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Understanding the impacts of thermokarst lakes on atmospheric methane, carbon cycling, and climate change.

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Lakes, a prominent feature in the Arctic (up to 48% of the land surface), are net emitters of important greenhouse gases, carbon dioxide (CO_2) and methane (CH_4); yet the contributions of arctic lakes to global greenhouse gas budgets are poorly understood. We provide a first-order estimate of CH_4 emissions from arctic lakes that suggests their importance at the global scale: Arctic lakes contribute as much as $\sim$6% ($\sim$24.2 $\pm$ 10.5 Tg CH_4 yr^{-1}) annually to atmospheric CH_4 sources. We estimated point-source ebullition (bubbling) from lakes, which is often the dominant mode of lake emissions, by mapping the distribution of bubble clusters frozen in early winter ice across surfaces of 40 lakes in Siberia and Alaska that represent common arctic lake types: post-glacial, coastal plain, alluvial floodplain, peatland and thermokarst lakes. Ongoing research aims to differentiate the importance of modern organic carbon substrates for CH_4 and CO_2 (i.e. aquatic productivity) from ancient substrates. Thermokarst lakes, formed when permafrost thaws and the ground surface subsides, had particularly high emissions compared to other lakes and to wetlands because they release CH_4 produced from labile organic matter previously sequestered in permafrost. Stable isotope analysis suggests that methane emitted from thermokarst lakes is biologically produced,

and $^{14}C_{CH4}$ up to 36,000 to 43,000 years in Siberia and 14,000 to 26,000 years in Alaska point to the importance of ^{14}C-depleted permafrost organic matter as a fuel for methanogenesis. During recent decades new thermokarst lakes have been forming and existing lakes have been expanding in conjunction with climate warming in regions of continuous permafrost. Enhanced CH_4 emission from thermokarst lakes constitutes a positive feedback to climate warming.

Surface permafrost in arctic soils contains $\sim$950 Gt of organic C, an amount that exceeds the current atmospheric C burden. Roughly 50% of permafrost C occurs in the extremely ice-rich permafrost in Siberia known as *yedoma*. Upon thaw, organic matter in yedoma is nearly 100% degraded by microbes under aerobic conditions producing CO_2, and under anaerobic conditions, CH_4 is produced. A mass balance calculation based on patterns of C lost from permafrost that thawed beneath yedoma lakes in the Holocene was used to roughly predict the magnitude of past and future CH_4 emission from lakes. Paleorecords suggest that thermokarst lakes were responsible for up to 87% of northern atmospheric methane sources that abruptly increased in during the last deglaciation. If significant permafrost warming and thaw occurs in the future as projected by some models, tens of thousands of Tg of CH_4 will be emitted from new and expanding thermokarst lakes, an amount that exceeds the current atmospheric CH_4 burden (4,850 Tg CH_4) as much as 10-fold. Understanding rates of permafrost thaw and associated greenhouse gas emissions is the subject of ongoing collaborative research using numerical modeling, remote sensing, and field validation.