Modeling of CO_2 and CH_4 Fluxes in the Arctic

Qianlai Zhuang

Department of Earth & Atmospheric Sciences and Department of Agronomy, Purdue University, West Lafayette, IN, USA, Email: qzhuang@purdue.edu

Jerry M. Melillo

The Ecosystems Center, Marine Biological Laboratory, Woods Hole, MA

Ronald G. Prinn

MIT Joint Program on the Science and Policy of Global Change

MIT, Cambridge, MA

The Arctic stores a one-third of earth surface soil carbon, occupies a half of world wetlands, and is dominated by continuous or discontinuous permafrost. It has experienced unique changes in its atmospheric climate comparing to other regions on Earth in the last half century. Wildfires in its terrestrial ecosystems have been increasingly more active. Consequently, permafrost degradation has been expedited. The fate of its large amount of carbon is uncertain. One speculation is that the release of CO_2 and CH_4 to the atmosphere will be dramatic due to enhanced soil aerobic and anaerobic decomposition. In turn, these gases will exert a positive feedback to the global climate system.

While the potential increase of soil carbon release is of great concern, the climate will also affect plant growing season length and productivity. The possible enhanced photosynthesis due to warming will alter the net CO_2 exchanges between the terrestrial ecosystems and atmosphere in the region. Changes of snow cover, soil hydrology, and nutrient condition, especially nitrogen availability, all will affect plant carbon uptake through photosynthesis. Permafrost stability directly associated with soil hydrology will affect the growing season length and plant productivity. In the meantime, the increase of soil decomposition due to warming may provide more nutrients (e.g., nitrogen) to plant, enhancing photosynthesis. Permafrost degradation will lead to a drier condition for some areas and a wetter one for others. Different soil wetness and drainage conditions will influence plant carbon uptake and affect CO_2 and CH_4 fluxes, as dry soils tend to be a CO_2 source and a CH_4 sink, while wet conditions will enhance CH_4 production and suppress aerobic decomposition. Fires will lead to a large amount of immediate greenhouse gas emissions. Fire disturbances will decrease plant productivity, change soil decomposition, alter soil nutrient conditions, degrade permafrost, change soil hydrological cycle, and likely lead to a more complex pattern of CO_2 and CH_4 dynamics in the region.

To quantify the net budget of CO_2 and CH_4 fluxes, a process-based biogeochemistry model, the Terrestrial Ecosystem Model (TEM), is used. TEM incorporates spatially-explicit data pertaining to climate, vegetation, soil, and elevation to estimate the changes of carbon and nitrogen pool sizes and CO_2 and CH_4 fluxes. To model CO_2 dynamics, the model and parameters have been well documented, and the model was augmented by incorporating the permafrost dynamics, fire disturbances, and more sophisticated hydrological models (Zhuang et al., 2001, 2002, 2003; Euskirchen, 2006; Balshi et al., 2007). In TEM, the net exchange of CO_2 between the terrestrial biosphere and atmosphere (NEP) is calculated as the difference between the uptake of atmospheric CO_2 associated with photosynthesis (i.e., gross primary production or GPP) and the release of CO_2 through autotrophic respiration (R_A) associated with plant growth and maintenance and through heterotrophic respiration (R_H) associated with decomposition of organic matter. The difference between GPP and R_A is defined as net primary production (NPP). The fluxes GPP, R_A and R_H are influenced by changes in atmospheric CO_2, climate variability and change, and the freeze-thaw status of the soil. To model CH_4 fluxes, TEM explicitly simulates the processes of CH_4 production (methanogenesis) and CH_4 oxidation (methanotrophy), as well as the transport of the gas between the soil and the atmosphere. The net CH_4 emissions from soils to the atmosphere are the total of the CH_4 fluxes at the soil/water-atmosphere boundary via different transport pathways (Zhuang et al., 2004, 2006, 2007). The transport pathways include molecular diffusion, ebullition, and plant-mediated emissions through the stems of vascular plants. CH_4 production is modeled as an anaerobic process that occurs in the saturated zone of the soil profile. Soil CH_4 production is influenced by carbon substrate availability, soil temperature, soil pH, and the availability of electron acceptors, which is related to redox potentials. Monthly NPP estimates in TEM are used to capture the effect of the spatial and temporal variations in root exudates on methanogenesis. CH_4 oxidation, which is modeled as an aerobic process that occurs in the unsaturated zone of the soil profile, is a function of the soil CH_4 concentration, soil temperature, soil moisture, and redox potential.

We apply TEM to quantify the current combined CO_2 and CH_4 budget and to project a set of alternative future budgets associated with various climate change scenarios and alternative assumptions about the importance of CO_2 stimulation of plant growth and carbon storage in plants and soils (Zhuang et al., 2006). For our regional simulations, we use gridded (0.5°x0.5°) input data on vegetation distribution, elevation, soil texture, soil-water pH, wetland distribution, and fractional inundation of wetlands. Climate data, including the monthly mean temperature, precipitation, and vapor pressure for each land grid cell in the high northern latitudes are developed using the MIT Integrated Global System Model (IGSM). We conduct a set of TEM simulations with a factorial design considering three plausible climate scenarios, with and without a CO_2 fertilization effect on photosynthesis, and three different fire disturbance regimes. In each simulation, TEM estimates the terrestrial CO_2 and CH_4 dynamics of each 0.5° latitude x 0.5° longitude grid cell from 1860 to 2100. We find that currently the region is a net source of carbon to the atmosphere at 276 Tg C yr^{-1}. We project that throughout the 21st century, the region will most likely continue as a net source of carbon and the source will increase by up to 473 Tg C yr^{-1} by the end of the century compared to the current emissions. Our simulations show that the arctic wetlands will function as a source of between 4.1 and 5.8 Pg C over the century, mainly as CH_4. By 2100, we project CH_4 emissions from the wetlands of the region would more than double over the century when anthropogenic emissions are high. Using a simulation modeling approach, Gedney and colleagues (Gedney et al., 2004) have also estimated a projected doubling of CH_4 emissions over this century. We calculate the greenhouse gas budget as the difference between net CO_2 and CH_4 exchanges using the measure of global warming potentials (GWPs). The calculation shows that the local-scale changes in radiative forcing can be large (Figure 1). However, our coupled carbon and climate model simulations show that these emissions will exert relatively small radiative forcing on the global climate system compared to large amounts of anthropogenic emissions. We estimate that the change in global radiative forcing associated with climate-related biogeochemical changes in the Arctic will be less than +/- 0.1 W m^{-2} over the course of the 21st Century.

In doing above analyses, however, we were lack of better information in the following areas at the time: 1) effects of CO_2 fertilization on net primary production and net ecosystem production in the region; 2) the fire history of forests in the region and the controls to the spatial and temporal patterns of this important disturbance; 3) the linkages between dynamic hydrology, lake formation and drainage, and permafrost thawing; and 4) the effects of atmospheric depositions including nitrogen and ozone on plant productivity. In addition, we were not able to consider large potential CH_4 emissions from thawing lakes as indicated by Walter et al., (2007) and the potential increase of emissions of CO_2 and CH_4 due to abundant carbon stored in permafrost (Zimov et al., 2007). Factoring these effects, processes, and sources into our future modeling of CO_2 and CH_4 dynamics will revise our quantification of these greenhouse gases budget in the Arctic.

Reference:

Balshi M.S., A.D.McGuire, Q. Zhuang, J.M.Melillo, D.W. Kicklighter, E.Kasischke, C. Wirth, M. Flannigan, J.Harden, J.S.Clein, T.J. Burnside, J.McAllister, W.A.Kurz, M.Apps, and A. Shvidenko, 2007, The role of historical fire disturbance in the carbon dynamics of the pan-boreal region: A process-based analysis. *J. Geophys. Res.*, 112, G02029.

Euskirchen, E.S., A.D. McGuire, D.W. Kicklighter, Q. Zhuang, J.S. Clein, R.J. Dargaville, D.G. Dye, J.S. Kimball, K.C. McDonald, J.M. Melillo, V.E. Romanovsky, N.V. Smith, 2006, Importance of recent shifts in soil thermal dynamics on growing season length, productivity, and carbon sequestration in terrestrial high-latitude ecosystem, *Global Change Biology,* 12, 731-750, doi:10.1111/j.1365-2486.2006.01113.x.

Gedney, N., P. M. Cox, and C. Huntingford, 2004, Climate feedback from wetland methane emissions, *Geophys. Res. Lett.*, **31**, L20503, doi:10.1029/2004GL020919.

Prinn, R., H. Jacoby, A. Sokolov, C. Wang, X. Xiao, Z. Yang, R. Eckaus, P. Stone, D. Ellerman, and J. M. Melillo et al. 1999, Integrated global system model for climate policy assessment: Feedbacks and sensitivity studies. *Climatic Change* **41**(3/4), 469-546.

Walter, K.M., Smith, L.C. and Chapin, F.S., III. 2007, Methane bubbling from northern lakes: Present and future contributions to the global methane budget. *Philosophical Transactions of the Royal Society A*, 365, 1657-1676

Zhuang, Q., J. M. Melillo, A. D. McGuire, D. W. Kicklighter, R. G. Prinn, P. A. Steudler, B. S. Felzer, and S. Hu, 2007, Net emissions of CH4 and CO2 in Alaska: implications for the region's greenhouse gas budget, *Ecological Applications*, 17(1), 203–212.

Zhuang, Q., J. M. Melillo, M. C. Sarofim, D W. Kicklighter, A. D. McGuire, B. S. Felzer, A. Sokolov, R. G. Prinn, P. A. Steudler, and S. Hu, 2006, CO2 and CH4 exchanges between land ecosystems and the atmosphere in northern high latitudes over the 21st century, *Geophys. Res. Lett*., 33, L17403, doi:10.1029/2006GL026972.

Zhuang, Q., J. M. Melillo, D. W. Kicklighter, R. G. Prinn, D. A. McGuire, P. A. Steudler, B. S. Felzer, and S. Hu, 2004, Methane fluxes between terrestrial ecosystems and the atmosphere at northern high latitudes during the past century: A retrospective analysis with a process-based biogeochemistry model, *Global Biogeochemical Cycles*, 18, GB3010, doi:10.1029/2004GB002239.

Zhuang, Q., A. D. McGuire, J. M. Melillo, J. S. Clein, R. J. Dargaville, D. W. Kicklighter, R. B. Myneni, J. Dong, V. E. Romanovsky, J. Harden, and J. E. Hobbie, 2003, Carbon cycling in extratropical terrestrial ecosystems of the Northern Hemisphere during the 20th Century: A modeling analysis of the influences of soil thermal dynamics, *Tellus*, 55B, 751-776.

Zhuang, Q., A. D. McGuire, K. P. O'Neill, J. W. Harden, V. E. Romanovsky, J. Yarie, 2002, Modeling the soil thermal and carbon dynamics of a fire chronosequence in Interior Alaska, *J. Geophy. Res.*, 107, 8147, doi:10.1029/2001JD001244 [Printed 108(D1), 2003].

Zimov, S. A., E. A. G. Schuur, and F. S. Chapin III, 2006, Permafrost and the global carbon budget, *Science,* **312**, 1612-1613.

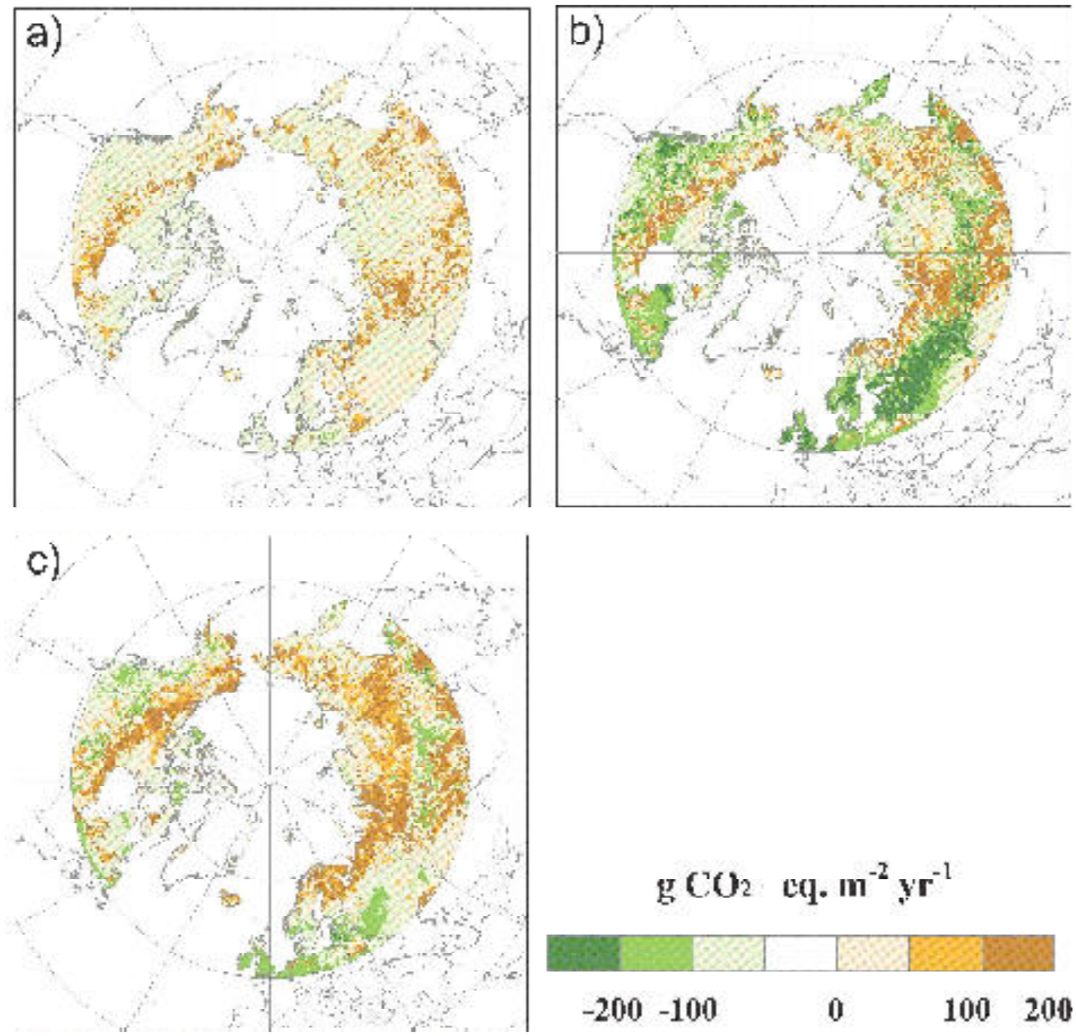

Figure 1. Spatial distribution of net greenhouse gas exchanges simulated with TEM (a) in the 1990s, (b) in the 2090s with CO_2 fertilization effects, and (c) in the 2090s without CO_2 fertilization effects. Positive values indicate greenhouse gas sources to the atmosphere. Negative values indicate greenhouse gas sinks from the atmosphere to terrestrial ecosystems. The CO_2 equivalent of net CH_4 exchanges is calculated as global warming potentials (GWPs) on the 100-year time horizon, i.e., one gram CH_4 is equivalent to 23 g CO_2. The maps are simulation results of the "Reference" climate and atmospheric CO_2 scenario. The MIT Integrated Global Systems Model (IGSM) is used to develop monthly estimates of surface air temperature, precipitation, and vapour pressure for three future climate and atmospheric CO_2 concentration scenarios for input into TEM by mapping the projected zonal-average IGSM changes to latitude and longitude by adjusting observed current climate (Prinn et al., 1999). The annual anthropogenic CO_2 emissions in 2100 for the "Reference" scenario are equivalent to 73 Pg CO_2. The emissions correspond to projected atmospheric CO_2 mole fraction (parts per million, ppm) by 2100 of about 694 ppm. In these maps, the effects of fire disturbances have also been considered (Zhuang et al., 2006).