Towards a Comprehensive Understanding of Peatland Greenhouse Gas Exchanges in Permafrost Environments – a Ground-Based Measurement Perspective

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The concept of a potential for a peatland permafrost associated methane "bomb" has been widely spread in the press over the past decade and is well established as an issue in the public domain. For example new insights into the dramatic dynamics of permafrost melting and associated expansion of thaw lakes with huge organic carbon deposits (Zimov et al., 2006) leading to increased methane emissions and many of these as extremely spatially restricted hotspots have attracted attention in recent years (Walter et al., 2006; 2007).

Also in northern Sweden we have documented changes in peatland permafrost dynamics and effects on ecosystems and their feedbacks on climate in terms of methane emissions (Christensen et al., 2004; Johansson et al., 2006) and in relation to catchment scale greenhouse gas exchanges (Christensen et al., 2007). Moreover, recently we observed some extremely surprising and interesting autumn emission dynamics in a high arctic permafrost peatland in NE Greenland (Mastepanov et al., 2008). These observations were made possible through a prolonged opening of a research station that was part of the International Polar Year. We have done collaborative work with atmospheric scientists and preliminary concluded that autumn emission spikes could well be a likely general feature of peatland permafrost areas in that it help explain better the observed seasonal dynamics in atmospheric methane concentrations during the autumn (Mastepanov et al., 2008).

In terms of N_2O emissions a general assumption has been that the generally nutrient poor arctic terrestrial ecosystems plays a minor role. We conducted some early manipulative studies documenting N_2O emission potential in organic subarctic heath soils but low emissions from control plots (Christensen et a., 1999). However, a recent study (Repo et al., 2009) now document unexpectedly large N_2O emissions from vegetation-free patches of peat - known as peat circles – in East European tundra. The authors suggest that the absence of vegetation in these bare peat circles frees up nitrogen that would otherwise be locked away in plants, allowing bacterial transformations to proceed but the temporal dynamics and spatial distribution of these emissions are still poorly described.

So there are several unresolved and also recently appeared new major question marks to our basic understanding of the peatlands at high northern latitudes, their greenhouse gas source strength as well as the distribution of this in time and space. These are reflected in our lacking capability of explaining major variations in the growth rate of atmospheric methane. After a decade of unexplained variations (down

to zero) in the atmospheric growth rate of methane is with the most recent data back up at a substantial rate of increase and evidence from the atmospheric data indicates that the increasing source is largely wetlands at high northern latitudes.

This presentation will review the most recent data from studies on ground based source variations in major greenhouse gas exchanges and highlight the importance of gathering more data on the ground of year-round emission dynamics.

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Contributions of High Northern Latitude Ecosystems to Observed Atmospheric CO_2 and CH_4

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Quantitative understanding of atmospheric carbon sources and sinks is necessary to develop a reasonable strategy to mitigate the potential influence of CO_2 and CH_4 on climate. High northern latitudes, which are warming at twice the globally averaged rate, are especially vulnerable to climate change. Large stores of carbon there, if released to the atmosphere, would provide strong positive feedbacks on climate. Are we in position to detect changes in fluxes of CO_2 and CH_4 from high northern latitudes and attribute the changes to ecosystems rather than changing anthropogenic emissions? Our current air sampling network is sufficient to detect changes in emissions of ~3 Tg CH_4 yr^{-1}, for example, but attribution to a specific source is not possible. To do so, we need to understand all of the processes that contribute to observed signals today.

Northern ecosystems clearly contribute to the observed signals in atmospheric CO_2 and CH_4 at high northern latitudes. For example, northern wetlands contribute to an annual CH_4 seasonal cycle with a peak-to-peak amplitude of ~50 ppb. Our ability to simulate the CH4 seasonal cycle with a chemical transport model was improved by recent measurements of a fall "freeze-in" burst of CH_4 from tundra in Greenland [Mastepanov et al., 2008]. When these emissions were included for all similar ecosystems, agreement between simulated and observed seasonal cycles improved,

particularly in autumn. For CO_2, changes in the length of the growing season would affect the phase of the CO_2 annual cycle, even in the case where late-season respiration canceled some carbon uptake during summer.

Super-imposed on annual signals is interannual variability related to variations in precipitation and temperature. These affect sources such as emissions from wetlands and biomass burning. To separate these signals, other tracers such as stable isotopes of CO_2 and CH_4 and CO abundances can be used. During 2002 and 2003, increases in CH_4 growth rate correlated with increases in CO, suggesting a temporary increase in biomass burning emissions. The large increase in CH_4 at high northern latitudes in 2007 did not have a CO increase associated with it, but $\delta^{13}C$ in CH_4 was lighter than average at Alert, Canada in late-summer, consistent with a wetland source.

Contributions of high northern latitude ecosystems to observations of atmospheric CO_2 and CH_4 will be described. Emphasis will be placed on current limitations of constraining the carbon cycle at high northern latitudes using atmospheric observations, especially on our ability to detect increased emissions as permafrost melts.

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Following the Freezing Tundra Methane Burst: Field and Lab Approaches

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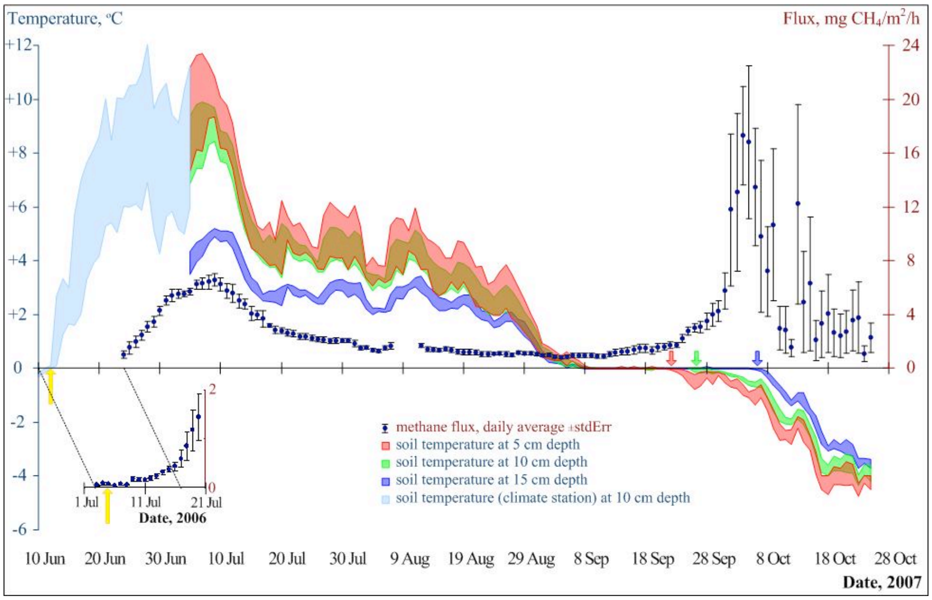
Terrestrial wetland emissions are the largest single source of the greenhouse gas methane (Mikahoff et al. 2004). Northern high-latitude wetlands contribute significantly to the overall methane emissions from wetlands, but the relative source distribution between tropical and high-latitude wetlands remains uncertain. As a result, not all the observed spatial and seasonal patterns of atmospheric methane concentrations can be satisfactorily explained, particularly for high northern latitudes. For example, a late-autumn shoulder is consistently observed in the seasonal cycles of atmospheric methane at high-latitude sites (Dlugokencky et al., 1994), but the sources responsible for these increased methane concentrations remain uncertain. Recently we found (Mastepanov et al., 2008) that methane emissions in arctic tundra (Zackenberg, NE Greenland) fall to a low steady level after the growing season but then increase significantly during the freeze-in period. The integral of emissions during the freeze-in period is approximately equal to the amount of methane emitted during the entire summer season. The mechanism of this phenomena and its abundance is still uncertain. Here we present a snapshot of our field and lab investigation of this effect after the publication (Mastepanov et al., 2008).



Full-season methane emission and soil temperature (Mastepanov et al., 2008)

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Response of Soil Carbon to Permafrost Degradation under a Warming Climate

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The zone of discontinuous permafrost is being subjected to atmospheric warming, yet the fate of both permafrost and carbon is spatially variable owing to a number of ecosystem and landscape attributes and their complex interactions. Using thermal modeling and empirical evidence to evaluate ecosystem attributes typical of Interior Alaska, we found that mean annual temperatures in soil or water in central Alaska ranged from -4 °C for tussock scrub to +8 °C for shallow water under current mean annual air temperatures of -2.2 °C, indicating very strong effects of ecosystem

characteristics (Jorgenson et al, in press). Permafrost stability was particularly sensitive to open water, soil moisture, snow depth, and organic-layer thickness, factors that interact with slope and groundwater movement to make permafrost more sensitive to thaw. As a result, permafrost is more or less susceptible to thaw if moisture, snow, or peaty soils are changed either gradually by climate change or more abruptly by fire or other disturbances (Yoshikawa et al., 2002; Romanovsky et al, 2008).

The most dramatic permafrost degradation was found in two diametric landscape types and the hydrological response to gradual and abrupt changes: (1) rocky forested uplands that were subjected to abrupt change by wildfires, with ice-rich permafrost being drained vertically and through the subsurface to nearby channels. (2) flat lowlands that were subjected to subsidence, increased snowmelt and runoff, and impoundment of surface water. In both landscape types, there is evidence that such disturbances have been cyclic, with a return to permafrost-dominated features in the past. Under a warming climate, however, reestablishment of permafrost may not be possible. The impact of permafrost degradation on carbon accumulation rates of these two landscape types was evaluated through simple mass balance and radiometric dating techniques using comparisons of frozen to thawed landscapes. Since the 1960's as assessed by inventories of radiocarbon, 137Cs and 210Pb, C accumulation rates to upper organic soils were approximately 40 +/- 30 gC/m^2/yr (uplands) and 80 +/- 70 gC/m^2/yr (wetlands). We attribute slower C accumulation in draining soils to loss of permafrost and rapid C accumulation in inundated soils to acidification and ground collapse.

In rocky uplands, soil and surface waters in locations subject to fire-induced thaw contained higher concentrations of inorganic species such as bicarbonate, and lower concentrations of organic species such as DOC, indicating more extensive or longer mineral contact and carbon loss. In lowland areas, surface waters subjected to inundation contained higher concentrations of organic species (DOC). In addition, the hydrophobic acid content of DOC was generally higher following inundation.

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Climate Warming Accelerates CO_2-Release from Subsurface Carbon in a Sub-Arctic Peatland

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Northern peatlands store about one-third of the total global soil carbon pool in only 3% of the earth's land surface (Gorham, 1991). Considerable increases in temperature have been recorded at high latitudes over the past decades and continued warming is projected for the coming century (ACIA, 2005). Release of the large carbon stores in northern peatlands, through temperature-enhanced decay rates, might form a major, positive feedback to our global climate, but it has been suggested that climate warming may only affect the respiration of plants, fresh litter and young soil organic matter, while older, more recalcitrant peat might be hardly sensitive to warming Christensen et al., 1999). However, differences in the responsiveness of short-term and longer-term C-cycles to climate change under realistic field conditions have received little attention so far, and the long-term effects on carbon release from peatlands therefore remain uncertain.

Our aims were: (1) to investigate the responses of ecosystem respiration of a sub-arctic peatland to climate change, and (2) to identify the sources of increased respired CO_2 (plants *versus* shallow, young peat *versus* deeper, older peat). We used open-top chambers to subject a sub-arctic peatland (Abisko, north Sweden) to realistic climate-change scenarios, each a combination of summer warming, spring warming, and/or winter snow addition.

Our findings are: (1) Experimental climate warming in spring and/or summer strongly enhanced ecosystem respiration rates within their respective seasons of application (May or June-September), and these effects were sustained for at least 8 years. Winter snow addition, however, did not affect ecosystem respiration rates during the subsequent spring and summer seasons. (2) To find out whether climate warming only enhances the fast turn-over of recently fixated carbon in plants, the decay of freshly senesced, superficial organic material or whether even older, subsurface peat layers respond, we used two different approaches. Removal of the aboveground vegetation showed that the respiration of peat without living vegetation or roots was as responsive to summer warming as respiration in the presence of vegetation, indicating that climate warming may stimulate both plant-related respiration (recently fixated carbon) and microbial breakdown of the peat. In addition to this we developed a novel method to track the origin of the respired carbon by comparing the $\delta^{13}C$ isotopic signatures of the emitted CO_2 with that of different peat layers. Laboratory analyses and incubations of peat layers down to -50 cm showed that $\delta^{13}C$ values of bulk and respired carbon consistently increase along our peat profile (up to 1.7 ‰). Subsequent field measurements showed clear increases in delta ^{13}C signatures

of respired CO_2 upon warming, indicating that the decay of subsurface peat layers is strongly enhanced by climate warming.

Taken together, our data demonstrate a high sensitivity of the respiration of both young and old, long-term peatland carbon stocks to climate warming, which – because of the large size of peatland carbon stocks – may feedback to the atmospheric carbon balance and climate at a global scale.

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