Spatiotemporal variability of methane emissions of tundra landscapes in the Lena River Delta, Siberia

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Contribution of arctic CH$_4$ emissions to global climate-carbon cycle feedback?

Figure adapted from V. Brovkin

Kutzbach et al. (2014) In Lozán et al. (eds.) Warnsignale Klima: Die Polarregionen
Heterogeneity of tundra landscapes → Large spatial variability of CH$_4$ fluxes on multiple scales
Example: Lena River Delta, Siberia (73° N, 126° E)
Research questions

• How do CH$_4$ emission dynamics differ between the main tundra landscape types of the Lena River Delta – river terraces and active floodplains?
• How important is small-scale variability of CH$_4$ emissions within the two landscape types?
• Which environmental drivers control CH$_4$ emissions on seasonal and interannual scales?
Eddy covariance flux measurements

River terrace

- Anemometer (Campbell Sci. C-SAT3)
- Open-path CH$_4$ analyser (LICOR LI-7700)

Floodplain

- Closed-path CH$_4$ analyser (FMA, Los Gatos Research)

Photo: P. Schreiber

Photo: N. Rößger

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River Terrace: 16 campaigns of eddy covariance measurements of CH$_4$ fluxes

Time series of daily means of CH$_4$ fluxes $F_{\text{CH}_4}$. Gap-filled by regression tree model. (Rößger et al., in prep.)
River Terrace: Average annual course of CH$_4$ emissions

Median annual CH$_4$ flux course:
- lowest (near zero) in April;
- continuous increase from May to August;
- steep decrease in September;
- gradual further decrease from October to April.

Pooled half-hourly data for CH$_4$ fluxes F$_{CH_4}$ and air temperature $T_{air}$ from all studied years: 2002-2006, 2009-2019 (Rößger et al., in prep.)
River Terrace: Mean annual CH$_4$ budget

- Total: 165 ± 31 mmol m$^{-2}$
- Thaw season (June-September): 100 ± 25 mmol m$^{-2}$ (61 %)
- Freezing season (October-May): 65 ± 19 mmol m$^{-2}$ (39 %)
- Contribution of freezing season similar to Alaskan tundra sites (Zona et al., 2016)

Contribution of monthly CH$_4$ fluxes (mean ± stdev) to the mean annual CH$_4$ budget (Rößger et al., in prep.)
River Terrace: Small-scale variability of CH$_4$ fluxes due to polygonal microrelief

- Elevated, moist-dry polygon rims: *Glacic Turbic Cryosols*
- Depressed, water-saturated polygon centers: *Histic Cryosols*
- Vegetation dominated by different moss and sedge species

Small-scale CH$_4$ flux measurements by transparent closed chambers and an Ultraportable Greenhouse Gas Analyzer (UGGA 30-p, Los Gatos Research)
River Terrace: Small-scale variability of CH$_4$ fluxes due to polygonal microrelief

- Strong contrast of CH$_4$ emissions between microforms within polygons
- Mean fluxes mid-July to end of September 2015:
  - Center: 0.019 ± 0.005 μmol m$^{-2}$ s$^{-1}$
  - Rim: 0.001 ± 0.0003 μmol m$^{-2}$ s$^{-1}$
- Distinct seasonality with flux maxima in:
  - Center: beginning of September
  - Rim: end of September

Mean CH$_4$ fluxes ($n = 4$) at rim and center of polygon in summer 2015, measured by closed-chamber method (Eckhardt, 2017)
Floodplain: Heterogeneous eddy covariance footprint: Opportunity to estimate CH₄ fluxes for 3 vegetation classes

- Elevated emissions scaled well with contributions from vegetation classes 2 (low *Salix* and *Carex*) and 3 (*Carex*), whereas very little emissions were sampled when vegetation class 1 (large *Salix*) largely contributed to the flux.

**Left panel:** Vegetation map of the floodplain on Samoylov Island. The flux tower was situated in the centre of the footprint climatology isolines, which indicate the averaged area from which 10 to 90 % of the flux originated (increments of 10 %).

**Right panel:** Wind direction dependencies of both CH₄ flux and relative vegetation class contributions sorted by 2° wind direction bins utilising data from both measurement periods 2014 and 2015.

(Rößger et al., 2019)
Floodplain: Eddy covariance footprint CH$_4$ emissions can be decomposed into contributions of 3 vegetation classes

- Estimation of contributions by 3 vegetation classes ($\Omega_1, \Omega_2, \Omega_3$) to the observed eddy covariance CH$_4$ flux by combining an analytical footprint model (Kormann and Meixner, 2001) with a high-resolution vegetation map.

- Estimating parameters ($a_1, a_2, a_3, b_2, b_3, c$) of a mechanistical flux decomposition model by nonlinear regression (inputs: soil temperature $T_{soil}$, friction velocity $u^*$, $\Omega_i$):

$$F_{CH_4} = \Omega_1 a_1 + \Omega_2 a_2 e^{b_2 T_{soil,2} + c u^*} + \Omega_3 a_3 e^{b_2 T_{soil,3} + c u^*}$$


**Lower panel**: CH$_4$ fluxes for the 3 vegetation classes with 95% confidence bounds calculated by the respective sub-models of the flux decomposition model (Rößger et al., 2019).
Floodplain has 70% higher CH$_4$ emissions during thaw season than river terrace

- **Floodplain**
  - 2014: 162.7 ± 31.7 mmol m$^{-2}$
  - 2015: 168.6 ± 31.9 mmol m$^{-2}$

- **River Terrace**:
  - 2014: 95.6 ± 0.5 mmol m$^{-2}$
  - 2015: 98.7 ± 0.4 mmol m$^{-2}$
  - Long-term estimate 100.1 ± 24.9 mmol m$^{-2}$

Cumulative CH$_4$ fluxes ‘CumF$_{CH4}$’ over the thaw period for the floodplain (2014, 2015) and the river terrace (2014, 2015 and long-term estimate (16 campaigns 2002-2019)). River terrace: Gap-filled eddy covariance measurements. Floodplain: Calculated by vegetation class sub-models of the flux decomposition model weighed by their respective spatial coverage.

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River Terrace: CH$_4$ emissions well explained by soil temperature and atmospheric turbulence strength

**Daily means:**

\[
F_{CH_4} = b_1 + b_2 e^{(b_3 T_{soil})} + b_4 e^{(b_5 u^*)}
\]

**Monthly means:**

\[
F_{CH_4} = b_1 + b_2 e^{(b_3 T_{soil})}
\]

**Left panel:** Dependency of daily mean CH$_4$ fluxes on soil temperature $T_{soil}$ (polygon centre, 20 cm depth) and friction velocity $u^*$. Explanatory power by additive exponential functions model $R^2 = 0.68$.

**Right panel:** Dependency of monthly mean CH$_4$ fluxes on soil temperature $T_{soil}$ (polygon centre, 20 cm depth). Explanatory power by exponential function model $R^2 = 0.86$. (Rößger et al., in prep.)
River Terrace inter-annual variability: Linear increase of thaw season CH$_4$ emissions with growing degree days

- Thaw season (June-September) mean CH$_4$ fluxes show positive correlation with cumulative growing degree days (base temperature of 5 °C).
- Higher soil temperatures appear to enhance CH$_4$ production more than CH$_4$ oxidation leading to higher net CH$_4$ emissions.
- However, no increasing temporal trend in CH$_4$ emissions observed since thaw season soil temperatures did neither show a warming trend over the study period (see Boike et al. 2019).
Conclusions

- CH$_4$ emissions show high spatial variability between the main tundra landscape types: Active floodplains emit about 70% more CH$_4$ during the thaw season than river terraces, probably due to higher nutrient inputs from regular flooding.

- Both tundra landscape types are characterized by pronounced small-scale variability of CH$_4$ fluxes:
  - On the river terrace, depressed polygon centers are much stronger CH$_4$ emitters than elevated polygon rims.
  - On the floodplain, low-lying, wet and sedge-moss-dominated areas (backswamps) are much stronger CH$_4$ emitters than elevated natural levees covered mainly by shrubs.

- Warmer thaw seasons lead to higher CH$_4$ emissions.

- Our findings suggest that a warmer climate stimulates the production of CH$_4$, which is directly reflected in increased CH$_4$ emissions. On the other hand, warming effects on CH$_4$ oxidation appear limited because transport processes that bypass the soil oxidation zone, i.e. plant-mediated transport and ebullition, dominate CH$_4$ emission from wet tundra landscapes (see, e.g., Kutzbach et al., 2004; Knoblauch et al., 2015).

- Since CH$_4$ emissions strongly vary with (micro-)topographical situation within tundra landscapes, the changes of geomorphology and hydrology due to permafrost degradation will probably be the dominating drivers of future CH$_4$ emissions from arctic tundra landscapes.

- Furthermore, changes in tundra vegetation composition will have important effects on future CH$_4$ emissions.


