DOE Final Report on
Quantifying Feedbacks from Abrupt Changes in High-Latitude Trace-Gas Emissions
(Grant: DE-FG02-08ER64599)

Qianlai Zhuang
Purdue University

This is a collaborative project that includes MIT, University of Alaska Fairbanks, Marine Biological Laboratory at Woods Hole, MA in addition to Purdue. The major role of Purdue is to further develop Methane Dynamics Model (MDM) that can be integrated to MIT Integrated Global System Model (MIT-IGSM), which is used to test our research hypotheses. During the three-year project period, Purdue University has specifically accomplished the following.

(1) Revised the existing Methane Dynamics Model (MDM) to consider the effects of changes of atmospheric pressure. The algorithms of soil methane production, soil methane consumption, and methane transport to the atmosphere have been revised to consider the effects of changes of atmospheric methane concentrations and pressure changes due to dynamics of various gases in soil profile in addition to other existing factors. We have further evaluated these revisions with observed methane fluxes at various wetland ecosystem sites (Tang et al., 2010).

(2) Applied the methane dynamics model (MDM) to Siberian region to demonstrate that ebullition estimates could increase previous estimates of regional terrestrial CH₄ emissions 3- to 7-fold in Siberia (Anthony Walter et al., 2010).

(3) Conducted an analysis of the carbon balance of the Arctic Basin from 1997 to 2006 to show that terrestrial areas of the Arctic were a net source of 41.5 Tg CH₄ yr⁻¹ that increased by 0.6 Tg CH₄ yr⁻¹ during the decade of analysis, a magnitude that is comparable with an atmospheric inversion of CH₄. Because the radiative forcing of the estimated CH₄ emissions is much greater than the CO₂ sink, the analysis suggests that the Arctic Basin is a substantial net source of green house gas forcing to the climate system (McGuire et al., 2010).

(4) Improved the quantification of CH₄ fluxes in the Arctic with inversion methods, we developed a series of inversion and transport techniques to assimilate the satellite retrieval data methane into inversion models (Tang and Zhuang, 2010, 2011). Our developed scheme to propagate correlations between online and off-line state variables in atmospheric inversion is extended to the fixed-lag ensemble square root Kalman smoother and fixed-lag square root sigma-point Kalman smoother, allowing us to treat nonlinear observation operators easily.

(5) Evaluated AIRS CH₄ retrieval data with a transport and inversion model and surface flux and aircraft data (Xiong et al., 2010). Our study demonstrated that an apparent increase of CH₄ over Alaska associated with the 2004 Alaska forest fire and a negative bias of the atmospheric transport and chemistry model in northern high latitudes. The larger bias of the model simulations in the late winter to early spring may indicate possible unidentified CH₄ emission sources (e.g., the use of energy or gas leakage) during this period, but more studies will be needed due to the retrieval uncertainties in the polar winter season. The summer increase of

MUT-CH₄ is related to surface emission, but the enhanced convection in summer is likely the most important driver.

(6) To better quantify methane emissions from wetlands, we extended the MDM within a biogeochemistry model, the Terrestrial Ecosystem Model (TEM), to include a large-scale hydrology model, the variable infiltration capacity (VIC) model. The VIC model provides the required inputs, including freezing and thawing fronts, soil temperature and moisture, to the methane module. The effect of topography on the redistribution of soil moisture and water table depth was explicitly modeled using the TOPMODEL approach. The coupled modeling framework was applied to the Yukon River basin at a spatial resolution of 1 km from 1986 to 2005. The simulations show that the average annual net emissions of CH₄ from the region are 4.01 Tg CH₄ yr⁻¹. El Niño phenomena usually lead to positive emission anomalies, while decreases in net CH₄ emissions may be associated with strong La Niña events. Precipitation was found to be more closely related to CH₄ dynamics than to soil temperature and active layer depth during the study period. This study suggests that the effects of soil freezing and thawing processes and the effects of microtopography on hydrology should be considered in the quantification of CH₄ emissions (Lu and Zhuang, 2012).

(7) More recently, we developed a single box atmospheric chemistry model involving atmospheric methane (CH₄), carbon monoxide (CO) and radical hydroxyl (OH) to analyze atmospheric CH₄ concentrations from 1984 to 2008. We found that, when OH is allowed to vary, the modeled CH₄ is 20 ppb higher than observations from the NOAA/ESRL and AGAGE networks for the end of 2008. However, when the OH concentration is held constant at 106 molecule cm⁻³, the simulated CH₄ shows a trend approximately equal to observations. Both simulations show a clear slowdown in the CH₄ growth rate during recent decades, from about 13 ppb yr⁻¹ in 1984 to less than 5 ppb yr⁻¹ in 2003. Furthermore, if the constant OH assumption is credible, we think that this slowdown is mainly due to a pause in the growth of wetland methane emissions. In simulations run for the Northern and Southern Hemispheres separately, we find that the Northern Hemisphere is more sensitive to wetland emissions, whereas the southern tends to be more perturbed by CH₄ transportation, dramatic OH change, and biomass burning. When measured CO values from NOAA/ESRL are used to drive the model, changes in the CH₄ growth rate become more consistent with observations, but the long-term increase in CH₄ is underestimated. This shows that CO is a good indicator of short-term variations in oxidizing power in the atmosphere. The simulation results also indicate the significant drop in OH concentrations in 1998 (about 5% lower than the previous year) was probably due to an abrupt increase in wetland methane emissions during an intense El Niño event. Using a fixed-lag Kalman smoother, we estimate the mean wetland methane flux is about 128 Tg yr⁻¹ through the period 1984–2008. This study demonstrates the effectiveness in examining the role of OH and CO in affecting CH₄ (Tan and Zhuang, 2012).

PUBLICATIONS

Anthony, K. M. W., D. A. Vas, L. Brosius, F. S. Chapin III, S. A. Zimov, and Q. Zhuang (2010), Estimating methane emissions from northern lakes using ice bubble surveys, *Limnol. Oceanogr.: Methods*, 8, 592-609.

Jiang, Y., Q. Zhuang, and O'Donnell, A. J. (2012) Modeling thermal dynamics of active layer soils and near-surface permafrost using a fully coupled water and heat transport model, *Journal of Geophysical Research*, Vol. 117, No. D11, D11110.

Jiang, Y., Q. Zhuang, S. Schaphoff, S. Sitch, A. Sokolov, D. Kicklighter, and J. Melillo (2012) Uncertainty analysis of vegetation distribution in the northern high latitudes during the 21st century with a dynamic vegetation model, *ecology and Evolution*, doi: 10.1002/ece3.85.

Jiang, Y. and Q. Zhuang (2011), Extreme value analysis of wildfires in Canadian boreal forest ecosystems, *Canadian Journal of Forest Research* 41:1836-1851, 10.1139/x11-102.

Lu, X. and Q. Zhuang (2011), Areal changes of land ecosystems in the Alaskan Yukon River Basin from 1984 to 2008, *Environ. Res. Lett.* 6 034012, DOI 10.1088/1748-9326/6/3/034012

Lu, X. and Q. Zhuang (2012) Modeling methane emissions from the Alaskan Yukon River basin, 1986-2005, by coupling a large-scale hydrological model and a process-based methane model, *Journal of Geophysical Research*, DOI:10.1029/2011JG001843.

McGuire, A.D., D.J. Hayes, D.W. Kicklighter, M. Manizza, Q. Zhuang, M. Chen, M. J. Follows, K. R. Gurney, J. W. McClelland, J. M. Melillo, B. J. Peterson, and R. G. Prinn (2010), An analysis of the carbon balance of the Arctic Basin from 1997 to 2006, *Tellus*, DOI: 10.1111/j.1600-0889.2010.00497.x.

Tang, J. and Q. Zhuang (2010), Technical Note: Methods for interval constrained atmospheric inversion of methane, *Atmos. Chem. Phys. Discuss.*, 10,1998120004, 2010, www.atmos-chem-phys-discuss.net/10/19981/2010/doi:10.5194/acpd-10-19981-2010.

Tang, J. and Q. Zhuang (2011), Technical Note: Propagating correlations in atmospheric inversions using different Kalman update smoothers, *Atmos. Chem. Phys.*, 11, 921-929, doi:10.5194/acp-11-921-2011.

Tang, J., Zhuang, Q., Shannon, R. D., and White, J. R. (2010), Quantifying wetland methane emissions with process-based models of different complexities, *Biogeosciences*, 7, 3817-3837, doi:10.5194/bg-7-3817-2010.

Tan, Z. and Q. Zhuang (2012), An analysis of atmospheric CH₄ concentrations from 1984 to 2008 with a single box atmospheric chemistry model, *Atmos. Chem. Phys. Discuss.*, 12, 1-23, 2012, www.atmos-chem-phys-discuss.net/12/1/2012/doi:10.5194/acpd-12-1-2012.

Xiong, X., C. D. Barnet, Q. Zhuang, T. Machida, C. Sweeney, and P. K. Patra (2010), Mid-upper tropospheric methane in the high Northern Hemisphere: Spaceborne observations by AIRS, aircraft measurements, and model simulations, *J. Geophys. Res.*, 115, D19309, doi:10.1029/2009JD013796.

Zhu, X. and Q. Zhuang and M. Chen Sirin A., Melillo J., Kicklighter D., Sokolov A., Song L.

(2011), Rising methane emissions in response to climate change in Northern Eurasia during the 21st century, Environ. Res. Lett. 6 045211 doi:10.1088/1748-9326/6/4/045211.

Zhuang, Q., J. Melillo, and R. Prinn (2012) Modeling of CO₂ and CH₄ Fluxes in the Arctic, in Proceedings of the Northern Eurasian Earth Science Partnership Initiative (NEESPI) Regional Science Team Meeting devoted to the High Latitudes, 2-6 June, 2009, Helsinki, Finland, University of Helsinki Press, Helsinki, Finland ~ 153pp. REPORT SERIES IN AEROSOL SCIENCE N:o 130 (2012), Groisman, P.Ya., A. Reissell, and M. Kaukolehto (eds.)

Zhuang, Q., Y. Lu, and M. Chen (2011), An inventory of global N₂O emissions from the soils of natural terrestrial ecosystems, Atmospheric Environment. 1352-2310.doi: 10.1016/j.atmosenv.2011.11.036.