**Degrading offshore permafrost as a source of methane on the East Siberian Arctic Shelf and the fate of this methane in surface ocean waters**

This project represents an international collaborative effort between the Joye Research Group and Drs. Igor Semiletov and Natasha Shakohova (University of Alaska), Dr. Christof Meile (UGA), and scientists from Russia (Dr. D. Nicolsky, M. Grigoriev, O. Dudarev, and R. Pekant, and A. Kholodov). Drs. Vladimir Samarkin and Niko Finke from the Joye Research Group are involved in the work.

**The Problem**

The Arctic Ocean is a vulnerable environment with unique ecosystems that are adapted to harsh conditions. Global warming has driven drastic large-scale environmental change in Arctic environments much moreso than almost any other environment on Earth. The Arctic Ocean contains abundant offshore and onshore permafrost that is increasingly unstable and degrading under warmer conditions. The most pronounced warming in the Arctic is in the East Siberian region, where surface air temperature increased by 5ºC between 2000-2005 (<http://www.eoearth.org/article/State_of_the_Arctic_Report>). Enormous stores of methane (CH4) gas are present in the Arctic tundra soils and marine sediments. Most of this CH4 is present offshore, stored as gas hydrate. Accelerated warming and the resultant thawing of offshore permafrost may increase CH4 emission gradually, or there may be a “tipping point,” at which time CH4 emissions increase dramatically.

Biological processes in the Arctic’s cold waters are generally slower relative to those occurring in warmer seas areas, so perturbations to the Arctic system may require a significantly longer recovery period, if the system recovers at all. Our research in the Arctic aims to further our knowledge of the processes mediating methane dynamics in sediments since these environments play both a critical role in the regulation of global climate, and is sensitive to the increased global temperatures resulting from increased concentrations of greenhouse gases in Earth’s atmosphere.

**The Arctic is a critical component of the global carbon cycle**

Biogenic CH4 is produced in shallow (river deltas, estuaries, and harbors) and deep (continental shelves and slopes) sediments along continental margins worldwide when sufficient organic matter is available. Methane production proceeds in earnest in sediments where sulfate is absent; in organic rich sediments, methanogenesis can occur in shallow (even surficial) sediments. Recent estimates suggest that globally, about 20 Tg of CH4 per year escapes from the seabed into the atmosphere. This amounts to ~15% of global CH4 emission from natural sources. This estimate is based on limited data, and major knowledge gaps exist in polar regions when it comes to constraining the amount of methane stored in the sediments, its current and potential release rates into the water column and atmosphere, and the factors that regulate CH4 production and release from sediments and the ocean.

Arctic shallow seabed sediments have received little attention with regard to their contribution to the global carbon budget and, particularly, the marine CH4 budget, because of their small areal extent. However, recent work has highlighted the potential for significant CH4 release from Arctic sediments and suggests CH4 release from the Arctic is increasing over time, at least in some regions. The low temperatures that characterize Arctic sediments are not considered conducive to methanogenesis, but psychrophilic methanogens exist. In the case of the East Siberian Arctic Shelf (ESAS), shallow sediments have not been considered a CH4 source to the hydrosphere or atmosphere because submarine (offshore) permafrost, defined as sediments with a 2-year mean temperature below 0°C, acts as an impermeable lid, preventing CH4 escape.

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**Fig. 1. Dissolved CH4 in surface seawater (nM, upper) and the overlying atmosphere (ppm, lower) along the East Siberian shelf (from 10/2005). Matching areas of increased CH4 concentration noted by red circles.**

However, recent data (2003-2005) from the ESAS showed extreme surface water CH4 supersaturation (up to 22,000% saturation), implying high sea-to-air fluxes. Elevated CH4 concentrations in the air above the sea surface along the ship route were detected in the SE Laptev Sea (Fig. 1). Moreover, extremely high dissolved CH4 concentrations (up to 20 µM) were detected in the surface layer of seawater beneath the sea ice during winter. Understanding the factors responsible for the observed high CH4 concentrations in the ESAS surface waters requires additional research.

The Arctic region contains a huge amount of organic carbon buried inland and within the Arctic Ocean sedimentary basin. The Russian Arctic shelf acts as an estuary of the Great Siberian Rivers and has the highest known coastal sedimentation rates, about 10×106 t Corg yr-1, which approximately equals the amount of sediment accumulated over the entire offshore pelagic zone of the World Ocean. The rapid sedimentation rates typical of the ESAS means that much of the deposited organic carbon survives decomposition and is buried within seabed sediments. Some of these sediments are seasonally or annually frozen (“offshore permafrost”), representing a substantial reservoir of potentially labile organic carbon. Upon permafrost melting, the old organic carbon it contains will be reintroduced into the active biogeochemical C cycle and may potentially fuel *in situ* methanogenesis, providing an additional and new source of CH4 to the region.

A second, potentially more dynamic, sedimentary CH4 pool exists in deeper layers beneath the permafrost. Methane generated by microbial methanogenesis and/or the thermogenic breakdown of organic matter migrates through deep sediments towards the seafloor where it can be sequestered in gas hydrates or may escape at natural seeps. A recent global survey by Rigby et al. (2008) documented that the first increase in atmospheric CH4 levels this century—by about 28 million tonnes since mid-2006—was due in part to CH4 release in and near the Arctic. This CH4 spike appears to be generated by the rapid melting of sea ice across the Arctic Circle and thawing of permafrost, driven by higher than average summer temperatures.

**Could offshore permafrost be a methane source to overlying sediments and the atmosphere?**

No data are available to constrain the distribution, thickness, and thermal conditions of offshore permafrost along the ESAS. Estimates for the depth of the permafrost upper boundary (permafrost table), its distribution, and its degradation rate range from <10 m to 1400 m per 1000 yrs. The general assumption is that permafrost is distributed continuously along the shallow Laptev shelf; this permafrost did not thaw completely during the last glacial-interglacial transgression, except along active fault zones with high geothermal heat flux. Emission of CH4 from permafrost gas hydrates is believed to occur only along the deeper shelf (>70 m), with the exception of taliks, thawed zones that form within fault zones along the shallow shelf and provide conduits for the release of CH4-rich groundwater. Interestingly, release of permafrost CH4 from seafloor vents (called ‘pingos’) along the Beaufort Shelf was reported recently.

Repeated expeditions to the eastern Laptev Sea and western East Siberian Sea in the mid-1990s documented CH4 concentrations usually less than 15 nM. Since 2003, an increasing number of “hotspots” of CH4 release has been documented. The International Siberian Shelf Expedition in 2008 brought a broad combination of state-of-the-art sampling and analytical techniques to the region. This expedition revealed large expanses of methane bubbles in the East Siberian and Laptev seas, with CH4 levels up to 10,000 times higher than previously observed. While there are inter-annual variations, the long-term data demonstrates higher levels at locations that have been revisited. Moreover, pingo-like structures, and acoustical gas chimneys were found recently in the shallow and mid-depths (40-70m) of the ESAS where “continuous permafrost” exists according to a general thermodynamic model of permafrost freezing/thawing.

Taliks formed beneath thermokarst lakes serve as a source of Pleistocene CH4 to the overlying waters and atmosphere. While developing, these taliks melt through the permafrost, providing a conduit for rapid release of ascending gas. The range of variability in CH4 concentrations dissolved in the waters of thermokarst lakes (up to 20 µM) is comparable to that in offshore waters where the existence of taliks is hypothesized. The CH4 concentration of water of Ugly Laguna (west coast of the Lena Delta), where open taliks presumably exist, was up to 480 µM. Taliks may act as “conduits” for release of CH4 of mixed biogenic-thermogenic origin, which provides a positive feedback on climate warming via the release of the old carbon previously stored in permafrost.

**What we are doing**

We are performing intensive field sampling – both drilling through sediments into the permafrost to collect solid phase samples and collecting water samples on cruises – and experimentation linked to an integrative, predictive modeling framework through the cooperative efforts of Russian and US scientists. To evaluate the role of changing sub-sea permafrost in the regional carbon budget of the ESAS, an area significantly impacted by current and future global warming, we are examining the current and potential release of CH4 from different types of seabed sediments, obtained from various bottom landscapes and representing different stages of permafrost development or degradation. We are estimating the **current methane potential** (CMP) of sediments by determining the CH4 content at specific depth intervals and integrating the total amount of CH4 over depth. The **full methane potential** (FMP) will be estimated as net CH4 production by methanogenic bacteria from the same sediment cores. In addition to these direct measurements, we will establish a model describing the transformation of CMP into FMP under different climate conditions, i.e. at increased temperature. Spatial extrapolation will be applied across areas of defined sediment characteristics to estimate CH4 sources at a regional scale. We will use a suite of sensitive radiotracer methods for quantifying rates of CH4 production and oxidation as well as other organic carbon oxidation processes (i.e., sulfate reduction) in deep modern, talik, and permafrost sediments.

Our water column work is aimed at determining the factors that regulate methane flux from the benthos to the atmosphere. As such, we are critically evaluating the extent of the biological methane filters, both in the sediments, through anaerobic oxidation, and in the water column, through aerobic oxidation. It is possible that geological processes – mainly the magnitude of the methane flux term – are as or more important than biological processes in regulating methane dynamics. Rapid seepage may essentially swamp the biological capacity for uptake, diminishing in situ consumption. In all likelihood, annual atmospheric emissions are modulated further by seasonal factors including water-column mixing, ice cover, open water duration, and wind speed. During winter, some of the CH4 accumulating beneath fast sea ice may be oxidized by aerobic methanotrophs while some escapes to the atmosphere through polynyas. During ice breakup, water column CH4 escapes to the atmosphere*.* Our interdisciplinary studies will permit us to address these and other questions.

**What we hope to do**

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**Researchers**

Dr. Vladimir Samarkin

Dr. Niko Finke

**Papers**

none to date

**Presentations**

Joye, S.B., V.A. Samarkin, N. Shakova, I. Semiletov, and M.W. Bowles, 2011. Methane dynamics along the East Siberian Arctic Shelf: sources, sinks, and fluxes to the atmosphere. Gordon Research Conference on Polar Marine Science, Ventura, California.

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Finke, N., V. Samarkin, D. Kosmach, I. Semiletov, N. Shakova, and S.B. Joye, 2012. Methane oxidation in the oligotrophic surface waters of the Laptev Sea and East Siberian Arctic Shelf. Gordon Research Conference on Gas Hydrates, Ventura, CA, March.

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