C41B-0405: Predicting CO_2 and CH_4 Emissions from the Active Layer in Response to Climate Warming

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Science Question:

How does permafrost thaw and degradation, and the associated changes in landscape evolution, hydrology, vegetation dynamics and soil biogeochemical processes, affect feedbacks to the climate system?

Figure 1. Ice wedges in permafrost soil, low centered polygons, transitional polygons, high centered polygons. Even in the high Arctic where mean soil temperatures are well below zero C, polygonal ground is degrading as ice wedges melt and the rims of polygons collapse to form troughs, eventually leading to topographic inversion and sometimes landscape drainage and drying. Photos by: E. Schuur, K. Peil, L. Hinzman, C. Wilson

ABSTRACT:

Permafrost resides beneath 25% of the land in the northern hemisphere. An estimated 1600 GT of carbon resides in permafrost. Observations and models suggest that permafrost is warming and thawing, the active layer is thickening, and previously frozen old soil carbon is being converted and released as CH_4 and CO_2. GHG release amounts and rates are poorly constrained, as is the ratio between CH_4 and CO_2. This ratio is important because CH_4 is significantly more powerful as a greenhouse gas than is CO_2. The arctic is projected to experience more precipitation, and more thermokarst pond and lake formation, both of which could result in wetter conditions that favor CH_4 production. At the same time, thermokarst depressions drain the surrounding soil and can lead to thermal erosion and drainage network expansion that promote drier soil conditions that favor CO_2 production.

As the community continues to develop techniques to identify how the soil moisture status of the Arctic landscape will evolve, we are developing a model to assess how a range of soil moisture conditions, from very wet to very dry, will drive changes in GHG emissions as warming continues. Our numerical model (named ARCHY) is designed to simulate coupled surface and subsurface processes in freezing environments. It can operate in 1-D, 2-D or 3-D, is time-dependent, and includes vertical and lateral water and vapor and gas movement in heterogeneous soils and between soils and atmosphere, snow cover, heat transport, solar irradiation, precipitation, temperature, small scale topography, change of phase between water, ice and vapor, and three spatially distributed species of microbes including aerobes, anaerobes, and methanotrophs. A number of comparisons to data, including a set of soil temperatures and CO_2 and CH_4 emissions vs time at Toolik lake, as well as experiments on unsaturated flow in a domain with a freezing boundary, provide validation of the coupled thermal, hydrologic and microbiological processes in our model. We are using this calibrated model to contrast gas emissions from thawing permafrost over a range of soil moisture conditions, from a warmer but drier soil to a warmer and wetter soil column. The simulations spin up the soil column from present conditions to a warmer climate over several years. Significantly more CH_4 evolution occurs in a wet, anoxic column compared to the present day climate, while a drier, oxic column shows more CO_2 evolution but less CH_4. Amounts and rates of emissions can be quantified and related to soil moisture contents and climate temperature increases.

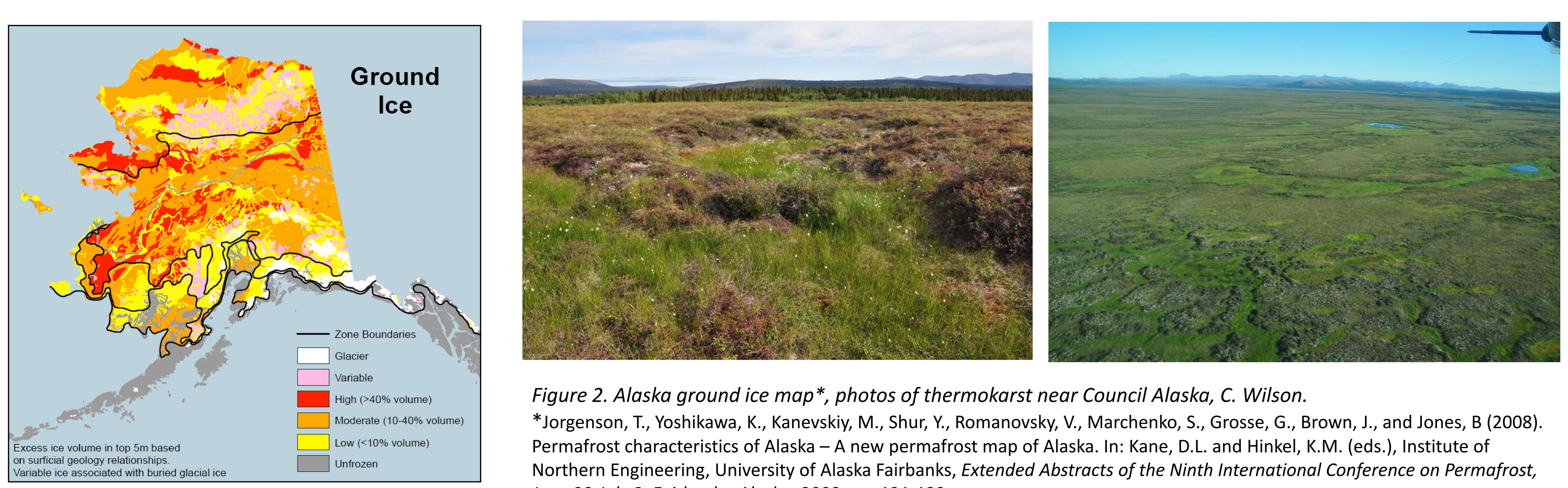
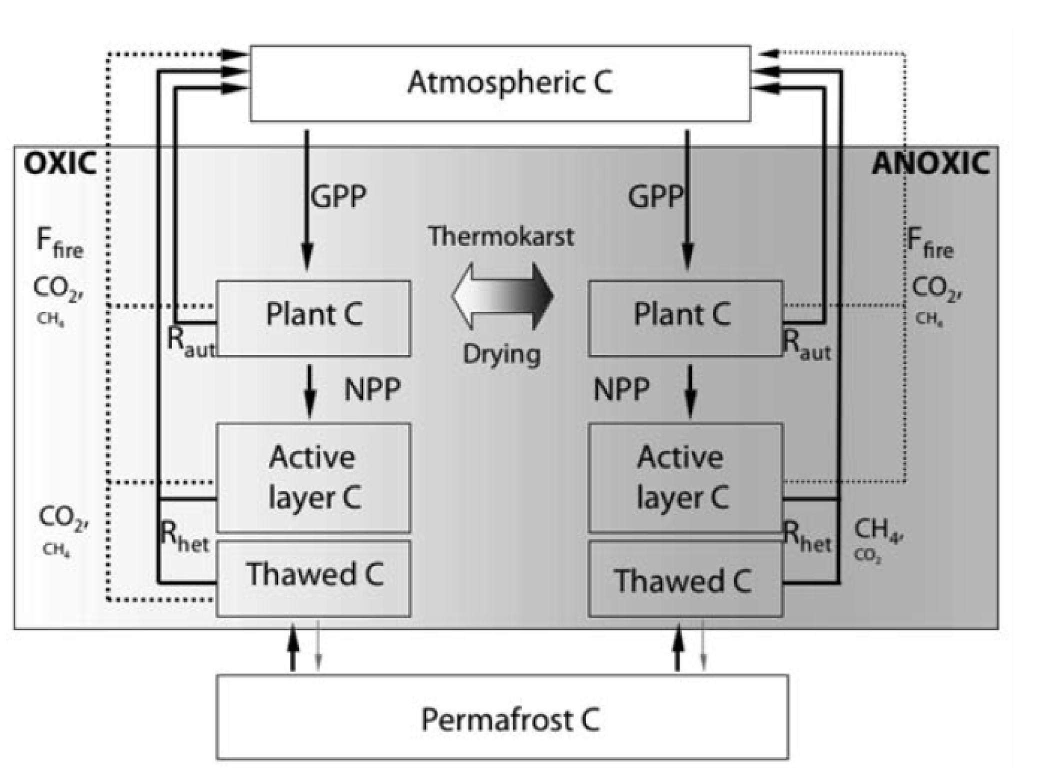


Figure 2. Alaska ground ice map, photos of thermokarst near Council Alaska, C. Wilson.*

*Jorgenson, T., Yoshikawa, K., Kanevskiy, M., Shur, Y., Romanovsky, V., Marchenko, S., Grosse, G., Brown, J., and Jones, B (2008). Permafrost characteristics of Alaska – A new permafrost map of Alaska. In: Kane, D.L. and Hinkel, K.M. (eds.), Institute of Northern Engineering, University of Alaska Fairbanks, *Extended Abstracts of the Ninth International Conference on Permafrost, June 29-July 3, Fairbanks, Alaska, 2008, pp. 121-122.*



CONCEPTUAL MODEL: Ground ice is pervasive throughout the Arctic and past and present warming drives the development of thermokarst which redistributes soil moisture at the local scale and across the landscape. This in turn drives changes in plant ecosystem processes and soil biogeochemistry that effects the amount and ratio of CO_2 and CH_4 produced in the subsurface through microbial decomposition of soil carbon. These processes are currently poorly characterized and represented in Earth System Models, limiting our ability to predict how much carbon will be released to the atmosphere, how quickly it will be released and in what form.

Figure 3. Conceptual diagram of role of permafrost degradation and thermokarst on soil moisture and oxygen content and their influence on CO_2 and CH_4 production in the subsurface.* *Schuur, E.A.G., J. Bockheim, J. Canadell, E. Euskirchen, C.B. Field, S.V Goryachkin, S. Hagemann, P. Kuhry, P. Lafleur, H. Lee, G. Mazhitova, F. E. Nelson, A. Rinke, V. Romanovsky, N. Shiklomanov, C. Tarnocai, S. Venevsky, J. G. Vogel, S.A. Zimov. 2008. Vulnerability of permafrost carbon to climate change: Implications for the global carbon cycle. BioScience 58: 701-714.

The ARCHY, ARCtic Hydrology model

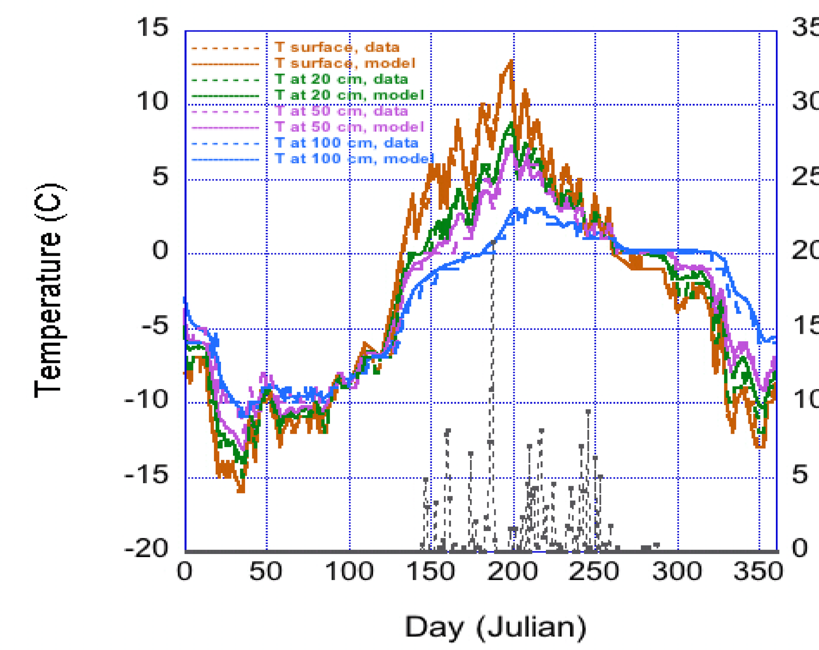


Figure 4. Toolik Lake data vs simulation of soil temperature at depths over time

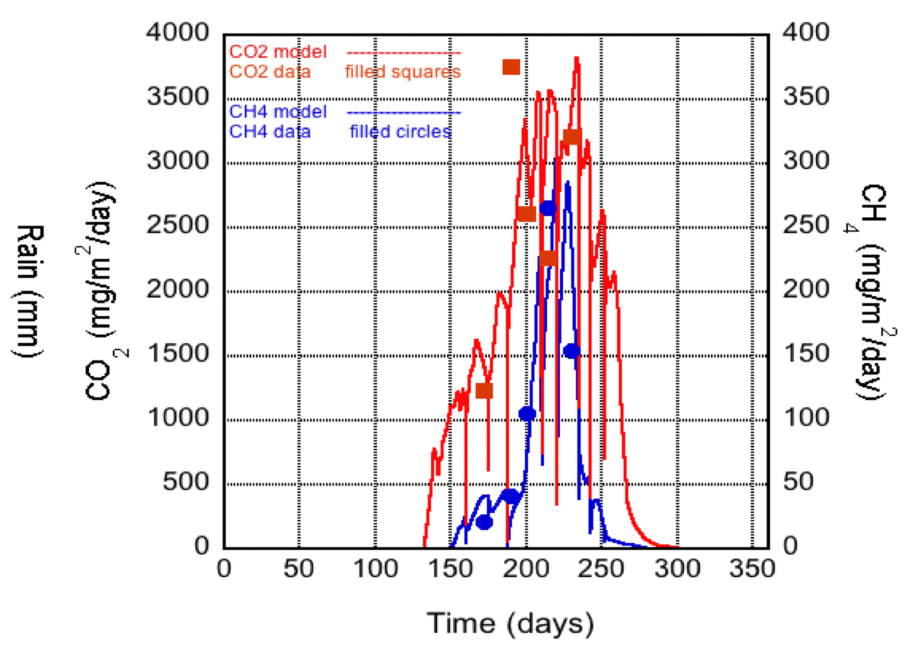


Figure 5. Comparison of observed CO_2 and CH_4 soil surface emissions (dashed) vs model simulation (solid curves)

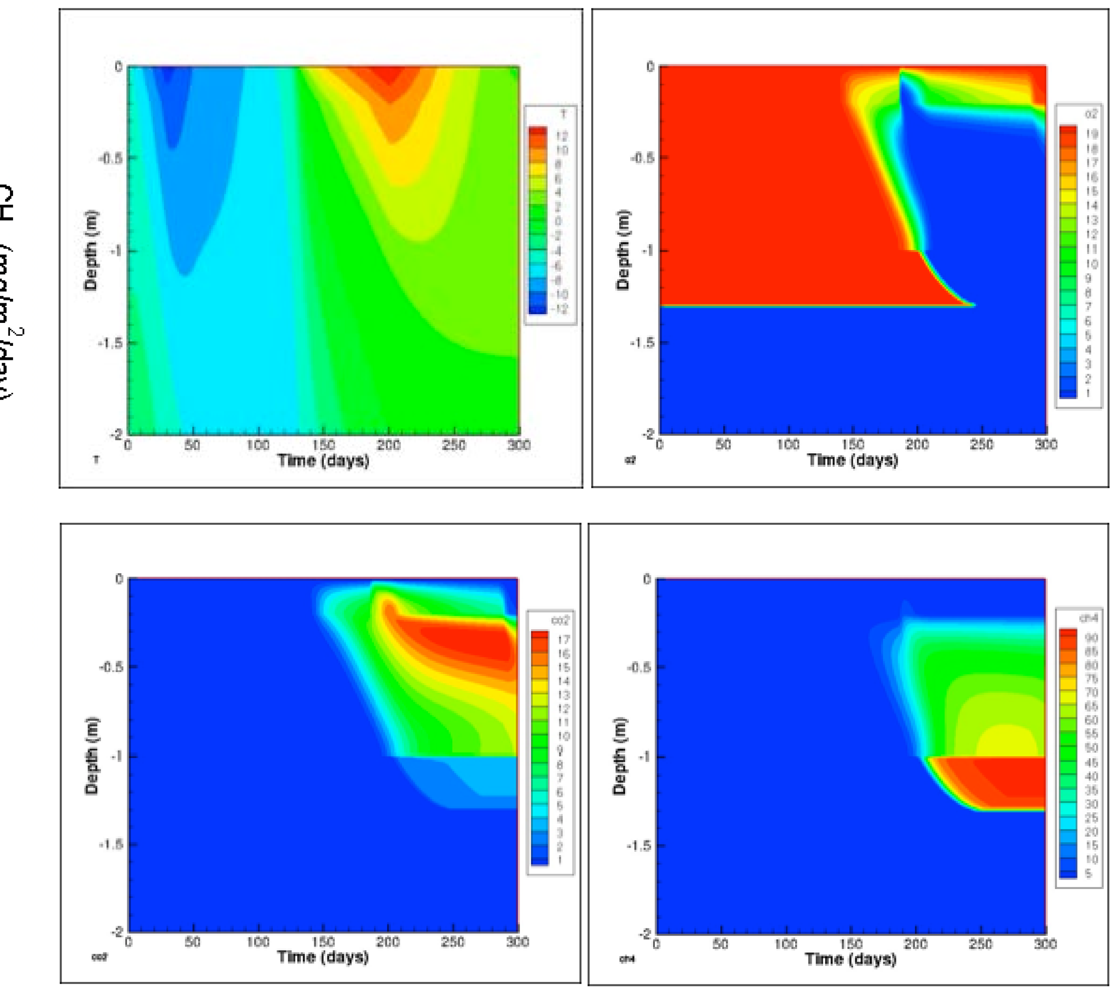


Figure 6. Active Layer Gas Concentrations and Microbial Populations: Evolution Over 1 Year Temperature Cycle - Present Climate

ARCHY MODEL DESCRIPTION: The ARCHY model allows numerical simulation studies of cold soil systems such as arctic permafrost and tundra. The primary use of this model is to simulate dynamics of interacting thermal, hydrologic, chemical and microbial processes in soils, constrained by conservation laws of mass, momentum (in reduced form as Darcy's law) and energy, with mass action principles, for flow in permeable media. Using ARCHY, we are able to simulate an arctic subsurface that includes multiple layers of varying soil dynamics with variable topography, activity of several microbial species, and vertical and horizontal thermal energy transport with freezing and thawing. Precipitation (as rain or snow), air temperature, humidity, solar irradiance and atmospheric gas concentrations are specified as boundary conditions. The ARCHY model presently considers three generic types of microbial species –aerobes, anaerobes and methanotrophs- that are known to populate the dynamic active layer/permafrost system. Each species' respiration rate is assumed to be of multiplicative Monod form, and is dependent on temperature (using a modified Arrhenius form), oxygen and carbon availability[8]. Transport of gases through root systems is ignored in this model.

APPLICATION: We applied ARCHY to a set of thermal and GHG emissions data from the Toolik lake LTER in Alaska. Our simulation utilizes a 1993 data set provided by the Toolik Field Station. The station is located on the North Slope region of Alaska (68°37'39"N, 149°35'51"W). At this site, the permafrost environment consists of three soil layers. The top 16 cm is moss and other high organic content material, with high porosity, and a water saturation of about 30%. The second layer, from 16 cm to 36 cm depth has a porosity of 28%, a water saturation of 40% and an organic content of 3%. The third layer, below 36 cm depth, has a porosity of 28%, a water saturation of 50% and a lower organic content. Average annual precipitation at the site for 1993 is about 19 cm, close to the average annual of about 20 cm/yr. Figure 4 displays the temperature history at four depths (0 cm, 20 cm, 50 cm and 100 cm) for the year 1993. Data at 0 cm depth provides the top boundary temperature condition for the simulations, thereby avoiding complications of possible snow cover, solar irradiance/ cloud cover, shielding or vegetation. Precipitation occurs at a low level on a number of days, with one large event in mid-summer.

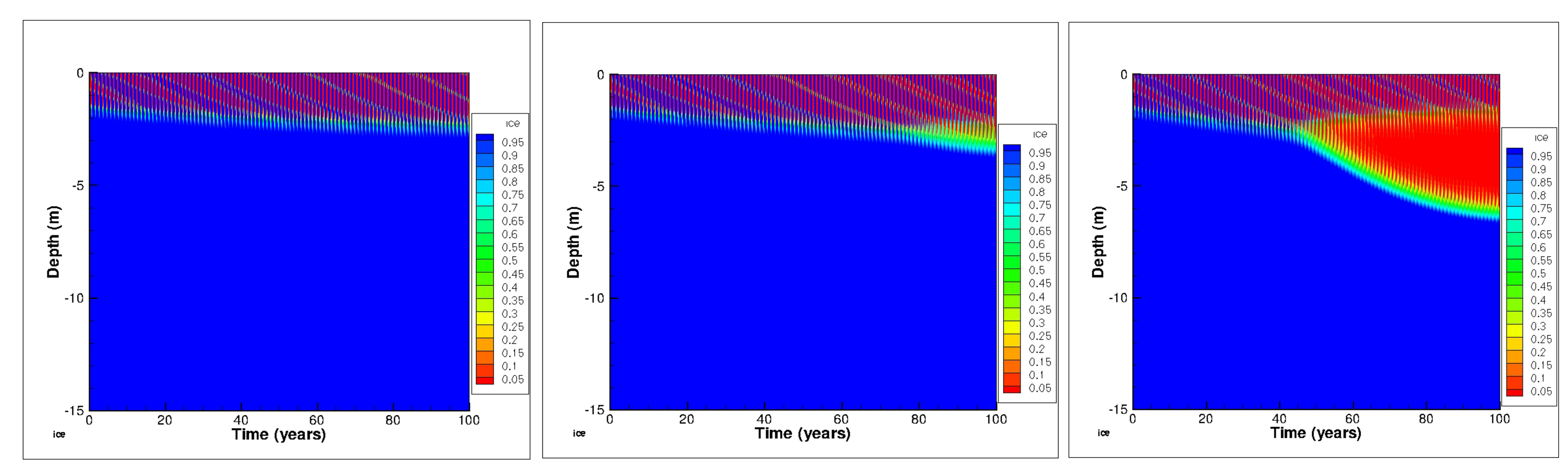


Figure 7. Annual pattern and depth of freeze and thaw of the active layer over 100 years of warming to targets of +3° C, +4° C and +6° C above present mean annual temperature. For the Toolik lake conditions, about 4° C of warming will be required for talik to begin to form.

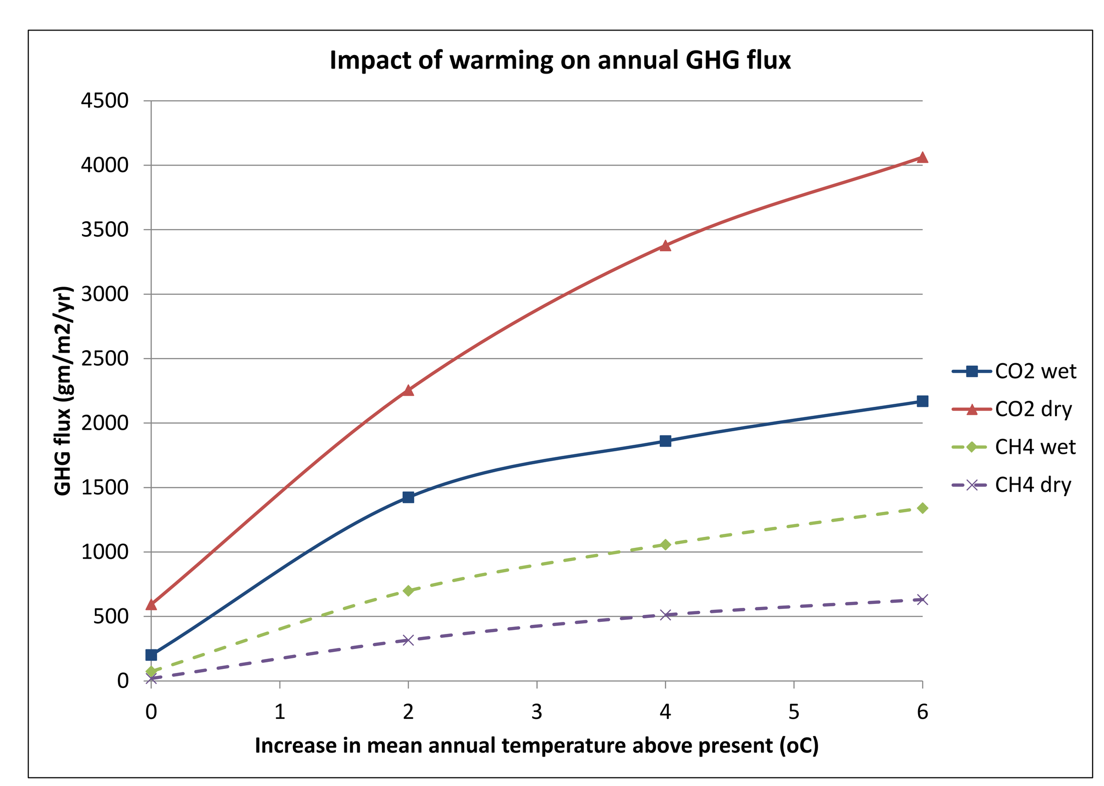


Figure 8. Increase in annual flux of CO_2 and CH_4 from the soil to the atmosphere due to warming for a wet site and a drier site. The wet site is fully saturated in the summer months throughout the 100 year period of simulation and aims to represent the impact of warming on GHG production at the center of a wet, low centered polygon or thermokarst pond/depression. The drier site uses the Toolik precipitation data (repeated annually) to drive soil moisture during the 100 year warming simulation.

RESULTS: The agreement between data and model (Fig. 4) indicates that the thermal properties (thermal conductivity, specific heat) as well as material properties (porosity, density, water/ice content) are reasonably well constrained. Figure 5 compares gas emission data (dashed lines) to model simulation (solid lines). Peak values of CH_4 and CO_2 are very close to data peaks. The sudden drop in emissions following the large summer rain event (about an inch of rain on day 186) with a rebound, seen in the data, is also seen in the model results. In the model, this is due to clogging of pores in the top layer as they become fully saturated immediately following the rain event. As water flows deeper into the soil, pores re-open and gases can escape through the surface again. The temporarily increased water content reduces ability of oxygen to diffuse in, and decreases aerobic activity while enhancing anaerobic generation of methane. The temporal and depth dependence of GHG production is shown in Figure 6 which indicates a hot spot of CO_2 production at about .5m depth where both aerobes and methanotrophs. After confidence building with the Toolik data set, we simulated future climate scenarios by slowly increasing the mean of the current annual temperature cycle to +3° C, +4° C and +6° C above present conditions over a 100 years. Figure 7. indicates talik (perennially unfrozen ground) formation within 80 and 40 years for the +4° C and +6° C scenarios respectively, providing conditions conducive to year-round microbial decomposition and GHG production. While the +3° C scenario does not develop talik, the active layer remains thawed for a greater portion of the year as time progresses. ARCHY biogeochemistry simulations show the potential for very large increases in GHG emissions from the active layer. CO_2 fluxes rise from 600 to 4000 gm/m^2/yr under moderately dry conditions, and CH_4 fluxes rise from 70 to 1350 gm/m^2/yr under wet conditions, over 100 year warming period when carbon supply to microbes is unlimited (Figure 8.)

ACKNOWLEDGEMENTS: The Authors would like to acknowledge the DOE Office of Science, Biological and Environmental Research program and the Los Alamos National Laboratory, Laboratory Directed Research & Development program for funding this research.