MEETING REPORT

Carbon dioxide in the atmosphere*

There is a strong consensus amongst scientists and planners today that the earth's climate is entering a warm episode, nudged primarily by human activities of fossil-fuel burning and land-use changes that inject steadily increasing amounts of CO_2 into the atmosphere. Systematic measurements of atmospheric CO_2 levels made since 1958 at Mauna Loa, Hawaii, show a monotonic increase by about 20% over the past 45 years, over three quarters of which is identified with the isotopic colour of fossil fuels.

The source of most of the ~0.6°C warming that occurred during the past century[1], is ascribed to redistribution of carbon in the earth system, transferred from its oxygen-sequestered repositories of fossil fuels to the atmosphere as heat-trapping molecules of CO_2. However, if this transfer were so straightforward, it would be a simple matter to predict future concentrations of atmospheric CO_2 and thereby the rate of warming, from a knowledge of the global annual consumption of fossil fuels of which, there is fairly reliable data. But, this is complicated by the as yet dimly understood exchange processes that constantly redistribute any additional CO_2 appearing in the atmosphere again between the three major repositories of carbon: land, air and sea. The process is further complicated by variations in the sensitivity of the oceans and land biosphere to CO_2 exchanges with the atmosphere at varying levels of atmospheric CO_2 concentration and temperature. Formulation of a validated model of global carbon cycle defined by the operative physico-chemical interface processes mediating inter-reservoir fluxes under varying conditions of boundary parameters, thus remains an outstanding problem of climate change research. The oceanic and land components of the carbon cycle and transport of carbon from emission sources are the major causes of uncertainty.

Apart from direct measurements which must necessarily be limited, one approach to estimate atmospheric CO_2 fluxes is to exploit the recognition that the measurable atmospheric CO_2 concentration at any given site (x^*, y^*, z^*, t) on the globe can be expressed as a convolution between the CO_2 fluxes $F(x_k, y_k, z_k, t_q)$ at distributed sites on the globe and the atmospheric transport Green's function $G(X^*, X_k, t^*, t_q)$. Using this approach, the carbon fluxes $F(x_k, y_k, z_k, t_q)$ in different regions of the globe can be estimated by inverting measured values of atmospheric concentrations at geographically well-distributed sites on the globe via the Green's Function. These estimates are at present poorly known over Asia and the Indian Ocean, because of the sparseness of the spatial data that lowers the resolution of inverse solutions. Current space–time estimates of fluxes are found to be coarse, as brought out by a wide range of studies. In order to improve the inverse estimates over the Asian region, we need to establish an adequate network of CO_2 concentration monitoring stations in India and other Indian Ocean countries.

The inverse problem for estimating CO_2 fluxes (sources and sinks) using observations of CO_2 concentrations from a network of stations, in turn, requires several conditions to be fulfilled: a good coverage of stations, high-quality measurements, good temporal coverage, good transport model and a robust inversion procedure[2]. Measurements have to be made at relatively clean sites which are reasonably far away from large local sources such as major cities and with high measurement precision (~50–100 ppb). Some inverse model results have already yielded certain counter-intuitive results, notably that both the Southern Ocean and the tropical lands are neutral with respect to the atmospheric carbon budget, whereas these regions were generally regarded in the past to be important sinks for carbon. Notwithstanding these early puzzles, inverse modelling of globally monitored CO_2 concentrations, provides a major visualization tool for identifying and quantifying carbon fluxes, whether for improving the global carbon cycle model or for monitoring compliance with emission protocols and appraising the efficacies of ameliorative measures.

Recognizing the significance of this key endeavour for climate change research, the International Geosphere–Biosphere Programme (IGBP) initiated the TransCom[3] experiment, where a dozen groups from all over the world (none from India) performed inversions using the GlobalView[4] dataset. Each group used its own transport model. The TransCom results[5–9] showed a wide range of estimates with large error bars and highlighted the need for a better network of CO_2 stations to reduce this uncertainty, which is smaller in North America and Europe, and rather large over Tropical Asia due to poor coverage. Loss of the only Indian station (flask data at Cape Rama), which has been discontinued since 2001, has further widened the data gap. A first initiative was taken to improve this situation through a joint project by the Indian Institute of Astrophysics (IIA), Bangalore and CSIR, Centre for Mathematical Modelling and Computer Simulation (C-MMACS), Bangalore supported by an Indo-French collaboration with Laboratoire des Sciences du Climat et de l'Environnment (LSCE) of Centre National de la Recherche Scientifique (CNRS) to set up: (i) a continuous ultra high precision CO_2 concentration measuring station at Hanle, Leh where atmospheric samples had been collected weekly in flasks during the preceeding two years, and (ii) an inverse computational model at C-MMACS to invert this data along with others from Asia and Europe. These became operational in August 2005, yielding a continuous time series of CO_2 concentration at Hanle and an inverse model for related numerical investigations at C-MMACS. Meanwhile, a number of other institutions and research groups in the country evinced keen interest in helping augment this endeavour to a critical level, which highlighted the need for creating a wider base of scientific and technical expertise in the country, especially in enriching our understanding of the fundamental issues in inverse modelling, which would be needed not only for estimating fluxes from observed concentration data, but also for a more

*A report on the Discussion Meeting on 'Inverse Problems with Special Reference to Atmospheric Transport', held at Orange Country, Coorg during 23–26 November 2006, and organized and sponsored by the Indian Academy of Sciences, Bangalore.

analytical approach to various related issues, notably estimating the quality of estimates and numerical experiments to progressively improve these as well as selection of future measurement sites that would have the potential of adding meaningfully to the information content of the data acquired.

To address these issues requiring a high level of understanding involved in inverse modelling and the desirability of sharing these with a wider group in the country, scientists at C-MMACS and IIA, proposed a discussion meeting on inverse problems with special reference to atmospheric transport. It was attended by 15 scientists from different institutions in the country as well as three scientists from LSCE/CNRS France. Peter Rayner, Philippe Bousquet and Michel Ramonet, who have worked on the estimation of CO_2 fluxes over the globe under the transcom set-up, were the main speakers.

This discussion meeting commenced with an introduction by V. K. Gaur outlining some of the outstanding scientific issues of carbon cycle research, especially the estimation of reliable global carbon fluxes and determination of the source of uncertainties. He stressed the need to develop a good network of monitoring sites and a robust modelling framework to achieve this goal. Thereafter, P. K. Gupta (Raja Ramanna Centre for Advanced Technology, Indore) delivered a talk on inverse problems and initiated discussion on critical issues involved in inverse problems and model reduction. This was followed by Bousquet's presentation on the comparative estimates of CO_2 for land and oceans from different models.

Ramonet gave a description of the CO_2 network around the world. He also suggested a few stations in India and emphasized the necessity of setting up an analysis laboratory in India equipped with gas chromotograph or mass spectrometer to determine greenhouse gas (GHG) concentrations of flask samples collected at a dozen sites over India and the adjoining regions.

In the succeeding sessions Rayner led a wide-ranging discussion on the specifics of different atmospheric transport inverse models and issues of numerical modelling and advection schemes in the Transcom reference frame. This was followed by further discussion on source/sink attribution through inverse modelling at climate scales, by Bousquet and on the design of observing networks by Rayner.

The final session was devoted to presentations by scientists from various institutions: Attri talked about the work on CO_2 measurements and related area with other organizations that India Meteorological Department (IMD) has initiated. Yogesh Tiwari (Indian Institute of Tropical Meteorology (IITM)), Pune expressed interest in installing a few additional stations in India to augment the geographical spread of CO_2 monitoring sites in India among the network stations proposed by Ramonet based on his analysis of back trajectories computed for a dozen sites over India. Vikram Reddy explained his recent project jointly designed with C-MMACS to analyse the GHG concentrations from flask samples collected at the shore site of Pondicherry University, Puducherry to highlight the winter fluxes (northeast monsoon) over the Bay of Bengal and P. S. Swathi discussed the work done in C-MMACS on estimation of carbon fluxes. The meeting concluded with presentations made by Bousquet on methane emissions and their estimates in Europe, and by Rayner on carbon cycle data assimilation.

1. Houghton, J. T. *et al.* (eds), *Climate Change 2001: The Scientific Basis*, IPCC Report, Cambridge Univ. Press, 2001.
2. Enting, I. G., *Inverse Problems in Atmospheric Constituent Transport*, Cambridge University Press, Cambridge, 2002.
3. GlobalView-CO_2, Cooperative Atmospheric Data Integration Project–Carbon dioxide, NOAA Clim. Model and Diagnostics Lab, Boulder, Colorado, 2000.
4. Gurney, K., Law, R. and Rayner, P., TransCom 3 Experiment Protocol, July 2000.
5. Gurney, K. *et al.*, *Nature*, 2002, **415**, 626–630.
6. Gurney, K. *et al.*, *Global Biogeochem. Cycles*, 2004, **18**,
7. Law, R. *et al.*, *Tellus B*, 2002, **55**, 580–595.
8. Bousquet, P., Cais, P., Peylin, P., Ramonet, M. and Monfray, P., *J. Geophys. Res.*, 1999, **104**, 26161–26178.
9. Bousquet, P., Cais, P., Peylin, P., Ramonet, M. and Monfray, P., *J. Geophys. Res.*, 1999, **104**, 26179–26193.

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MEETING REPORT

Third Kerala Environment Congress*

A healthy environment is the most critical component essential for the well-being of a society and the foundation for a sustainable and strong economy. A spirit of partnership among the stakeholders in the environmental spectrum should be fostered so as to ensure the sustainable use of natural resources. It is in this context that the relevance of the Kerala Environment Congress (KEC), initiated by the Centre for Environment and Development (CED) in 2005, with the main objective of providing an annual platform for interaction among various experts, scientists, institutions and groups, discussing the major environmental issues that Kerala is facing, comes into focus.

The focal theme of this year's Congress (KEC 2007) was 'Wetland Resources of Kerala'. The wetlands in Kerala are currently being subjected to acute pressure owing to rapid developmental activities and indiscriminate utilization of land and water. A deeper appreciation of ecosystem complexities and biological resources and sustainable multiple-use management which rests on ecosystem approaches should be the strategy for wetland conservation. Lack of understanding of the values of wetlands and the functions they render are considered as the major factors responsible for the callous attitude towards this natural resource. Many efforts have been initiated in this direction at the gov-

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