

Cold season emissions dominate the Arctic tundra methane budget

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Arctic terrestrial ecosystems are major global sources of methane (CH₄); hence, it is important to understand the seasonal and climatic controls on CH₄ emissions from these systems. Here, we report year-round CH₄ emissions from Alaskan Arctic tundra eddy flux sites and regional fluxes derived from aircraft data. We find that emissions during the cold season (September to May) account for $\geq 50\%$ of the annual CH₄ flux, with the highest emissions from noninundated upland tundra. A major fraction of cold season emissions occur during the “zero curtain” period, when subsurface soil temperatures are poised near 0 °C. The zero curtain may persist longer than the growing season, and CH₄ emissions are enhanced when the duration is extended by a deep thawed layer as can occur with thick snow cover. Regional scale fluxes of CH₄ derived from aircraft data demonstrate the large spatial extent of late season CH₄ emissions. Scaled to the circumpolar Arctic, cold season fluxes from tundra total 12 ± 5 (95% confidence interval) Tg CH₄ y⁻¹, $\sim 25\%$ of global emissions from extratropical wetlands, or $\sim 6\%$ of total global wetland methane emissions. The dominance of late-season emissions, sensitivity to soil environmental conditions, and importance of dry tundra are not currently simulated in most global climate models. Because Arctic warming disproportionately impacts the cold season, our results suggest that higher cold-season CH₄ emissions will result from observed and predicted increases in snow thickness, active layer depth, and soil temperature, representing important positive feedbacks on climate warming.

permafrost | aircraft | fall | winter | warming

Emissions of methane (CH₄) from Arctic terrestrial ecosystems could increase dramatically in response to climate change (1–3), a potentially significant positive feedback on climate warming. High latitudes have warmed at a rate almost two times faster than the Northern Hemisphere mean over the past century, with the most intense warming in the colder seasons (4) [up to 4 °C in winter in 30 y (5)]. Poor understanding of controls on CH₄ emissions outside of the summer season (6–10) represents a large source of uncertainty for the Arctic CH₄ budget. Warmer air temperatures and increased snowfall can potentially increase soil temperatures and deepen the seasonal thawed layer, stimulating CH₄ and CO₂ emissions from the vast stores of labile organic matter in the Arctic (11). The overwhelming majority of prior studies of CH₄ fluxes in the Arctic have been carried out during the summer months (12–15). However, the fall, winter, and spring months represent 70–80% of the year in the Arctic and have been shown to have significant emissions of CO₂ (16–18). The few measurements of CH₄ fluxes in the Arctic

that extend into the fall (6, 7, 9, 10) show complex patterns of CH₄ emissions, with a number indicating high fluxes (7, 10). Winter and early spring data appear to be absent in Arctic tundra over continuous permafrost.

Beginning usually in late August or early September, the seasonally thawed active layer (i.e., ~ 30 – 50 cm, near-surface soil layer over the permafrost that thaws during the summer growing season) in the Arctic starts freezing both from the top and the bottom, moving downward from the frozen, often snow-covered soil surface and upward from the permafrost layer (Fig. 1). A significant portion of the active layer can stay unfrozen for months, with temperatures poised near 0 °C because of the large thermal mass and latent heat of fusion of water in wet soils, and for the insulating effects of snow cover and low density surface

Significance

Arctic ecosystems are major global sources of methane. We report that emissions during the cold season (September to May) contribute $\geq 50\%$ of annual sources of methane from Alaskan tundra, based on fluxes obtained from eddy covariance sites and from regional fluxes calculated from aircraft data. The largest emissions were observed at the driest site ($< 5\%$ inundation). Emissions of methane in the cold season are linked to the extended “zero curtain” period, where soil temperatures are poised near 0 °C, indicating that total emissions are very sensitive to soil climate and related factors, such as snow depth. The dominance of late season emissions, sensitivity to soil conditions, and importance of dry tundra are not currently simulated in most global climate models.

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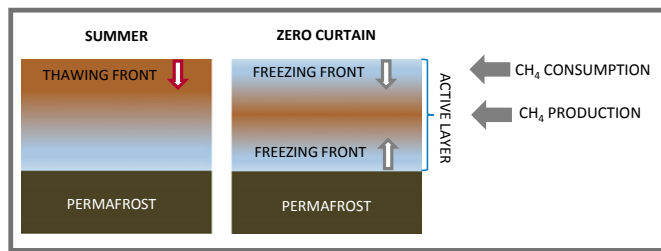


Fig. 1. Diagram of the hypothesized soil physical processes influencing CH_4 production and oxidation depending on the time of the season. We expect that during the zero curtain, the frozen near surface soil layer decreases CH_4 oxidation, resulting in substantial CH_4 emissions, even with lower CH_4 production. Light blue represents cooler soil temperatures, and light brown represents warmer soil temperatures; the arrows point in the direction of the thawing fronts in the summer and freezing front during the cold period.

material. This period has been denoted as the “zero curtain” (19). Soil freezing toward the end of the zero curtain period was considered responsible for sporadic peaks in CH_4 emissions observed in the fall (7, 10), but very sparse data are available to evaluate the importance of fall emissions over a larger scale. The processes influencing CH_4 production and emission in tundra during the cold period (Fig. 1) are not fully explored or understood.

In this paper, we present, to our knowledge, the first year-round eddy flux observations for CH_4 in the Arctic tundra over continuous permafrost to address the critical knowledge gap in

cold season CH_4 emissions. Data were obtained from five eddy covariance (EC) towers along a 300-km latitudinal transect on the North Slope of Alaska, with sites extending south from Barrow [Barrow Environmental Observatory (BEO) tower; Biocomplexity Experiment, South (BES) tower; Climate Monitoring and Diagnostics Laboratory (CMDL) tower] to Atkasuk (ATQ) and Ivotuk (IVO) (Fig. 2 and *Materials and Methods*), spanning from June 2013 to January 2015 to capture two summer–fall–winter cycles. We investigated the spatial representativeness of the EC tower data at the regional scale by comparing to CH_4 fluxes estimated from analysis of 15 aircraft flights over the North Slope (2012 to 2014), part of National Aeronautics and Space Administration’s Carbon in Arctic Vulnerability Experiment (CARVE). We also examined the correlation between CH_4 concentrations and CO from the High-performance Instrumented Airborne Platform for Environmental Research (HIAPER) Pole-to-Pole Observation (HIPPO) global-scale measurement program to assess whether biological emissions during the cold season measurably influence global distributions of atmospheric CH_4 .

Results and Discussion

Site-Level CH_4 Fluxes. Fig. 2 shows continuous eddy flux data for five tundra sites in Alaska: three in Barrow (CMDL, BEO, and BES), one in ATQ, and one in IVO (*Materials and Methods*). Methane emission rates from the cold seasons (September to May) were comparable to (e.g., BEO and ATQ; Fig. 1 C and D) or higher than (e.g., CMDL; Fig. 1B) emissions in summer over a prolonged period. Cumulative emissions for the cold season

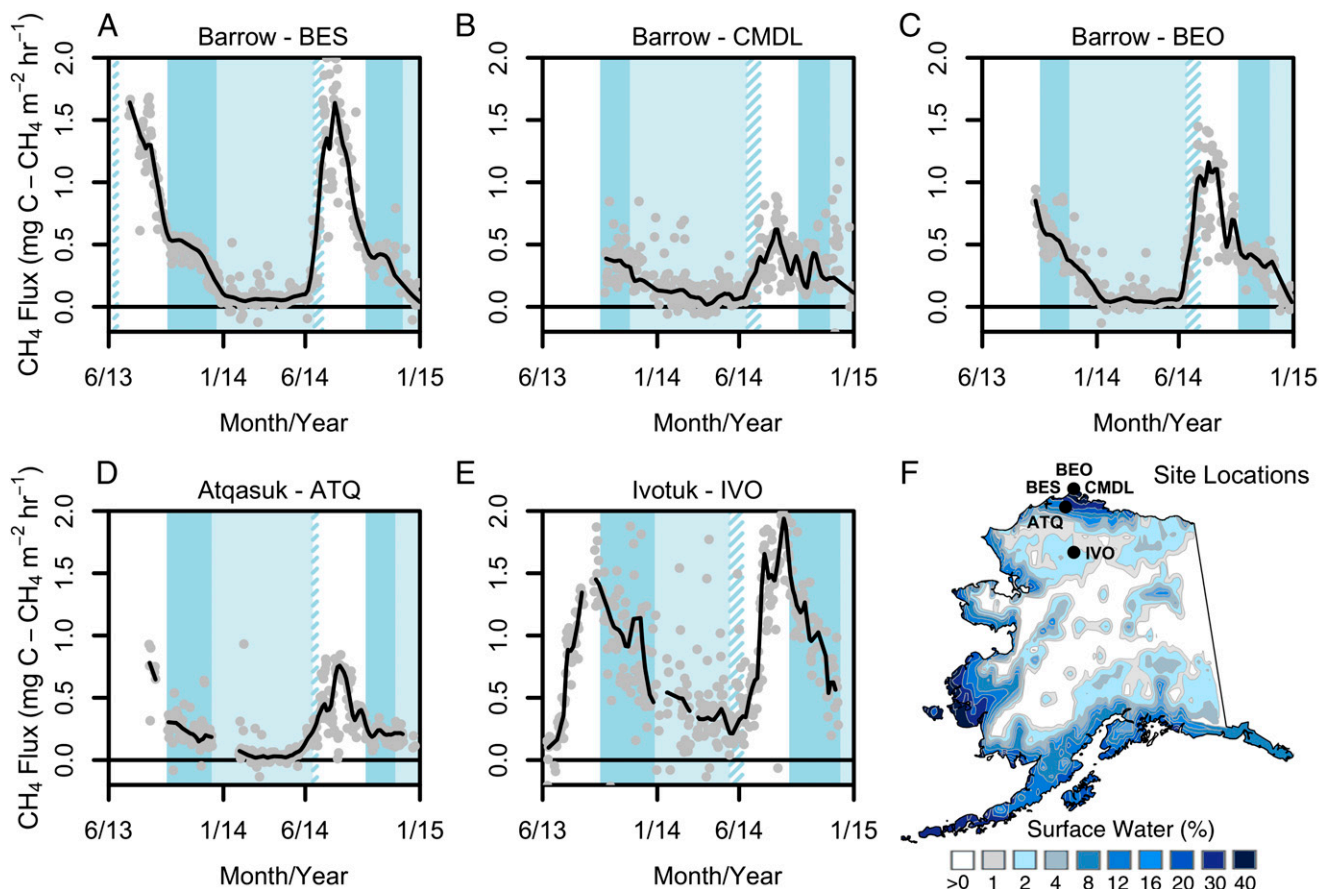


Fig. 2. Methane flux ($\text{mg C-CH}_4 \text{ m}^{-2} \text{ h}^{-1}$) measured at the five EC sites on the North Slope, AK: Barrow-BES (A), Barrow-BEO (B), Barrow-CMDL (C), ATQ (D), and IVO (E) from June 2013 to January 2015 [the gray dots are daily median for a minimum of 24 points per day, and the black line is a 35-d smoothing (lowess) applied to that daily median]. (F) Map of Alaska indicating the location of the sites and the percentage of surface inundation (*SI Materials and Methods*). The zero curtain (dark blue), spring thawing with soil temperature around 0 ± 0.75 °C (diagonal hatching) (Fig. S1 and Table S1), summer (no shading), and the balance of the cold season below -0.75 °C (light blue) periods are indicated (A–E).

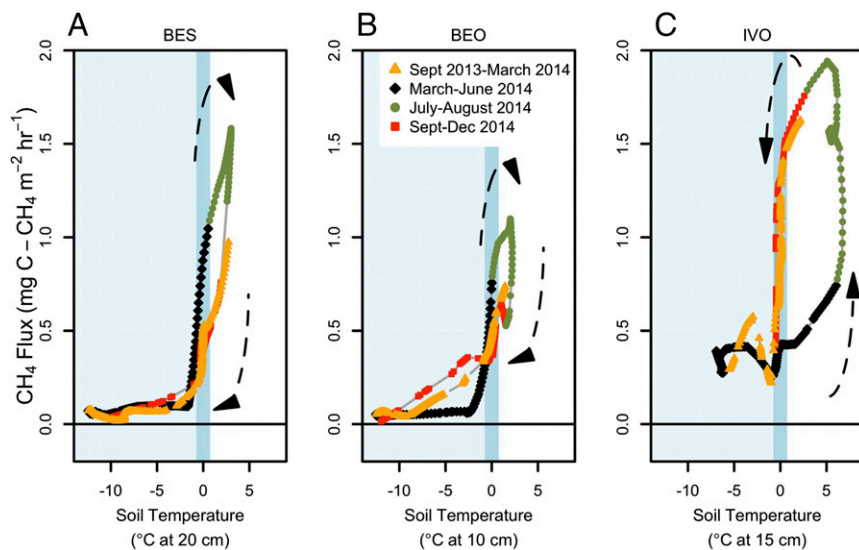


Fig. 3. The methane flux variation with soil temperature on the North Slope of Alaska at Barrow-BES (BES) (A), Barrow-BEO (BEO) (B), and IVO (C) during the indicated periods. The zero curtain period is shaded in dark blue, with soil temperatures below -0.75°C in lighter blue. The seasonal progression of each phase is indicated by the black arrows. Winter-time data are shown as orange triangles (September 1, 2013 to March 12, 2014) and red squares (September 1, 2014 to December 31, 2014). Data collected during the spring (March 13, 2014 to June, 30, 2014) are shown as black diamonds. Data during the summer period (July 1, 2014 to August 31, 2014) are shown as green circles.

averaged 1.7 ± 0.2 [mean \pm confidence interval (CI)] $\text{g C-CH}_4 \text{ m}^{-2}$ at our five sites, accounting on average for $50 \pm 9\%$ (mean \pm CI) of the annual budget (BES, 37%; BEO, 43%; CMDL, 64%; ATQ, 47%; IVO, 59%). Cold-season emissions dominated the annual CH_4 budget in the driest sites (CMDL, ATQ, IVO), representing a notably higher contribution than previously modeled (6) in other continuous permafrost sites (35%) and also higher than observed year round in boreal Alaska [40%, using periodic sampling of static chambers (20)]. The boreal systems are underlain by discontinuous or sporadic permafrost and are therefore subject to different soil processes than Arctic sites underlain by continuous permafrost (which prevents drainage for extended areas for example).

The highest fall and winter CH_4 fluxes were observed at IVO, an upland tundra site (with a water table below the surface for most of the summer), which had the longest zero curtain period (101 d; Table S1), the warmest soil temperatures during the cold season (Fig. 3 and Fig. S1), the deepest snow depth (SI Materials and Methods), and the deepest active layer (Fig. S2 A and B). Soil temperatures were also poised near 0°C for more than 90 d at much wetter sites near Barrow (BES). In both cases, the zero curtain period lasted as long as, or longer than, the summer season (Fig. S1 and Table S1). Based on direct measurement of the active layer depth and on soil temperature data, the maximum thaw depth did not begin to decrease appreciably until November or later in all of the sites measured (Fig. S2 A and B), even though the surface froze in September. During the zero curtain period, we observed strong CH_4 emissions from all five sites, $0.3\text{--}2.4 \text{ g C-CH}_4 \text{ m}^{-2}$ (Fig. 2), albeit somewhat lower than the peak summer season CH_4 fluxes observed. The overall contribution of these zero curtain periods to annual emissions was important because of their extended duration (Fig. 2, Fig. S1, and Table S1): emissions of CH_4 during the zero curtain period alone contributed $\sim 20\%$ of the annual budget (BES, 18%; BEO, 20%; CMDL, 20%; ATQ, 16%; IVO, 32%).

A few previous studies reported measurements of Arctic CH_4 fluxes during the fall (6, 7, 9, 10), but the measurements did not extend to winter and spring. We found that sites with similar summertime CH_4 fluxes had different zero curtain emissions because of different durations and depths of unfrozen soil (Fig. 2 and Fig. S2). For example, summertime cumulative emissions in IVO were $1.9 \text{ g C-CH}_4 \text{ m}^{-2}$ in 2013 and $2.7 \text{ g C-CH}_4 \text{ m}^{-2}$ in 2014, similar to the $2.3 \text{ g C-CH}_4 \text{ m}^{-2}$ (in both years) at BES. However, cumulative CH_4 emissions during the zero curtain were much higher in IVO (2.4 and $2.1 \text{ g C-CH}_4 \text{ m}^{-2}$ in 2013 and 2014, respectively) than

BES (0.9 and $0.7 \text{ g C-CH}_4 \text{ m}^{-2}$ in 2013 and 2014, respectively) probably because of interacting effects of greater CH_4 production at IVO, the inhibition of surface oxidation in the fall (Fig. 1), and the deeper thaw depth delaying the complete soil freezing in IVO (Figs. S1 and S2). The emissions of CH_4 produced deeper in the soil continued during the cold season, presumably through cracks and pathways in the near-surface frozen soils (7).

Linear mixed effects modeling (SI Materials and Methods) suggested that the depth of the active layer was a critical control on CH_4 fluxes during the summer. The presence of this unfrozen soil layer in the fall and early winter was also a major control on cold season CH_4 emissions; warmer soils resulted in greater CH_4 emission over the entire year. The importance of warm soil temperatures and deep active layer is consistent with the observed higher winter emissions in IVO, where soil temperature at 15 and 30 cm below the surface never dropped below approximately -8°C compared with at or below -15°C at the northern sites (e.g., BES and ATQ). The observed CH_4 emissions during fall and winter are consistent with data showing significant microbial populations and metabolic activity at and below 0°C in the Arctic (16, 21), reflecting the availability of unfrozen water films (22) under these conditions (16). Measurable metabolism has been observed down to -40°C (23), and CH_4 production has been observed down to -16°C (21, 24). Soil particles maintain liquid water films until a temperature of at least -10°C (25), and this unfrozen water can sustain microbial metabolism and greenhouse gas production (26), even as the soil bulk water freezes (25). The direct effect of higher temperature on metabolic activity and the indirect effect of temperature through greater liquid water volume should result in a larger population size and more activity in the methanogenic (i.e., methane-producing) community in the winter at IVO compared with the other, colder, sites. Unfortunately, IVO is the only tower collecting CH_4 fluxes and environmental variables continuously year round over upland tundra at this latitude in Alaska. Therefore, we encourage the establishment of similar upland sites in the Arctic to confirm these observations.

Across all our sites, areas of lower inundation (i.e., less surface area with water table above the surface for most or all of the growing season) had the greatest percentage of total emissions from the cold season, with the highest emissions from IVO with $<5\%$ inundation (Fig. 2). In contrast, most modeling studies limit CH_4 emissions to areas with inundated or saturated soils (27). The observed CH_4 emissions that persisted, even when temperatures were well below 0°C (Fig. 2), present a remarkably

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