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

L. Kutzbach[1], N. Rößger[1,2], T. Eckhardt[1], C. Knoblauch[1], T. Sachs[2], C. Wille[2], J. Boike[3], E.-M. Pfeiffer[1]

[1)] *Institute of Soil Science, Center for Earth System Research and Sustainability (CEN), Universität Hamburg*

[2)] *Helmholtz-Zentrum Potsdam, Deutsches Geoforschungszentrum*

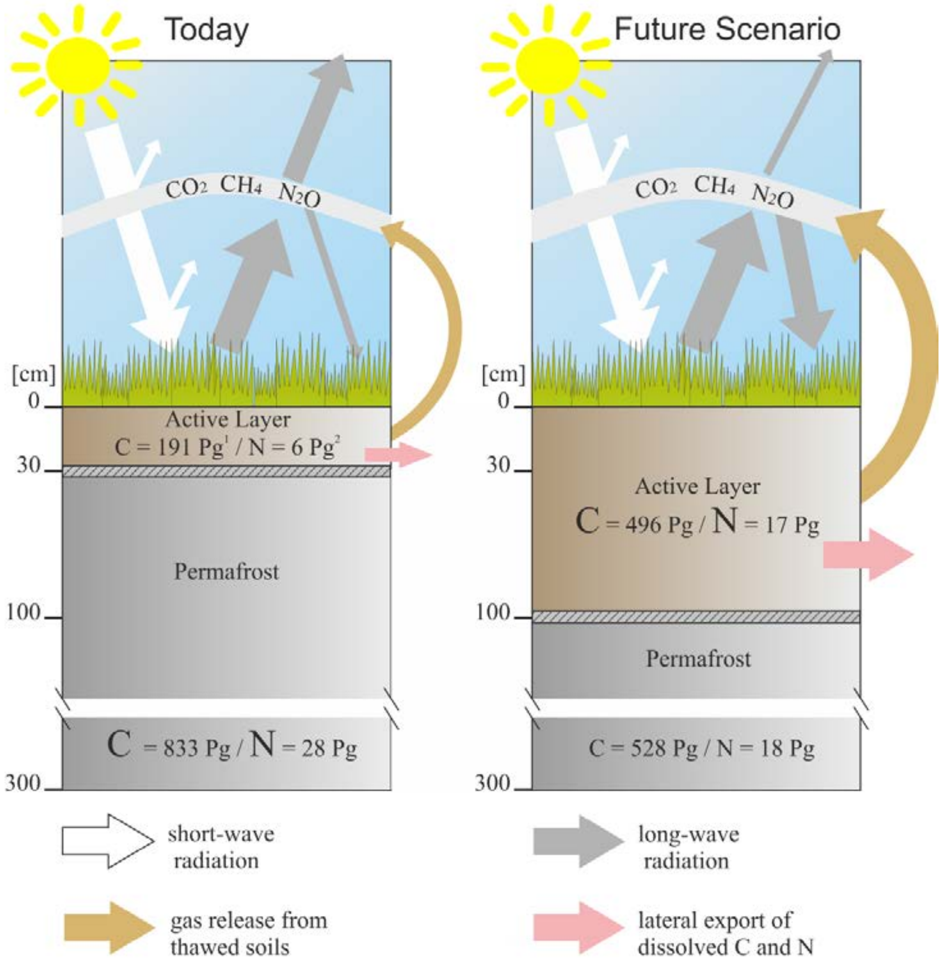
[3)] *Alfred Wegener Institute for Polar and Marine Research, Potsdam*

Photo: M. Helbig

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

Contribution of arctic CH_4 emissions to global climate-carbon cycle feedback?

CLUSTER OF EXCELLENCE
CLIMATE, CLIMATIC CHANGE, AND SOCIETY (CLICCS)



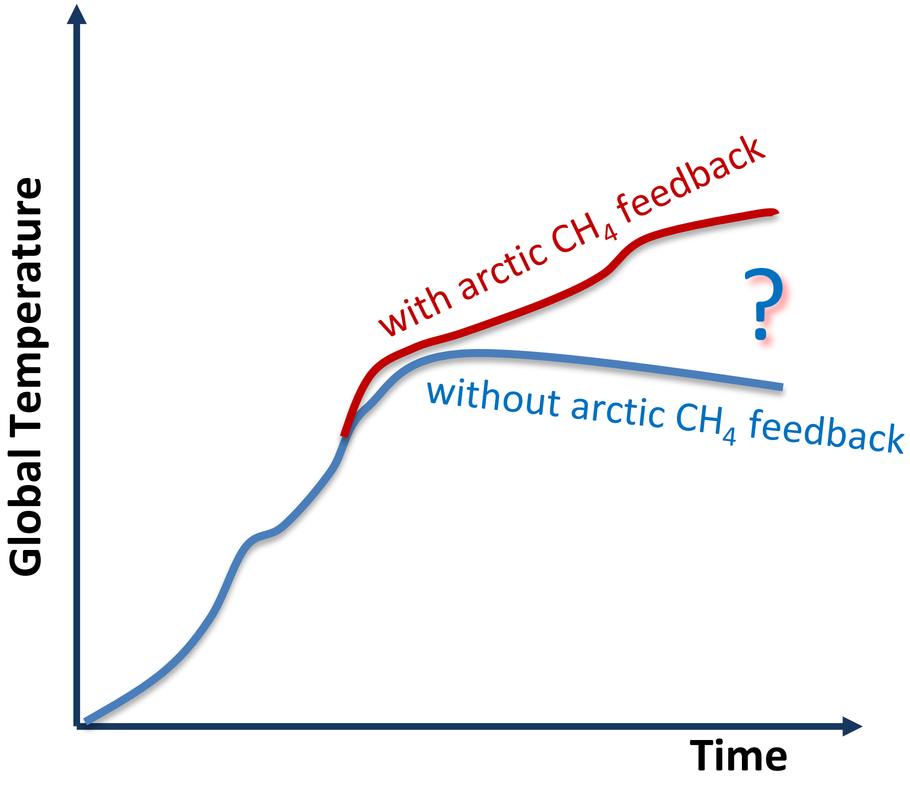


Figure adapted from V. Brovkin

Kutzbach et al. (2014) In Lozán et al. (eds.) *Warnsignale Klima: Die Polarregionen*

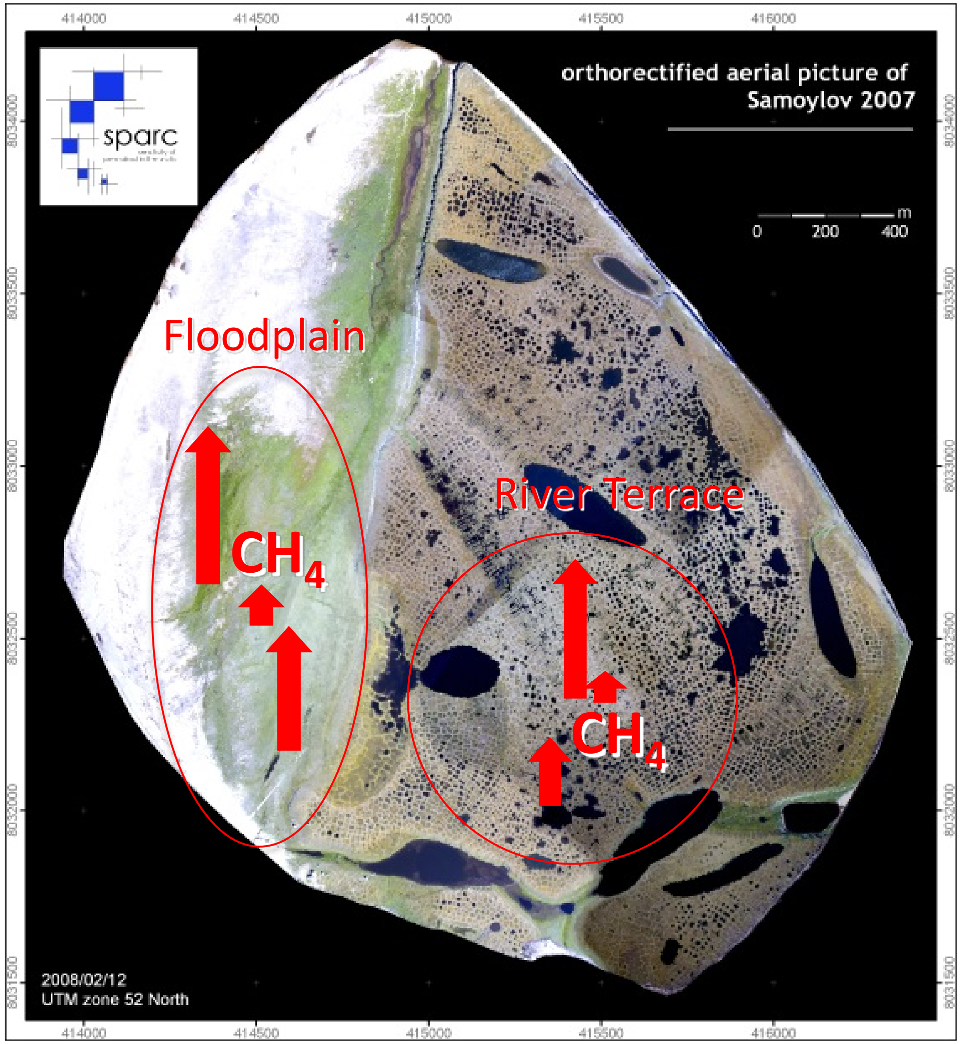
Heterogeneity of tundra landscapes
→ Large spatial variability of CH_4 fluxes on multiple scales
Example: Lena River Delta, Siberia (73° N, 126° E)

Photo: G. Stoof

UHH Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

Research questions

CLUSTER OF EXCELLENCE
CLIMATE, CLIMATIC CHANGE, AND SOCIETY (CLICCS)



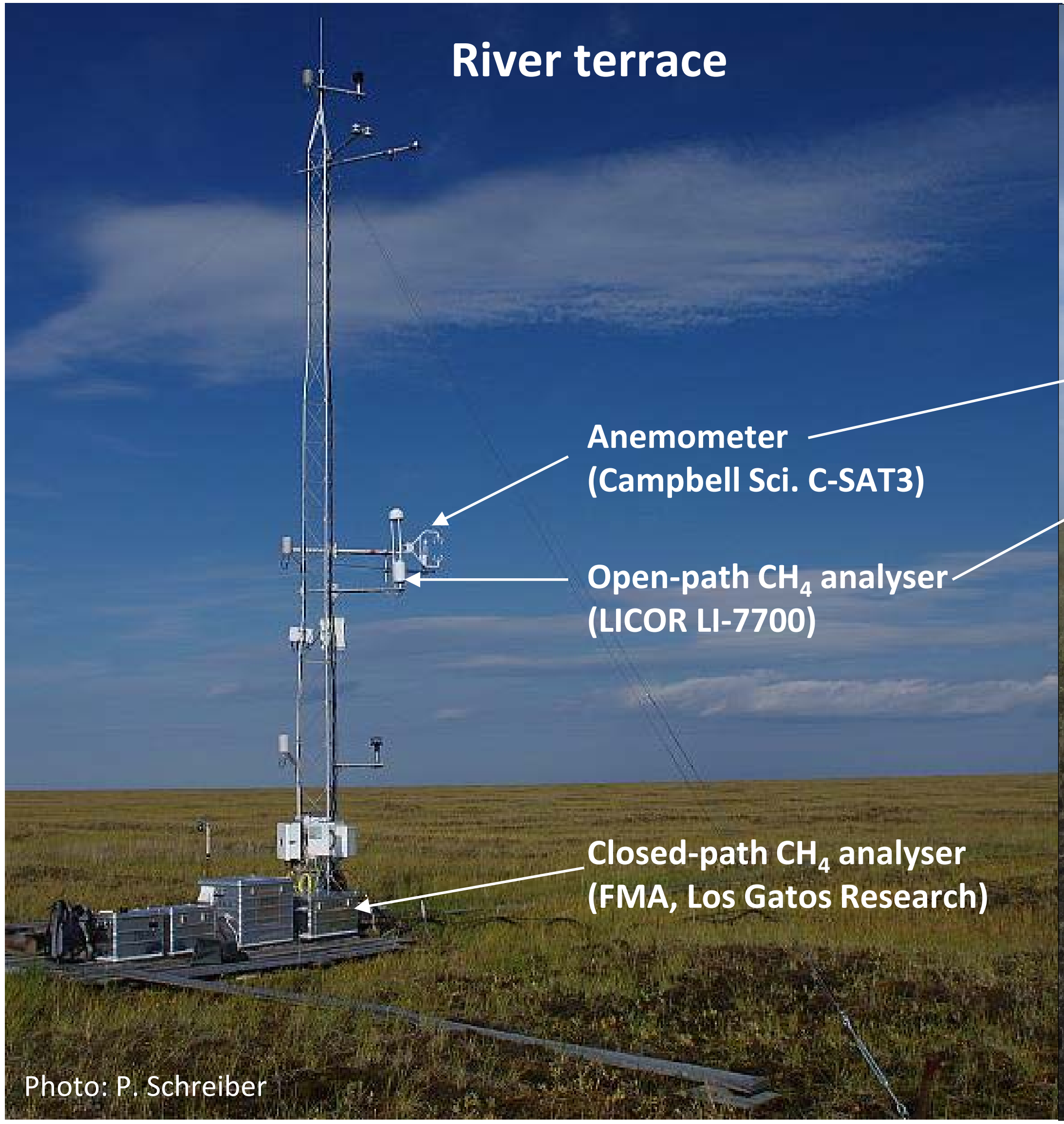
Aerial picture of Samoylov Island (Boike et al, 2012)

- **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?**

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

Eddy covariance flux measurements

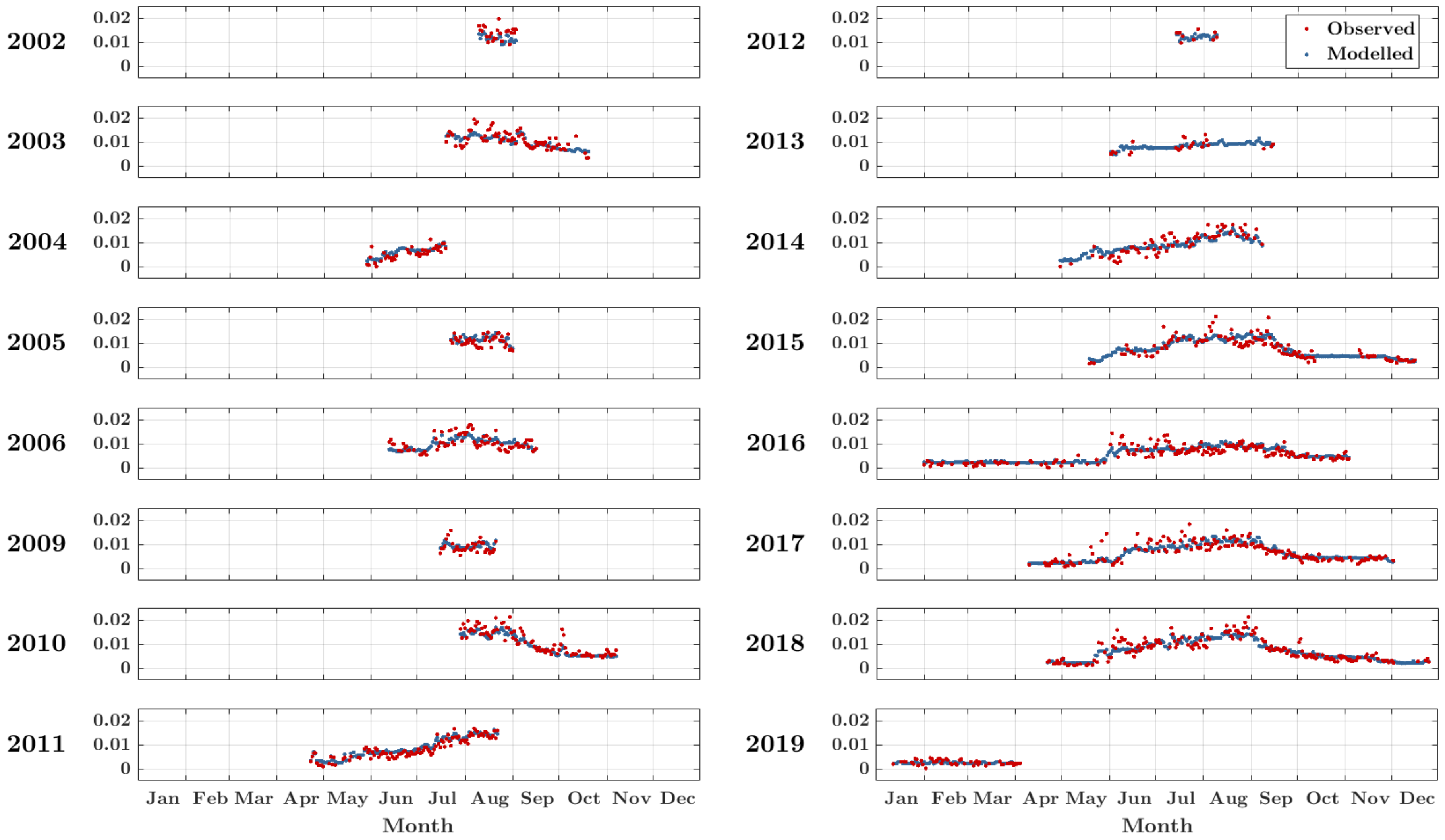
CLUSTER OF EXCELLENCE
CLIMATE, CLIMATIC CHANGE, AND SOCIETY (CLICCS)



Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

River Terrace: 16 campaigns of eddy covariance measurements of CH_4 fluxes

CLUSTER OF EXCELLENCE
CLIMATE, CLIMATIC CHANGE, AND SOCIETY (CLICCS)

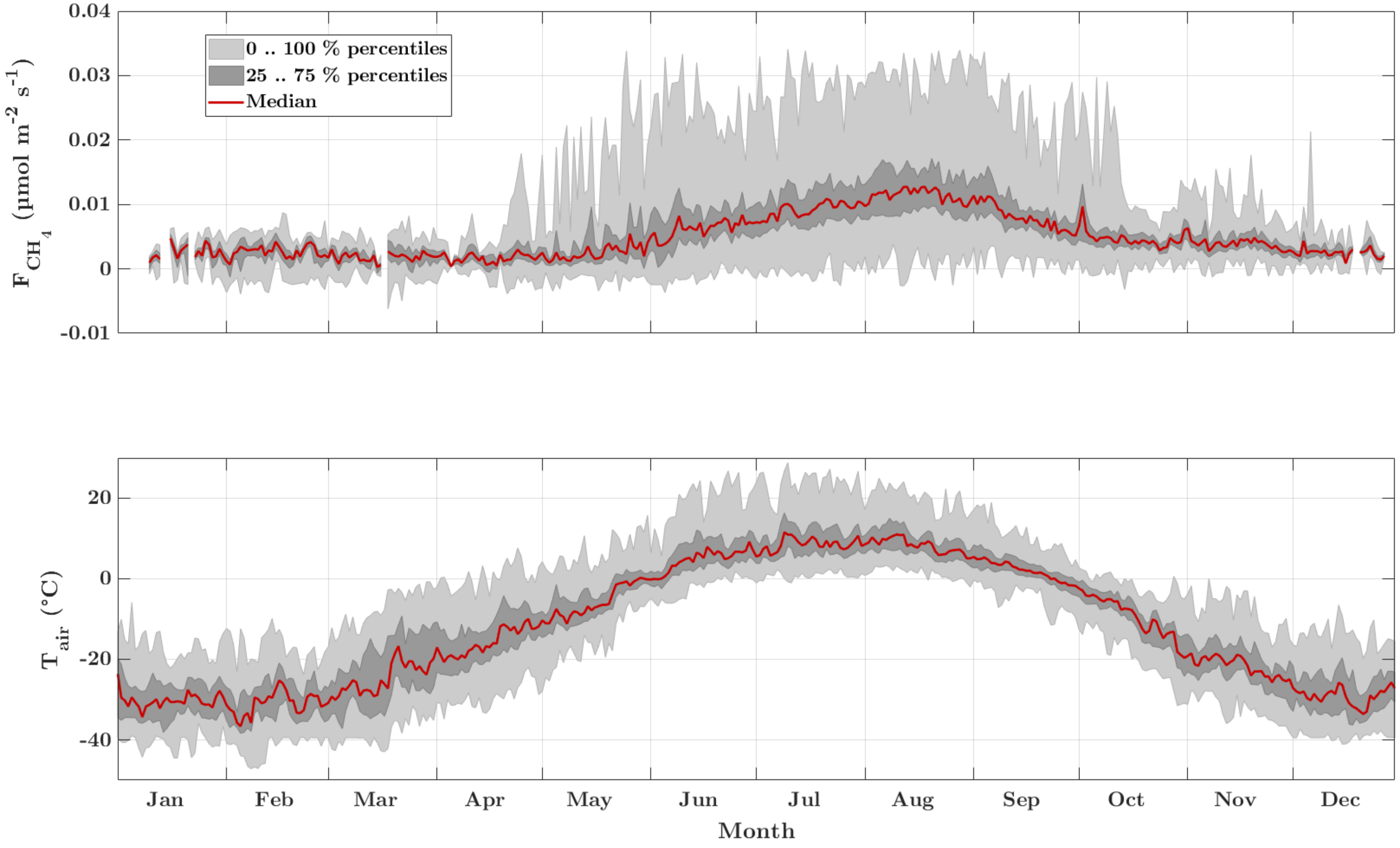


Time series of daily means of CH_4 fluxes F_{CH4}. Gap-filled by regression tree model. (Rößger et al., in prep.)

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

River Terrace: Average annual course of CH_4 emissions

CLUSTER OF EXCELLENCE
CLIMATE, CLIMATIC CHANGE, AND SOCIETY (CLICCS)



Median annual CH_4 flux course:

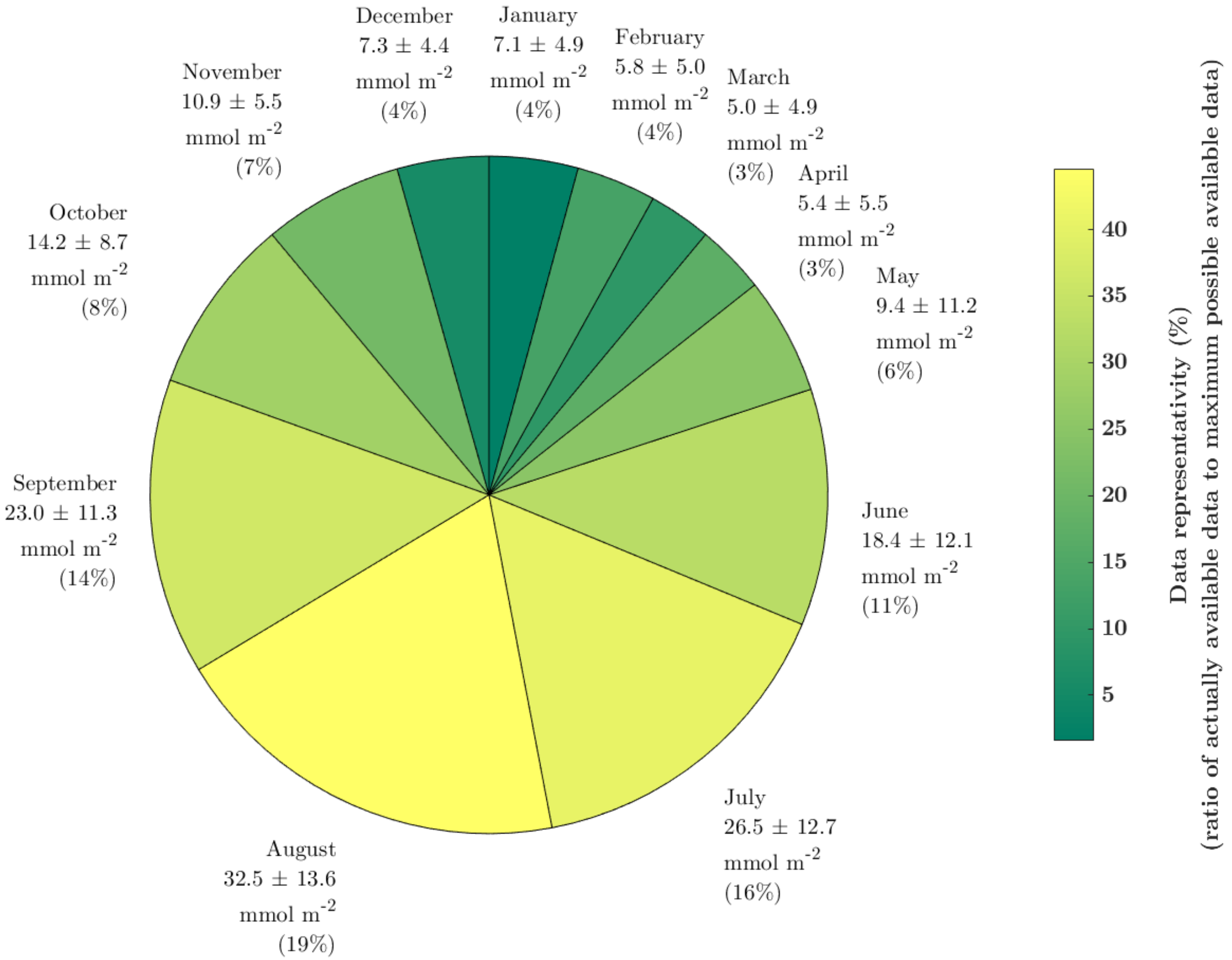
- **lowest (near zero) in April;**
- **continuous increase from May to August;**
- **steep decrease in September;**
- **gradual further decrease from October to April.**

Pooled half-hourly data for CH_4 fluxes F_{CH4} and air temperature T_{air} from all studied years: 2002-2006, 2009-2019 (Rößger et al., in prep.)

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

River Terrace: Mean annual CH_4 budget

CLUSTER OF EXCELLENCE
CLIMATE, CLIMATIC CHANGE, AND SOCIETY (CLICCS)



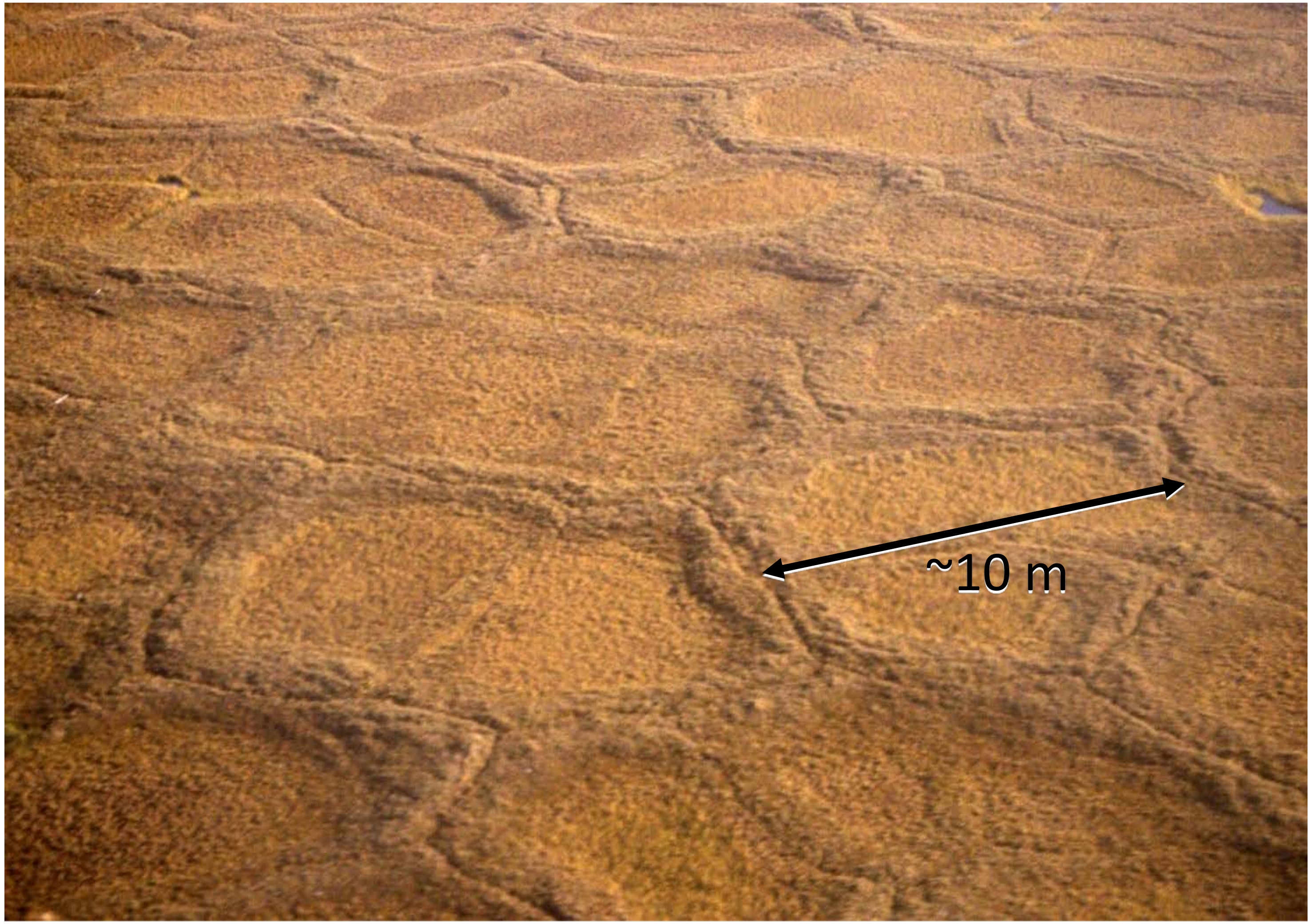
- **Total: 165 ± 31 mmol m^{-2}**
- **Thaw season (June-September): 100 ± 25 mmol m^{-2} (61 %)**
- **Freezing season (October-May): 65 ± 19 mmol m^{-2} (39 %)**
- **Contribution of freezing season similar to Alaskan tundra sites (Zona et al., 2016)**

Contribution of monthly CH_4 fluxes (mean ± stdev) to the mean annual CH_4 budget
(Rößger et al., in prep.)

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

River Terrace: Small-scale variability of CH_4 fluxes due to polygonal microrelief

CLUSTER OF EXCELLENCE
CLIMATE, CLIMATIC CHANGE, AND SOCIETY (CLICCS)



Thermal contraction low-center polygons at Samoylov Island (Photo L. Kutzbach)

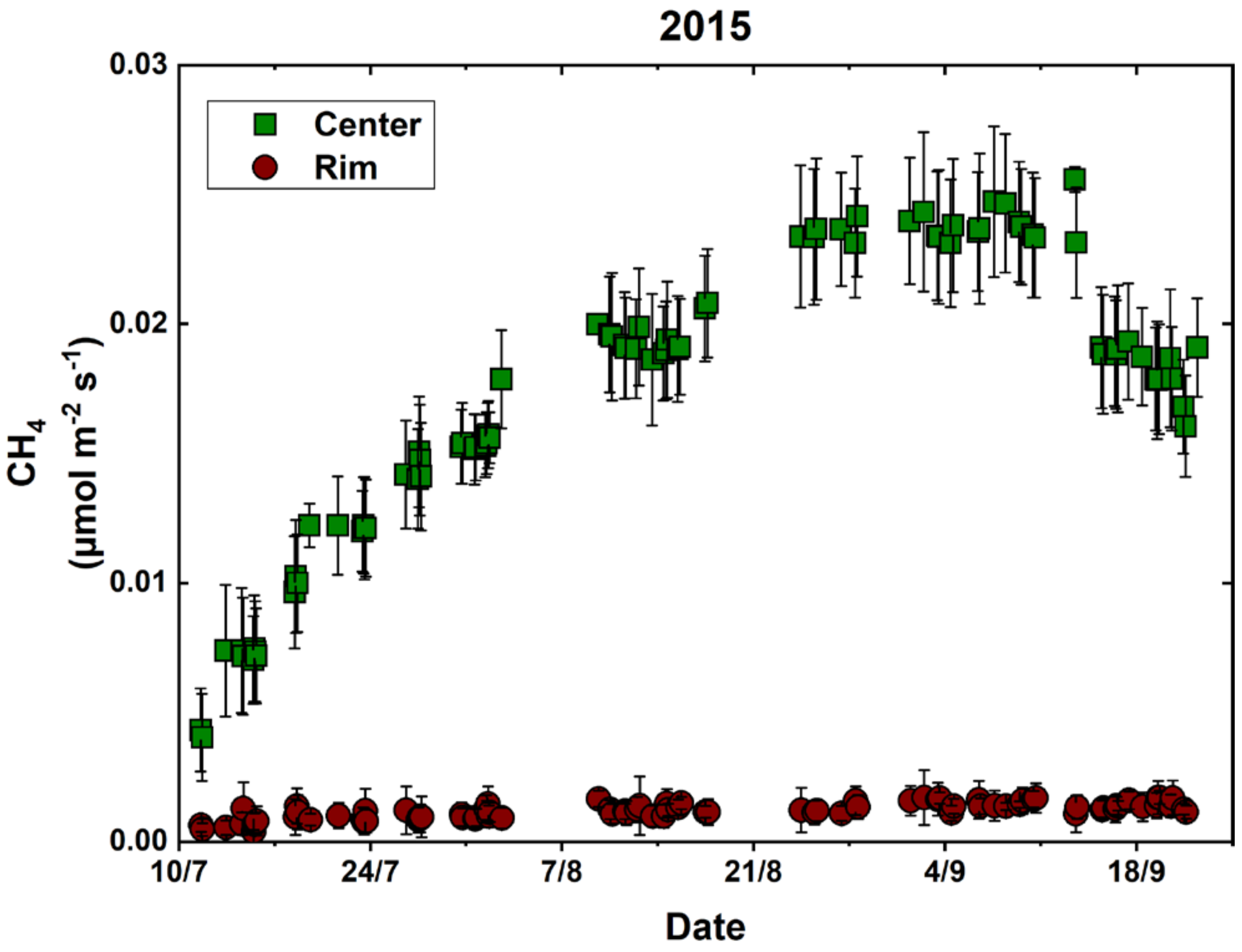
- **Elevated, moist-dry polygon rims: *Glacic Turbic Cryosols***
- **Depressed, water-saturated polygon centers: *Histic Cryosols***
- **Vegetation dominated by different moss and sedge species**

Small-scale CH_4 flux measurements by transparent closed chambers and an Ultraportable Greenhouse Gas Analyzer (UGGA 30-p, Los Gatos Research)

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

River Terrace: Small-scale variability of CH_4 fluxes due to polygonal microrelief

CLUSTER OF EXCELLENCE
CLIMATE, CLIMATIC CHANGE, AND SOCIETY (CLICCS)

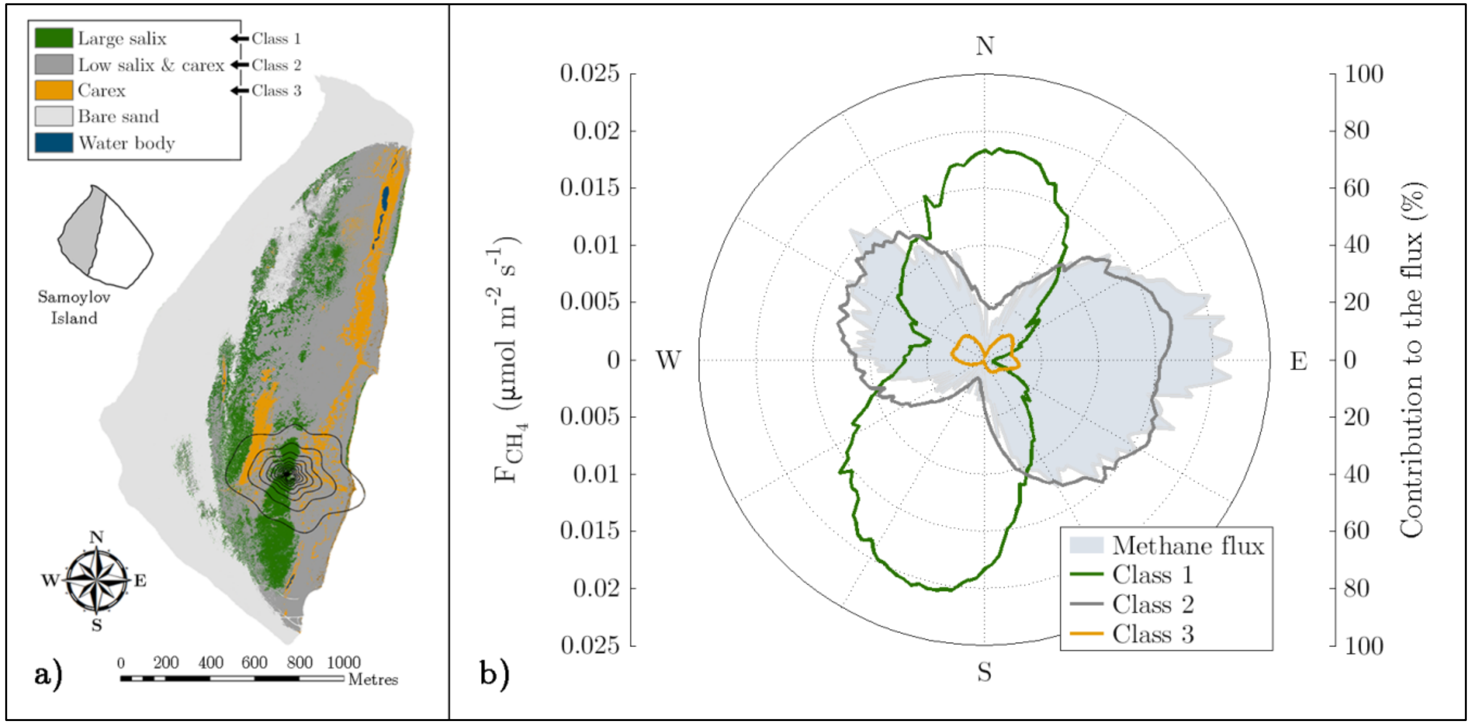


Mean CH_4 fluxes (n = 4) at rim and center of polygon in summer 2015, measured by closed-chamber method (Eckhardt, 2017)

- **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**

Floodplain: Heterogeneous eddy covariance footprint: Opportunity to estimate CH_4 fluxes for 3 vegetation classes

CLUSTER OF EXCELLENCE
CLIMATE, CLIMATIC CHANGE, AND SOCIETY (CLICCS)



- **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 %).

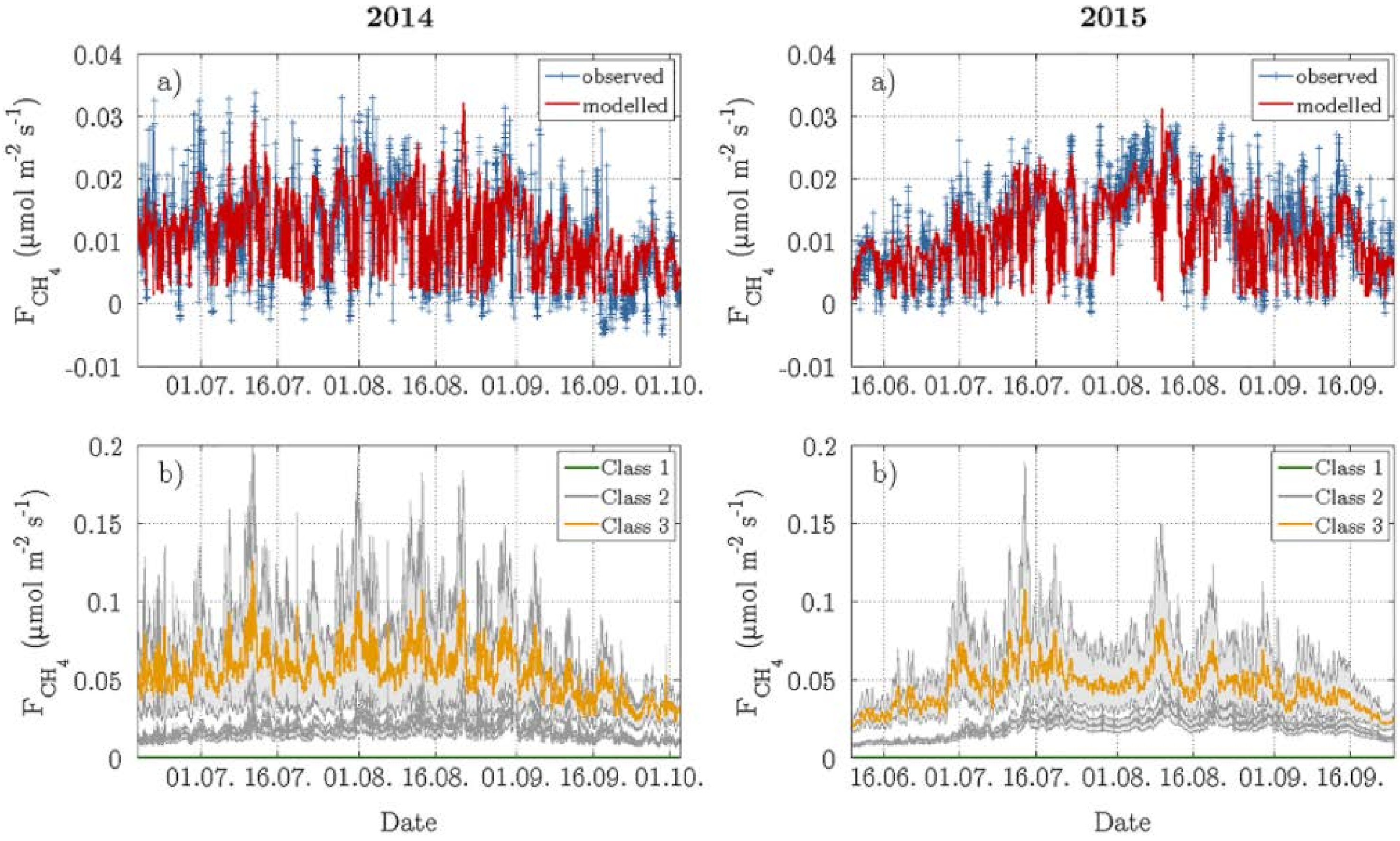
Right panel: Wind direction dependencies of both CH_4 flux and relative vegetation class contributions sorted by 2° wind direction bins utilising data from both measurement periods 2014 and 2015.

(Rößger et al., 2019)

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

Floodplain: Eddy covariance footprint CH_4 emissions can be decomposed into contributions of 3 vegetation classes

CLUSTER OF EXCELLENCE
CLIMATE, CLIMATIC CHANGE, AND SOCIETY (CLICCS)



- **Estimation of contributions by 3 vegetation classes (*Ω_1, Ω_2, Ω_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^**, *Ω_i*):**

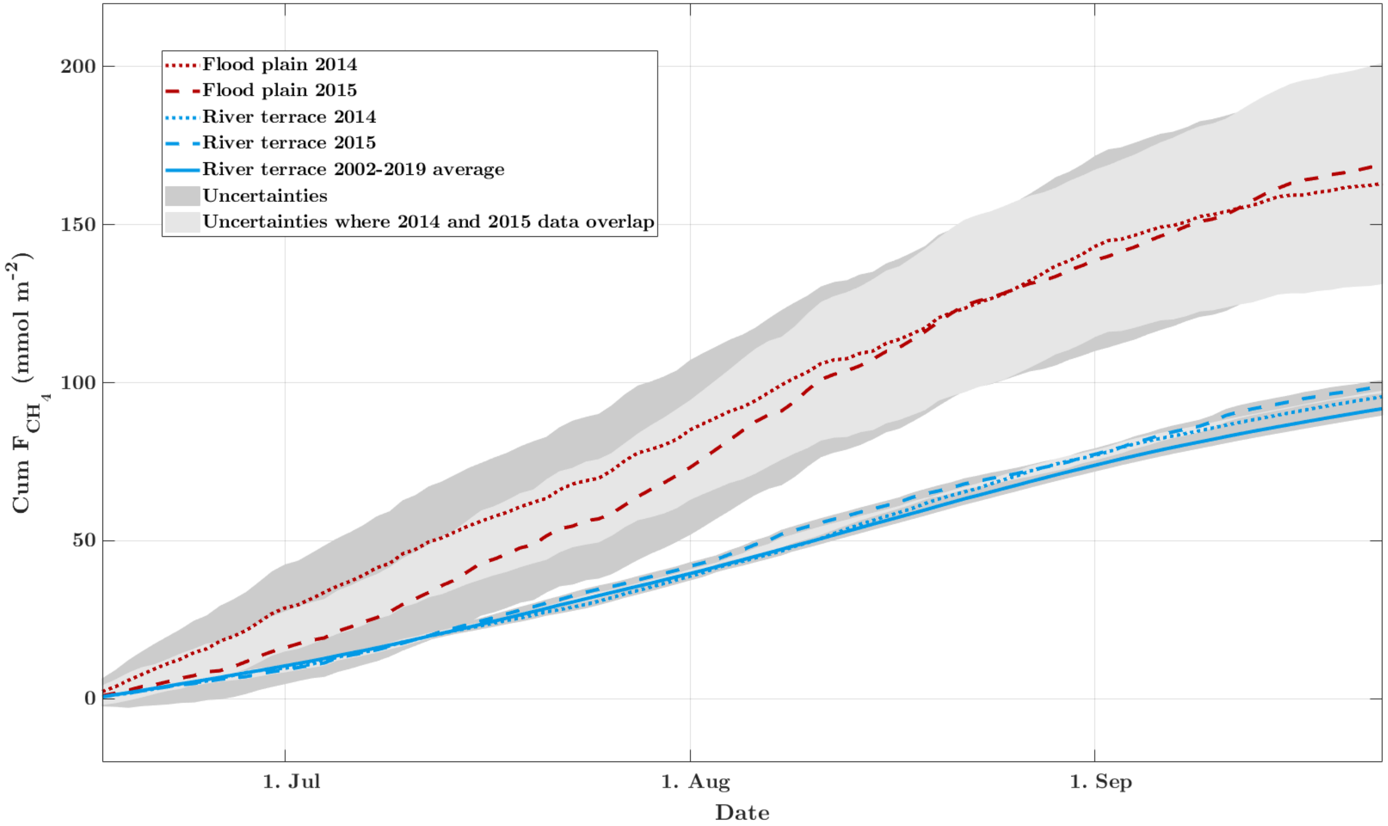
$$F_{CH_4} = \Omega_1\ a_1 + \Omega_2\ a_2\ e^{b_2\, T_{soil,2} + c\, u^*} + \Omega_3\ a_3\ e^{b_2\, T_{soil,3} + c\, u^*}$$

Upper panel: Time series of eddy covariance CH_4 fluxes during mid-June to end of September, 2014 and 2015.
Blue: Observed fluxes. Red: Modelled by mechanistic flux decomposition model.
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).

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

Floodplain has 70% higher CH_4 emissions during thaw season than river terrace

CLUSTER OF EXCELLENCE
CLIMATE, CLIMATIC CHANGE, AND SOCIETY (CLICCS)



- **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}**

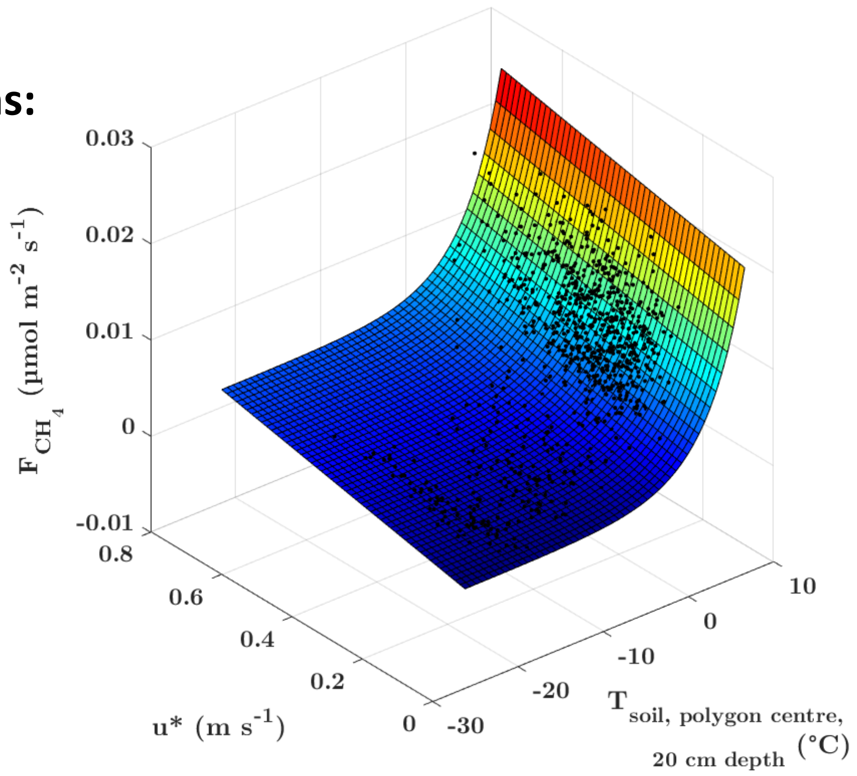
Cumulative CH_4 fluxes ‘CumF_{CH4}’ over the thaw period for the floodplain (2014, 2015) and the river terrace (2014, 2015 and long-term estimate (16 campaigns 2002-2019)). River terrace: Gap-filled eddy covariance measurements. Floodplain: Calculated by vegetation class sub-models of the flux decomposition model weighed by their respective spatial coverage.

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

River Terrace: CH_4 emissions well explained by soil temperature and atmospheric turbulence strength

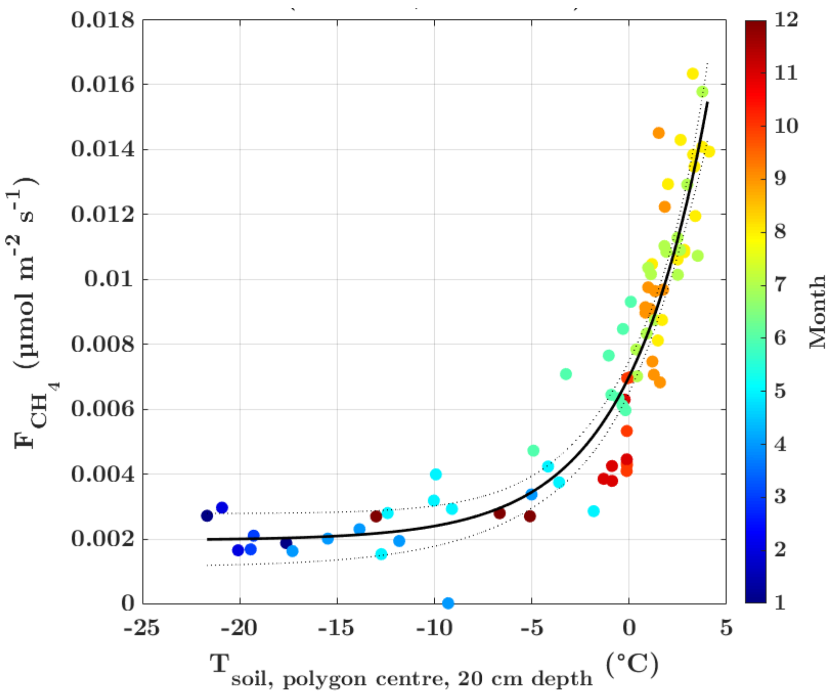
CLUSTER OF EXCELLENCE
CLIMATE, CLIMATIC CHANGE, AND SOCIETY (CLICCS)

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.).

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

River Terrace inter-annual variability: Linear increase of thaw season CH_4 emissions with growing degree days

CLUSTER OF EXCELLENCE
CLIMATE, CLIMATIC CHANGE, AND SOCIETY (CLICCS)

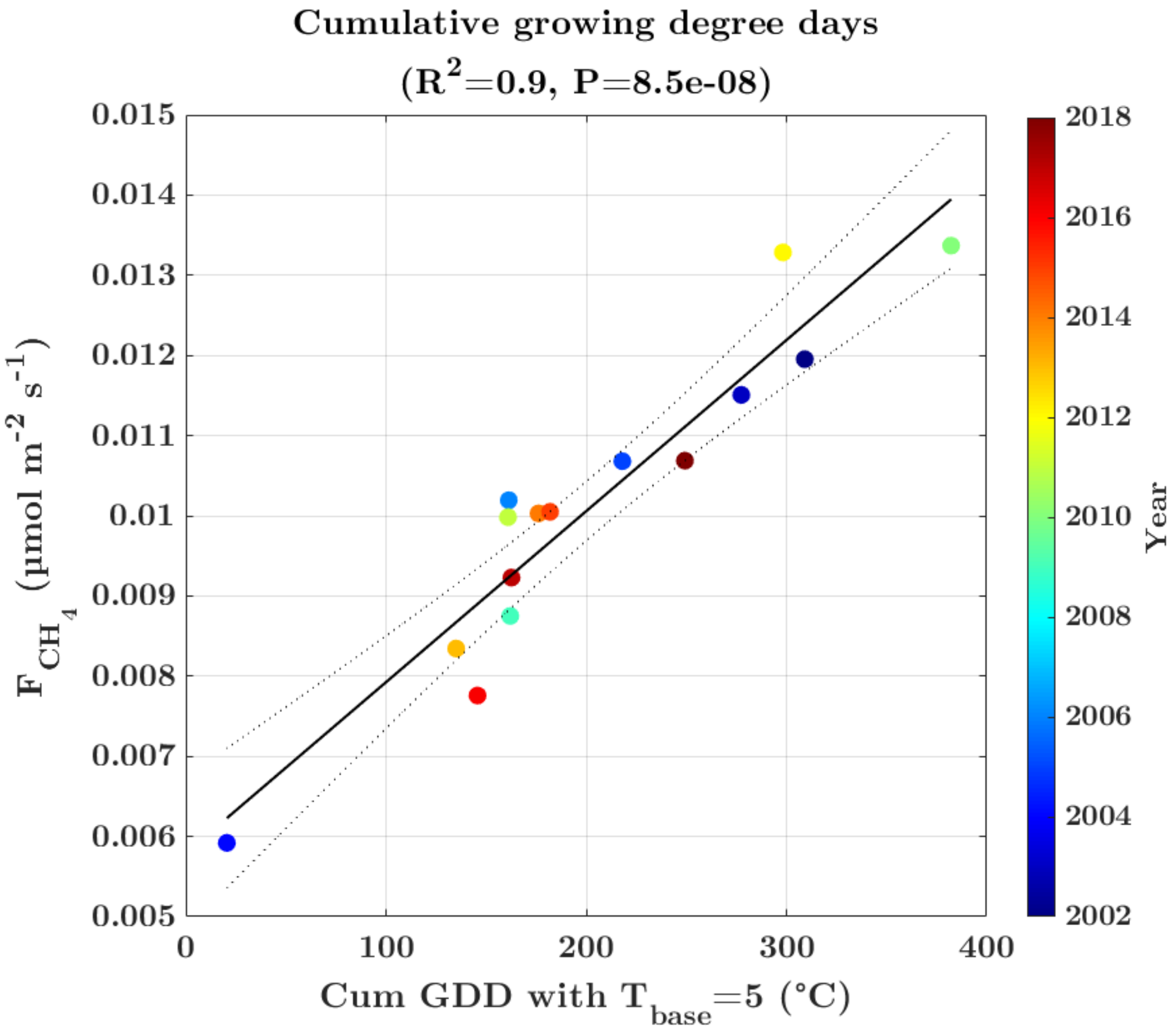


Figure: Rößger et al., in prep.

- 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).

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

Conclusions

CLUSTER OF EXCELLENCE
CLIMATE, CLIMATIC CHANGE, AND SOCIETY (CLICCS)

- 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 fom 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.

References

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

CLUSTER OF EXCELLENCE
CLIMATE, CLIMATIC CHANGE, AND SOCIETY (CLICCS)

Boike, J., Grüber, M., Langer, M., Piel, K., Scheritz, M. (2012). Orthomosaic of Samoylov Island, Lena Delta, Siberia. Alfred Wegener Institute - Research Unit Potsdam, PANGAEA. https://doi.org/10.1594/PANGAEA.786073

Boike, J., Nitzbon, J., Anders, K., Grigoriev, M., Bolshiyanov, D., Langer, M., ... & Kutzbach, L. (2019). A 16-year record (2002–2017) of permafrost, active-layer, and meteorological conditions at the Samoylov Island Arctic permafrost research site, Lena River delta, northern Siberia: an opportunity to validate remote-sensing data and land surface, snow, and permafrost models. Earth System Science Data, 11, 261-299.

Eckhardt, T. (2017). Partitioning carbon fluxes in a permafrost landscape. Dissertation Universität Hamburg. http://ediss.sub.uni-hamburg.de/volltexte/2017/8716/

Knoblauch, C., Spott, O., Evgrafova, S., Kutzbach, L., & Pfeiffer, E. M. (2015). Regulation of methane production, oxidation, and emission by vascular plants and bryophytes in ponds of the northeast Siberian polygonal tundra. Journal of Geophysical Research: Biogeosciences, 120(12), 2525-2541.

Kormann, R., & Meixner, F. X. (2001). An analytical footprint model for non-neutral stratification. Boundary-Layer Meteorology, 99(2), 207-224.

Kutzbach, L., Wagner, D., & Pfeiffer, E. M. (2004). Effect of microrelief and vegetation on methane emission from wet polygonal tundra, Lena Delta, Northern Siberia. Biogeochemistry, 69(3), 341-362.

Kutzbach, L., Zubrzycki, S., Knoblauch, C., Fiencke, C., Pfeiffer, E.-M. (2014). Permafrostbeinflusste Böden (Kryosole) im Klimawandel. In Lozán, J.L. et al. (eds.) Warnsignal Klima – Die Polarregionen. Verlag Wissenschaftliche Auswertungen, Hamburg, pp. 275-284. https://www.klima-warnsignale.uni-hamburg.de/wp-content/uploads/2014/04/kutzbach.etal.pdf

Rößger, N., Wille, C., Veh, G., Boike, J., Kutzbach, L. (2019). Scaling and balancing methane fluxes in a heterogeneous tundra ecosystem of the Lena River Delta. Agricultural and Forest Meteorology, 266, 243-255.

Wagner, D., & Liebner, S. (2009). Global warming and carbon dynamics in permafrost soils: methane production and oxidation. In Margesin, R. (ed.) Permafrost soils (pp. 219-236). Springer, Berlin, Heidelberg.

Wille, C., Kutzbach, L., Sachs, T., Wagner, D., & PFEIFFER, E. M. (2008). Methane emission from Siberian arctic polygonal tundra: eddy covariance measurements and modeling. Global Change Biology, 14(6), 1395-1408.