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Quantifying Climate Feedbacks from Abrupt Changes in High-Latitude Trace-Gas Emissions

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1) Overview of Project Goals

Our overall goal was 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 extent to 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 in the extent of wetlands and lakes, especially thermokarst (thaw) lakes, over the Arctic. Through a coordinated effort of field measurements, model development, and numerical experimentation with an integrated assessment model framework, we have investigated the following hypothesis:

There exists a climate-warming threshold beyond which permafrost degradation becomes widespread and thus instigates strong and/or sharp increases in methane emissions (via thermokarst lakes and wetland expansion). These would outweigh any increased uptake of carbon (e.g. from peatlands) and would result in a strong, positive feedback to global climate warming.

In the next sections, we provide an overview of the key research activities, supported under this DOE award, that we completed in order to test our overarching hypothesis. We also provide a list of publications that resulted from these endeavors.

2) Overview of Key Accomplishments

To quantify these feedbacks and their uncertainties, we combined field observations, empirical evidence, and a global integrated assessment model framework that was used to conduct a suite of numerical experiments to explore the potential strength of a climate-warming feedback via permafrost degradation, the potential for subsequent inundation and associated methane emissions. Field observations, overseen by Prof. Walter-Anthony and conducted by her team at the University of Alaska, were also taken in support of empirically based enhancements to the

Global Land System (GLS) of the MIT Integrated Global Systems Model Version 2 (IGSM2). These enhancements allowed for more explicit estimates of methane emissions that result from yedoma and non-yedoma inundated areas. The model framework also accounted for the extent to which thawed permafrost regions may become inundated – and therefore become emission sources for methane. Further, a pattern-scaling procedure was developed (Schlosser et al., 2012) whereby the uncertainty in regional climate shifts, based on the climate-model results from the Coupled Model Intercomparison Project Phase 3 (CMIP3) was integrated within the IGSM2. With these model enhancements, a suite of simulation experiments were conducted with the IGSM2 that focused on the fate of pan-Arctic permafrost extent and the potential feedback of subsequent methane emissions with projected (global) climate warming. The IGSM2 estimates greenhouse gas (GHG) emissions from both natural and anthropogenic sources, and therefore allow for a comprehensive assessment of human and natural system responses.

During the course of the study, other field research was conducted in support of our overall assessment of natural methane emissions in a warmer world. In particular, field observations were documented (Anthony et al., 2012) on the release of ^{14}C-depleted methane to the atmosphere from abundant gas seeps concentrated along boundaries of permafrost thaw and receding glaciers in Alaska and Greenland, using aerial and ground surface survey data and *in situ* measurements of methane isotopes and flux. The University of Alaska team mapped and identified over 150,000 seeps as bubble-induced open holes in lake ice. These seeps were characterized by anomalously high methane fluxes, and in Alaska by ancient radiocarbon ages and stable isotope values that matched those of coal bed and thermogenic methane accumulations. Younger seeps in Greenland were associated with zones of ice-sheet retreat since the Little Ice Age. Their findings imply that in a warming climate, disintegration of permafrost, glaciers and parts of the polar ice sheets could facilitate the transient expulsion of 14C-depleted methane trapped by the cryosphere cap.

In addition to exploring how future changes in permafrost degradation might influence CO_2 and CH_4 emissions from high latitudes, we also used the Terrestrial Ecosystem Model (TEM) to assess the net effect of the so-called “permafrost carbon feedback” in recent decades (*Hayes et al. 2013*). As the northern permafrost region experiences double the rate of warming as the rest of the Earth, the vast amount of carbon in permafrost soils is vulnerable to thaw, decomposition and release as GHGs. Our simulations showed that a wide-spread mean decrease of 2.8 mm/yr in the depth to permafrost between 1990 and 2006 exposed 281 Tg C/yr of previously frozen SOM to decomposition and resulted in an estimated net GHG forcing of 534 $MtCO_2$*eq*/yr directly tied to active layer dynamics. Enhanced decomposition from the newly exposed SOM accounted for the release of both CO_2 (562 $MtCO_2$*eq*/yr) and CH_4 (52 $MtCO_2$*eq*/yr), but was partially compensated by CO_2 uptake (-80 $MtCO_2$*eq*/yr) associated with enhanced net primary production (NPP) of vegetation. This net forcing represents a significant factor in the estimated 640 $MtCO_2$*eq*/yr pan-arctic GHG source, and an additional 6.9% contribution on top of the combined 7792 $MtCO_2$*eq*/yr fossil fuel emissions from the eight Arctic nations over this time period.

In other efforts, we recognized that land-to-atmosphere fluxes in the Arctic region have received considerable attention, but land-water interactions also influence the ability of terrestrial ecosystems to store carbon, and have been studied much less. To examine how changes in the Arctic environment may be influencing land-water interactions, we used TEM to simulate the lateral transfer of dissolved organic carbon (DOC) from land to the Arctic Ocean via riverine transport (*Kicklighter et al. 2013*). We estimate that over the 20^{th} 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.

Overall, these aforementioned studies and model enhancements to the IGSM2 enable a comprehensive suite of simulations aimed to address our driving hypothesis (*Gao et al. 2012, 2013*). Based on the results of these simulations our key findings are: 1) increases in atmospheric CH_4 and radiative forcing from increased lake emissions of CH_4 are very small when weighed against unconstrained human emissions; 2) the additional warming from these CH_4 sources across the range of climate policy and responses is no greater than 0.1^{o}C by 2100; 3) the CH_4 emission response would require a 25-fold in order for a discernible biogeochemical temperature feedback by 2100. Therefore, in light of these findings we conclude that: *the potential biogeochemical (global) climate-warming feedback resulting from thawed, inundated boreal and Arctic permafrost regions is relatively small through the end of this century - whether or not humans choose to constrain global greenhouse gas emissions.*

3) Supported Peer-reviewed Publications:

Schlosser, C. A., X. Gao, K. Strzepek, A. Sokolov, C. E. Forest, S. Awadalla, and W. Farmer, 2012: Quantifying the likelihood of regional climate change: A hybridized approach, *J. Climate*, doi: 10.1175/JCLI-D-11-00730.1.

Anthony, K. M. W., P. Anthony, G. Grosse, and J. Chanton, 2012: Geologic methane seeps along boundaries of Arctic permafrost thaw and melting glaciers, *Nature Geoscience*, doi: 10.1038/NGEO1480.

Gao, X., C. A. Schlosser, A. Sokolov, K. W. Anthony, Q. Zhuang, and D. Kicklighter, 2013: Permafrost degredation, methane and their biogeochemical climate-warming feedback, Environ. Res. Letters (submitted to special issue on Permafrost Impacts).

Hayes, D. J., D. W. Kicklighter, A. D. McGuire, M. Chen, Q. Zhuang, F. Yuan, J. M. Melillo, and S. D. Wullschleger (2013) The impacts of recent permafrost thaw on land-atmosphere greenhouse gas exchange. To be submitted to *Environmental Research Letters*.

Kicklighter, D. W., D. J. Hayes, J. W. McClelland, B. J. Peterson, A. D. McGuire and J. M. Melillo (*in press*) Insights and issues with simulating terrestrial DOC loading of arctic river networks. *Ecological Applications*.

4) Other Supported Publications:

Gao, X., C.A. Schlosser, A. Sokolov, K. Walter Anthony, Q. Zhuang and D.W. Kicklighter, 2012: Permafrost, Lakes, and Climate-Warming Methane Feedback: What is the Worst We Can Expect? *Joint Program Report Series* (May 2012), 15 pages.

Schlosser, C.A., X. Gao, K. Strzepek, A. Sokolov, C. Forest, S. Awadalla and W. Farmer, 2011: Quantifying the Likelihood of Regional Climate Change: A Hybridized Approach, *Joint Program Report Series* (September 2011), 32 pages.