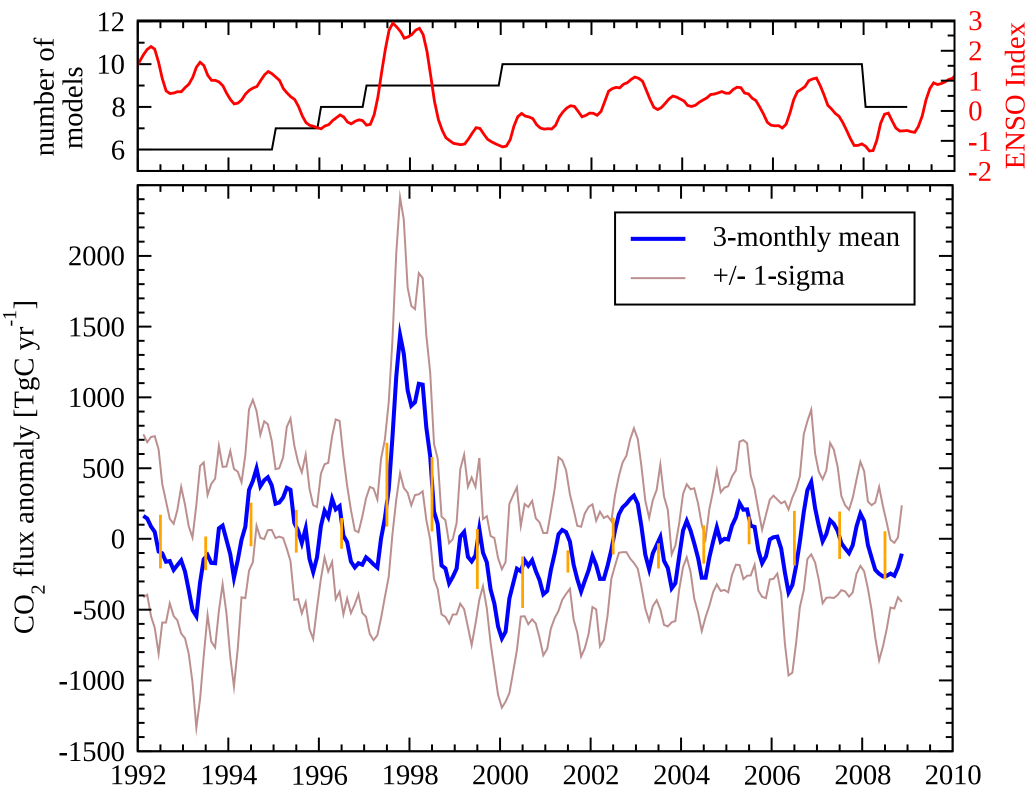


Figure 4: Interannual variations in CO_2 emission estimated by the inverse models (bottom panel) showing close link with the ENSO index (top panel) for the Southeast Asia.

3.7. Seasonal variability of CO_2 fluxes

Figure 5 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 (~3000 TgC 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.

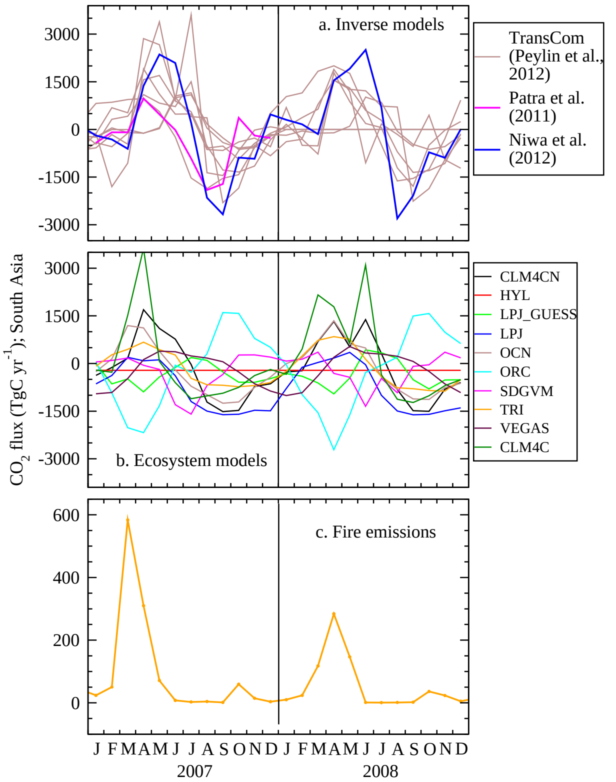


Figure 5: Seasonal cycles of South Asian fluxes (TgC yr^{-1}) as simulated by atmospheric inversions (a. top panel), terrestrial ecosystem models (b. middle panel) and fire emissions modelling (c. bottom panel).

3.8. Inter-annual 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 (Figure 6). 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-year net carbon flux estimated by the average of the ten models is 63 TgC yr^{-1} measured by standard deviation, or 30% measured by coefficient of variation (CV). In fact, the CV of the 30-year 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 (HR), 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 modelled 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 (Figure 6) 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).

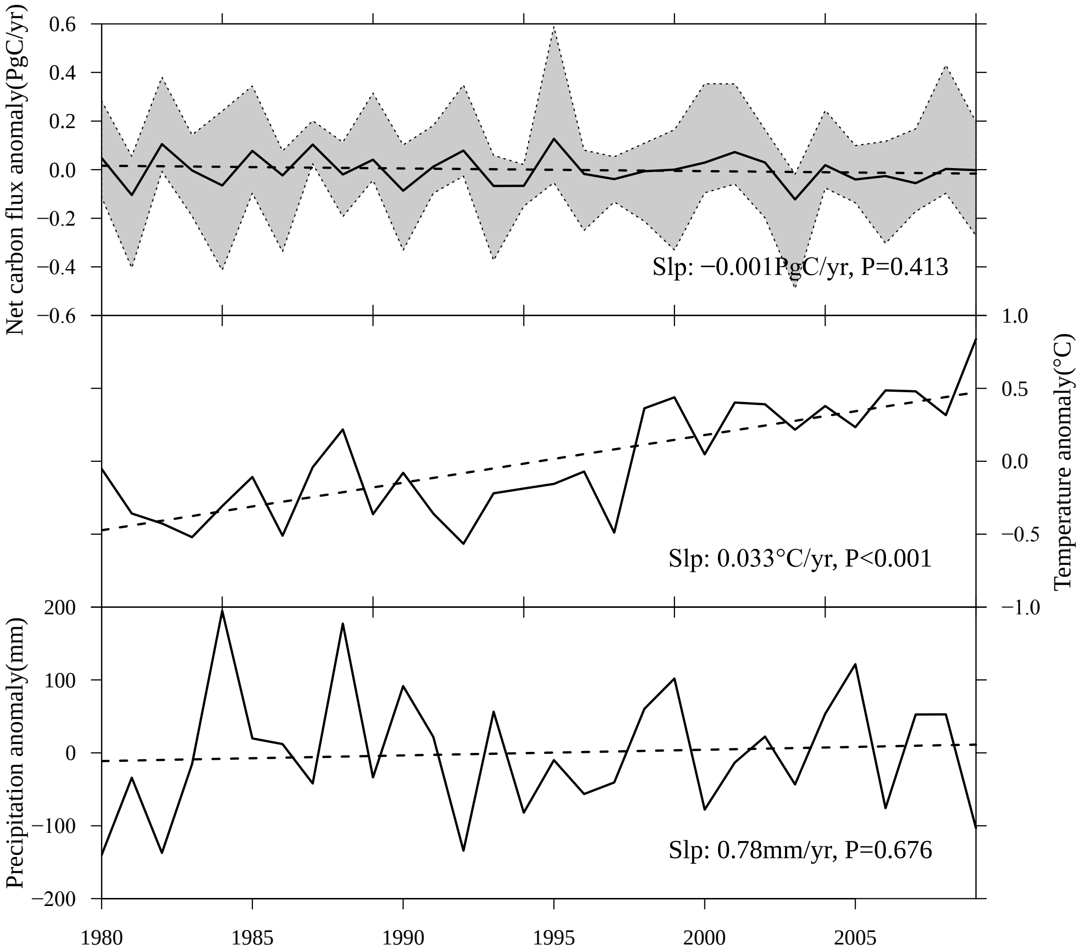


Figure 6. Interannual variations in net carbon flux (a, top panel), annual temperature (b, middle panel) and annual precipitation (c, bottom panel) over South Asia from 1980 to 2009. Dashed lines show the least squared linear fit with statistics shown in text. Grey area in the top panel shows the range of net carbon flux anomalies estimated by the eleven ecosystem models.

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 TgC-CH_4 yr^{-1} for the period of 2000-2009, with an average value of 37.2±3.7 (1σ of 6 emission scenarios) TgC-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 TgC-CH_4 yr^{-1} and 3.1 TgC-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 kgC-CH_4 /ha (Manjunath et al, 2011). The total mean emission (revised estimate) from the rice lands of India was estimated at 2.5 TgC-CH_4 yr^{-1}. The wet season contributes about 2.3 TgC-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 TgC-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 livestock 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 kgC-CH_4 ha^{-1} feed/fodder area (Chhabra et al., 2009). The milching livestock constituting 21.3% of the total livestock contribute 2.4 TgC-CH_4 yr^{-1} of emission. Thus, the CH_4 emission per kg milk produced amounts to 26.9 gC-CH_4/kg milk (Chhabra et al., 2009b).

These CH_4 emission estimations of 8.8 TgC yr^{-1} from livestocks are in good agreement with those of 8.8 (enteric fermentation + manure management) TgC 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 TgC yr^{-1} is about half of 4.6 TgC 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 TgC yr^{-1} for the year 2000, with 6.5, 11.3 and 7.2 TgC 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.

3.9.3 Southeast Asia

We use bottom-up emission of CH_4 from three-selected emission scenarios developed in Patra et al. (2011). These emissions are constructed from EDGAR3.2 anthropogenic emissions (Olivier and Berdowski, 2005), emissions from rice fields (Yan et al., 2009), and natural emissions from Fung et al. (1991) (referred to as CH_4_CTL). The CH_4_BB scenario is prepared by partly replacing the biomass burning (BB) emissions by interanually varying emission field from GFEDv3.2 (van der Werf et al., 2010). For CH_4_BB_VISIT emissions, the wetland emissions are taken from an ecosystem model (VISIT; Ito and Inatomi, 2012). Like that of CO_2, the 1997/1998 El Niño period led to anomalously high emissions of CH_4 from the peat burning (Figure 7). The average CH_4 emission from these three emission scenarios is calculated as 47.5±4.4 TgC-CH_4 yr^{-1}. When scaled by the global warming potential of CH_4 (23) compared to CO_2 (IPCC, 2007), the CO_2-equivalent CH_4 emission is 1092 TgC yr^{-1}.

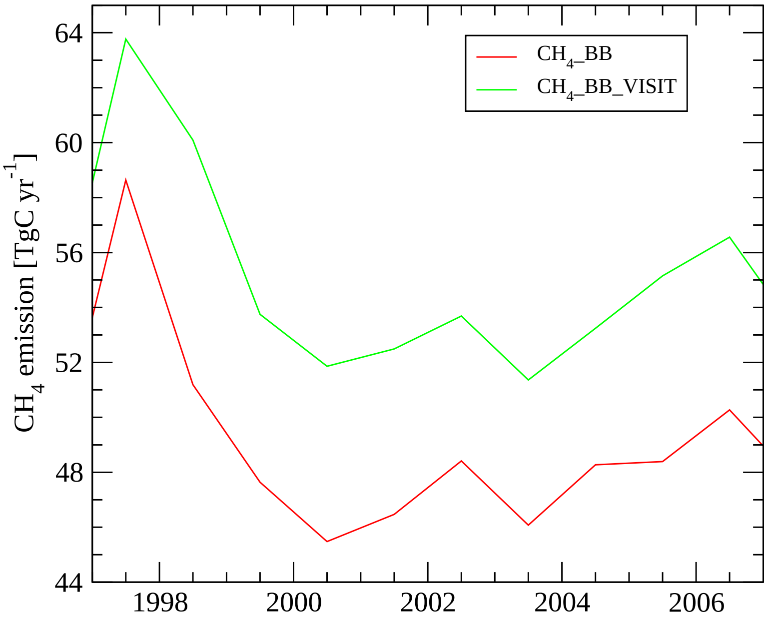


Figure 7: Interannual variations in CH4 emissions as estimated by the VISIT ecosystem model and GFEDv3 for biomass burning.

3.10. The carbon budget

3.10.1 Mean annual CO_2 budget

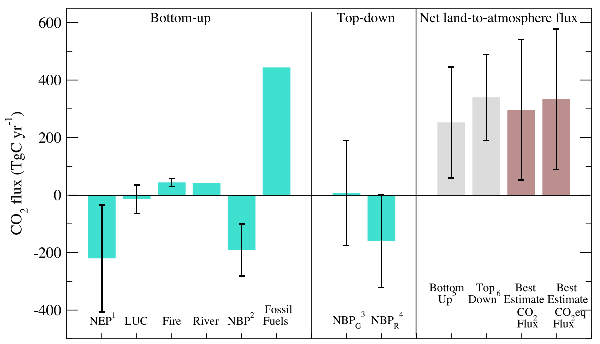
Figure 8 and Table 2 show the estimates of regional total CO_2-carbon emissions from different source types as discussed above. A fraction of the CO_2 emissions from fossil fuel burning (444 TgC yr^{-1}, averaged over 2000-2009) is taken up by the ecosystem within the region as suggested by the net biome productivity (NBP) estimated at -191±193 TgC yr^{-1} by bottom-up methods, and at -104±150 TgC 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 TgC yr^{-1}) is of similar magnitude than the flux transported out of the land to the coastal oceans by riverine discharge (42.9 TgC 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) TgC yr^{-1} in the period 2000-2009. We choose the mean value of 297±244 TgC yr^{-1} from the two estimates as our best estimate for the net land-to-atmosphere CO_2 flux for the South Asia region.

Table 2: 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 (TgC 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

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

Figure 8 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 TgC yr^{-1}, calculated with the average CH_4 emissions of 37 TgC yr^{-1} and best estimate of CO_2 emissions of 297 TgC yr^{-1}. For this CO_2-eq flux, we assumed all CH_4 is oxidized to CO_2 in the atmosphere within about 10 years (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-year 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) TgC 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.



(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

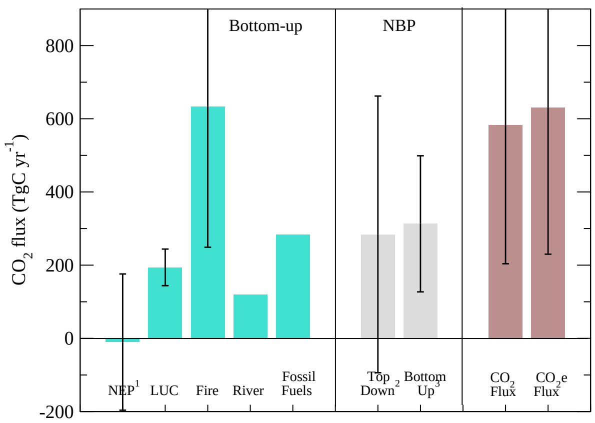


Figure 8: Decadal mean CO_2 fluxes from various estimates and flux components (a. for the South Asia region (top panel), b. for the Southeast Asia region (bottom panel)). The period of estimations defer for source types (ref. Table 2 for details).

4. 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 TgC 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 TgC 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 TgC 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 TgC yr^{-1} for the 2000s. We calculate that the RF-weighted total CH_4 emission is 851 TgC 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.

5. Future 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 Figure 9. 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 TgC yr 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 Figure 9, could be addressed in the future projects of the Asia-Pacific Network.

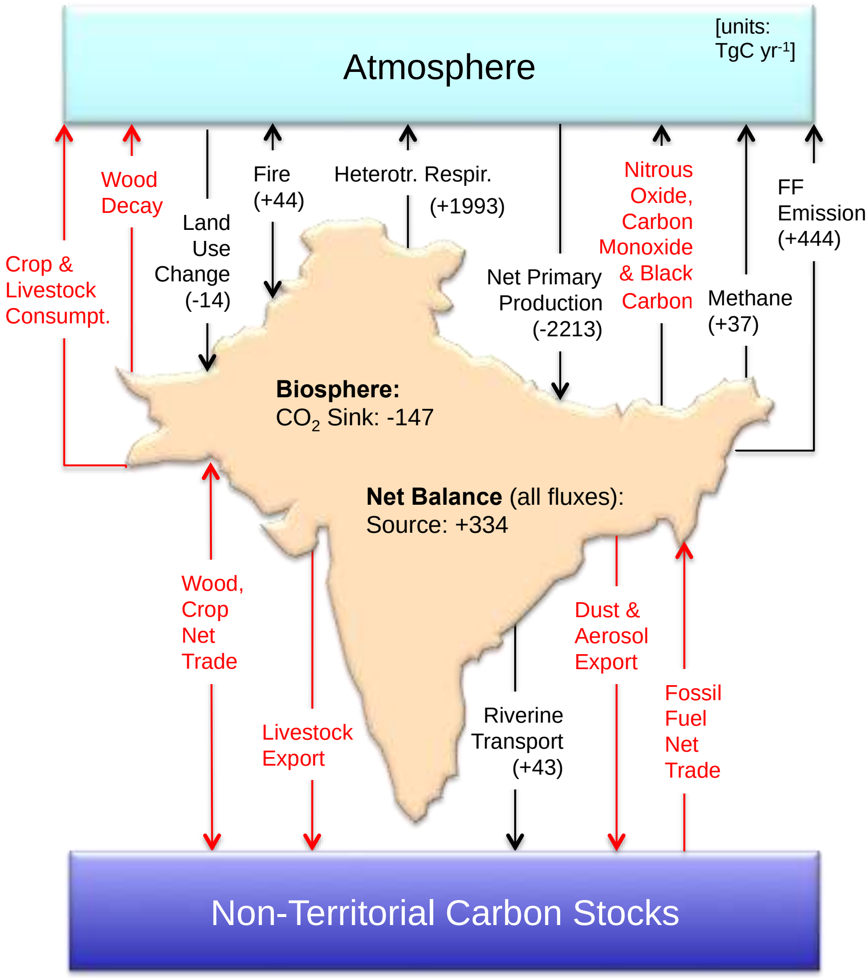
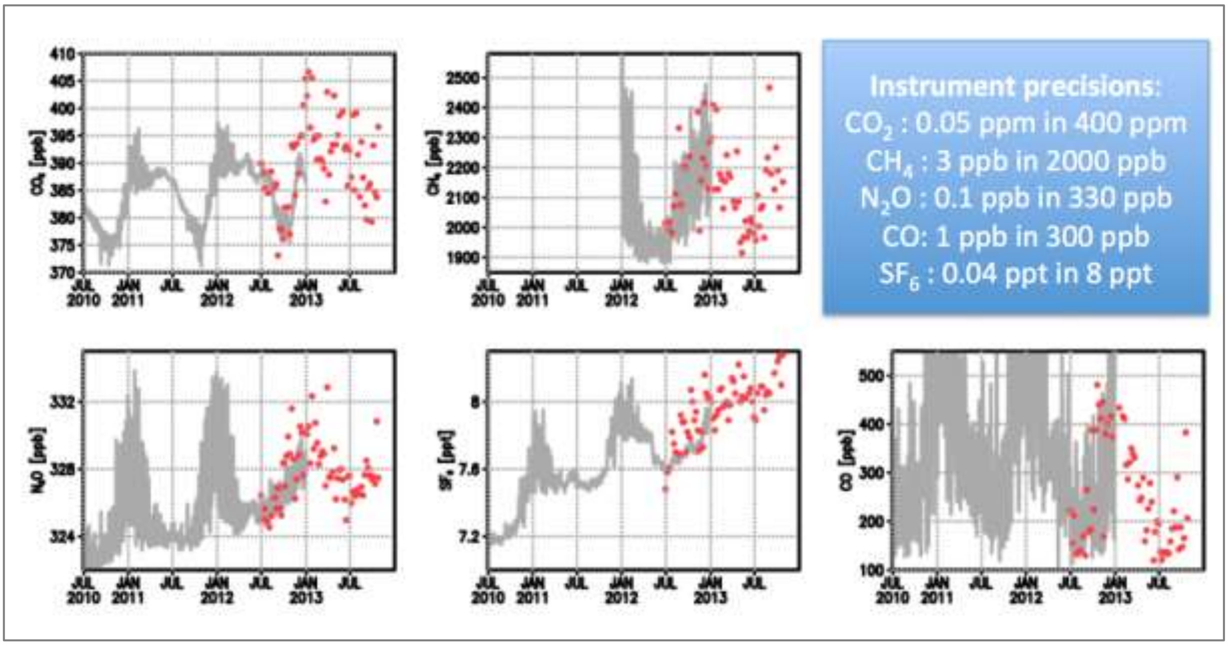


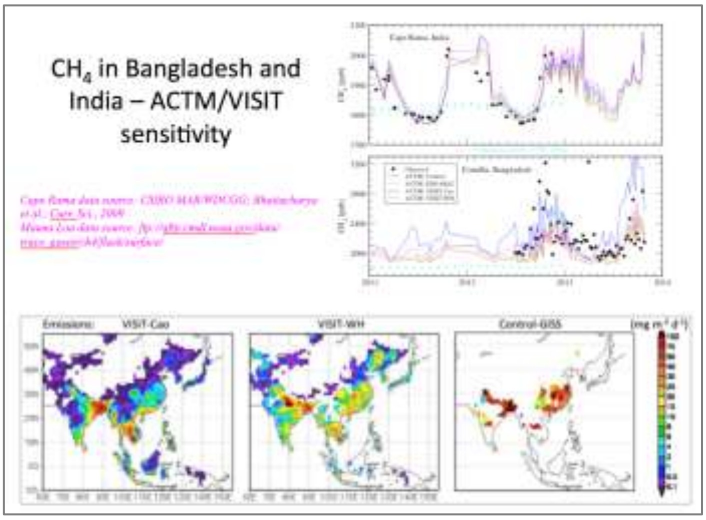
Figure 9: Schematic diagram of major fluxes of CO_2, CH_4, nitrous oxide (N_2O) and related species in South Asia region. The flux components written in black ink are discussed in this work, and those marked in red ink requires attention for further strengthening our knowledge of regional GHGs budget. 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.

5.1 New initiatives

Atmospheric measurements of GHGs: More observations are needed from the South and South Asia region, and we have taken a small step towards that. The figures below show the establishment of the air sampling system at the Bangladesh Meteorological Department building in Comilla, and a first look in to the measurements of greenhouse gases by the National Institute for Environmental Studies in Tsukuba. The Dhaka University and JAMSTEC provided logistic supports using APN funds.


Newly established site in collaboration
- by JAMSTEC/Dhaka Univ./NIES
Comilla (23.45ºN, 91.20ºE),
Observatory of Bangladesh Meteorol. Dept.


Instrument precisions:
CO2 : 0.05 ppm in 400 ppm
CH4 : 3 ppb in 2000 ppb
N2O : 0.1 ppb in 330 ppb
CO: 1 ppb in 300 ppb
SF6 : 0.04 ppt in 8 ppt
CO2 [ppm]
CH4 [ppb]
N2O [ppb]
SF6 [ppt]
CO [ppb]
JUL 2010
JAN 2011
JUL
JAN 2012
JUL
JAN 2013
JUL


CH4 in Bangladesh and India – ACTM/VISIT sensitivity
Cape Rama, India
Comilla, Bangladesh
Emissions:
VISIT-Cao
VISIT-WH
Control-GISS

Computer support to University of Sri Jayewardenepura: In our ongoing South and Southeast Asian greenhouse gases budget, high resolution inversion flux maps of CO_2 or the ecosystem model results were not available. Work is in progress in JAMSTEC for estimating CO_2 fluxes at every latitude-longitude grids of the chemistry-transport model. Similar results of high resolution CO_2 fluxes using another chemistry-transport model would be extremely useful for quantifying transport model error in the estimated CO_2 fluxes. In addition, as expressed earlier, a terrestrial ecosystem model with explicit treatment of major crops in the Asian countries is required for understanding the carbon uptake and release in the croplands.

Our colleagues, Dr. R. Lokupitiya and Dr. E. Lokupitiya, in Sri Lanka are going to work on improvements to the CO_2 data assimilation system and crop ecosystem modelling for the Asia region. Both of them have worked on these modelling systems for the North America region while working in Colorado State University in Fort Collins. We have purchased the much needed computing resources for running the models in Sri Lanka (Picture below). This investment is critical for the success of the APN proposal because the group will perform new atmospheric inversions and terrestrial ecosystem modelling which are required for the final synthesis of the Asian GHGs budget. In addition, the investment will leave a long legacy by bringing the country to become part of an international network of atmospheric scientists and ecosystem modellers.

Air and water sampling in Papua New Guinea: Support for air and water sampling from Papua New Guinea was offered to Prof. C.-T. Chen. For over ten years now Prof. Chen has been sampling carbonate related parameters in rivers and estuaries in Taiwan, SE China and Southeast Asia. The countries covered are the Philippines, Malaysia, Brunei, Indonesia, Singapore, Thailand, Myanmar, Cambodia, Laos and Vietnam. It leaves a void in Papua New Guinea, a large area with essentially no carbonate data. In view of the rough terrain and very high precipitation there, it is expected that the riverine transports of carbon and related elements are substantial.

APN project partially supported a field trip led by Prof. Chen to sample selected rivers and estuaries in Papua New Guinea. The parameters measured are temperature (both in water and the air), wind speed, conductivity/salinity, dissolved oxygen, nitrate, nitrite, phosphate, silicate, pH, alkalinity, dissolved inorganic carbon, dissolved organic carbon, CH_4 (both in water and the air), N_2O (both in water and the air), total suspended particles, particulate inorganic carbon, particulate organic carbon, etc. In addition, every effort will be made to measure pCO_2 if the problem with transporting standard CO_2 gas can be solved. If not, the

pCO_2 will be calculated based on pH, alkalinity and dissolved inorganic carbon. Prof. Chen's laboratory is equipped to sample and measure all above-mentioned parameters.

The above data are being used to calculate the air-water fluxes of CH_4, N_2O and CO_2. The horizontal transports of nitrate, nitrite, phosphate, silicate, alkalinity, dissolved inorganic carbon, dissolved organic carbon as well as total suspended particles, particulate inorganic carbon and particulate organic carbon will also be calculated.

The above data and fluxes will be provided for a modelling effort will be performed to relate these data to parameters such as temperature, rainfall, roughness of the terrain, soil/sediment and rock type/composition of the catchments, and population density, etc.

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65	Lingxi Zhou	Chinese Academy of Meteorological Sciences (CAMS), China Meteorological Administration (CMA), 46 Zhongguancun Nandajie, Beijing 100081, China	Tel: +86-10-5899-5279 Fax: +86-10-6217-6414 Email: zhoulx@cams.cma.gov.cn
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68	Ting-Hsuan Huang	Department of Oceanography, National Sun Yat-sen University, Kaohsiung 80424, Taiwan, R.O.C	Email: apsara@mail.nsysu.edu.tw
69	Alessandro Baccini	Woods Hole Research Center, Massachusett, USA	Email: abaccini@whrc.org
70	Benjamin Poulter	Montana State University, Department of Ecology, Bozeman, MT 59717-3460, USA	tel: +1 (406) 994-3231 fax: (406) 994-3190 Email: benjamin.poulter@montana.edu
71	Hideki Kobayashi	Department of Environmental Geochemical Cycle Research, JAMSTEC, Yokohama	Email: hkoba@jamstec.go.jp
72	Ram Avtar	United Nations University, Institute for the Advanced Study of Sustainability (UNU-IAS), 5-53-70 Jingumae, Shibuya-ku, Tokyo 150-8925, Japan	Email: ram.envjnu@gmail.com
73	Shilong Piao	Peking University, Beijing, China	Email: slpiao@pku.edu.cn
74	Lars Nieradzik	CSIRO, Canberra	Email: Lars.Nieradzik@csiro.au

75	Xu Ri	ITPCAS, Beijing, China	Email: xu-ri@itpcas.ac.cn
76	Hanqin Tian	School of Forestry and Wildlife Sciences, Auburn University, 602 Duncan Drive, Auburn, AL 36849, USA.	Tel: (334) 844-1059 Fax: (334) 844-1084 Email: tianhan@auburn.edu
77	Eri Saikawa	Department of Environmental Sciences, Rollins School of Public Health, Emori University, Atlanta, USA	Tel: +1 404 727-0487 Email: eri.saikawa@emory.edu
78	Rona Thompson	NILU (Norwegian Institute for Air Research), Oslo, Norway	Tel: +47 6389 8148 Email: rlt@nilu.no
79	Siegfried Gonzi	University of Edinburgh, Crew Building, West Mains Road, Edinburgh EH9 3FF, Scotland, United Kingdom	Tel: +44 131 6505247 Email: siegfried.gonzi@ed.ac.uk
80	Tazu Saeki	Department of Environmental Geochemical Cycle Research, JAMSTEC, Yokohama	Email: tazu.saeki@jamstec.go.jp
81	Jun-Ichi Kurokawa	Asia Center for Air Pollution Research, Atmospheric Research Department, 1182 Sowa, Nishi-ku, Niigata-shi 950-2144, Japan	Tel:+81-25-263-0558 Fax: +81-25-263-0567 E-mail : kurokawa@acap.asia
82	Marilena Muntean	EDGAR team, Joint Research Centre of the European Commission, Ispra, Italy	Email: Marilena.Muntean@jrc.it
83	Shu Tao	Peking University, Beijing, China	Email: taos@urban.pku.edu.cn
84	Keiya Yumimoto	Meteorological Research Institute, Tsukuba, Japan	Email: yumimoto@mri-jma.go.jp
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86	Shohei Nomura	National Institute for Environmental Studies, 16-2 Onogawa, Tsukuba 305-8506, Japan	Email: nomura.shohei@nies.go.jp

87	Kazuhito Ichii	Department of Environmental Geochemical Cycle Research, JAMSTEC, Yokohama	Tel: +81-45-778-5556 Email: ichii@jamstec.go.jp
88	Hon-Kit Lui	Department of Oceanography National Sun Yat-Sen University 70 Lien-Hai Road, Kaohsiung 80424,Taiwan, R.O.C.	Tel: 886-7-5255155 e-mail: m955030005@student.nsysu.edu.tw
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First International workshop on Asian greenhouse gases budget,

Physical Research Laboratory, Ahmedabad, 27-29 September 2011

DAY 1	27-Sep-11	K. R. Ramanathan Auditorium
Registration	8:45	
Prabir Patra	0930-0935	Welcome
A. S. Joshipura, Dean, PRL	0935-0950	Inauguration
Josep Canadell	0950-1025	Importance of regional synthesis, regional participation
Shyam Lal	1025-1030	Vote of thanks
HIGH TEA	1030-1115	
Prabir Patra	1115-1125	APN project summary and immediate (first year) targets
Michel Ramonet	1125-1145	Greenhouse gases measurement programme of IAGOS
Yosuke Niwa	1145-1205	Aircraft measurements and inverse modeling for estimating Asian carbon budgets
NK Indira	1205-1220	High Precision Measurements of Carbon dioxide in India
P. S. Swathi	1220-1235	First results of regional inversion using Hanle CO_2 data
Tapas Bhattacharya	1235-1255	Estimation of carbon stock and its changes in Indian soils
LUNCH	1300-1400	
Kentaro Ishijima	1400-1420	Signal of N_2O and CH_4 emission from the South and Southeast Asia detected by aircraft observation and modeling
Ravindra Lokupitiya	1420-1440	Carbon inversions with MLEF using insitu and satellite observations
VVSS Sarma	1440-1500	Riverine input of carbon to the coastal Indian

		oceans
K. R. Manjunath	1500-1520	Use EO Sensors in Reducing Uncertainty in Methane Emission Inventory
Divya Pandey	1520-1540	Net global warming potential of rice-wheat cultivation
TEA/COFFEE	1540-1610	
BREAKOUT SESSION	1610-1730	Ground floor lecture hall & 6th floor meeting room
28-Sep-11	DAY 2	K. R. Ramanathan Auditorium
Prabir Patra	0930-0950	Top-down estimation of CO_2 fluxes using insitu measurements and validations
Neung-Hwan Oh	0950-1010	Budgeting riverine carbon exports in the global carbon cycle
Erandi Lokupitiya	1010-1030	Prediction of land-atmosphere exchanges in croplands
Manish Naja	1030-1050	Greenhouse gases measurements at Nainital, India
Chun-Ho Cho	1050-1110	CarbonTracker-Asia, a tool to quantify CO_2 uptake/release focused on Asia
TEA/COFFEE	1110-1140	
Rodel Lasco	1140-1200	Philippines Greenhouse Gas Inventory for 2000s
Iman Rusmana	1200-1220	Potentials for rice methane mitigation in Indonesia
Alan Koropitan	1240-1300	Estimation of terrestrial carbon transport to marginal seas
LUNCH	1300-1400	
		Ground floor lecture hall
M. M. Sarin	1400-1420	Acidification of coastal waters: Relative impacts of CO_2 versus other anthrpogenic gases

Srabanti Ballav	1420-1440	High resolution CO_2 simulation over Japan using WRF-CO_2 model
Lokesh Sahu	1440-1500	CO and black carbon as an indicator of anthropogenic CO_2 emission in India
R. Nayak	1500-1520	Forest carbon fluxes from Satellite remote sensing
TEA/COFFEE	1520-1550	
BREAKOUT SESSION	1550-1730	Ground floor lecture hall & 6th Floor meeting room
28-Sep-11	DAY 3	K. R. Ramanathan Auditorium
N. R. Patel	0930-0950	Carbon fluxes over terrestrial ecosystems by using remote sensing and flux-towers
Shyam Lal	0950-1010	Trace gases measurements and modelling - an ISRO-GBP perspective
Michel Ramonet	1010-1030	Outlook for asian GHG measurments
Yogesh Tiwari	1030-1050	On developing high precision CO_2 monitoring techniques at the IITM Pune India
TEA/COFFEE	1050-1110	
Planerary discussion	1110-1230	Advances and specific products and/or papers
Workshop adjourned		
LUNCH	1230-1400	
Josep Canadell	1600-1700	Colloquium

Photo: Participants at the workshop in Ahmedabad

Second International workshop on "Asian Greenhouse Gases Budget"; CIFOR, Bogor; 9-11 October 2012

Name	Time	Talk title (10 min talk and 5 min discussion)
09 September 2012 (Tuesday)		
Registration	09:00 - 09:30	
Daniel Murdiyarso	09:30 - 09:40	Welcome address, announcement, etc.
Pep Canadell/ Prabir Patra	09:40 - 10:15	Workshop context/objectives
Pep Canadell	10:15 - 10:30	The carbon budget of Southeast Asia
Takashi Hirano	10:30 - 10:45	Carbon balance of tropical peat swamp forest
Coffee/Tea Break	10:45 - 11:15	
Edvin Aldrain	11:15 - 11:30	Riverine export to the Indonesian marginal seas
Yosuke Niwa	11:45 - 12:00	Transport and inverse modeling analyses with the

		CONTRAIL data for estimating surface CO_2 fluxes
Nobuko Saigusa	12:00 - 12:15	Carbon Budget Estimations Based on AsiaFlux Network Observations
Solichin Manuri	12:15 - 12:30	Improving accuracy of forest carbon accounting at district level
Lunch Break	12:30 - 14:00	
Daniel Murdiyarso	14:00 - 14:15	Overview of SWAMP
Joko Pubopuspito	14:15 - 14:30	Belowground carbon dynamics in mangrove ecosystems
Haruni Krisnawati	14:30 - 14:45	Development of allometric equations to predict aboveground C accumulation in mangrove stands
Group discussion	14:45 - 15:30	Panel discussions - general topics
Coffee/Tea Break	15:30 - 16:00	
Breakout sessions	16:00 - 17:30	Group 1: AAAA; Group 2: BBBB
BBQ Dinner	19:00 - 21:00	

10 September 2012 (Wednesday)

Prabir Patra	09:00 - 09:15	TransCom forward simulations of N_2O - implications for inverse modelling
J. Van Lent	09:15 - 09:30	Land-use change effects on soil emissions of N_2O and NO in the tropics and subtropics worldwide: a meta-analysis
VVSS Sarma	09:30 - 09:45	Emission of trace gases, CO_2, CH_4, N_2O and DMS from the Indian estuaries and adjacent coastal ocean
AL Hooijer	09:45 - 10:00	Peatland management in Indonesia
Coffee/Tea Break	10:30 - 11:00	
Group discussion	11:00 - 12:30	Panel discussions - general topics
Lunch Break	12:30 - 14:00	
Akihiko Ito	14:00 - 14:15	Process-based modeling of greenhouse gas fluxes at natural and human-disturbed ecosystems in Southeast

		Asia
Govindswamy Bala	14:15 - 14:30	Trends and variability of satellite derived NPP in India
Rodel D. Lasco	14:30 - 14:45	Climate change mitigation through REDD+: will it make a difference in financing forest development in the Philippines?
Ye Huang	14:45 - 15:00	China black carbon emission from 1949 to 2050 and global CO_2 emissions in 2007
Coffee/Tea Break	15:30 - 16:00	
Breakout sessions	16:00 - 17:30	Group 1: AAAA; Group 2: BBBB
Dinner at De Leuit	19:00 - 21:00	

11 September 2012 (Thursday)

Lingxi Zhou	09:00 - 09:20	Accurate and compatible measurement of atmospheric greenhouse gases in China
Yogesh Tiwari	09:20 - 09:35	Atmospheric CO_2 and other GHG monitoring in India
Xuhui Wang	09:45 - 10:00	Modelling terrestrial carbon cycle over Southeast Asia during 1980-2009, the Trendy perspective
N. R. Patel	10:00 - 10:15	Measurement and modeling of carbon fluxes over cropland and forest plantation in northen India
Fuu-Ming Kai	10:15 - 10:30	Recent findings shine light on puzzling growth rate of methane
Coffee/Tea Break	10:30 - 11:00	
K.R. Manjunath	11:00 - 11:15	Spatio-temporal Methane emission pattern from South Asia using remote sensing and GIS approach
Ting-Hsuan Huang	11:15 - 11:30	Fluvial carbon fluxes in tropical rivers
Alan Koropitan	11:30 - 11:45	Carbon fluxes over the waters near mangrove, seagrass and coral reef ecosystems
Prabir Patra	11:45 - 12:00	South/Southeast Asia Regional Network

Lunch Break	12:30 - 14:00	
Group discussion	14:00 - 15:30	Panel discussions - whole Asia synthesis
Coffee/Tea Break	15:30 - 16:00	
Papers and products	16:00 - 17:30	Specific project, subject, etc.

Photo: Participants at the workshop in Bogor, Indonesia

Third International workshop on "Asian Greenhouse Gases Budget"

Miyoshi Hall, JAMSTEC, Yokohama; 8-10 April 2014

Programme co-chairs : Prabir Patra, JAMSTEC & Pep Canadell, GCP/CSIRO

Name	Time	(10 min talk and 5 min discussion)
08 April 2014 (Tuesday)		Title of talk
Registration	08:30 - 09:00	
Pep & Prabir	09:00 - 09:10	Welcome and logistics
Rikie Suzuki	09:10 - 09:20	Terrestrial ecosystem research focus in JAMSTEC
Pep & Prabir	09:20 - 09:45	Toward a grand synthesis of Asian greenhouse gases budget
Nobuko Saigusa	09:45 - 10:00	Measurements of CO_2 fluxes at AsiaFlux network sites
Alessandro Baccini	10:00 - 10:15	Landuse and landuse change in Asia from remote sensing
session discussions	10:15 - 10:30	
Coffee/Tea Break	10:30 - 11:00	
Benjamin Poulter	11:00 - 11:15	Global/regional forest age-carbon cycle mapping
Hideki Kobayashi	11:15 - 11:30	Satellite remote sensing of terrestrial vegetation dynamics in the Asia region and climate sensitivity
Ram Avtar	11:30 - 11:45	State of Southeast Asian ecosystems - detection of landuse change at 50m resolution
Akihiko Ito	11:45 - 12:00	VISIT: terrestrial ecosystem model simulation of CO2, CH_4 , N_2O and fire emissions
Shilong Piao	12:00 - 12:15	Carbon budget of terrestrial ecosystems in East Asia
session discussions	12:15 - 12:30	

Lunch Break	12:30 - 14:00	
Lars Nieradzik	14:00 - 14:15	CABLE terrestrial ecosystem model results for Asia
Xu Ri	14:15 - 14:30	Carbon-nitrogen dynamics in LPJ-DyN model
Hanqin Tian	14:30 - 14:45	The balance of GHG in the terrestrial ecosystems of monsoon Asia: the concurrent estimation of CO2, CH_4 and N_2O using DLEM
session discussions	14:45 - 15:30	
Coffee/Tea Break	15:30 - 16:00	
Breakout sessions	16:00 - 17:30	Ecosystem monitoring, modelling and bottom-up targets
Dinner: YES Guest House	18:00 - 20:30	2000 yen/person
09 April 2014	(Wednesday)	Title of talk
Eri Saikawa	09:00 - 09:15	Modelling of soil nitrous oxide emissions from natural processes
Benjamin Poulter	09:15 - 09:30	CH_4 emissions from wetlands and other source categories
Rona Thompson	09:30 - 09:45	Methane emissions in East Asia estimated using a Bayesian inversion approach
Siegfried Gonzi	09:45 - 10:00	GOSAT: CO_2 and CH_4 inversion fluxes using GEOS-Chem
Tazu Saeki	10:00 - 10:15	Inverse modelling of CO_2 emissions using Asian observations
session discussions	10:15 - 10:30	
Coffee/Tea Break	10:30 - 11:00	
Yosuke Niwa	11:00 - 11:15	CONTRAIL: Inverse modelling of CO_2 fluxes using NICAM
Shamil Maksyutov	11:15 - 11:30	GOSAT: CO_2 & CH_4 Inversion fluxes using NIES-TM

Jun-Ichi Kurokawa	11:30 - 11:45	Trend of anthropogenic emissions of GHGs, black carbon, and carbon monoxide estimated in REAS
Marilena Muntean	11:45 - 12:00	EDGAR: Asian emission inventories for greenhouse gases
Shu Tao	12:00 - 12:15	CO2, CO and Black carbon emission inventories of Asia
session discussions	12:15 - 12:30	
Lunch Break	12:30 - 14:00	
Breakout sessions	14:00 - 15:30	Inverse modelling, Bottom-up emission inventories
Coffee/Tea Break	15:30 - 16:00	
Group discussion	16:00 - 17:00	Ecosystem - Emission connections
Philippe Ciais	17:00 - 17:30	Special (Skype) talk from IPCC AR5 Chapter 6 overall lead author
Dinner: at Kamakura	19:00 - 21:00	approx. 6000 yen/person; http://www.kamakurawakamiya.jp/dinner/kaiseki.html

10 April 2014 (Thursday)		Title of talk
Keiya Yumimoto	09:00 - 09:15	Inverse estimation of CO and black carbon emissions
Kentaro Ishijima	09:15 - 09:30	Inverse estimation of N_2O fluxes
Sandipan Mukherjee	09:30 - 09:45	CO_2 and energy fluxes in the northern India
Michel Ramonet	09:45 - 10:00	Measurements and modelling of atmospheric CO_2 and CH_4 over India
Shohei Nomura	10:00 - 10:15	Measurements of greenhouse gases in Asia
session discussions	10:15 - 10:30	
Coffee/Tea Break	10:30 - 11:00	
Kazuhito Ichii	11:00 - 11:15	Bottom-up estimation of CO_2 fluxes using flux tower oservations

Neung-Hwan Oh	11:15 - 11:30	Carbon export from Asian rivers
Hon-Kit Lui	11:30 - 11:45	Riverine export of carbon, nitrogen to the marginal seas
Prabir Patra	11:45 - 12:00	Issues on chemical transformation of reduced carbon
session discussions	12:00 - 12:30	
Lunch Break	12:30 - 14:00	
Group discussion	14:00 - 15:30	Major remaining issues and potential ramification
Coffee/Tea Break	15:30 - 16:00	
Papers and products	16:00 - 17:30	State of the Ecosystems, Budgets of GHGs and BC for 2000s, …
Dinner: Patra's Home	18:30 onwards	Complimentary for the participants

Photo: Participants at the workshop in Yokohama, Japan

Training workshop in
Dhaka University, Earth & Environmental Sciences Faculty
~Fundamental of atmospheric research~

Lecturers: Dr. Prabir K. Patra, Dr. Masayuki Takigawa, Prof. Utpal K. De

Course Schedule

23/11/2014
Arrive in Dhaka

24/11/2014 (Monday)

10:00~11:30	Presentation on Greenhouse Gases research (Lecture-1)
11:30~12:00	Q & A
12:00	Meeting with the Vice Chancellor
12:30~1:30	Lunch
1:30~2:30	Lecture – fundamentals of atmospheric science (Lecture-2)
2:30~3:30	Interaction with students
3:30~4:30	Introduction to basic tools in atmospheric and oceanic research

25/11/2014 (Tuesday)

10:00~11:00	Lecture – fundamentals of atmospheric science (Lecture-3)
11.00~12:00	Interaction with students
12:30~1:30	Lunch
1:30~2:30	Lecture – observational basics and hands on training (Lecture-4)
2:30~3:30	Interaction with students
3:30~4:30	Lecture – observational basics and hands on training (Lecture-5)

26/11/2014 (Wednesday)

10:00~11:00	Lecture – numerical modeling (Lecture-6)
11.00~12:00	Interaction with students
12:30~1:30	Lunch
1:30~2:30	Lecture – numerical modeling (Lecture-7)
2:30~3:30	Interaction with students
3:30~4:30	Lecture – numerical modeling (Lecture-8)

27/11/2014 (Thursday)

10:00~11:00	Hands-on learning of the basic tools – WRF model
11.00~12:00	Interaction with students
12:30~1:30	Lunch
1:30~2:30	Hands-on learning of the basic tools – WRF model
2:30~3:30	Interaction with students
3:30~4:30	Hands-on learning of the basic tools – WRF model

Check-out, SAYONARA

List of Participants (Masters and Doctoal Course students, and junior faculties)**:**

1. Mir Shariful Islam, Lecturer, Dept. of Oceanography, DU.
2. Abu Hena Muhammad Yousuf, Lecturer, Dept. of Oceanography, DU.
3. Md. Zavid Iqbal Bangalee, Assistant Professor, Dept. of Mathematic, DU.
4. Mrs. Jahida Gulshan, Associate Professor, ISRT, DU.
5. Mr. Paritosh Kumar Roy, Assistant Professor, ISRT, DU.
6. Mrs. Farhana Sadia, Lecturer, ISRT, DU.
7. Mr. Mohammad Samsul Alam, Lecturer, ISRT, DU.
8. Salahuddin Hawlader, Assistant Professor, Dept. of Natural Sciences, UITS, Dhaka.
9. Ms. Farzana Ahmed Mohua, Asst. Prof., Dept. of Geography & Environment, DU.
10. Mrs. Fatima Akter, Lecturer, Dept. of Geography & Environment, DU.
11. Md. Marufur Rahman, Lecturer, DSM, DU
12. BM Rabbi Hossain, Lecture, DSM, DU
13. Md. Tariqul Islam, Lecturer, Dept. of Civil Engineering, UITS, Dhaka.
14. Mr. Md. Abul Kalam Mallik, Bangladesh Meteorological Department, Dhaka.
15. Mr. Md. Hashem Uddin, Senior Scientific Officer, SPARSO, Dhaka.
16. K M Azam Chowdhury, M.S. Student, Dept. of Oceanography, DU.
17. Rupok Lodh, M.S. Student, Dept. of Oceanography, DU.
18. Md. Nazim Uddin, M.S. Student, Dept. of Oceanography, DU.
19. Nishat Tasnim, M.S. Student, Dept. of Math, DU.
20. Roushanara Begum, M.S. Student, Dept. of Math, DU.
21. Md. Mahfuzur Rahman Khan, MS student, ISRT, DU.
22. Mr. Md. AL-Imran, Student, (Thesis), Dept. of Geography & Environment, DU.
23. A.K.M. Moshiur Rahman, Geology Department, DU.
24. Nafisa Shamim, Geology Department, DU.
25. Saiful Alam, Geology Department, DU.


Photos from Training course in Dhaka University (left: view of the class room). The pro-vice chancellor (Prof. (Ms.) Nasreen Ahmad) attended the certificate-award ceremony (right).

NATIONAL

Bangladesh Today 2

International Day for Elimination of VAW observed

CAREER OPPORTUNITY

ULTIMATE FASHIONS LTD.

Japanese and Indian Scientists meet DU VC

Government of the People's Republic of Bangladesh
Department of Public Health Engineering
Office of the Executive Engineer,
Gazipur District, Gazipur.

Tender Notice
Tender No : 02 / (2014-2015)

Follow-up of fire, structural inspections stressed in RMG sector

NATIO

Terrorists destroy 100 yr old graves on land issues

The training course and desire to continue this type of training course in coming years also welcomed by the university officials and participants. News coverage in Bangladesh Today (Japanese and Indian Scientists meet DU Vice Chancellor; 27 November 2014; Thursday).

<u>Funding sources outside the APN</u>

JAMSTEC (~30,000 USD/year for travel grants, air sampling flask transportation and administrative support)

CSIRO (~10,000 USD/year for travel support)

NIES (~20,000 USD/year for air sampling analysis)

Dhaka University (~20,000 USD per year for sampling flask storage and handling)

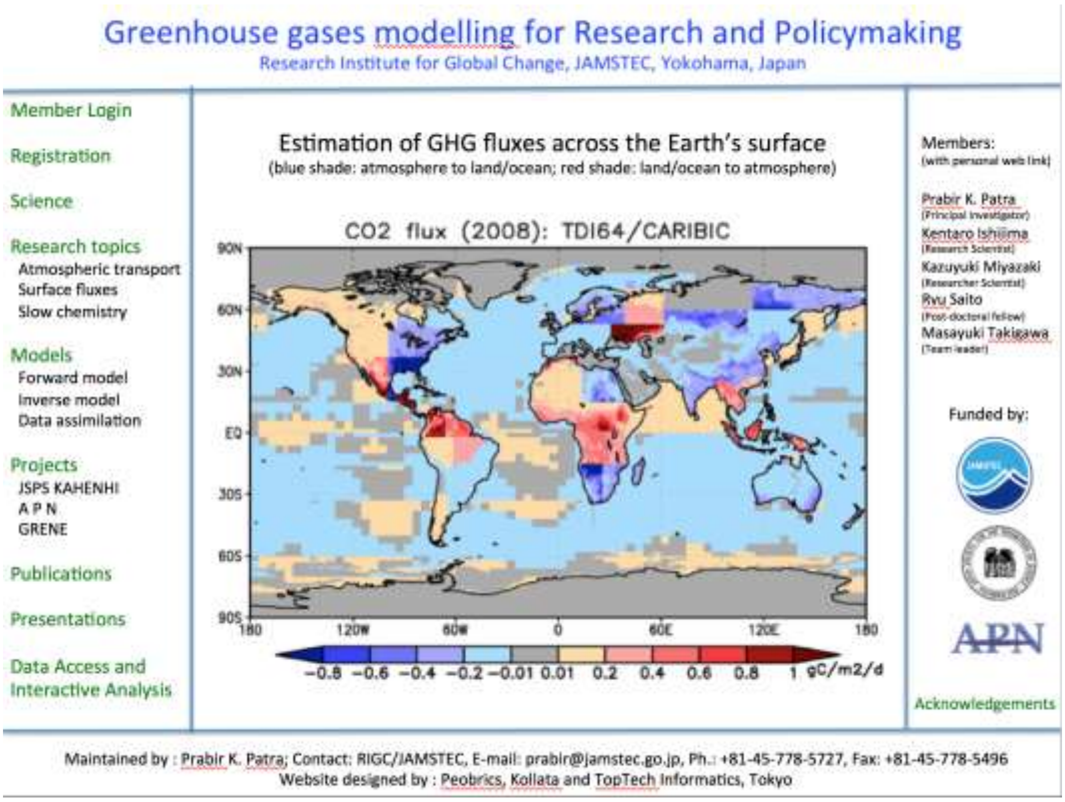
PRL (~10,000 USD for organising the first workshop)

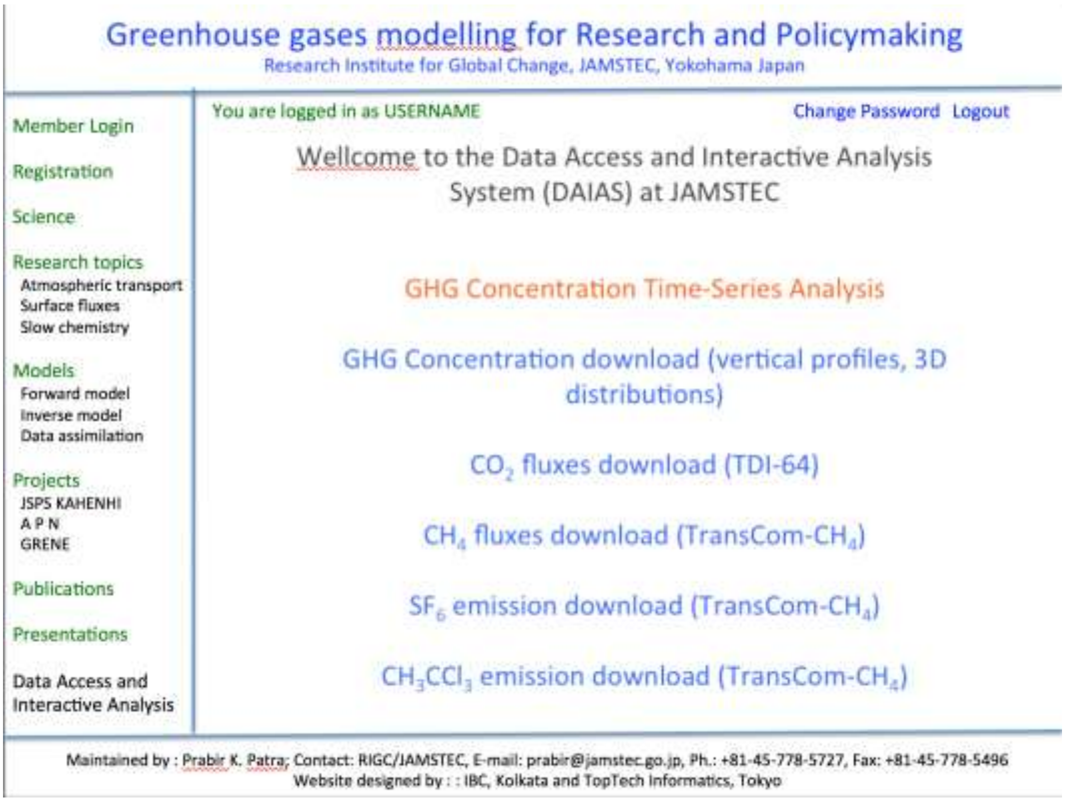
CIFOR (~20,000 USD for organising the second workshop)

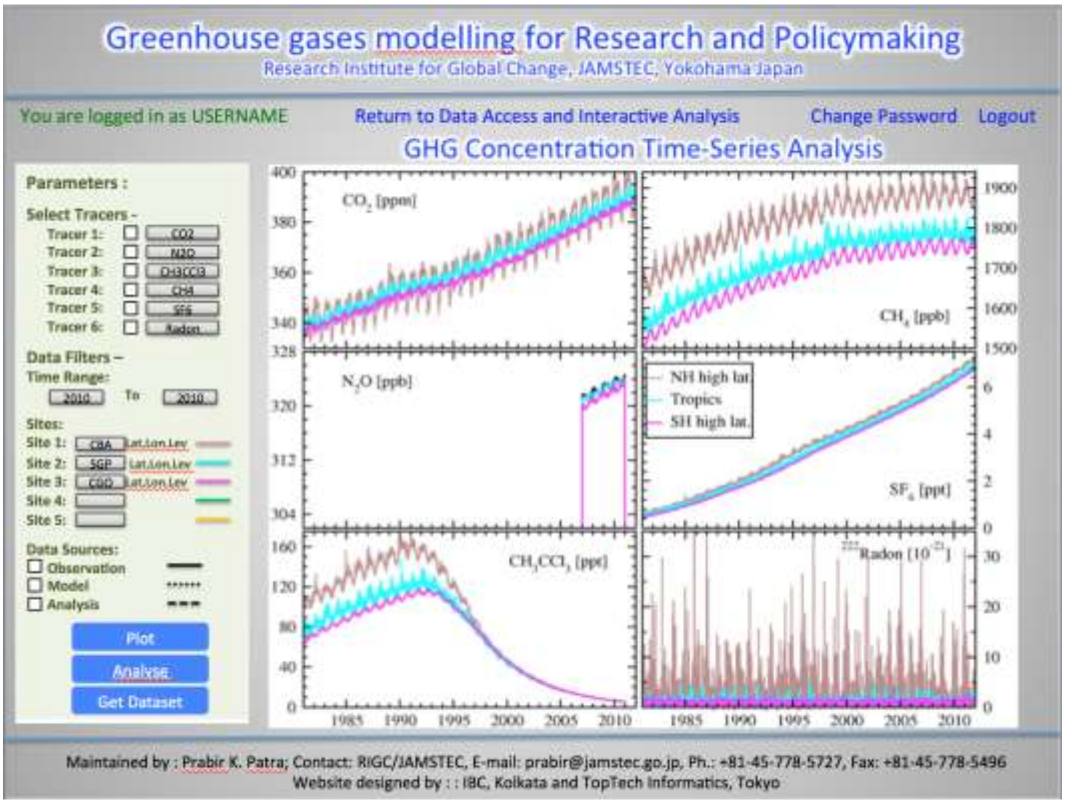
Website templates and example pages:

We have developed a webserver design during the first year of the project. The website contains fluxes of major greenhouse gases between the earth's surface and the atmosphere, and 4-dimensional distribution of atmospheric concentrations of the GHGs. The webserver allows the registered users to plots and extract data interactively.

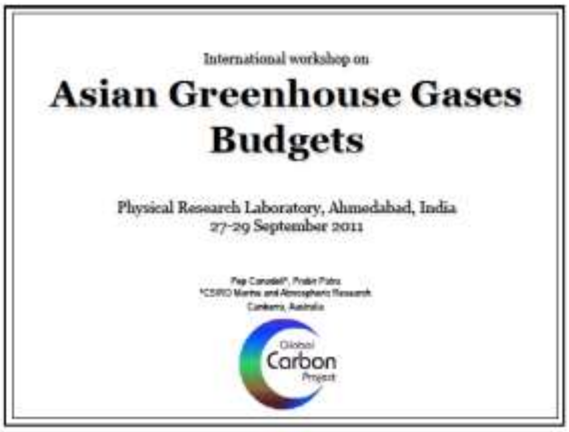
Due to the lack of sufficient infrastructure the website could not be put online from JAMSTEC. However, we will continue to work towards this philosophy of data sharing with the project participants and interested parties around the world.

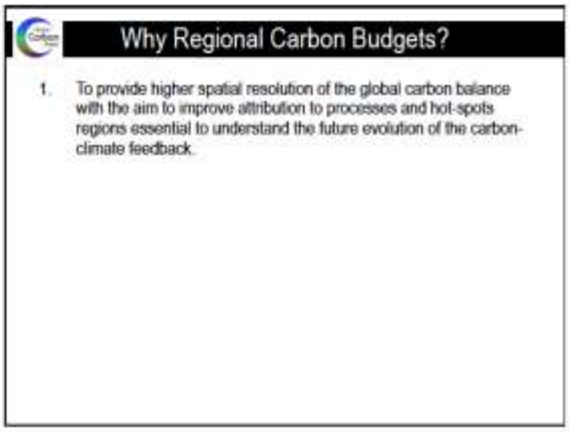


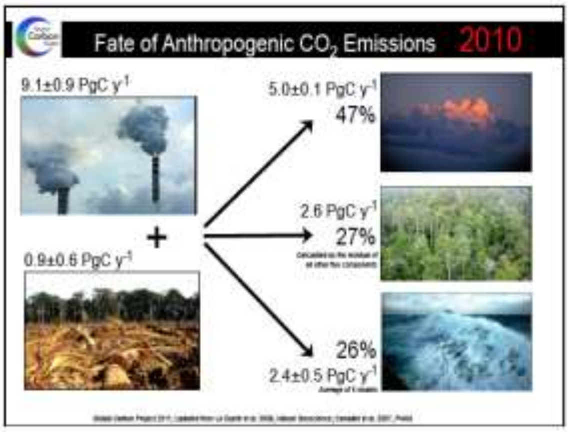

Greenhouse gases modelling for Research and Policymaking
Research Institute for Global Change, JAMSTEC, Yokohama Japan
Member Login
Registration
Science
Research topics
Atmospheric transport
Surface fluxes
Slow chemistry
Models
Forward model
Inverse model
Data assimilation
Projects
JSPS KAHENHI
A P N
GRENE
Publications
Presentations
Data Access and Interactive Analysis
You are logged in as USERNAME
Change Password Logout
Wellcome to the Data Access and Interactive Analysis System (DAIAS) at JAMSTEC
GHG Concentration Time-Series Analysis
GHG Concentration download (vertical profiles, 3D distributions)
CO2 fluxes download (TDI-64)
CH4 fluxes download (TransCom-CH4)
SF6 emission download (TransCom-CH4)
CH3CCl3 emission download (TransCom-CH4)
Maintained by : Prabir K. Patra; Contact: RIGC/JAMSTEC, E-mail: prabir@jamstec.go.jp, Ph.: +81-45-778-5727, Fax: +81-45-778-5496
Website designed by : : IBC, Kolkata and TopTech Informatics, Tokyo

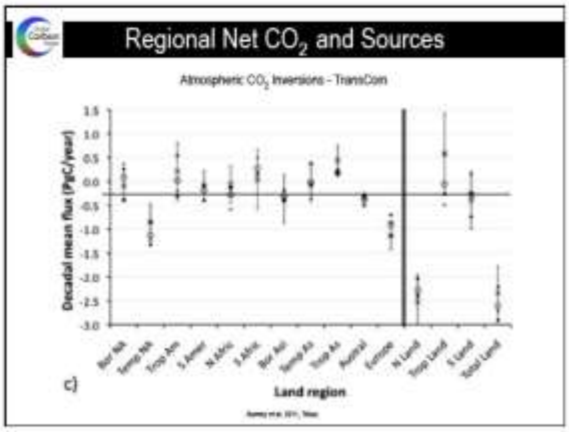

Greenhouse gases modelling for Research and Policymaking
Research Institute for Global Change, JAMSTEC, Yokohama Japan
You are logged in as USERNAME
Return to Data Access and Interactive Analysis
Change Password Logout
GHG Concentration Time-Series Analysis
Parameters :
Select Tracers -
Tracer 1: CO2
Tracer 2: N2O
Tracer 3: CH3CCl3
Tracer 4: CH4
Tracer 5: SF6
Tracer 6: Radon
Data Filters –
Time Range:
2010 To 2010
Sites:
Site 1: CBA Lat,Lon,Lev
Site 2: SGP Lat,Lon,Lev
Site 3: CGO Lat,Lon,Lev
Site 4:
Site 5:
Data Sources:
Observation
Model
Analysis
Plot
Analyse
Get Dataset
CO2 [ppm]
CH4 [ppb]
N2O [ppb]
NH high lat
Tropics
SH high lat
SF6 [ppt]
CH3CCl3 [ppt]
222Radon [10^-21]
1985 1990 1995 2000 2005 2010
Maintained by : Prabir K. Patra; Contact: RIGC/JAMSTEC, E-mail: prabir@jamstec.go.jp, Ph.: +81-45-778-5727, Fax: +81-45-778-5496
Website designed by : : IBC, Kolkata and TopTech Informatics, Tokyo

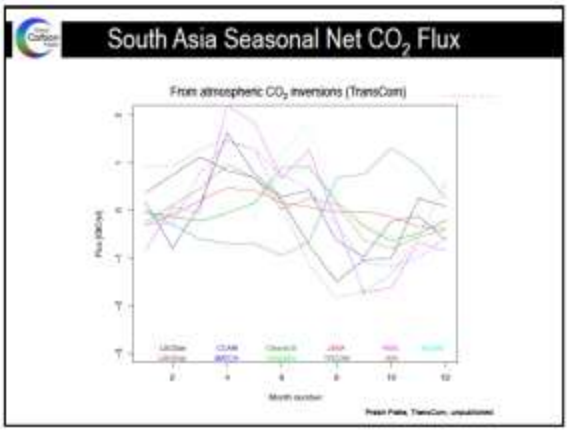
First presentation of the APN project in PRL, Ahmedabad by Pep Canadell and Prabir Patra, showing the status report and research plans/targets for the next 3 years.

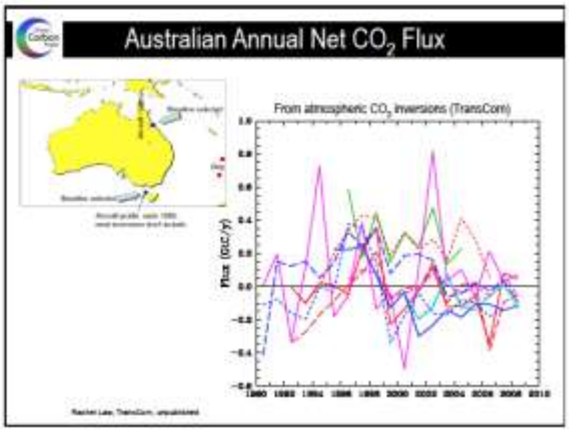








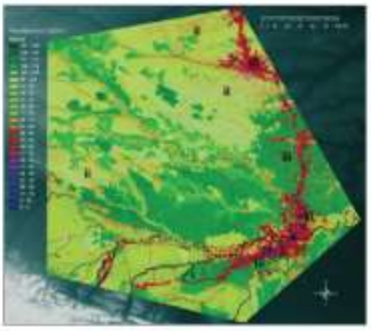




Why Regional Carbon Budgets?

1. To provide higher spatial resolution of the global carbon balance with the aim to improve attribution to processes and hot-spots regions essential to understand the future evolution of the carbon-climate feedback.
2. To address a growing demand for a capacity to Measure, Report, and Verify (MRV) the evolution of regional fluxes and the outcomes of climate mitigation policies.

Monitoring and Reporting Carbon Reductions



e.g., REDD – Reduced Emissions from Deforestation and Degradation

Tracking Vegetation Carbon in the Amazon

Only 3% of tropical countries have the capacity to monitor and report changes in forest cover and C stocks (e.g., Panama)

Why Regional Carbon Budgets?

1. To provide higher spatial resolution of the global carbon balance with the aim to improve attribution to processes and hot-spots regions essential to understand the future evolution of the carbon-climate feedback.
2. To address a growing demand for a capacity to Measure, Report, and Verify (MRV) the evolution of regional fluxes and the outcomes of climate mitigation policies.
3. To support regions to further develop the technical capacity to synthesize their carbon balances and enhance observations.

Why Regional Carbon Budgets?

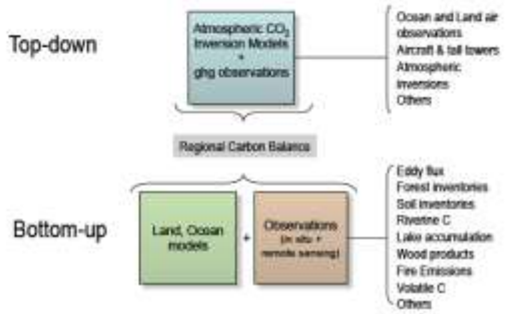
1. To provide higher spatial resolution of the global carbon balance with the aim to improve attribution to processes and hot-spots regions essential to understand the future evolution of the carbon-climate feedback.
2. To address a growing demand for a capacity to Measure, Report, and Verify (MRV) the evolution of regional fluxes and the outcomes of climate mitigation policies.
3. To support regions to further develop the technical capacity to synthesize their carbon balances and enhance observations.
4. To respond to the Group on Earth Observations (EOS) in establishing a global carbon observatory to track the evolution of natural and anthropogenic carbon sources and sinks.

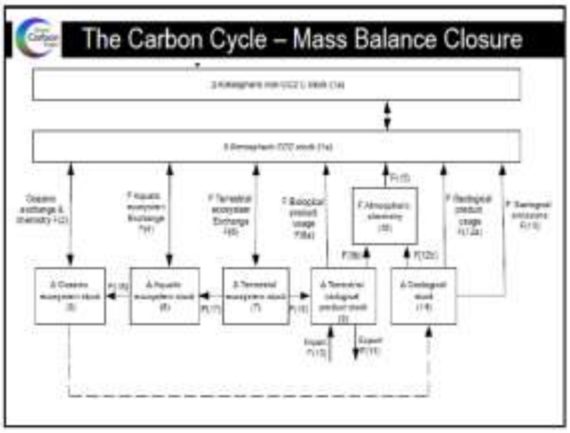
REgional Carbon Cycle Assessment and Processes (RECCAP)

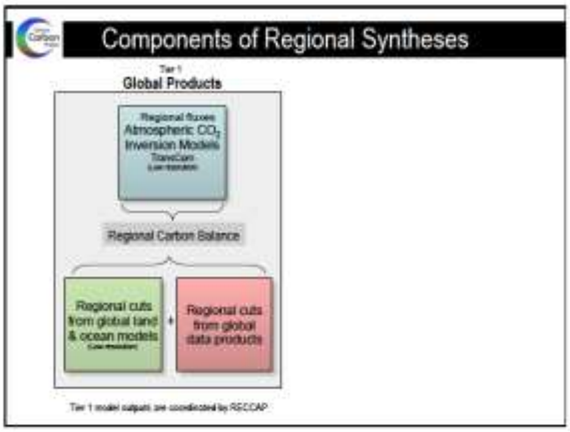
- To establish the mean carbon balance of large regions of the globe at the scale of continents and large ocean basins, including their component fluxes.
- To do it by comparing and reconciling multiple bottom-up estimates with the results of regional top-down atmospheric inversions, with attribution to main flux components.
- To evaluate the regional 'hot-spots' of interannual variability and possibly the trends and underlying processes over the past two (or more) decades by combining available long-term observations and modeling.

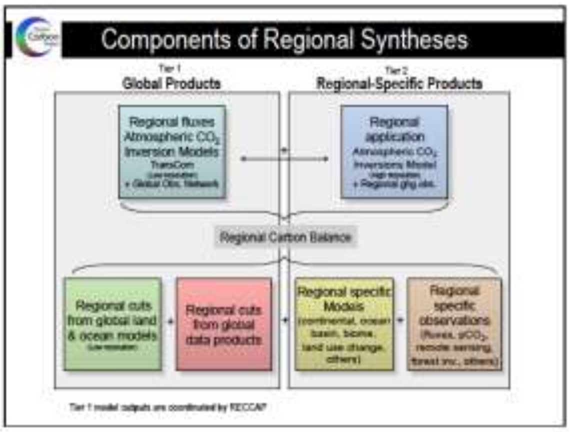
Principle of RECCAP

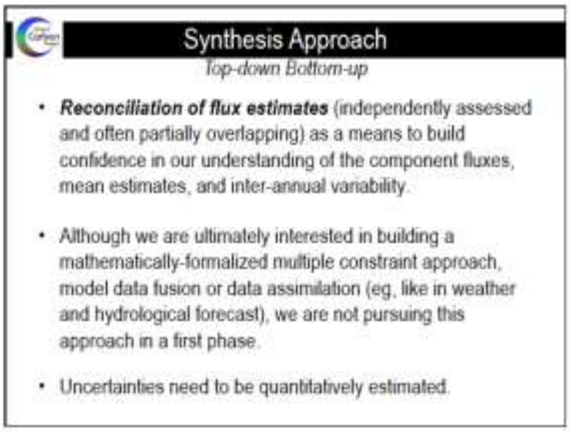
Multiple Constraints to Understand One Carbon Budget

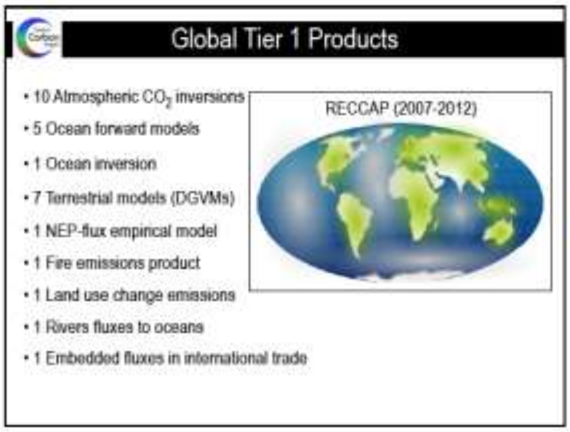


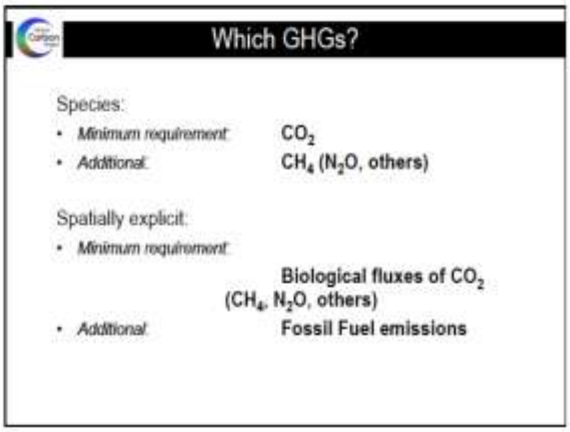

The Carbon Cycle – Mass Balance Closure
F(5)
F(12b)
Import
Export


Components of Regional Syntheses
Tier 1
Global Products
Regional fluxes
Atmospheric CO2
Inversion Models
TransCom
Regional Carbon Balance
Regional cuts from global land & ocean models
+
Regional cuts from global data products
Tier 1 model outputs are coordinated by RECCAP


Components of Regional Syntheses
Tier 1
Global Products
Tier 2
Regional-Specific Products
Regional fluxes
Atmospheric CO2
Inversion Models
TransCom
+ Global Obs. Network
Regional application
Atmospheric CO2
Inversions Model
+ Regional ghg obs.
Regional Carbon Balance
Regional cuts from global land & ocean models
+
Regional cuts from global data products
+
Regional specific Models (continental, ocean basin, biome, land use change, others)
+
Regional specific observations (fluxes, pCO2, remote sensing, forest inv., others)
Tier 1 model outputs are coordinated by RECCAP


Synthesis Approach
Top-down Bottom-up
• Reconciliation of flux estimates (independently assessed and often partially overlapping) as a means to build confidence in our understanding of the component fluxes, mean estimates, and inter-annual variability.
• Although we are ultimately interested in building a mathematically-formalized multiple constraint approach, model data fusion or data assimilation (eg, like in weather and hydrological forecast), we are not pursuing this approach in a first phase.
• Uncertainties need to be quantitatively estimated.


Global Tier 1 Products
• 10 Atmospheric CO2 inversions
• 5 Ocean forward models
• 1 Ocean inversion
• 7 Terrestrial models (DGVMs)
• 1 NEP-flux empirical model
• 1 Fire emissions product
• 1 Land use change emissions
• 1 Rivers fluxes to oceans
• 1 Embedded fluxes in international trade
RECCAP (2007-2012)


Which GHGs?
Species:
• Minimum requirement: CO2
• Additional: CH4 (N2O, others)
Spatially explicit:
• Minimum requirement: Biological fluxes of CO2 (CH4, N2O, others)
• Additional: Fossil Fuel emissions

RECCAP Period

Variable but centered around:

- Budget period:
  - » 1990-2009
- Trend analyses:
  - » Land: 1958-2009
  - » Ocean: 1983-2009

Land and Ocean Regional Syntheses

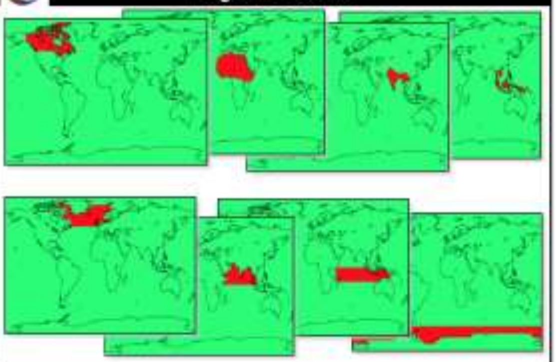
Land

L1	Africa
L2	Arctic tundra
L3	Australia
L4	Europe
L5	North America
L6	Russia
L7	South America
L8	East Asia
L9	**South Asia**
L10	**Southeast Asia**

Oceans

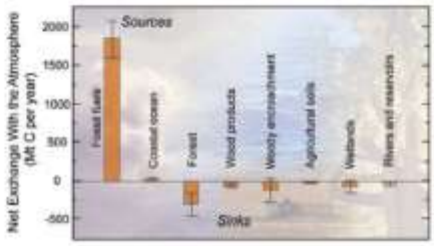
O2	Pacific
O3	Atlantic and Arctic
O4	Southern Ocean
O5	Indian

Regional Masks

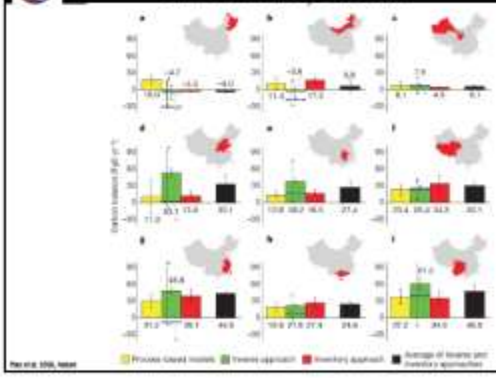


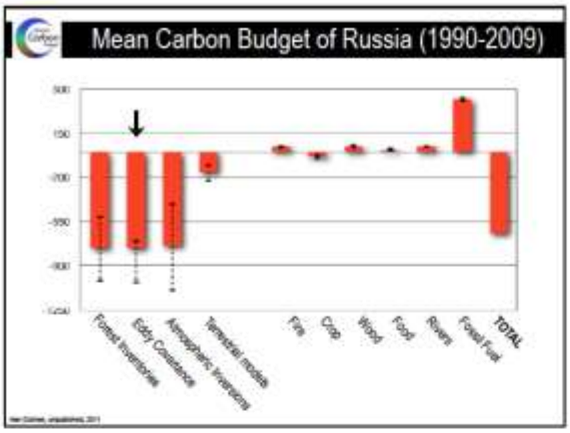
GHG Balance of Europe

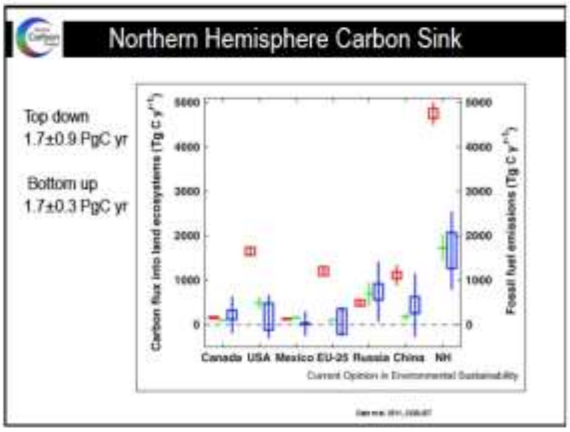
Carbon Balance of North America

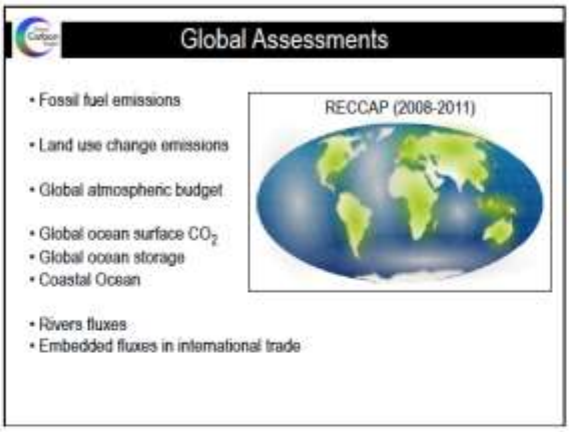


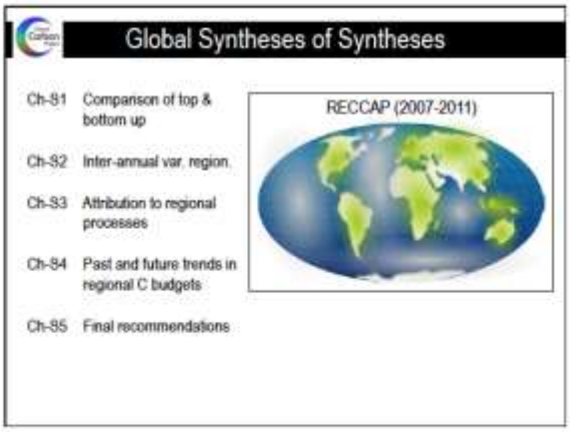
Carbon Balance of China



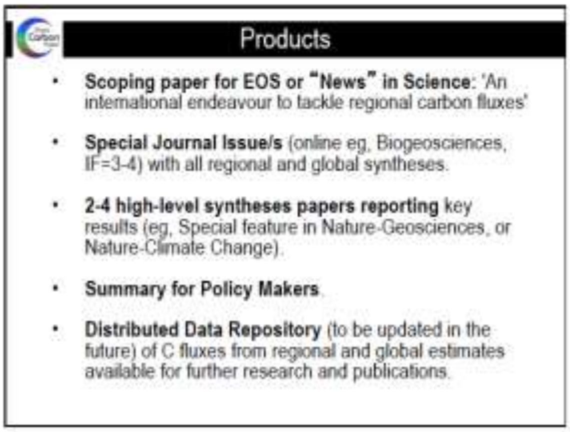

Mean Carbon Budget of Russia (1990-2009)
Forest Inventories
Eddy Covariance
Atmospheric Inversions
Terrestrial models
Fire
Crop
Wood
Food
Rivers
Fossil Fuel
TOTAL


Northern Hemisphere Carbon Sink
Top down
1.7±0.9 PgC yr
Bottom up
1.7±0.3 PgC yr
Carbon flux into land ecosystems (Tg C y⁻¹)
Fossil fuel emissions (Tg C y⁻¹)
Canada USA Mexico EU-25 Russia China NH
Current Opinion in Environmental Sustainability

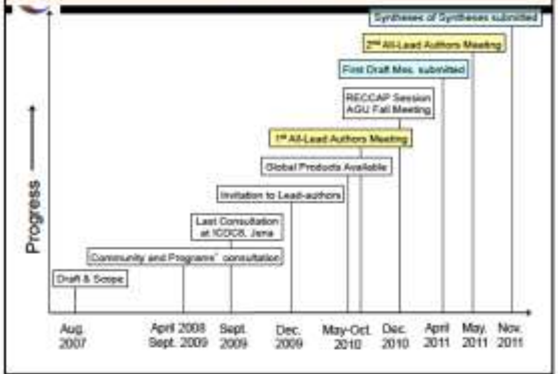

Global Assessments
• Fossil fuel emissions
• Land use change emissions
• Global atmospheric budget
• Global ocean surface CO2
• Global ocean storage
• Coastal Ocean
• Rivers fluxes
• Embedded fluxes in international trade
RECCAP (2008-2011)


Global Syntheses of Syntheses
Ch-S1 Comparison of top & bottom up
Ch-S2 Inter-annual var. region
Ch-S3 Attribution to regional processes
Ch-S4 Past and future trends in regional C budgets
Ch-S5 Final recommendations
RECCAP (2007-2011)


RECCAP
www.globalcarbonproject.org/RECCAP


Products
• Scoping paper for EOS or "News" in Science: 'An international endeavour to tackle regional carbon fluxes'
• Special Journal Issue/s (online eg, Biogeosciences, IF=3-4) with all regional and global syntheses.
• 2-4 high-level syntheses papers reporting key results (eg, Special feature in Nature-Geosciences, or Nature-Climate Change).
• Summary for Policy Makers.
• Distributed Data Repository (to be updated in the future) of C fluxes from regional and global estimates available for further research and publications.

Timetable



2nd Workshop: Syntheses of Syntheses

Initial Ideas

- Comparison of atmospheric and bottom up fluxes (mean decadal).
- Inter-annual variability at regional scale.
- Attribution to regional processes over the globe.
- Future regional carbon trends.
- Methods (protocols and uncertainty analyses).
- Final recommendations

Scientific Steering Committee

- Philippe Ciais, *Chair* (France)
- Pep Canadell, *Coordinator* (Australia)

- Han Dolman (The Netherlands)
- Niki Gruber (Switzerland)
- Kevin Gurney (USA)
- Corinne Le Quere (UK)
- Mac Post (USA)
- Mike Raupach (Australia)
- Chris Sabine (USA)
- Piao Shilong (China)
- Stephen Sitch (UK)

Partners and Sponsors

- COordination action Carbon Observation System (COCOS), Europe
- Carbon Cycle Science Program - CCIWG, USA

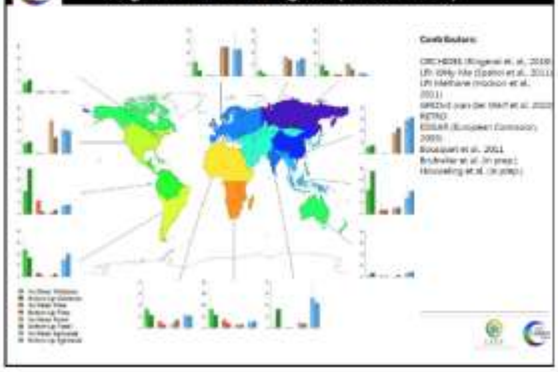
- International Ocean Carbon Coordination Project (IOCCP)
- Chinese Science Academy (CAS), China
- CSIRO Marine and Atmospheric Research, Australia
- National Institute for Environmental Studies (NIES), Japan

- Carbo-Africa
- Quantifying and Understanding the Earth System (QUEST), UK

How do we expect to achieve it?

- Establishing a large global coordination effort.
- Developing of a "soft protocol" to guide and ensure consistency among regional syntheses (so they can be compared and add up at the end).
- Relying primarily on:
  - existing analyses,
  - ongoing analyses from regional and national programs (eg, North American Carbon Plan, CarboEurope, Australian NCAS),
  - global modeling and assessment efforts (eg, GCP Carbon Budget, GCP-TRENDY, TRANSCOM, SOCAT).
- Relying secondarily on:
  - the establishment of new synthesis teams in regions where there is not an established carbon program.

Regional CH_4 Budgets (2000-2008)



Data Fair-Use Policy

- Inspired on the successful model of the AmeriFlux data policy (also used in FluxNet):
  - Request permission to use.
  - Assess possible clashes with other users.
  - Determine which arrangement are appropriate:
    - co-authorship
    - acknowledgements

Examples Tier 1 Global Products

Product	Specifications	Coordinator
Atmospheric CO_2 inversions	TransCom (12 models), 1° x 1° grid, regional integrated fluxes according to RECCAP mask. To 2008	Kevin Gurney, Rachel Law, Philippe Peylin
Ocean forward biogeochemical models	Five global models at 1° x 1° for all major flux components. To 1958-2009	Corinne Le Quere
Ocean inversion	1 model.	Niki Grubber
Terrestrial biogeochemical models and NEP-flux model	Five Dynamic Global Vegetation Models, gridded output for all major flux components. To 2009. GPP and NEP from eddy flux data-driven model	Stephen Sitch, Pierre Friedlingstein, Markus Reichstein
Fire emissions	0.5° x 0.5°, monthly, burned area and fire emissions (C, CO_2, CO, CH_4, NOx, N_2O, BC others) 1997-2009.	Guido van Werf

Carbon balance of South Asia, and modelling GHGs concentrations and fluxes

P. K. Patra
Asian Greenhouse Gases Budget
Ahmedabad; 28 September 2011

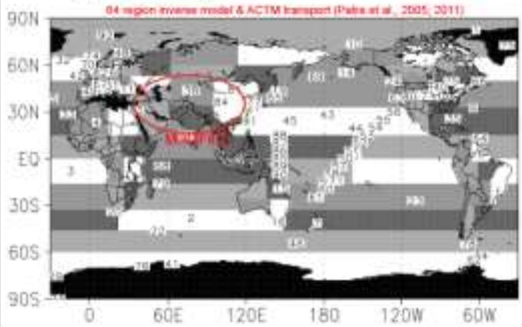
Research Institute for Global Change

Introduction

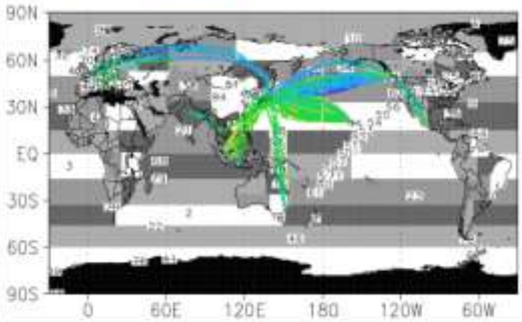
- Carbon cycle of Asian regions is poorly studied (*terra incognita*), compared to the North America or Europe
- More and more regions are now covered by mega-projects from the European Union and USA
- The CARIBIC and CONTRAIL aircraft projects offer new view of the South Asian air (shown by transport model intercomparison)
- Here we attempt to conduct inversion using the CO_2 observations in the upper troposphere

CARBON DIOXIDE (CO_2)

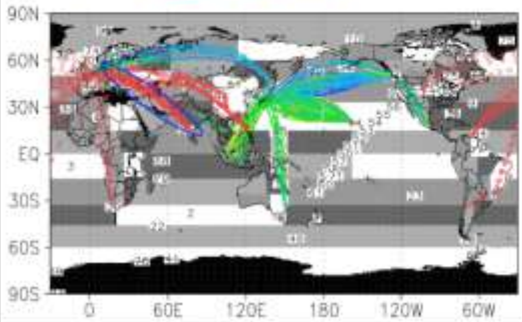
Inverse modelling and lack data coverage (surface mainly)

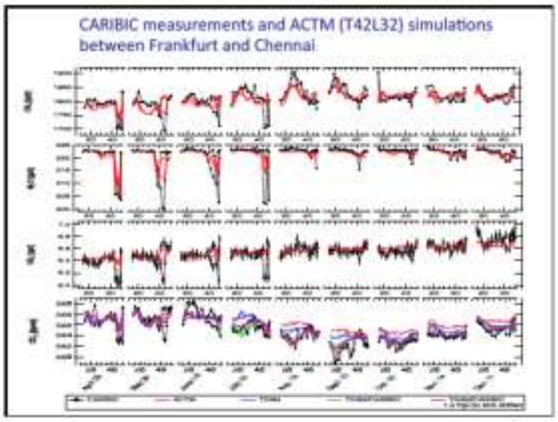


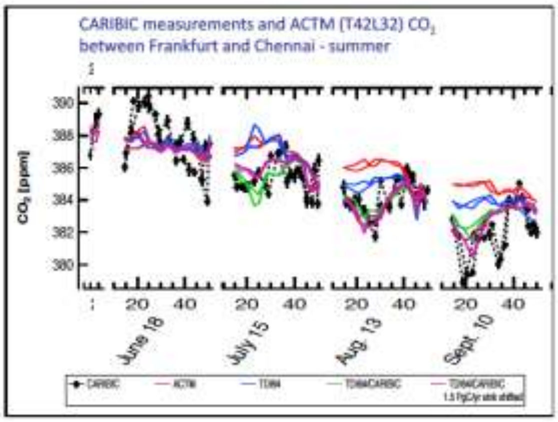
Inverse modelling and lack data coverage? (surface + CONTRAIL)

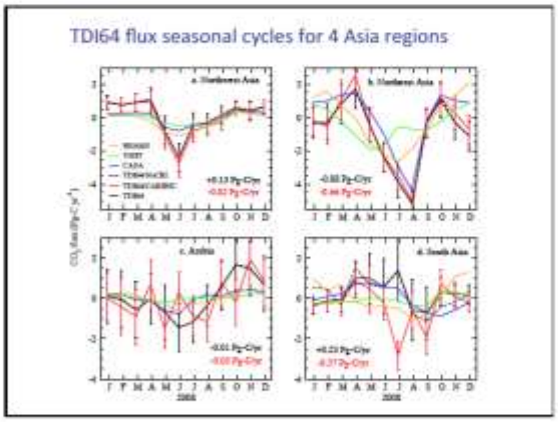


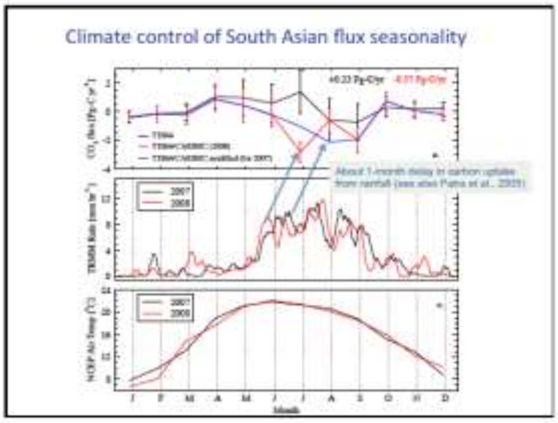
Inverse modelling and lack data "usage" (surface + CONTRAIL + CARIBIC)

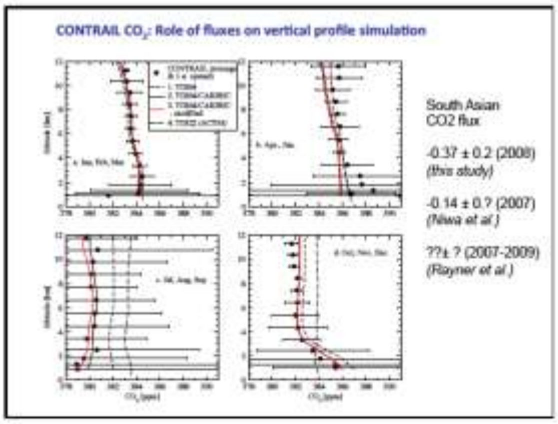


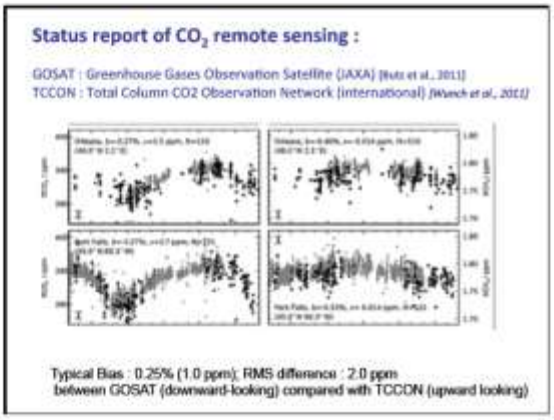

CARIBIC measurements and ACTM (T42L32) simulations
between Frankfurt and Chennai

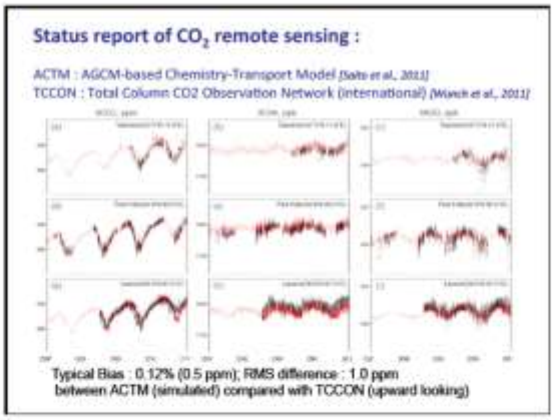

CARIBIC measurements and ACTM (T42L32) CO_2
between Frankfurt and Chennai - summer
CO_2 [ppm]
June 18
July 15
Aug 13
Sept. 10
CARIBIC
ACTM
TDI64
TDI64/CARIBIC
TDI64/CARIBIC
1.5 PgC/yr sink shifted

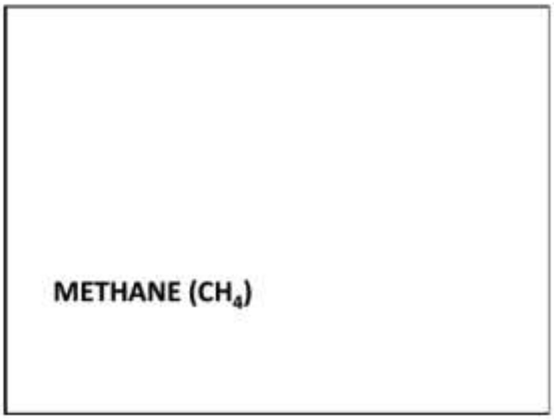

TDI64 flux seasonal cycles for 4 Asia regions

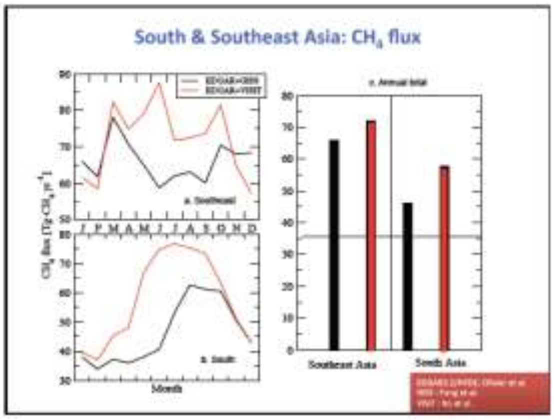

Climate control of South Asian flux seasonality

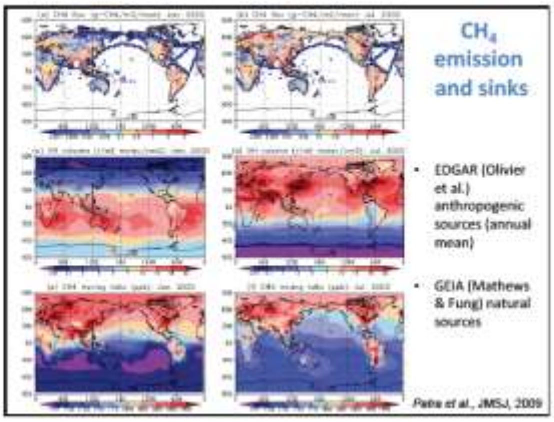

CONTRAIL CO_2: Role of fluxes on vertical profile simulation
South Asian
CO2 flux
-0.37 ± 0.2 (2008)
(this study)
-0.14 ± 0.? (2007)
(Niwa et al.)
??± ? (2007-2009)
(Rayner et al.)

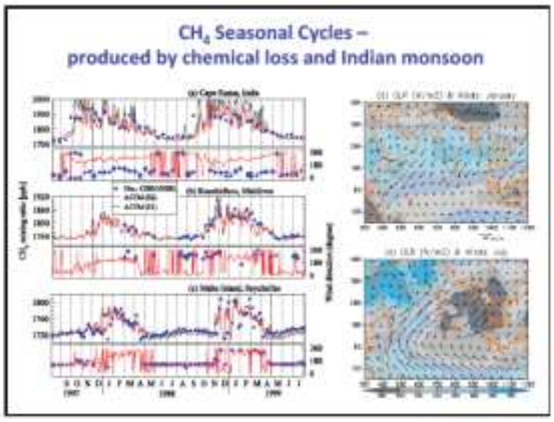

Status report of CO_2 remote sensing :
GOSAT : Greenhouse Gases Observation Satellite (JAXA)
TCCON : Total Column CO2 Observation Network (international)
Typical Bias : 0.25% (1.0 ppm); RMS difference : 2.0 ppm
between GOSAT (downward-looking) compared with TCCON (upward looking)


Status report of CO_2 remote sensing :
ACTM : AGCM-based Chemistry-Transport Model
TCCON : Total Column CO2 Observation Network (international)
Typical Bias : 0.12% (0.5 ppm); RMS difference : 1.0 ppm
between ACTM (simulated) compared with TCCON (upward looking)


METHANE (CH_4)


South & Southeast Asia: CH_4 flux
c. Annual total
a. Southeast
b. South
Month
Southeast Asia
South Asia


CH_4 emission and sinks
EDGAR (Olivier et al.) anthropogenic sources (annual mean)
GEIA (Mathews & Fung) natural sources
Patra et al., JMSJ, 2009


CH_4 Seasonal Cycles – produced by chemical loss and Indian monsoon

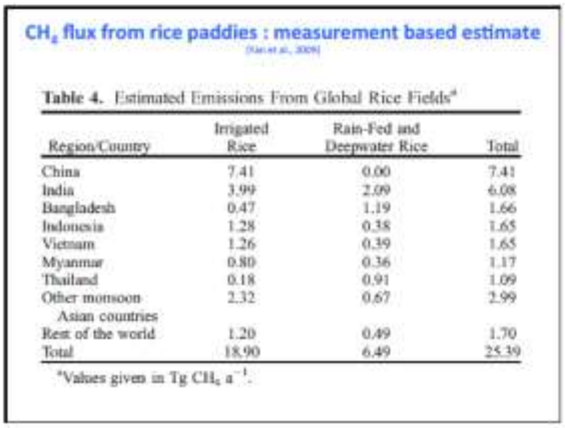
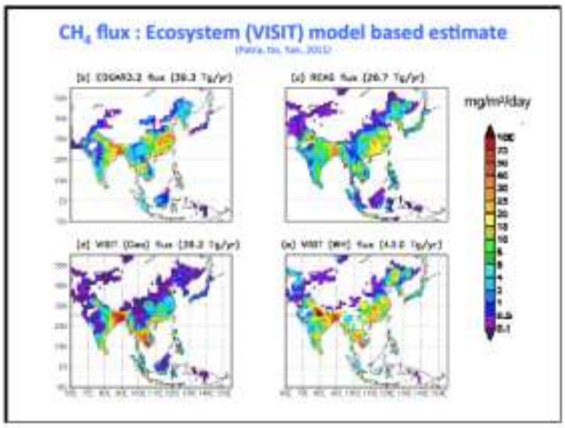
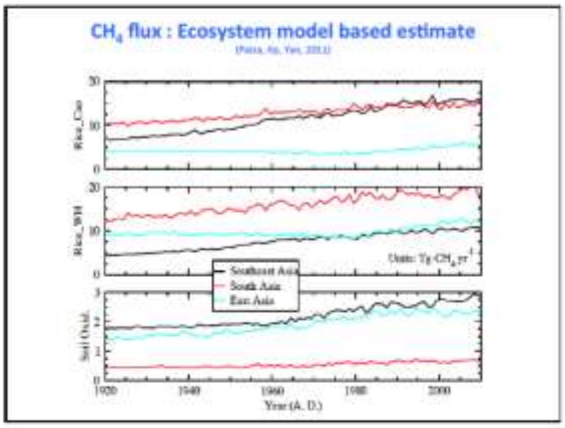


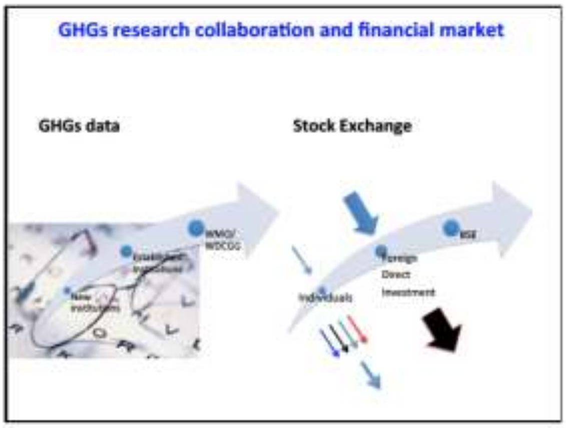
Table 4. Estimated Emissions From Global Rice Fields[a]

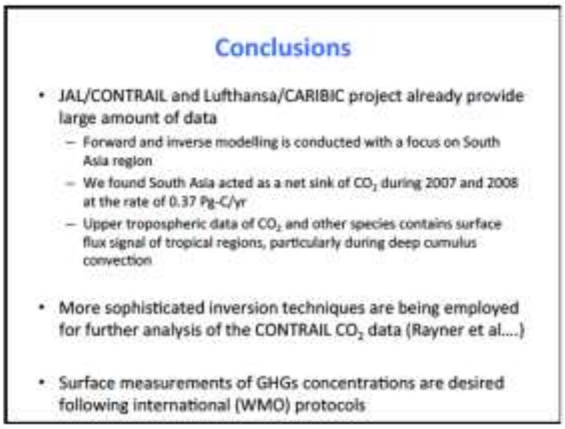
Region/Country	Irrigated Rice	Rain-Fed and Deepwater Rice	Total
China	7.41	0.00	7.41
India	3.99	2.09	6.08
Bangladesh	0.47	1.19	1.66
Indonesia	1.28	0.38	1.65
Vietnam	1.26	0.39	1.65
Myanmar	0.80	0.36	1.17
Thailand	0.18	0.91	1.09
Other monsoon Asian countries	2.32	0.67	2.99
Rest of the world	1.20	0.49	1.70
Total	18.90	6.49	25.39

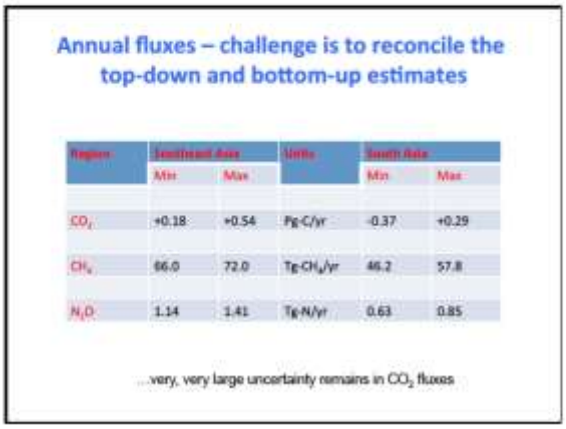
[a]Values given in Tg CH_4 a^{-1}.





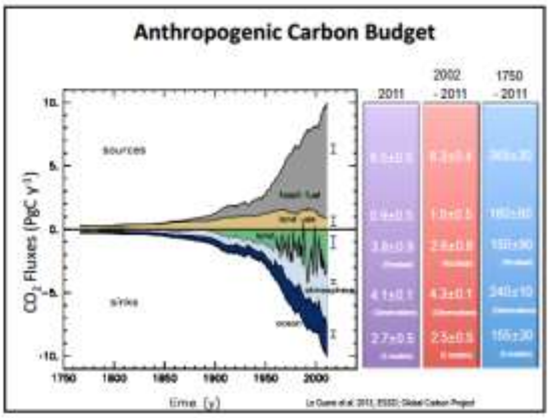


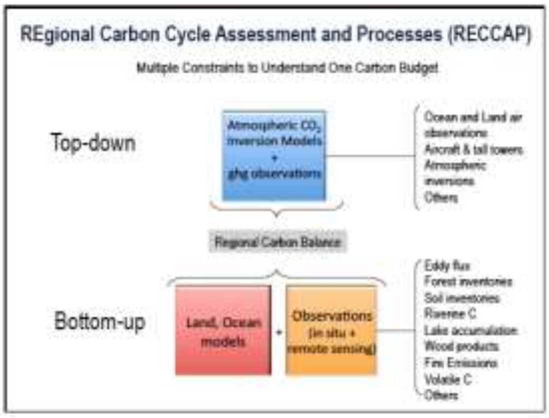


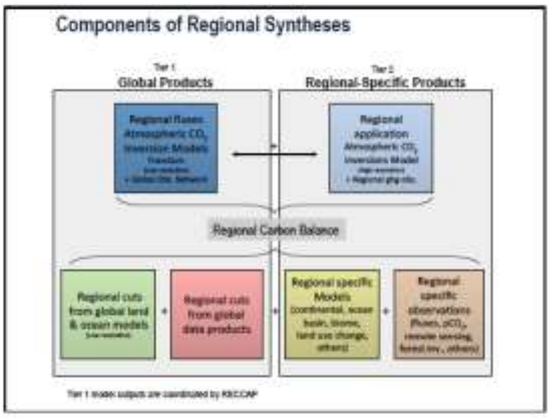


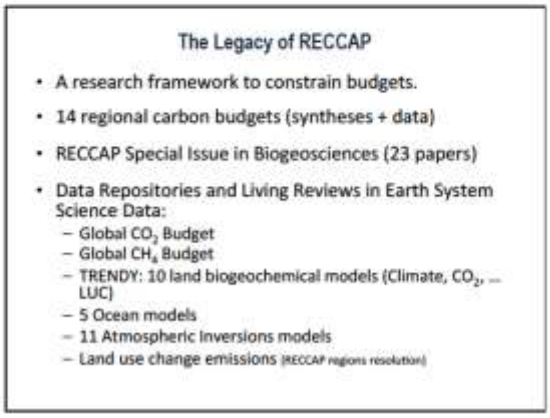
Region	Southeast Asia		Units	South Asia	
	Min	Max		Min	Max
CO_2	+0.18	+0.54	Pg-C/yr	-0.37	+0.29
CH_4	66.0	72.0	Tg-CH_4/yr	46.2	57.8
N_2O	1.14	1.41	Tg-N/yr	0.63	0.85

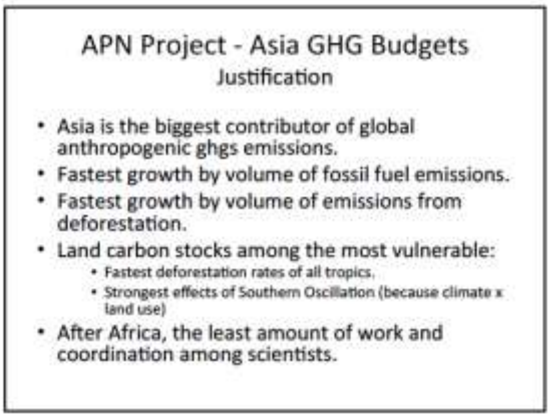
Final presentations at the APN project meeting in JAMSTEC, Yokohama and Korea Meteorological Agency, Daejeoung, showing the outcome of the project and some of the future directions.



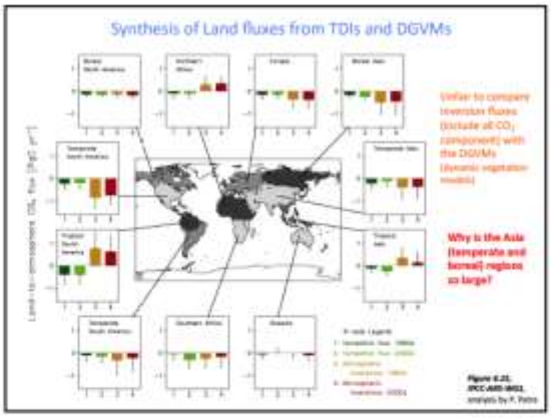


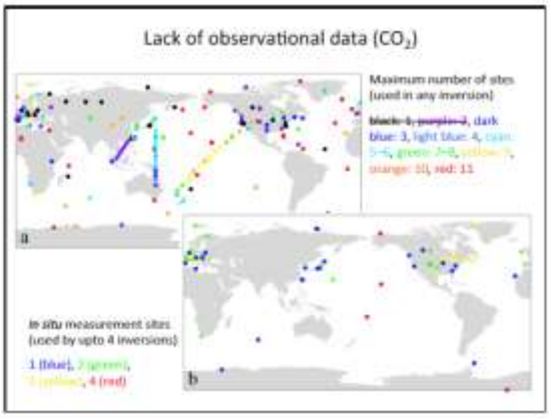


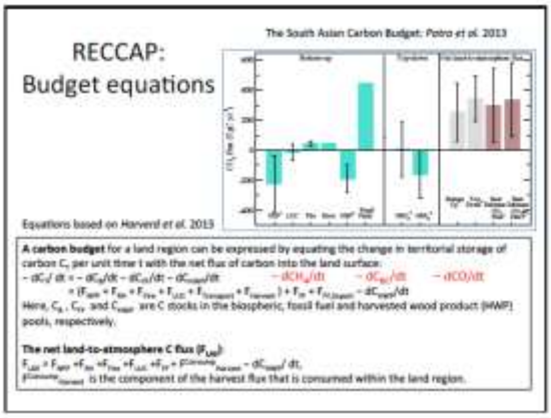


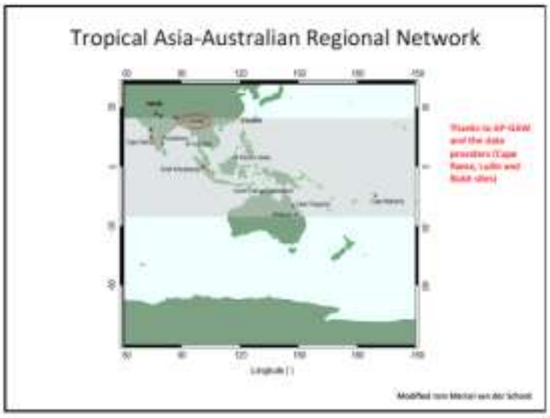



Upcoming synthesis of
"Asian Greenhouse Gases Budget"
Prabir K. Patra
on behalf of the APN project participants and supporting institutions
At
Korea Research Institute of Standards and Science
Daejeong, 20-22 October 2014
APN
GLOBAL CARBON


Synthesis of Land fluxes from TDIs and DGVMs
Why is the Asia (temperate and boreal) regions so large?

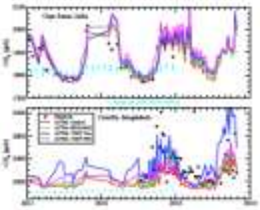

Lack of observational data (CO_2)
Maximum number of sites (used in any inversion)
black: 1, purple: 2, dark blue: 3, light blue: 4, cyan: 5–6, green: 7–8, yellow: 9, orange: 10, red: 11
a
b
In situ measurement sites (used by upto 4 inversions)
1 (blue), 2 (green), 3 (yellow), 4 (red)

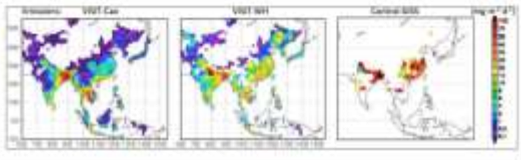

RECCAP:
Budget equations
The South Asian Carbon Budget: Patra et al. 2013
Equations based on Harverd et al. 2013
A carbon budget for a land region can be expressed by equating the change in territorial storage of carbon per unit time t with the net flux of carbon into the land surface:
Here, C_B, C_{FF} and C_{HWP} are C stocks in the biospheric, fossil fuel and harvested wood product (HWP) pools, respectively.
The net land-to-atmosphere C flux (F_{LA}):
is the component of the harvest flux that is consumed within the land region.


Tropical Asia-Australian Regional Network


JAMSTEC established site in collaboration with Dhaka Univ/ NIES
Comilla (23.45°N, 91.20°E),
Observatory of Bangladesh Meteorol. Dept.

CH_4 in Bangladesh and India – ACTM/VISIT sensitivity





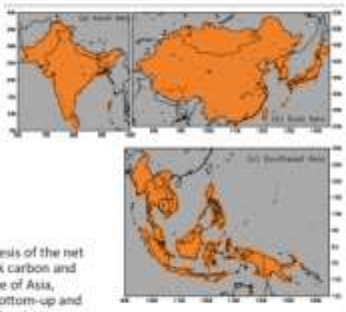
3rd APN* workshop on Asian GHG budget (8-10 April 2014, JAMSTEC)

discussion subgroups:

- Atmosphere (top-down/inventory) subgroup – CO_2, CH_4, N_2O, CO, BC
- Terrestrial subgroup – CO_2, CH_4 and N_2O
- Riverine export and coastal ocean

*APN: Asia Pacific Network
Project: Greenhouse gas budgets of South and Southeast Asia (ARCP2013-01CMY-Patra/Canadell)

Objective



To develop a grand synthesis of the net GHG (CO_2, CH_4, N_2O, black carbon and carbon monoxide) balance of Asia, excluding Siberia, using bottom-up and top-down constraints and estimates covering the 2000-2012 period.

Atmosphere sub-group

R. L. Thompson, M. Ramonet, P. K. Patra,
T. Saeki, K. Ishijima, S. Maksyutov, Y. Niwa, S. Gonzi, K. Yumimoto
M. Montean, J. Kurokawa, S. Tao,
H. Mukai, S. Nomura, K. Ahmed

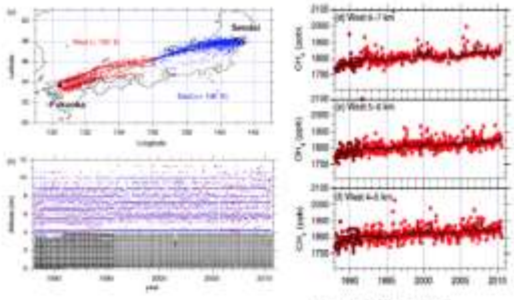
Top-down constraints – existing & new observations (list incomplete)

- Long-term record inversions (focus 2000-2012)
  - NOAA CCGG flask network
  - AGAGE in-situ network
  - CSIRO
  - JMA
  - NIES
- Short-term new observation inversions (focus 2010-2012)
  - GOSAT (CO_2, CH_4)
  - CONTRAIL ASE (CO_2, CH_4, N_2O, CO)
  - Tohoku Univ. aircraft and ships (CO_2, CH_4, N_2O, CO)
  - RAMCES ground-based sites (CO_2, CH_4, N_2O)
  - NIES flask sampling network (CO_2, CH_4, N_2O, CO)
  - CSIRO flasks (CO_2, CH_4, N_2O, CO)
  - JMA flights (CO_2, CH_4, N_2O, CO)

Attempt to collect atmospheric data (June 2014)

Name	Institute	Data
Ed Dlugokencky	ESRL/NOAA, USA	NOAA Flask
Mukai-san	NIES, Tsukuba, Japan	NIES flasks
Tohjima-san	NIES, Tsukuba, Japan	CH_4, N_2O, CO continuous
Nakazawa-san, Morimoto-san	Tohoku University	Ship and aircraft
Fukuyama-san	JMA, Japan	JMA flights and stations
Machida-san & Matsueda-san	MRI and NIES	CONTRAIL
M. Ramonet	LSCE, Saclay, France	RAMCES network
M. Van der Shoot	CSIRO, Aspendale, Australia	CSIRO network
Lingxi Zhou	CAMS, China	China network
I. Morino	NIES, Tsukuba, Japan	FTIR Japan (3 sites??)
Anita Ganesan	Bristol/AGAGE	CH_4, SF_6..
Yogesh Tiwari	IITM, Pune	CO_2, CH_4
N.-H. Lin/C.-F. Ou-Yang	NCU, Taiwan	Flask & Continuous data

Tohoku University database – aircraft example



Umezawa et al., Tellus, 2014

Top-down constraints – expected models

	CO_2	CH_4	N_2O	CO	Black Carbon
TM5[1]	✔✔	✔✔	✔	✔✔	
TM3[2]	✔✔		✔		
GeosChem[3]	✔✔	✔			
LMDZ-PYVAR[4]	✔✔	✔✔	✔	✔	✔[11]
ACTM[5]	✔✔	✔✔	✔✔		
NIES-TM[6]	✔✔	✔✔			
NICAM-TM[7]	✔✔				
FLEXINVERT[8]		✔✔			
GeosChem[9]				✔✔	
CHASER[10]				✔✔	
MOZART[11]			✔✔		

1. [illegible]
2. [illegible]
3. Univ. of Edinburgh
4. [illegible]
5. JAMSTEC
6. NIES
7. [illegible]
8. NILU
9. [illegible]
10. JAMSTEC
11. Emory Univ.
12. Univ. Chile

✔: Longterm, 2000-2012
✔: focussed, 2010-2012

Analysis plan for top-down constraints

We already have a Protocol Ready
(*Chevallier* et al., Greenhouse Gas inversion inter-comparison protocol for Asia)

Terrestrial sub-group - Carbon

B. Poulter (Montana State Univ.), S. Piao (Peking Univ.), K. Ichii (JAMSTEC), A Ito (NIES), L. Nieradzik, P. Canadell (CSIRO), A. Baccini (WHRC), et al.

Terrestrial sub-group – CH_4

(tied with GCP activity)

B. Poulter (Montana State University, USA),
A. Ito (National Institute for Environmental Studies, Japan),
H. Tian (Auburn University, USA) et al.

Terrestrial sub-group – N_2O

NMIP - Global and regional N_2O model Inter-comparison Project

Hanqin Tian (Auburn University, USA)
Eri Saikawa (Emory University, USA)
Xu-Ri (Chinese Academy of Sciences)
Akihiko Ito (NIES, Japan)