

GEOSCIENCES

Past, present and future of the carbon cycle

Zhenghui Xie^{1,*}, Ning Zeng^{1,2}, Huijun Wang¹, Zheng Lin¹,
Xiangjun Tian¹ and Binghao Jia¹

The recent Ninth International Carbon Dioxide Conference (ICDC9) held in Beijing highlighted the importance and urgency of global carbon management, research challenges, and recent efforts made by Chinese scientists in this area.

Emissions from fossil fuel use for energy and land use increase atmospheric carbon dioxide (CO₂) levels, but carbon sinks in the ocean and on land are currently absorbing half of fossil fuel emissions. However, neither it is clear how these sinks will change in the future in response to human management and climate nor it is known how such changes will feed back to climate and societal response. Thus, understanding and anticipating changes in the global carbon cycle as well as carbon management strategies for sustainable development is of critical scientific and socioeconomic importance. To present the latest scientific findings and identify the status of current knowledge, major knowledge gaps, and the steps needed to move forward on the science of the carbon cycle and its perturbation by human activities, ICDC9 was held in Beijing, China, on 3–7 June 2013 (<http://icdc9.lasg.ac.cn>). The plenary and poster sections of ICDC9 are shown in Figs 1 and 2. The topics of ICDC9 encompassed global and regional carbon budgets and processes, and also included specialized sessions on the individual components of the atmosphere, ocean and land in the past, present and future. The conference covered fundamental scientific advances, the generation of policy relevant information, and new observational platforms, datasets, and modeling approaches. ICDC9

highlighted the importance and urgency of global carbon management, research challenges and recent efforts made by Chinese scientists in this area.

URGENCY OF GLOBAL CARBON MANAGEMENT

Fossil fuel emissions have been growing at an alarming rate, especially in the last decade, and there have been increases of more than 80% in global energy consumption and CO₂ emissions in the past 30 years, as well as a 0.76°C increase in

the Earth's temperature when compared to the 1880s [1]. Global CO₂ emissions rose by 4.6% in 2010 after having declined in 2009 due to the impact of the financial crisis. Corinne Le Quéré, the Director of the Tyndall Center for Climate Change Research and Co-chair of the Global Carbon Project warned that the rate of increase in the 1990s was about 1% each year, but that it has been 3% per year since 2000 [2]. Indeed, the CO₂ emitted from fossil fuels combustion and cement production in 2012 may arrive at a record high of 35.6 billion tons, and there are no signs that this production will slow down.

Massive carbon emissions are also caused by urbanization and land exploitation. For example, peatlands have served as a large belowground carbon pool on Earth for thousands of years. In warm climates these areas tend to take in more carbon for sequestration; however, according to Zicheng Yu from Lehigh University, excessive land reclamation around the world has destroyed many peatlands and accelerated their



Figure 1. Plenary section of Ninth International Carbon Dioxide Conference (ICDC9).

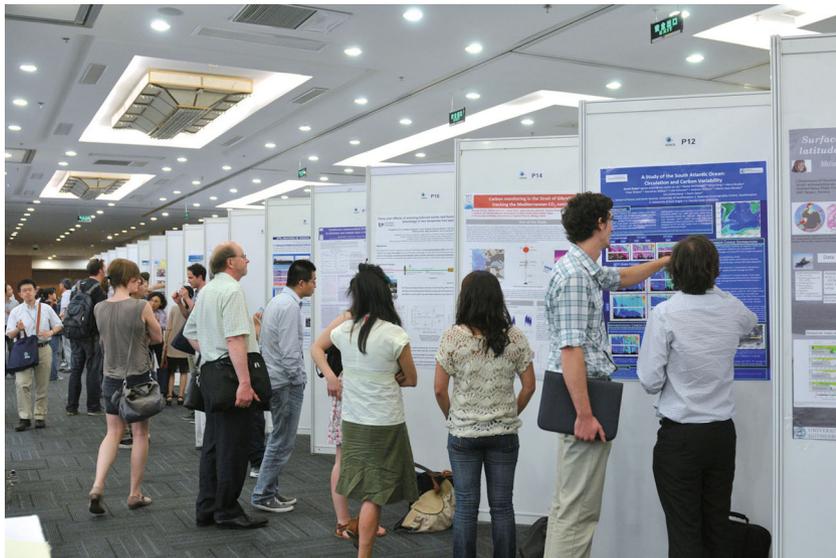


Figure 2. Poster section.

release of CO₂. As global temperature continues to increase, one of its negative feedback on the carbon cycle is a remarkable reduction in the efficiency of natural carbon reservoirs. Four factors, anthropogenic emissions from fossil fuel combustion and changes in land use, direct carbon cycle response, climate feedback, and direct and indirect impacts on terrestrial and oceanic ecosystems, will control the fate of atmospheric CO₂ in the 21st century [3]. CO₂ acts as a major driver of climate change behind the current and future warming of the world climate; therefore, it is essential that global carbon management be strengthened and CO₂ emissions be curbed scientifically and practically.

RESEARCH CHALLENGES

The fundamental natural science questions pertaining to the carbon cycle are: (1) what drives current carbon uptake on land, and (2) what is the climate sensitivity of the terrestrial and oceanic carbon cycle on different time scales? Martin Heimann pointed out that the carbon cycle research agenda has shifted gradually from investigation of the global redistribution of the anthropogenic CO₂ emissions into the ocean and land to the determination of regional carbon budgets and how these change with time under rising CO₂, climate

change and increasing anthropogenic impacts [1].

Addressing these questions has been fostered by expanded observational networks and a multitude of new observational windows, such as a reconstruction of past atmospheric CO₂ variations from ice cores, large-scale carbon inventory surveys in the ocean and on land, and the use of tracers and other indicators of carbon cycling including stable and radioactive isotopes in CO₂, atmospheric oxygen, etc. As studies go deeper, a new major challenge that has emerged for carbon scientists is development and securing of a global carbon observation system based on multiple data streams for science, ‘Kyoto’ monitoring, remote sensing of CO₂ from space and data assimilation. The observations include analysis of regional emissions from the country level to the factory level by statistical analysis and monitoring.

A host of process studies have amassed an impressive amount of information describing how carbon is exchanged between different reservoirs and how these fluxes are modified by various drivers. To enable integration and interpretation of the information, a modeling hierarchy has been developed from simple box models to comprehensive process-based three-dimensional carbon cycle descriptions in current Earth system models. Despite the major

progress made in the last two decades, there are still many uncertainties, particularly on land, which are reflected in the coupled carbon-climate model projections of future land carbon sinks. The ever expanding direct and indirect impacts of a growing world population, including food demands and associated land reclamation, will substantially impact the fate of atmospheric CO₂ in the 21st century. Assessing these impacts in a comprehensive way under various assumptions of future development constitutes a major research direction in the portfolio of global carbon cycle research. A challenge is determining how to assess, quantify, and potentially predict the multitude of direct and indirect anthropogenic impacts on the carbon cycle. These impacts include (1) land cover and land use changes, (2) land management for forestry practices, fire management, agriculture, and irrigation, (3) fertilization, plant species modifications (genetic engineering), etc., (4) land management history, (5) impacts through ocean biosphere, and (6) indirect effects from air pollution, aerosols, and nutrient inputs.

The conference attendees agreed that the main future challenge is to improve human well-being while simultaneously mitigating anthropogenic climate change. The main technology measures for reducing greenhouse gas (GHG) emissions are efficiency improvements, de-carbonization of fossil energy, improved land management, afforestation, carbon capture and storage, a shift toward less carbon-intensive and zero-carbon energy sources and processes and deployment of technologies with ‘negative’ emissions. The discussion highlighted the need for efforts to better integrate models with observations and land with ocean and the atmosphere, and to bridge the communities of natural sciences and social sciences. A better quantification of the coupling between land and ocean is needed while taking into account coastal areas and hot spots such as mega cities close to/at the sea. Studies of land–ocean–atmosphere integration should be strengthened to include the connection between land carbon, inland waters, coastal oceans and open oceans.

A special focus has to be placed on properly carrying out data assimilation of carbon cycle observations into models. Both regional and global perspectives have to be pursued in a connected way. The link between research on GHGs, air pollution and climate change also has to be fostered and extended through suitable research collaboration. Thus, the carbon cycle research community should not only focus on carbon cycle sensitivity to physical and chemical drivers (how carbon sources and sinks change with climate and CO₂ concentrations). The community should also be more active in quantifying climate sensitivity to drivers in a holistic way (stronger collaboration with physical climate researchers is needed).

The conference also drew attention to specific activities on land, in the atmosphere and in the ocean. The roles of soil organic carbon as sources and sinks for CO₂, N₂O and CH₄ have not been adequately quantified. Land modules in current climate models need to better represent the land carbon cycle and water cycle. Inland waters and their role in carbon cycling need to be included in future research. For the open ocean, which is the ultimate carbon sink, the Southern Ocean is the key source and sink area for CO₂ from the atmosphere; accordingly, this region needs to receive more attention for observations and modeling. Additionally, the coastal ocean and shelf seas have to be interlinked with open ocean studies.

To better identify interactions between climate management and carbon cycle research for both land and ocean, it is necessary to distinguish between natural variations and impacts and anthropogenic signals. Since current models used in land use change and forest management may lack the latest scientific data, better collaboration between carbon cycle researchers and people working in ecosystem management is necessary; accordingly, the link between ecosystem research/ecosystem modeling and carbon cycle research has to be fostered and extended. To accomplish this, more detailed regional studies and ecosystem impact studies are necessary, such as investigations of ocean acidifi-

cation and multi-stressor combined action. Moreover, uncertainties in GHG budgets for cities need more attention and consideration since urban areas are hot spots for carbon emissions that have not been adequately included in upscaling approaches for carbon sources/sinks to date. Additionally, the urban environment needs to be integrated into carbon cycle quantifications for existing and growing mega cities. Chinese priorities in carbon cycle research are currently improvements of Earth system models including the carbon cycle and reduction of GHG emissions to improve air quality within the context of climate change. Scientific results should be made available to all researchers so that they can be put to use. To accomplish this, easy access to data through use of established databases should be created. Data policies should encourage/facilitate data and model code sharing including proper acknowledgement of the originators.

CARBON CYCLE RESEARCH IN CHINA

The strong economic growth of developing countries such as China naturally requires more energy consumption. However, reducing GHG emissions to increase carbon sinks by using green technology is the responsibility of all nations, including China. To mitigate carbon emissions in China, we must first gain an objective and comprehensive understanding of the nation's overall emission situation. By making our own emission inventory, scientists may be able to help the government identify emission reduction targets and measures. The relationship between GHGs and climate change is a scientific issue closely related to the Earth's carbon cycle and anthropogenic influence. A strategic priority research program of the Chinese Academy of Sciences, 'Carbon Budget and Relevant Issues in Response to Climate Change', headed by Daren Lu, Institute of Atmospheric Physics, Chinese Academy of Sciences, was established to investigate this relationship. Recent advances of the program were presented at the ICDC9, including a

nationwide investigation of anthropogenic GHG emissions, particularly energy utilization efficiency in China, an investigation of ecological carbon sinks and new carbon sink enhancement technologies, climate system model development and an investigation of trends in climate change based on instrumental observations and proxy data, a new network of aerosol observations in China, past climate and ecological patterns in China, and some preliminary suggestions regarding related policies for national carbon reduction. Analysis of coal samples from across China provided data describing the average carbon content of coal, which was about 10% lower than the IPCC value for China. A 19% decrease in agricultural emissions of nitrous oxide from wheat, rice and corn combined was also observed during the 2001–8 period when compared with the two previous decades. These data are being used to piece together China's emission inventories based on nationwide investigations and to unravel the status, mechanism and potential for carbon fixation by terrestrial ecosystems in China. Through satellite monitoring, field survey and controlled experiments, the carbon density of forests has been slowly increasing in the past 30 years at 0.85% or a net uptake of 43.8TgC each year due to China's ecological restoration efforts. As of 2010, China's total carbon sequestration was about 355 TgC [4].

In addition to the carbon budget program, China is also developing the Tan-Sat satellite, which is scheduled to launch between 2015 and 2016, to monitor atmospheric CO₂ from space. As pointed out by Xiangjun Tian, Institute of Atmospheric Physics, Chinese Academy of Sciences, this will offer a new pathway to global and regional emission data acquisition and enable the combination of observational data with numerical simulation to better understand the spatial and temporal distributions of CO₂ fluxes and concentration. As planned, the Tan-Sat will bring two pieces of instruments onboard, a high resolution CO₂ sensor and a cloud and aerosol polarization imager. The prototypes of both devices are currently being developed. Xiangjun

Tian presented a joint assimilation system Tan-Tracker to simultaneously estimate surface CO₂ fluxes and 3D atmospheric CO₂ concentrations from observations. The system is based on the POD-based ensemble four-dimensional variational assimilation method [5–7] and a dual-pass optimization framework, which has the potential for monitoring carbon using the Tan-Sat satellite.

ICDC9 showed China's carbon research and achievements in climate mitigation and adaptation, such as reforestation and energy efficiency. Ye Qi from Tsinghua University reported China's economic growth and the global carbon budget. Specifically, he revealed the impacts of the new development agenda on future GHG emissions in China, as well as the implications for the global carbon budget. He also discussed large-scale, rapid urbanization and industrialization and their expected consequences on China's carbon emissions. Some outstanding achievements under China's low-carbon endeavor were also demonstrated. For example, it was revealed that there has been a sharp reversal in China's energy and carbon intensity since 2005, and that the country has been exceeding its renewable energy targets since 2006. The emission increase is driven by the economy, while the decreasing trend of energy and carbon intensity is a result of low carbon policies. With the inauguration of new leadership and associated shift in policies, China is putting ecological progress ahead of economic growth [8]. Shilong Piao from Beijing University provided insight into the processes underlying inter-annual variability of carbon fluxes over the past three decades using a combination of

observations and carbon cycle model and atmospheric inversion model approaches [9]. Nianzhi Jiao from Xiamen University presented an integrative consideration of the solubility pump and the microbial carbon pump, which could help identify responses of marine carbon sinks to climate changes as well as practices conducive to enhanced carbon sequestration in the ocean [10].

Great efforts to reduce GHG emissions have been made; however, the challenges faced by China are great, and China's efforts in sustaining green development can be a model for the nation and the world. The priorities of China in the current carbon cycle research are the improvement of Earth system models including the carbon cycle and reduction of GHG emissions to improve air quality within the context of climate change. Scientific results should be made available for all so that they can be put to use. Easy access to data through use of established databases should be created, and data policies should encourage/facilitate data and model code sharing, including proper acknowledgement of the originators.

Zhenghui Xie, Ning Zeng, Huijun Wang, Zheng Lin, Xiangjun Tian and Binghao Jia

¹The State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics (LASG), Institute of Atmospheric Physics, Chinese Academy of Sciences, China

²Department of Atmospheric and Oceanic Science and Earth System Science Interdisciplinary Center, University of Maryland, MD, USA

***Corresponding author.**

E-mail: zxie@lasg.iap.ac.cn

REFERENCES

1. Heimann, M. From ICDC1 in Bern 1981 to ICDC9 in Beijing 2013 a review of global carbon cycle research during the past three decades. *ICDC9: The Ninth International Carbon Dioxide Conference*, Beijing, 3–7 June 2013.
2. Le Quéré, C, Andres, RJ and Boden, T. *Earth Syst Sci Data*, 2013; **5**: 165–85
3. Yu, ZC, Loisel, J and Brosseau, DP et al. *Geophys Res Lett*, 2010; **37**: L13402
4. Lu, DR and Liao, H. Recent progresses of the program 'Carbon Budget and Relevant Issues in Response to Climate Change'—a strategic priority research program of the Chinese Academy of Sciences. *ICDC9: The Ninth International Carbon Dioxide Conference*, Beijing, 3–7 June 2013.
5. Tian, XJ, Xie, ZH and Dai, A. *J Geophys Res* 2008; **113**: D21124.
6. Tian, XJ and Xie, ZH. *Tellus Ser A* 2012; **64**: 18375.
7. Jia, BH, Tian, XJ and Xie, ZH et al. *J Geophys Res* 2013; **118**: 3972–85.
8. Qi, Y. China's economic growth and the global carbon budget. *ICDC9: The Ninth International Carbon Dioxide Conference*, Beijing, 3–7 June 2013.
9. Piao, SL, Fang, JY and Ciais, P et al. *Nature* 2009; **458**: 1009–13.
10. Jiao, NZ, Tang, K and Cai, HY et al. *Nat Rev Microbiol* 2011; **9**: 75–8.