DOE Final Report on

Collaborative Research: Quantifying Climate Feedbacks of the Terrestrial Biosphere under Thawing Permafrost Conditions in the Arctic

(Award No. DE-SC0007007)

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RESEARCH SUMMARY AND GOAL

Our overall goal is to quantify the potential for threshold changes in natural emission rates of trace gases, particularly methane and carbon dioxide, from pan-arctic terrestrial systems under the spectrum of anthropogenically-forced climate warming, and the conditions under which these emissions provide a strong feedback mechanism to global climate warming. This goal is motivated under the premise that polar amplification of global climate warming will induce widespread thaw and degradation of the permafrost, and would thus cause substantial changes to the landscape of wetlands and lakes, especially thermokarst (thaw) lakes, across the Arctic. Through a suite of numerical experiments that encapsulate the fundamental processes governing methane emissions and carbon exchanges – as well as their coupling to the global climate system - we intend to test the following hypothesis in the proposed research:

There exists a climate warming threshold beyond which permafrost degradation becomes widespread and stimulates large increases in methane emissions (via thermokarst lakes and poorly-drained wetland areas upon thawing permafrost along with microbial metabolic responses to higher temperatures) and increases in carbon dioxide emissions from well-drained areas. Besides changes in biogeochemistry, this threshold will also influence global energy dynamics through effects on surface albedo, evapotranspiration and water vapor. These changes would outweigh any increased uptake of carbon (e.g. from peatlands and higher plant photosynthesis) and would result in a strong, positive feedback to global climate warming.

MAJOR RESEARCH ACHIEVEMENTS AND FINDINGS

1) Development of a biogeochemistry model of Arctic lake systems (Led by Purdue and UAF)

To date, methane emissions from lakes in the pan-arctic region are poorly quantified. In order to investigate the response of methane emissions from this region to global warming, we developed a process-based climate-sensitive lake biogeochemical model (Figure 1). The processes of methane production, oxidation and transport were modeled within a one-dimensional sediment and water column. The sizes of ^{14}C-enriched and ^{14}C-depleted carbon pools were explicitly parameterized. The model was validated using observational data from five lakes located in Siberia and Alaska, representing a large variety of environmental conditions in the arctic. The model simulations agreed well with the measured water temperature and dissolved CH_4 concentration (mean error less than 1 °C and 0.2 μM respectively). The modeled CH_4 fluxes were highly consistent with observations from these lakes. We found that bubbling rate controlling nitrogen (N_2) stripping was the most important factor in determining CH_4 fraction in bubbles. Lake depth, as well as ice cover thickness in shallow waters, was also a controlling factor. This study demonstrated that the thawing of Pleistocene-aged organic-rich yedoma can fuel sediment methanogenesis by supplying a large quantity of labile organic carbon. Observations and modeling results both confirmed that methane emission rate at thermokarst margins of yedoma lakes was much larger (up to 538 mg CH_4 m^{-2} day^{-1}) than that at non-thermokarst zones in the same lakes and a non-yedoma non-thermokarst lake (less than 42 mg CH_4 m^{-2} day^{-1}). The seasonal variability of methane emissions can be explained primarily by energy input and organic carbon availability (*Tan et al., 2015*).

2) ***Quantification of regional lake emissions of CH_4 in the Arctic (Led by Purdue)***

Recent field studies showed that methane emissions from arctic thermokarst lakes are significant and could increase by two to four folds due to global warming. But the estimates of this source are still poorly constrained. By using a process-based climate-sensitive lake biogeochemical model, we estimated that the total amount of methane emissions from arctic lakes is 11.86 Tg yr^{-1}, which is in the range of recent estimates of 7.1-17.3 Tg yr^{-1} and is on the same order of methane emissions from northern high-latitude wetlands (Figure 2). The methane emission rate varies spatially over high latitudes from 110.8 mg CH_4 m^{-2} day^{-1} in Alaska to 12.7 mg CH_4 m^{-2} day^{-1} in northern Europe. Under Representative Concentration Pathways (RCP) 2.6 and 8.5 future climate scenarios, methane emissions from arctic lakes will increase by 10.3 and 16.2 Tg CH_4 yr^{-1}, respectively by the end of the 21st century (*Tan and Zhuang, 2015a*)

3) ***Modeling evolution of land and lake areas and its impacts on regional CH_4 emissions in the Arctic (Led by Purdue)***

The importance of methane emissions from northern high-latitude lakes in the global carbon cycle has been revealed in recent studies, but large uncertainty remains on how this methane source will respond to climate change. Here we adapt a region-specific landscape evolution model to a pan-arctic scale to constrain the estimate of these emissions, through simulating the evolution of thaw lakes and coupling it with a lake methane biogeochemical model for both thermokarst and non-thermokarst lakes in the pan-arctic. Our simulations show that the extent of thaw lakes will expand throughout the century in the northern areas of the pan-arctic where the reworking of epigenetic ice in drained lake basins will not be interrupted. The projected methane emissions by 2100 are 28.3±4.5 Tg CH_4 yr^{-1} under a low warming scenario (Representative Concentration Pathways (RCP) 2.6) and 32.7±5.2 Tg CH_4 yr^{-1} under a high warming scenario (RCP 8.5), which are about 2.5 and 2.9 times of the simulated present-day emissions. The cumulative amount of permafrost carbon that will be mineralized via methanogenesis is 3.4±0.8 Pg C under the weak warming condition and 3.9±0.9 Pg C under the strong warming condition, representing a small fraction of the global soil carbon pool (Figure 3). The study further indicates that energy input via air temperature is the dominant factor of controlling methane emissions from pan-arctic lakes in this century (*Tan and Zhuang, 2015b*).

4) ***Development of a coupled land surface biogeochemistry model for modeling wetland methane emissions (Led by Purdue and MIT)***

We have coupled our methane module (MDM) with the Community Land Surface Model (CLM 3.5) to have an integrated CLM-MDM. The model was parameterized for different plant function types. CLM-MDM was also revised to estimate the fraction of saturated areas in a grid cell and partition the whole grid into two subgrids: inundated subgrid and non-inundated subgrid. In the inundated subgrid, the water table is fixed at soil surface. In the non-inundated subgrid, the water table is calculated with soil water content conservation, which means the total soil water content of two subgrids should equal the soil water content without partitioning. Using the CLM-MDM simulated wetland distribution, a global wetland and lake database (GLWD), and a well-used wetland database (Matthews and Fung, 1987), we conducted three sets of simulations with the coupled model at the global scale for the period of 1950-2007 (Figure 4; *Zhuang et al., 2015*). Our simulations show that the global wetland emissions are, on average, 200, 275, and 300 Tg C per year with three wetland distribution datasets, respectively during the study period.

These estimates are within the current estimates of wetland emissions using both process-based modeling and atmospheric inversions.

5) Quantification of biophysical and biogeochemical feedbacks to the Climate system in the Arctic (Led by Purdue)

Terrestrial ecosystems in northern high latitudes exert both biogeochemical and biogeophysical feedbacks to the global climate system by modifying land-atmospheric fluxes of greenhouse gases, energy, and water. However, their relative importance has not been well understood. We use a process-based terrestrial ecosystem model (TEM) to quantify both feedbacks of terrestrial ecosystems north of 50°N under four climate change scenarios (Figure 5). The spatially explicit quantification accounts for both biogeochemical feedbacks associated with ecosystem net CH_4 exchanges (NME) and net CO_2 exchanges (NCE), and biogeophysical feedbacks associated with the changes in surface energy due to snow cover and vegetation biomass dynamics. Our results show that (1) northern terrestrial ecosystems will exert a positive feedback or heating effect to the atmosphere over the period 2010-2099, leading to a radiative forcing equivalent to a release of 40~225 Pg CO_2 into the atmosphere depending on different climate scenarios; (2) among four biogeochemical/biogeophysical feedbacks, feedbacks due to snow cover and NME will be consistently stronger than those due to NCE and biomass dynamcis under four climate scenarios; and (3) biogeophysical feedbacks will dominate the total feedbacks since the combination of NME-induced positive feedbacks and NCE-induced negative feedbacks results in a small positive biogeochemical feedback (*Zhu and Zhuang, 2015*).

6) Terrestrial Loading of Dissolved Organic Carbon (DOC) to Arctic River Networks (MBL Led)

Terrestrial carbon dynamics influence the contribution of dissolved organic carbon (DOC) to river networks in addition to hydrology. In this study, we use a biogeochemical process model to simulate the lateral transfer of DOC from land to the Arctic Ocean via riverine transport. We estimate that, over the 20th century, the pan-Arctic watershed has contributed, on average, 32 Tg C/yr of DOC to river networks emptying into the Arctic Ocean with most of the DOC coming from the extensive area of boreal deciduous needle-leaved forests and forested wetlands in Eurasian watersheds. We also estimate that the rate of terrestrial DOC loading has been increasing by 0.037 Tg C/yr^2 over the 20th century primarily as a result of climate-induced increases in water yield. These increases have been offset by decreases in terrestrial DOC loading caused by wildfires. Other environmental factors (CO2 fertilization, ozone pollution, atmospheric nitrogen deposition, timber harvest, agriculture) are estimated to have relatively small effects on terrestrial DOC loading to arctic rivers. The effects of the various environmental factors on terrestrial carbon dynamics have both offset and enhanced concurrent effects on hydrology to influence terrestrial DOC loading and may be changing the relative importance of terrestrial carbon dynamics on this carbon flux. Improvements in simulating terrestrial DOC loading to pan-Arctic rivers in the future will require better information on the production and consumption of DOC within the soil profile, the transfer of DOC from land to headwater streams, the spatial distribution of precipitation and its temporal trends, carbon dynamics of larch-dominated ecosystems in eastern Siberia, and the role of industrial organic effluents on carbon budgets of rivers in western Russia (Kicklighter et al., 2014).

In the ensuing time period, we have also collaborated with our Purdue and MIT colleagues to examine: 1) how evapotranspiration and water availability have been changing in Northern Eurasia and may change in the future including the impact of forcing uncertainties (Liu et al., 2013, 2014, 2015); 2) the impacts of recent permafrost thaw on land-atmosphere greenhouse gas exchange across the Pan-Arctic; 3) how climate-induced vegetation shifts may affect future land use and associated carbon fluxes in Northern Eurasia (Kicklighter et al. ,2014); and 4) how wetland inundation extent influences net CO_2 and CH_4 fluxes from northern high latitudes (Zhuang et al., 2015).

7) *Effects of Climate-induced Vegetation Shifts on Future Land Use and Carbon Fluxes (MBL and MIT led)*

Climate change will alter ecosystem metabolism and may lead to a redistribution of vegetation and changes in fire regimes in Northern Eurasia over the 21st century. Land management decisions will interact with these climate-driven changes to reshape the region's landscape. Here we present an assessment of the potential consequences of climate change on land use and associated land carbon sink activity for Northern Eurasia in the context of climate-induced vegetation shifts. Under a 'business-as-usual' scenario, climate-induced vegetation shifts allow expansion of areas devoted to food crop production (15%) and pastures (39%) over the 21st century. Under a climate stabilization scenario, climate-induced vegetation shifts permit expansion of areas devoted to cellulosic biofuel production (25%) and pastures (21%), but reduce the expansion of areas devoted to food crop production by 10%. In both climate scenarios, vegetation shifts further reduce the areas devoted to timber production by 6–8% over this same time period. Fire associated with climate-induced vegetation shifts causes the region to become more of a carbon source than if no vegetation shifts occur. Consideration of the interactions between climate-induced vegetation shifts and human activities through a modeling framework has provided clues to how humans may be able to adapt to a changing world and identified the tradeoffs, including unintended consequences, associated with proposed climate/energy policies (Kicklighter et al., 2014).

In a follow-up to the work described above, we have also examined potential teleconnections in land use and carbon and water dynamics between Northern Eurasia and the rest of the globe. The largest increase of surface air temperature and related climate extremes have occurred in Northern Eurasia in recent decades, and are projected to continue during the 21st century. The changing climate will affect biogeography, land cover and biogeochemical cycles in the region, which in turn, will affect how global land use evolves in the future as humans attempt to mitigate and adapt to climate change. Regional land-use changes, however, also depend on pressures imposed by the global economy and environmental changes. Feedbacks from future land-use change will further modify regional and global biogeochemistry and climate. With the modeling framework described by Kicklighter et al. (2014) we explored how climate-induced vegetation shifts in Northern Eurasia will influence land-use change and carbon cycling across the globe during the 21st century. We find that, at the global scale, while more land will be allocated towards food and biofuel crops due to increasing population and associated economic development, the climate-induced vegetation shifts in Northern Eurasia also significantly affect global land use and result in a global cumulative carbon sink of about 63 Pg C under the policy scenario that limits CO_2-equivelent greenhouse gas concentrations to 480 ppmv by the end of the 21st century. In comparison with the policy scenario, under a no-policy scenario where CO_2-equivelent greenhouse gas concentrations reach 870 ppmv by the end of 21st century, the global cumulative carbon sink is 11 Pg C less mainly due to carbon lost from global grasslands. Cumulative evapotranspiration from global terrestrial ecosystems considering global land-use changes with vegetation shifts in northern Eurasia is 8.05 and 8.35 million km^3 for the policy and no-policy scenarios, respectively. This analysis was presented at the European Geosciences Union General Assembly 2015 (Zhuang et al. 2015a).

8) Impacts of Recent and Future Permafrost Thaw on Land-Atmosphere Greenhouse Gas Exchange (Purdue and MBL led)

Permafrost thaw and the subsequent mobilization of carbon (C) stored in previously frozen soil organic matter (SOM) have the potential to be a strong positive feedback to climate. As the northern permafrost region experiences as much as a doubling of the rate of warming as the rest of the Earth, the vast amount of C in permafrost soils is vulnerable to thaw, decomposition and release as atmospheric greenhouse gases. Diagnostic and predictive estimates of high latitude terrestrial C fluxes vary widely among different models depending on how dynamics in permafrost, and the seasonally thawed 'active layer' above it, are represented. Here, we employ a process-based model simulation experiment to assess the net effect of active layer dynamics on this 'permafrost carbon feedback' in recent decades, from 1970 to 2006, over the circumpolar domain of continuous and discontinuous permafrost. Over this time period, the model estimates a mean increase of 6.8 cm in active layer thickness across the domain, which exposes a total of 11.6 Pg C of thawed SOM to decomposition. According to our simulation experiment, mobilization of this previously frozen C results in an estimated cumulative net source of 3.7 Pg C to the atmosphere since 1970 directly tied to active layer dynamics. Enhanced decomposition from the newly exposed SOM accounts for the release of both CO_2 (4.0 Pg C) and CH_4 (0.03 Pg C), but is partially compensated by CO_2 uptake (0.3 Pg C) associated with enhanced net primary production of vegetation. This estimated net C transfer to the atmosphere from permafrost thaw represents a significant factor in the overall ecosystem carbon budget of the Pan-Arctic, and a nontrivial additional contribution on top of the combined fossil fuel emissions from the eight Arctic nations over this time period (*Hayes et al., 2014).*

In the Kicklighter et al. (2014) analyses, the influence of permafrost degradation on future carbon fluxes from Northern Eurasia was not considered. Recent modeling studies have suggested that carbon sinks in pan-arctic ecosystems may be weakening partially as a result of warming-induced increases in soil organic matter (SOM) decomposition and the exposure of previously frozen SOM to decomposition. This weakening of carbon sinks is likely to continue in the future as vast amount of carbon in permafrost soils is vulnerable to thaw. To examine the importance of considering soil thermal dynamics when determining the effects of climate change and land-use change on carbon dynamics in Northern Eurasia during the 21st century, we compared results for a "business as usual" scenario between a version of the Terrestrial Ecosystem Model that does not consider soil thermal dynamics (TEM 4.4) and a version that does consider these dynamics (TEM 6.0). In this scenario, which is similar to the IPCC Representative Concentration Pathways (RCP) 8.5 scenario, the net area covered by food crops and pastures in Northern Eurasia is assumed to remain relatively constant over the 21st century, but the area covered by secondary forests is projected to double as a result of timber harvest and the abandonment of land associated with displacement of agricultural land. Enhanced decomposition from the newly exposed SOM from permafrost thaw also increases nitrogen availability for plant production so that the loss of carbon from the enhanced decomposition is partially compensated by enhanced uptake and storage of atmospheric carbon dioxide in vegetation. Our results indicate that consideration of soil thermal dynamics have a large influence on how simulated terrestrial carbon dynamics in Northern Eurasia respond to changes in climate, atmospheric chemistry (e.g., carbon dioxide fertilization, ozone pollution, nitrogen deposition) and disturbances. This analysis was also presented at the European Geosciences Union General Assembly 2015 (Kicklighter et al. 2015).

In addition to the Hayes et al. (2014) and Kicklighter et al. (2014) studies, we have also examined how permafrost-induced soil thermal gradients influence vegetation distributions and associated carbon dynamics in the circumpolar north (45-90°N). To date, global carbon models have represented the influence of permafrost on carbon dynamics using simple assumptions. We conducted a study where a soil thermal model that couples water and heat transport is incorporated into a dynamic global vegetation model (LPJ-DGVM) and includes a more detailed representation of the thermal gradient imposed by permafrost, the distribution of soil organic carbon (SOC) in the soil profile, and the influence of the permafrost-induced soil thermal gradient on hydrology and the decomposition of SOC. The detailed representation of soil thermal gradient and associated carbon dynamics improved the ability to simulate seasonal variations in soil temperatures and net ecosystem exchange of carbon between land ecosystems and the atmosphere observed at several sites across northern latitudes; and seasonal variations in atmospheric carbon dioxide concentrations across the globe. The extended model estimates ~0.5 Pg C yr^{-1} higher net primary production mainly due to less summer root respiration associated with lower soil temperatures. Together with higher NPP, lower heterotrophic respiration (by ~0.4 Pg C yr^{-1}) also as a result of cooler summer soil temperature, leads to a stronger land C sink (+0.8 - 1.0 Pg C yr^{-1}) across the circumpolar north at present. Driven by a series of future climate scenarios, the extended model projects a more rapid increase in soil respiration accompanied by extensive permafrost thaw. However, except for the extreme warming conditions, concurrent increases in plant photosynthetic rate, due to warming and rising CO_2, overwhelm the enhanced ecosystem respiration such that boreal ecosystems remain a net carbon sink throughout this century. Moreover, the detailed representation of permafrost-induced soil thermal gradient slows the transition of the northern permafrost region from a C sink to a C source. This study highlights the importance of adequate modeling of permafrost in global dynamic vegetation models to quantify the carbon budget of boreal ecosystems. A paper that describes this analysis (Jiang et al. 2015) is currently under review at *Global and Planetary Change*.

9) Role of Land-use Legacy, Future Land-use Change and Climate Change on Projections of Terrestrial Carbon Fluxes (MIT and MBL led)

Because Northern Eurasia is a major player in the global carbon budget, we also used the TEM to investigate possible changes in terrestrial fluxes of carbon dioxide over Northern Eurasia over the 21st century, including uncertainties, and the relative contributions of land legacy, future land use change and future climate change on these fluxes. We conducted three sets of simulations using: (1) a fixed land cover corresponding to year 2005; (2) historical land use land cover change from 1500 to 2005 and fixed land cover corresponding to year 2005 until 2100; and (3) historical land use land cover change from 1500 to 2005 and RCP land use land cover change scenarios until 2100. Each set of simulations is forced by a large ensemble of climate simulations using the MIT IGSM-CAM model, which accounts for the uncertainty in projections of future climate change in order to obtain robust estimates of the contribution of land legacy, land use change and climate change. The climate ensemble consists of: two emissions scenarios, a "business as usual" unconstrained emissions scenario and a stabilization scenario, similar to, respectively, the RCP8.5 and RCP4.5 scenarios; three values of climate sensitivity (2.0°C, 2.5°C and 4.5°C corresponding to the 5th percentile, median, and 95th percentile of the marginal posterior probability density function with uniform prior) and associated net aerosol forcing chosen to best reproduce observed climate change; and five different representations of natural variability. Results of the analysis show that the three sources of changes in future terrestrial carbon fluxes have similar magnitudes. Land-use change is a net source of carbon to the atmosphere, primarily driven with the conversion of primary forest to secondary forest caused by the timber sector. Climate change is a net sink of carbon, associated with enhanced land productivity of boreal forest in the northern region and decreased productivity in the southernmost edge due to a northward migration of optimal climate conditions. Finally, land legacy is net sink of carbon, even larger than climate change, largely associated with the uptake of carbon by forests and cropland. An uncertainty analysis taking into account the range of probable future climate change and two RCP scenario of land use change identifies these results as robust.

This analysis also provides several important insights into the fate of terrestrial carbon fluxes in Northern Eurasia during the 21st century. First, not properly accounting for the large role of land legacy could results in particularly misleading estimates of future changes in the carbon cycle. Second, land-use change scenarios that do not account for climate-induced changes in land productivity can lead to inconsistent projections. In the case of this study, climate change shows a significant negative impact on cropland under RCP8.5, yet the land-use change scenario shows very little if no change in cropland area. Finally, the non-linearity of the system, as evaluated by the residual term (difference between the full simulation and sum of the simulations isolating the effects of land use change, climate change and land legacy), is limited, most likely because of the lack of consistency between the climate change scenarios and the economically-driven only land use change scenarios. This highlights the need for integrated economic and climate driven land use change modeling frameworks. This analysis was also presented at the European Geosciences Union General Assembly 2015 (Monier et al. 2015).

10) Effects of Changes in Wetland Inundation Extent on Net Fluxes of Carbon Dioxide and Methane in Northern High Latitudes (Purdue led)

The seasonal and interannual exchanges of carbon dioxide (CO_2) and methane (CH_4) between boreal land ecosystems and the atmosphere are still uncertain due to uncertain changes of inundation area. We applied the Terrestrial Ecosystem Model (TEM) with its Methane Dynamics Module (MDM) to evaluate how seasonal and interannual changes in wetland inundation extent might have influenced carbon dynamics in the region during 1993-2004. We find that consideration of these variations, on average, results in regional estimates of net methane sources of 67.8±6.2 Tg CH_4 yr^{-1} and the use of two static inundation extent datasets estimates the sources between 51.3±2.6 and 73.0±3.6 Tg CH_4 yr^{-1} during the period. In contrast, interannual changes of wetland inundation extent result in regional estimates of a net carbon sink of 1.28±0.03 Pg C yr^{-1} with a persistent wetland carbon sink from 0.38 to 0.41 Pg C yr^{-1} and a upland sink from 0.6 to 1.1 Pg C yr^{-1}. Taken together, despite the large methane emissions from wetlands, the region is a consistent greenhouse gas sink measured with global warming potentials (GWP) irrespective of the type of wetland datasets being used. However, the use of satellite-detected wetland inundation extent estimates a smaller regional GWP sink than that estimated using static wetland datasets. Our sensitivity analysis indicates that if wetland inundation extent increases or decreases by 10% in each wetland grid cell, the regional source of methane increases 13% or decreases 12%, respectively. In contrast, the regional NEE responds with only 7-9% changes to the changes in wetland inundation extent. Our analysis further indicates that wetlands play a disproportionally important role in affecting regional greenhouse gas budgets given that they only occupy a small fraction of the total land area in the region. A paper that describes this analysis (Zhuang et al. 2015b) is currently in revision at *Environmental Research Letters*.

PUBLICATIONS

Bohn, T. J., Melton, J. R., Ito, A., Kleinen, T., Spahni, R., Stocker, B. D., Zhang, B., Zhu, X., Schroeder, R., Glagolev, M. V., Maksyutov, S., Brovkin, V., Chen, G., Denisov, S. N., Eliseev, A. V., Gallego-Sala, A., McDonald, K. C., Rawlins, M.A., Riley, W. J., Subin, Z. M., Tian, H., **Zhuang, Q**., and Kaplan, J. O.: WETCHIMP-WSL: intercomparison of wetland methane emissions models over West Siberia, *Biogeosciences*, 12, 3321-3349, doi:10.5194/bg-12-3321-2015, 2015

Hayes, D. J., D. W. Kicklighter, A. D. McGuire, M. Chen, Q. Zhuang, F. Yuan, J. M. Melillo and S. D. Wullschleger (2014) The impacts of recent permafrost thaw on land-atmosphere greenhouse gas exchange. *Environmental Research Letters* **9**, 045005, doi: 10.1088/1748-9326/9/4/045005.

He, Y., Q. Zhuang**,** J. W. Harden, A. D. McGuire, Z. Fan, Y. Liu and K. P. Wickland (2014), The implications of microbial and substrate limitation for the fates of carbon in different organic soil horizon types of boreal forest ecosystems: a mechanistically based model analysis. *Biogeoscience*, 11, 4477-4491, doi:10.5194/bg-11-4477-2014

He, Y., J. Yang, Q. Zhuang, A. D. McGuire, Q. Zhu, Y. Liu, and R. O. Teskey (2014), Uncertainty in the fate of soil organic carbon: A comparison of three conceptually different decomposition models at a larch plantation, *J. Geophys. Res. Biogeosci.*, 119, doi:10.1002/2014JG002701

He, Y., M. C. Jones, Q. Zhuang, C. Bochicchio, B. S. Felzer, E. Mason, Z. Yu (2014), Evaluating CO_2 and CH_4 dynamics of Alaskan ecosystems during the Holocene Thermal Maximum, *Quaternary Science Reviews*, Volume 86, 15 February 2014, Pages 63-77, ISSN 0277-379

Jiang, Y., Q. Zhuang, S. Sitch, J. a. O'Donnell, A. P. Sokolov, D. W. Kicklighter and J. M. Melillo (2015) Importance of permafrost-induced soil thermal gradients on estimates of the carbon budget in the circumpolar north. *Global and Planetary Change* (*in review*).

Jiang, Y**.,** A. V. Rocha, J. A. O'Donnell, J. A. Drysdale, E. B. Rastetter, G. R. Shaver, and Q. Zhuang (2015), Contrasting soil thermal responses to fire in Alaskan tundra and boreal forest, *J. Geophys. Res. Earth Surf*., 120, doi:10.1002/2014JF003180

Kanevskiy, M., Jorgenson, T., Shur, Y., O'Donnell, J. A., Harden, J. W., Zhuang, Q**.** and Fortier, D. (2014), Cryostratigraphy and Permafrost Evolution in the Lacustrine Lowlands of West-Central Alaska. *Permafrost Periglac. Process.* . doi: 10.1002/ppp.1800

Kicklighter, D. W., D. J. Hayes, J. W. McClelland, B. J. Peterson, A. D. McGuire and J. M. Melillo (2013) Insights and issues with simulating terrestrial DOC loading of arctic river networks. *Ecological Applications* **23**(8), 1817-1836, doi: 10.1890/11-1050.1.

Kicklighter, D. W., Y. Cai, Q. Zhuang, E. I. Parfenova, S. Paltsev, A. P. Sokolov, J. M. Melillo,

J. M. Reilly, N. M. Tchebakova and X. Lu (2014) Potential influence of climate-induced vegetation shifts on future land use and associated land carbon fluxes in Northern Eurasia. *Environmental Research Letters* **9**, 035004, doi: 10.1088/1748-9326/9/3/035004.

Liu, Y., Q. Zhuang, M. Chen, Z. Pan, N. Tchebakova, A. Sokolov, D. Kicklighter, J. Melillo, A. Sirin, G. Zhou, Y. He, J. Chen, L. Bowling, D. Miralles and E. Parfenova (2013) Response of evapotranspiration and water availability to changing climate and land cover on the Mongolian Plateau during the 21st century. *Global and Planetary Change* **108**, 85-99, doi: 10.1016/j.gloplacha.2013.06.008.

Liu, Y., Q. Zhuang, Z. Pan, D. Miralles, N. Tchebakova, D. Kicklighter, J. Chen, A. Sirin, Y. He, G. Zhou and J. Melillo (2014) Response of evapotranspiration and water availability to the changing climate in Northern Eurasia. *Climatic Change* 126, 413-427, doi: 10.1007/s10584-014-1234-9.

Liu, Y., Q. Zhuang, D. Miralles, Z. Pan, D. Kicklighter, Q. Zhu, Y. He, J. Chen, N. Tchebakova, A. Sirin, D. Niyogi and J. Melillo (2015) Evapotranspiration in Northern Eurasia: impact of forcing uncertainties on terrestrial ecosystem model estimates. *Journal of Geophysical Research-Atmospheres*, **120**(7), 2647-2660, doi: 10.1002/2014JD022531.

Liu, Y., Pan, Z., Zhuang, Q., Miralles, D., Teuling, A., Zhang, T., An, P., Dong, Z., Zhang, J., He, D., Wang L., Pan, X., Bai, W and Niyogi (2015), D Agriculture intensifies soil moisture decline in Northern China. *Sci. Rep.* 5, 11261; doi: 10.1038/srep11261.

Tan, Z and Zhuang, Q. (2015). Arctic lakes are continuous methane sources to the atmosphere under warming conditions. *Environ. Res. Lett.* **10** 054016 doi:10.1088/1748-9326/10/5/054016

Tan, Z**.,** Zhuang, Q., & Walter Anthony, K. (2015). Modeling methane emissions from arctic lakes: Model development and site-level study. *Journal of Advances in Modeling Earth Systems.* doi:10.1002/2014MS000344

Zhu, X., Q. Zhuang, X. Lu and L. Song (2014), Spatial scale-dependent land–atmospheric methane exchanges in the northern high latitudes from 1993 to 2004, *Biogeosciences*, 11, 1693-1704, doi:10.5194/bg-11-1693-2014.

Zhu, X., Q. Zhuang, X. Gao, A. Sokolov and A. Schlosser (2013), Pan-Arctic land–atmospheric fluxes of methane and carbon dioxide in response to climate change over the 21st century, *Eenviron. Res. Lett.*, doi:10.1088/1748-9326/8/4/045003.

Zhuang, Q., X. Zu, Y. He, C. Prigent, J. M. Melillo, A. D. McGuire, R. G. Prinn and D. W. Kicklighter (2015b) Influence of changes in wetland inundation extent on net fluxes of carbon dioxide and methane in northern high latitudes from 1993 to 2004. *Environmental Research Letters* (*in revision*).

PRESENTATIONS

Kicklighter, D., E. Monier, A. Sokolov, Q. Zhuang, and J. Melillo (2015) Importance of soil thermal dynamics on land carbon sequestration in Northern Eurasia during the 21st century. Geophysical Research Abstracts 17, EGU2015-6435, European Geosciences Union General Assembly 2015, Vienna, Austria, 12-17 April 2015.

Monier, E., D. Kicklighter, and A. Sokolov (2015) 21st century projections of terrestrial carbon fluxes over Northern Eurasia: the role of land legacy, future land use change and future climate change. *Geophysical Research Abstracts* **17**, EGU2015-7253, European Geosciences Union General Assembly 2015, Vienna, Austria, 12-17 April 2015.

Zhuang, Q., D. Kicklighter, Y. Cai, N. Tchebakova, J. Melillo, J. Reilly, A. Sokolov, and A. Sirin, (2015a) Quantifying the role of Northern Eurasia in global CO_2, CH_4, and water dynamics during the 21st Century. *Geophysical Research Abstracts* **17**, EGU2015-6651, European Geosciences Union General Assembly 2015, Vienna, Austria, 12-17 April 2015.

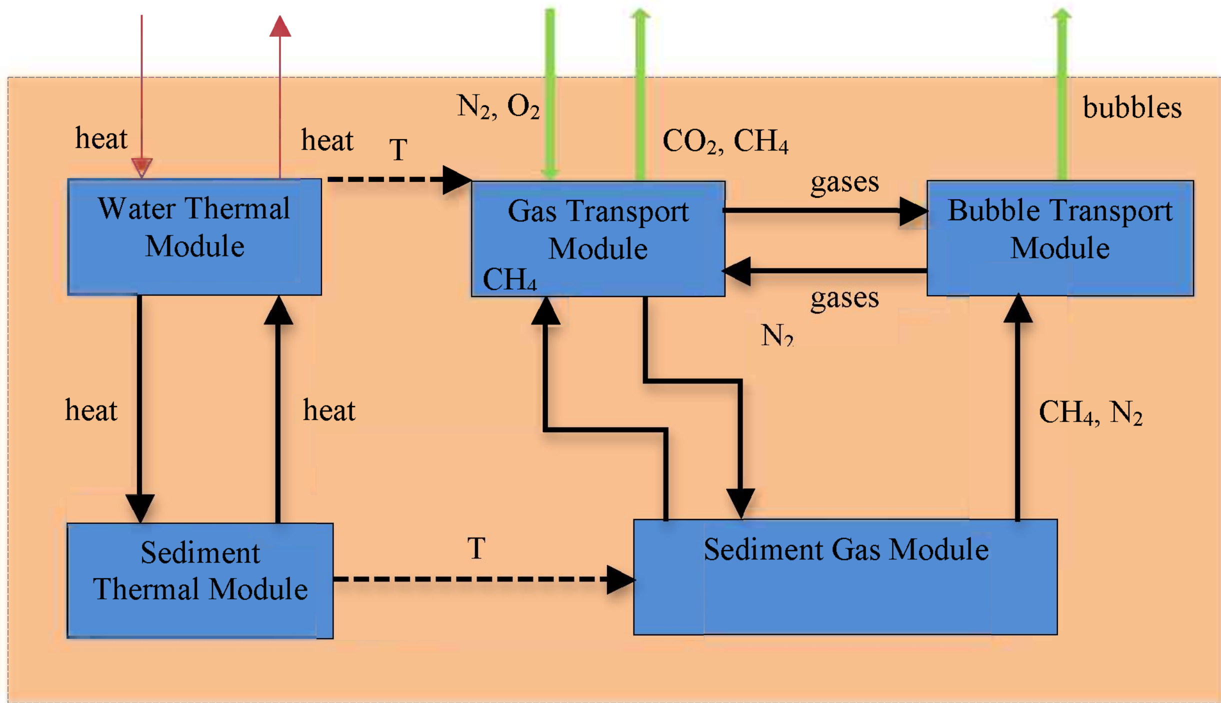

Figure 1. Schematic diagram of lake methane and carbon dioxide emission model (Tan et al., 2015).

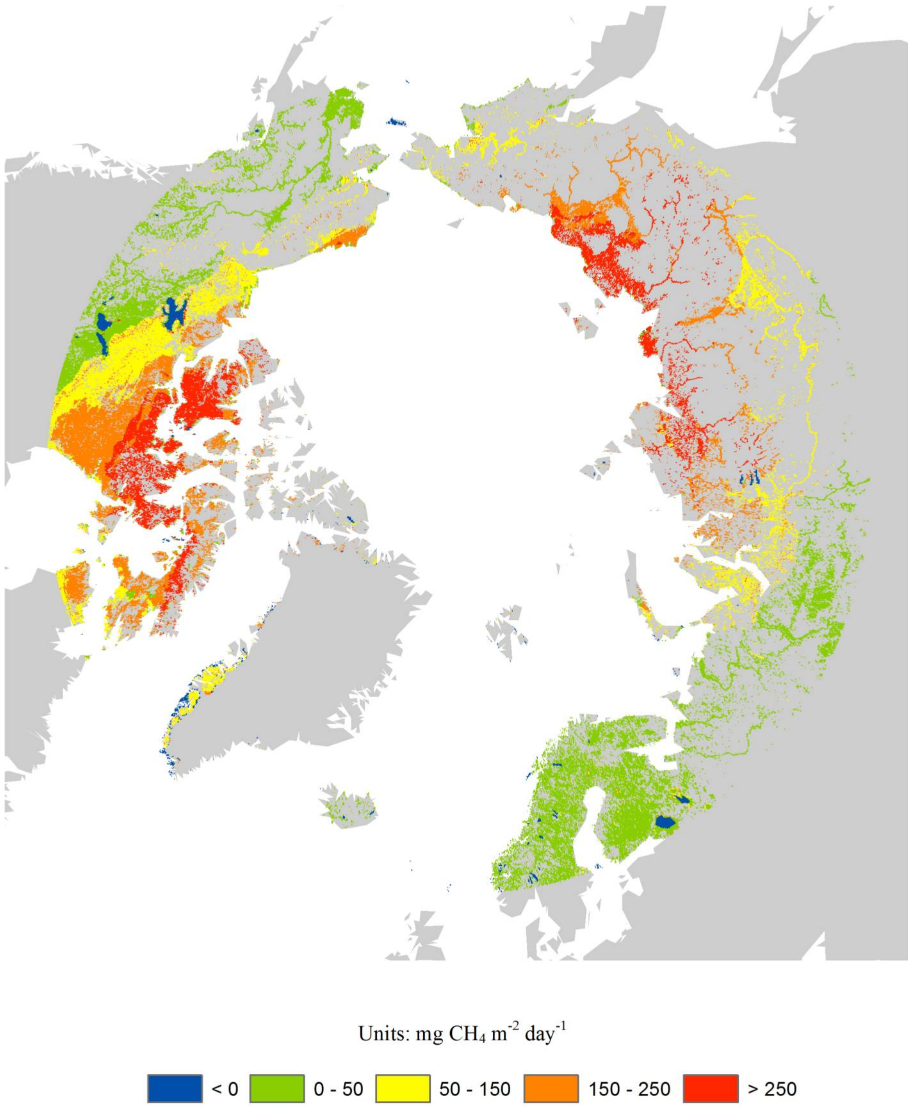

Figure 2. Distribution map of Arctic lake mean daily methane emission rates in 2003.

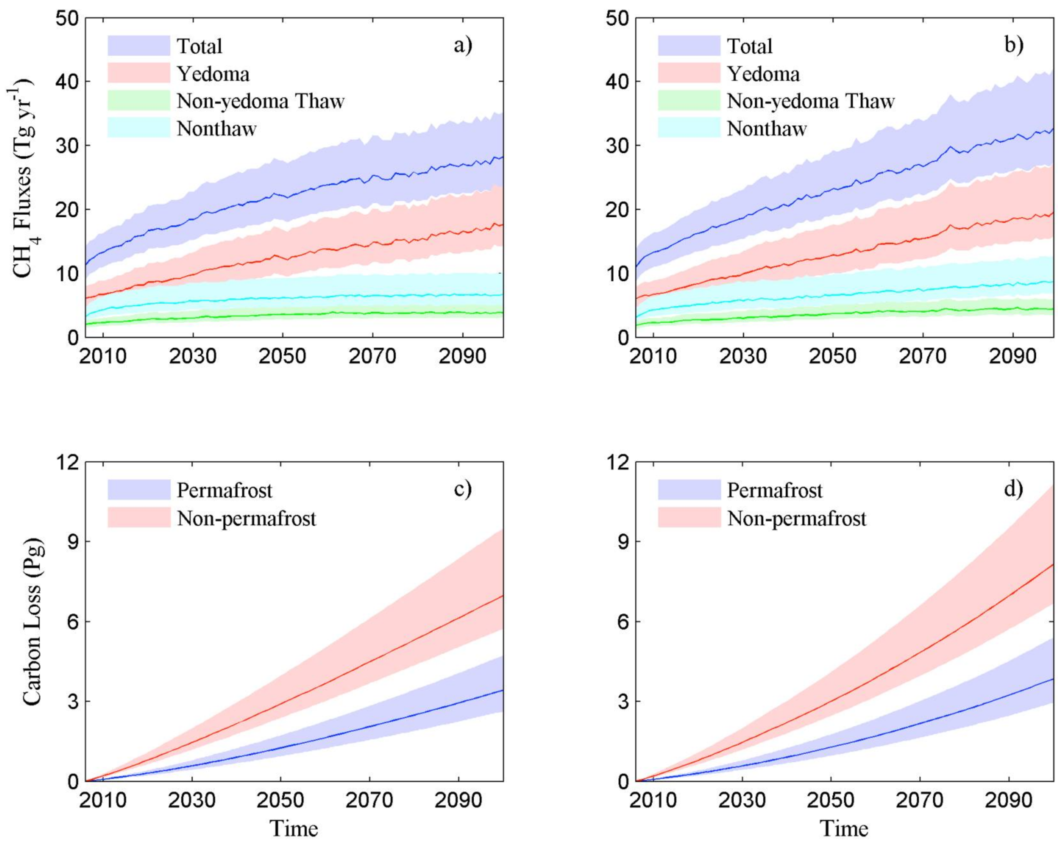

Figure 3. The variability of annual CH_4 emissions from all arctic lakes, all yedoma thaw lakes, and all non-yedoma lakes (non-yedoma thaw lakes and non-thaw lakes) and the variability of the cumulative amount of permafrost and non-permafrost carbon mineralization via methanogenesis in the pan-arctic during the 21st century (shaded areas represent the 95% percentile confidence region of projections.

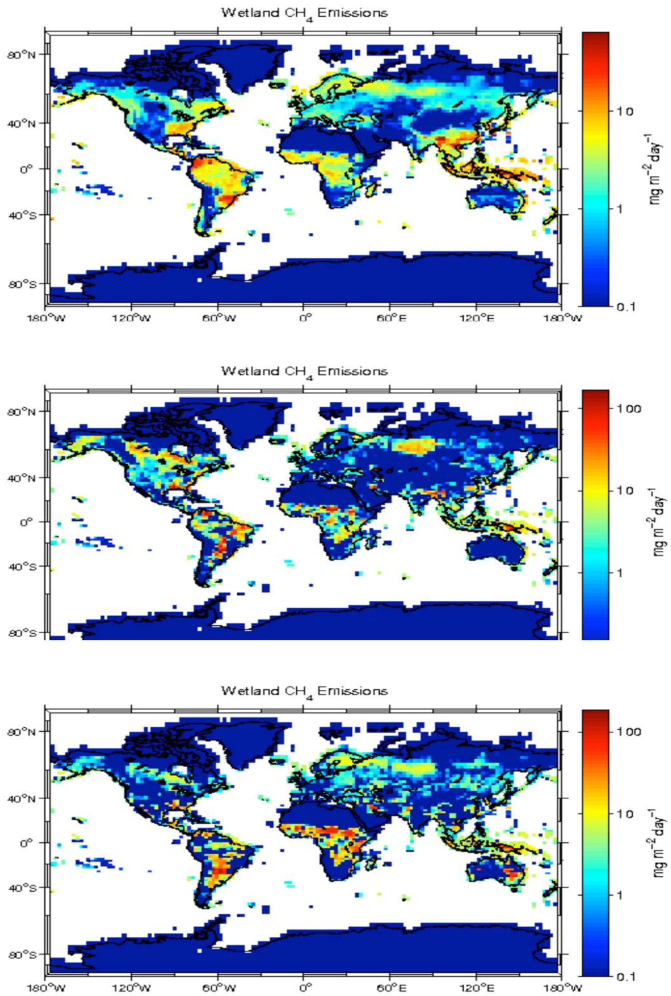

Figure 4. CLM-MDM simulated wetland methane emissions based on wetland distribution data of 1) CLM simulation (upper panel), 2) Global Lake and Water Database (GLWD) (middle panel), and 3) Matthews & Fung (1987) (lower panel). Values averaged for the simulation period of 1950-2007.

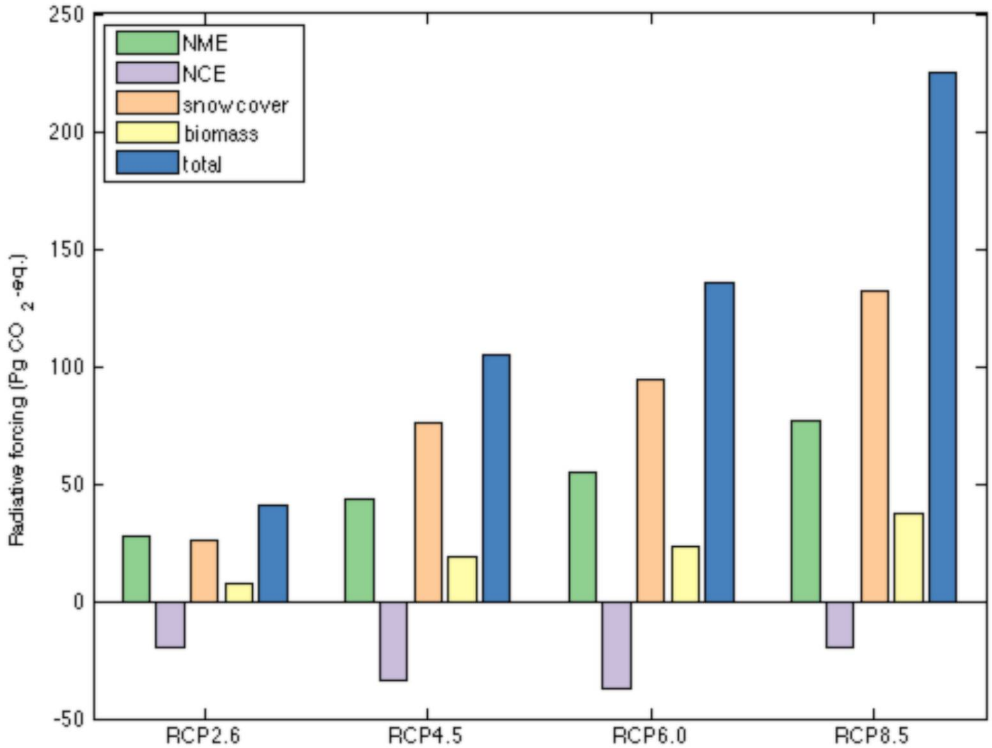

Figure. 5. Radiative forcing between 2010 and 2099 (Pg CO_2-eq.) due to the changes in net CH_4 exchanges (NME), net CO_2 exchanges (NCE), snow cover retreat, and vegetation biomass, under four climate change scenarios: RCP2.6, RCP4.5, RCP6.0 and RCP8.5. The values are expressed as regional equivalent CO_2 sources (positive) or sinks (negative) over northern vegetated area (north of 50°N) that would give same radiative forcing.