APN
Science Bulletin

ISSUE 6, APRIL 2016
ISSN 2185-761X

© 2016 Asia-Pacific Network for Global Change Research (APN)

■ While the information and advice in this publication are believed to be true and accurate at the date of publication, neither the editors nor the APN accept any legal responsibility for any errors or omissions that may be made. APN and its member countries make no warranty, expressed or implied, with respect to the material contained herein.

■ **Citation**: Boonjawat, J., Fukushi, K., & Stevenson, L. A., (Eds.). (2016). APN Science Bulletin (6). Asia-Pacific Network for Global Change Research (APN). ISSN 2185-761X.

■ **Electronic version**: An electronic version of the APN Science Bulletin is available on APN E-Lib at www.apn-gcr.org/resources.

■ **Design and layout**: Huong Long Dinh, Xiaojun Deng

■ **Cover image**: Local fishermen working for their morning catch on Ngu Ha (Royal River), Hue, Viet Nam. © Hieu Truong Minh (hieutruongminh@gmail.com).

■ EXECUTIVE EDITORS

- **Dr. Jariya Boonjawat**, Southeast Asia START Regional Center, Chulalongkorn University, Thailand
- **Prof. Kensuke Fukushi**, Integrated Research System for Sustainability Science, and Department of Urban Engineering, The University of Tokyo

■ MANAGING EDITOR

- **Dr. Linda Anne Stevenson**, Head, Communication and Scientific Affairs, APN Secretariat

■ EDITORIAL ADVISORY COMMITTEE

- **Dr. Varaprasad Bandaru**, Department of Geographical Sciences, Univeristy of Maryland, USA
- **Dr. Annadel Cabanban**, Angelo King Center for Research and Management, Silliman University, Philippines
- **Dr. Xuefeng Cui**, Beijing Normal University, China
- **Dr. Rasul Ghulam**, Pakistan Meteorological Department, Pakistan
- **Dr. Indrila Guha**, Vidyasagar College for Women, India
- **Dr. Srinivasan Krishnan**, Ministry of Environment and Forests, India
- **Prof. Surender Kumar**, University of Delhi, India
- **Dr. Louis Lebel**, Unit for Social and Environment Research, Chiang Mai University, Thailand
- **Dr. Rahman Md. Mahmudur**, Bangladesh Space Research & Remote Sensing Organization, Bangladesh
- **Dr. Subramanian Moten**, Malaysian Meteorological Department, Malaysia
- **Dr. Tho Hung Ngo**, Environment and Development Section, Asian Institute of Technology in Vietnam (AITVN), Viet Nam
- **Dr. Cam Nguyen**, RSP Architects Planners and Engineers, Singapore
- **Dr. Huu Ngu Nguyen**, Hue University of Agriculture and Forestry, Viet Nam
- **Prof. Jacob Park**, Green Mountain College, USA
- **Dr. Greg Picker**, Global Issues Group, Australia
- **Mr. Yahampath Poorna**, Plan International, Environmental Disaster Risk Management Group, Sri Lanka
- **Dr. Rodel Lasco**, The World Agroforestry Centre (ICRAF), Philippines
- **Prof. Henning Rodhe**, Stockholm University, Sweden
- **Dr. Thomas Shaju**, Tropical Institute of Ecological Sciences, India
- **Dr. Dinda Soumyananda**, University of Burdwan, West Bengal, India
- **Ms. Takako Wakiyama**, Institute for Global Environmental Strategies, Japan
- **Dr. Belinda Yuen**, Ako Knowledge Solutions, Singapore
- **Prof. Qianlai Zhuang**, Purdue University, USA

Contents

FEATURED ARTICLES

Sources and Sinks of Carbon Dioxide in Populous Asia

Prabir K. PATRA[a] ✉, Josep G CANADELL[b], Rona L. THOMPSON[c], Masayuki KONDO[d], Benjamin POULTER[e]

APN Project Reference: ARCP2013-01CMY-Patra/Canadell / Received: January 2016 / Published online: March 2016
Available online at APN E-Lib: http://www.apn-gcr.org/resources

HIGHLIGHTS

- CO_2 sources and sinks are estimated for East, South and Southeast Asia by inverse modelling and terrestrial ecosystem models.
- These Asian regions are either a carbon sink or source neutral but the uncertainties are significant between methods particularly for East Asia.
- High quality observations and model synthesis is recommended for monitoring and verification.

ABSTRACT The recently concluded 21st Conference of the Parties (COP21) under the United Nations Framework Convention on Climate Change (UNFCCC) agreed to limit the increase in global temperature to less than 2°C above pre-industrial levels, with a more aspirational target of 1.5°C. Achieving these policy goals will require extraordinary input from the scientific community to define anthropogenic emission targets that account for natural biosphere sources and sinks of carbon dioxide (CO_2), consistent with the climate targets. Asian countries, being densely populated and emerging global economic powers, are key players in defining future emission trajectories. The average fossil emissions from the three regions are estimated to be 2.4, 0.5 and 0.3 petagrammes of carbon per year (PgC yr^{-1}) for East, South and Southeast Asia, respectively, and have increased by 67, 58 and 33 percent over the period 2003–2012. Here, we estimate land biosphere CO_2 fluxes using: 1) simulations of terrestrial ecosystem models driven with global and regional atmospheric and climate observations and 2) atmospheric CO_2 inverse models. Based on observations of atmospheric CO_2 and inverse models, we show that on average over the period 2003–2012, the land biosphere (excluding fossil fuel emissions) in the three Asian regions in our study is either a CO_2 sink (0.35 PgC yr^{-1} in East Asia) or source neutral (South and Southeast Asia). Consistently, our terrestrial ecosystem modelling suggests that the land biosphere of South and Southeast Asia were nearly neutral, but disagrees for East Asia.

KEYWORDS *Asian CO_2 sources and sinks; atmospheric inversion; terrestrial ecosystem model*

1. Introduction

Tropical and temperate Asia is home to 3.72 billion people and is undergoing rapid social changes and economic growth. We define the three Asian regions for this study as: East Asia comprising China, Japan, the Koreas and Mongolia; South Asia comprising India, Bangladesh, Pakistan, Nepal, Sri Lanka and Bhutan; and Southeast Asia comprising Myanmar, Lao PDR, Viet Nam, Cambodia, Thailand, Philippines, Malaysia, Indonesia, Brunei, Singapore, Timor-Leste and Papua New Guinea (Figure 1).

This research was initiated from the larger international project "Asian Greenhouse Gases Budget" supported by

a Japan Agency for Marine-Earth Science and Technology, 3173-25 Showa-machi, Yokohama, 236-0001, Japan

b Global Carbon Project, CSIRO Oceans and Atmosphere Flagship, Canberra, ACT 2601, Australia

c Norwegian Institute for Air Research (NILU), NO-2027, Kjeller, Norway

d Montana State University, Bozeman, MT 59717-3460, USA

✉ Corresponding author. Email: prabir@jamstec.go.jp;

Tel: +81-45-778-5727.

the Asia-Pacific Network for Global Change Research (APN) and the Global Carbon Project (GCP). It fully relies on the participants' voluntary contribution. The ensemble of inverse and ecosystem modelling fluxes and uncertainties have been synthesised in the REgional Carbon Cycle Assessment and Processes (RECCAP) project (Patra et al., 2013; Piao et al., 2012; Canadell et al., unpublished). These results suggest large uncertainties in the estimated CO_2 fluxes by different methods and inconsistencies in the carbon flow accounted by the two modelling approaches.

This report aims to update the CO_2 source and sink budgets using recent model simulations as more atmospheric measurements have become available for inverse modelling, and by the terrestrial ecosystem model fluxes following inclusion due to land use and land cover change (LULCC).

2. Methodology

There are two main flux components in the terrestrial carbon balance: anthropogenic emissions (from fossil fuel consumption, cement production and deforestation) and ecosystem flux (balance between gross primary production and autotrophic respiration + heterotrophic respiration + disturbances such as fire and insect damage). Two principal approaches are used to estimate terrestrial CO_2 fluxes: top-down and bottom-up approaches. The top-down approach estimates the terrestrial CO_2 flux that is optimally consistent with atmospheric CO_2 concentration. The bottom-up approach estimates the ecosystem carbon cycle by considering the internal biochemical mechanisms of carbon flows.

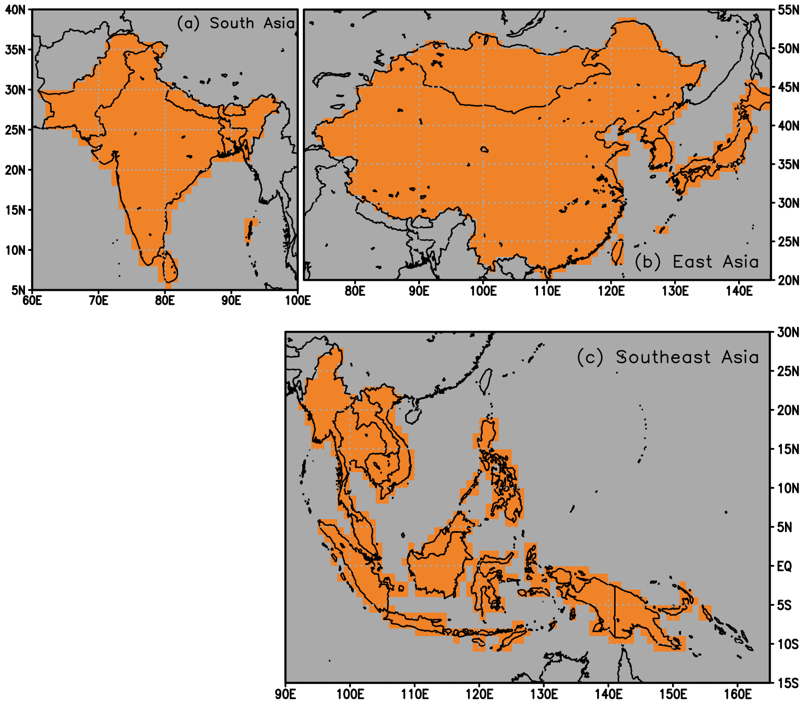

FIGURE 1. The three focus regions of our study - South Asia (top-left), East Asia (top-right) and Southeast Asia (bottom).

The bottom-up CO_2 fluxes are estimated as net biome production (NBP) using five dynamic global vegetation models (DGVMs), namely, the Community Land Model version 4.5 (CLM4), Joint UK Land Environment Simulator ver. 3.234 (JULES), Lund-Potsdam-Jena DGVM wsl (LPJwsl), LPJ GUESS, Orchidee-CN (O-CN), and the Vegetation Integrative SImulator for Trace gases (VISIT). The DGVMs are run using climate dataset from the Climate Research Unit (CRU) TS3.2 and prescribed annual LULCC dataset from the HistorY Database of the global Environment (HYDE) (ref. Kondo et al., 2016, and references therein). The models compute the land use fluxes by adjusting carbon pools over time for defined transitions, e.g., forest to pasture. Fire emissions associated with land use change are accounted by all models but only a few are able to estimate emissions from wildfires.

The top-down fluxes of CO_2 sources/sinks are estimated by using seven atmospheric transport models, observed CO_2 concentrations and inverse modelling/data assimilation. In this study, seven inverse models were used, namely, GELCA: 64-region inversion system using Lagrangian-Eulerian coupled transport, MACC: 4-dimensional variational data assimilation system, WU: CarbonTracker Europe, ACTM: 84-region matrix inversion system, CSIRO: 130-region matrix inversion system, JMA: 22-region matrix inversion system, and CAO: inversion system using empirical orthogonal functions (as described in Thompson et al., 2016). The inverse models were driven using different prior flux information, atmospheric transport models, and CO_2 observation datasets. In this way, the ensemble range resulting from the use of all inversions represents the uncertainties of these various components.

The top-down and bottom-up results are combined and compared to produce a mean average and uncertainty estimates for CO_2 fluxes for three Asian regions as defined in this study (Figure 1).

We additionally investigated trends in the normalised difference vegetation index (NDVI), precipitation (PCP) and temperature (T) for understanding the role of climate variations on the carbon assimilation capacity of the temperate (East Asia), tropical (Southeast Asia) and mixed (South Asia) ecosystems. Detailed results are not presented here for the sake of brevity.

3. Results and Discussions

Figure 2 shows the time-series of mean CO_2 fluxes estimated by top-down and bottom-up approaches and emissions due to Fossil Fuel consumption and Cement production (FFC) for the three Asian regions. Detailed statistics of uncertainties for model-to-model differences are given in Table 1 along with long-term mean normalised difference vegetation index (NDVI), precipitation (PCP) and temperature (T). The uncertainties in CO_2 fluxes are based on 1-σ standard deviation for model differences. The mean values and uncertainties in FFC emissions are

APN ASIA-PACIFIC NETWORK FOR GLOBAL CHANGE RESEARCH

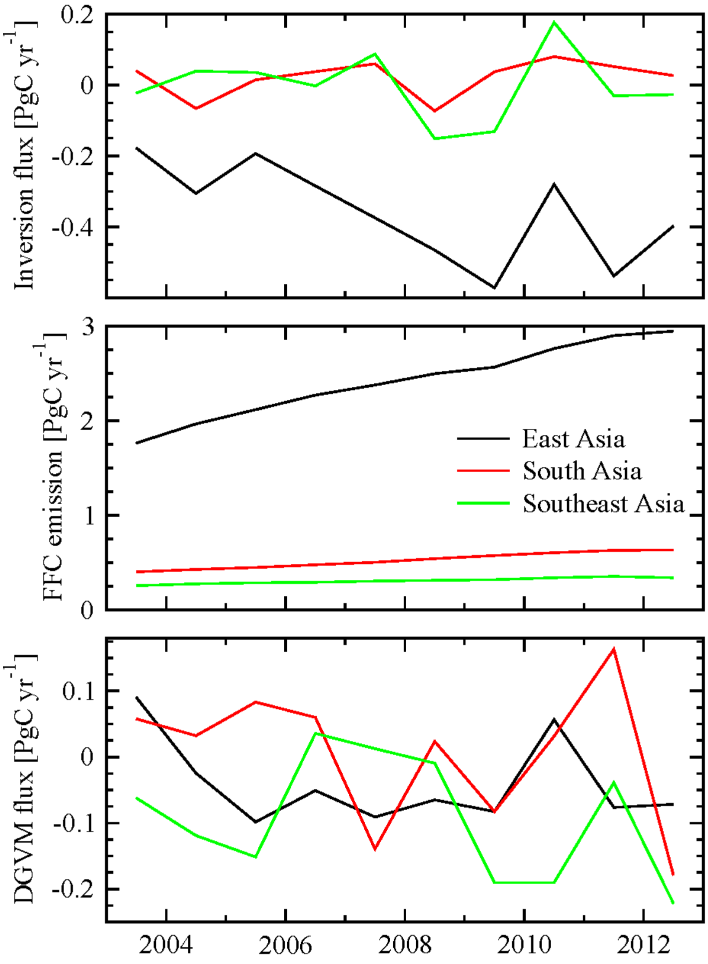

FIGURE 2. Time-series of multi-model mean CO_2 fluxes (top row: top-down method, bottom row: bottom-up method) and FFC emissions (middle row). Uncertainties for model-to-model differences are given in Table 1.

estimated from the values used by 7 inverse modelling systems.

In Figure 2, one can see that the FFC emissions increased rapidly for the East Asia region (118 TgC yr^{-2}), from 1.76±0.15 PgC yr^{-1} in 2003 to 2.95±0.58 PgC yr^{-1} in 2012. During the same period of time (2003–2012), the top-down models estimated an increase in the uptake of CO_2 by the terrestrial ecosystem at the mean rate of 22 TgC yr^{-2} (see also Thompson et al., 2016). The mean CO_2 uptake increase simulated by the bottom-up models is 16 TgC yr^{-2}. However, the net CO_2 flux estimated for 2012 is much greater with the top-down models (-0.40±0.29 PgC yr^{-1}) compared to the bottom-up models (-0.07±0.06 PgC yr^{-1}) for East Asia. The 2012 mean CO_2 fluxes for South and Southeast Asia are estimated to be 0.03±0.08 and -0.03±0.16 PgC yr^{-1}, respectively, with the top-down models, and -0.18±0.14 and -0.22±0.10 PgC yr^{-1}, respectively, with the bottom-up models. Although the net fluxes show reasonably good agreements for the South and Southeast Asia regions, the rates of uptake change are distinctly different for top-down (1 TgC yr^{-2} and 0.5 TgC yr^{-2}, respectively) and bottom-up (24 TgC yr^{-2} and 16 TgC yr^{-2}, respectively) models.

The DGVM simulated increase rates of uptake are quite similar for all three regions, while for the inverse models we find a large increase in uptake for East Asia but almost no trends for South and Southeast Asia. This could be due to overestimation of CO_2 fertilisation by the DGVMs given that most models do not include nitrogen-limitation on gross primary production (GPP) and/or the LULCC database prescribed lower trends in deforestation. The differences in the rate of regional CO_2 uptake increase could also arise from an overestimation of the uptake increase over East Asia and an underestimation over South and Southeast Asia. This may be possible because although the global uptake rates are constrained by atmospheric data, the distribution of the uptake between regions is only weakly constrained and may be reflected as weak or no increase in uptake over South and Southeast Asia. The latter two regions are also largely void of atmospheric CO_2 measurements, while the East Asian fluxes are fairly well constrained by measurements in Japan, South Korea and China. A further possibility for the weak to no increase in uptake over South and Southeast Asia may be an underestimate of the

	CO_2 flux (model mean ± 1-σ difference) units: PgC yr^{-1}			Biosphere and meteorology (mean ± 1-σ inter-annual variation)		
	TOP-DOWN	BOTTOM-UP	FFC	NDVI	PCP (MM D^{-1})	T (°C)
East Asia	-0.36 ±0.28	-0.04 ±0.08	2.40 ±0.33	0.33 ±0.005	51.39 ±2.90	6.81 ±0.38
South Asia	-0.02 ±0.17	0.005 ±0.14	0.52 ±0.11	0.39±0.007	79.88 ±5.32	22.3 ±0.24
Southeast Asia	0.00 ±0.19	-0.09 ±0.15	0.31 ±0.06	0.45 ±0.002	170.7 ±9.13	20.2 ±0.11

TABLE 1. Mean values (± 1-σ difference/variation) of top-down and bottom-up CO_2 fluxes (1 Pg = 1015 g; 1 Tg = 1012 g) and the climate drivers for the period 2003–2012. The model-to-model differences (1-σ standard deviations) are always greater than those estimated for interannual variations for the top-down and bottom-up fluxes.

increase in FFC emissions in these regions, which is assumed a posteriori and is subtracted from the total optimised CO_2 flux (see Thompson et al., 2016).

4. Conclusions

One of the biggest challenges in implementing mitigation policies is the capacity to monitor, report and verify (MRV) as required by the UNFCCC. The new Paris Agreement further emphasises the need for robust and transparent reporting of greenhouse gas fluxes in order to enable successful implementation. Here, we have estimated CO_2 fluxes using two complementary approaches (top-down and bottom-up) for the three regions of the populous Asia. Use of multiple models enable us to show more robust model ensemble means of CO_2 fluxes that suggest the Asian land biosphere is generally source-neutral, albeit there are large uncertainties associated with the ensemble mean values. Differences between top-down and bottom-up approaches also suggest both lack of higher density data to drive the models and possibly missing processes.

At the large regional scales such as those reported in this study, there will always be the need to employ a diverse array of models that capture enough variability and flux components. In order to further improve the models and ultimately the quantification of the Asian greenhouse gases budget, we require a higher density of atmospheric observations, biospheric flux measurements such as eddy-covariance, and increased spatial resolution of land use and land cover changes. We have initiated measurements of CO_2, CH_4, N_2O, SF_6, CO and H_2 from Comilla, Bangladesh since 2012. This site is strategically located for sampling the air mass from the South Asia region during most seasons of the year. Noting the importance, continuation of this measurement programme is now supported by the Ministry of Environment, Japan. We have also begun to work closely with inventory and space agencies, whose data provides new insights into the rapid land use and land cover changes in the region; this undoubtedly will reduce uncertainties of the resulting fluxes.

Acknowledgement

We gratefully acknowledge all those who contributed inversion estimates of land biosphere CO_2 fluxes: F. Chevallier, S. Maksyutov, T. Shirai, M. Ishizawa, R. M. Law, T. Ziehn, I. T. van der Laan-Luijkx, W. Peters, A. Ganshin, R. Zhuravlev, T. Maki, T. Nakamura, T. Saeki. We are also very grateful to all those who provided atmospheric observations that were used in the inversions and for validation. The terrestrial ecosystem model fluxes are provided by L. Calle, S. Sitch, P. Friedlingstein, A. Arneth, A. Harper, E. Kato, C. Koven, T. A. M. Pugh, S. Zaehle, A. Wiltshire. We thank APN for providing partial support for the activity that has led to the set of analysis presented here. JG Canadell thanks the Australian Climate Change Science Programme.

References

Calle, L., Canadell, J. G., Patra, P. K., Ciais, P., Ichii, K., Tian, H., … Poulter, B. (2015). Regional Carbon Emissions from Land Use and Land Cover Change in Asia, 1980-2009. *Env. Res. Lett.*, submitted.

Canadell, J. G., Patra, P. K., Piao, S., Houghton, R. A., et al. (2013). Mean, variability and attribution of the carbon budget of Southeast Asia. unpublished.

Kondo, M., Ichii, K., Patra, P. K., Canadell, J. G., Poulter, B., Saeki, T., … Rödenbeck, C. (2016). Decadal carbon balance shifts controlled by land use change and ENSO in Southeast Asia. submitted.

Patra, P. K., Canadell, J. G., Houghton, R. A., Piao, S. L., Oh, N.-H., Ciais, P., … Lasco, R. (2013). The carbon budget of South Asia. *Biogeosciences, 10*, 513-527.

Patra, P. K., Canadell, J. G., & Lal, S. (2012) The rapidly changing greenhouse gas budget of Asia, Meeting report. *EOS Trans. AGU, 93*, 237.

Piao, S. L., Ito, A., Li, S. G., Huang, Y., Ciais, P., Wang, X. H., … Zhu, B. (2012) The carbon budget of terrestrial ecosystems in East Asia over the last two decades. *Biogeosciences, 9*, 3571-3586.

Thompson, R. L., Patra, P. K., Chevallier, F., Maksyutov, S., Law, R. M., Ziehn, T., … Ciais, P. (2016). Top-down assessment of the Asian carbon budget since the mid 1990s. *Nature comm.*, in press.