# Seasonal deformation rates obtained from Sentinel-1 InSAR analyses across Arctic lowland permafrost regions reflect soil moisture gradients

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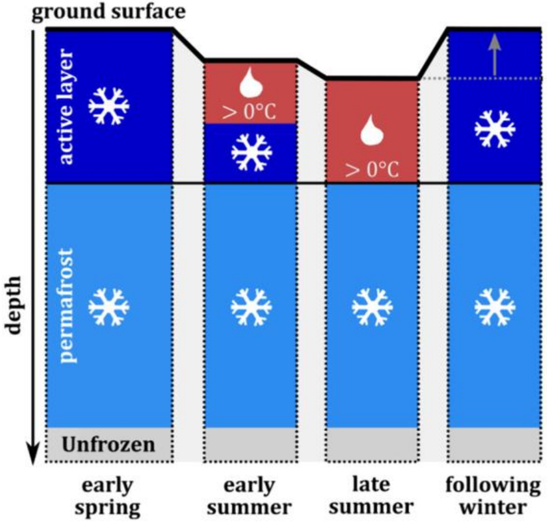
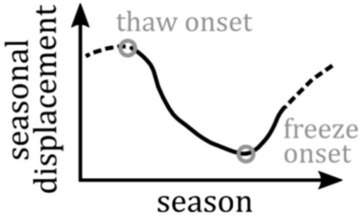
# Seasonal deformations in Arctic permafrost regions

Summer subsidence & winter heave
Considerable surface displacements especially for ice-rich permafrost




Source : Zwieback et al., 2024

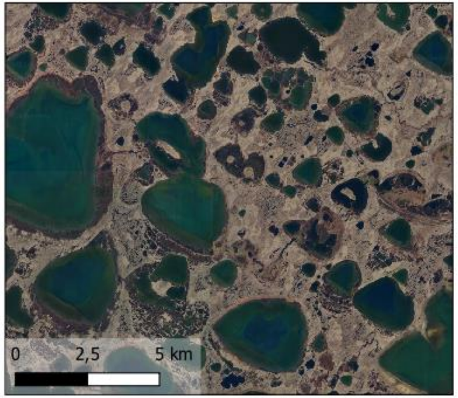
Zwieback, S., Liu, L., Rouyet, L., Short, N. and Strozzi, T. (2024), Advances in InSAR Analysis of Permafrost Terrain. Permafrost and Periglac Process, 35: 544-556. https://doi.org/10.1002/ppp.2248

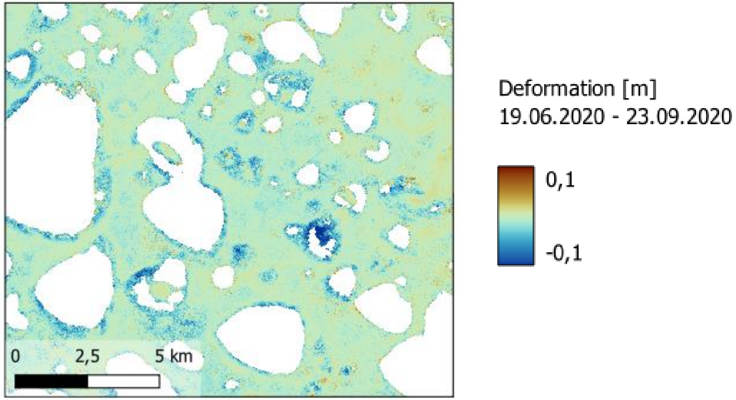
# Examples of remote sensing techniques for near-surface soil moisture

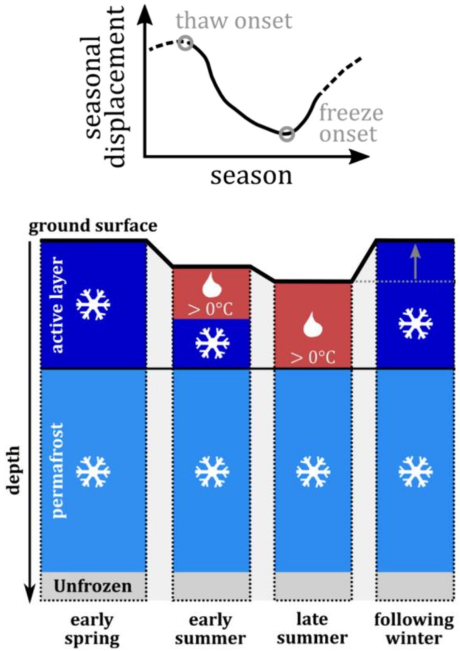
| Sensor type | Approach/observed property | Basic principle | Advantages | Disadvantages | Applicability in permafrost regions |
|---|---|---|---|---|---|
| **Optical** | reflectance indices and derivatives | albedo | high spatial resolution, broad coverage | cloud coverage, strongly perturbed by vegetation and other hampering factors | limited applicability due to frequent cloud coverage in Arctic regions (Sudmanns et al., 2020) |
| **Thermal infrared** | surface temperature | thermal inertia | high spatial resolution, broad coverage | cloud coverage, strongly perturbed by vegetation, influenced by meteorologic conditions | limited applicability due to frequent cloud coverage in Arctic regions (Sudmanns et al., 2020) |
| **Passive microwave** | brightness temperature | dielectric properties | high temporal sampling, broad coverage, all weather | low spatial resolution, perturbed by surface roughness and vegetation | limited applicability in heterogeneous Arctic (Wrona et al., 2017; Kim et al., 2023) |
| **Active microwave** | backscatter | dielectric properties | high spatial resolution, all weather | perturbed by surface roughness and vegetation | low reliability in Arctic regions (Högström et al., 2018; Kim et al., 2023) |

# Soil moisture & subsidence

Chersky region (Northeast Siberia)

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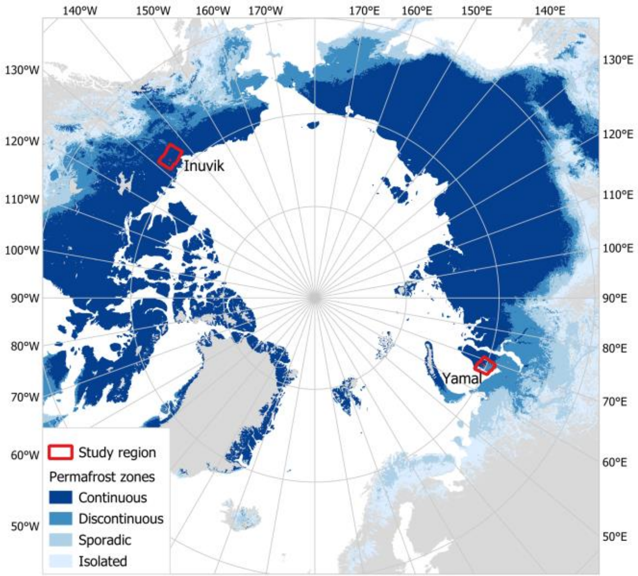
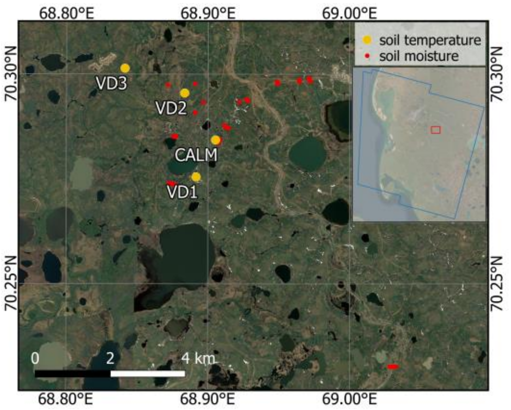
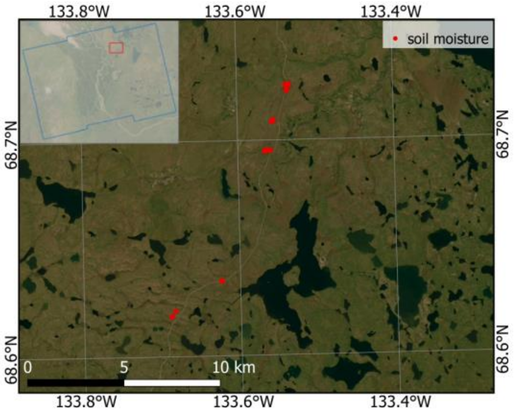
# Study sites




**Yamal**, Northwestern Siberia




**Inuvik**, Northwestern Canada




# In situ data

- Subsidence measurements at CALM grid (Yamal)
- Soil moisture measurements (Yamal, Inuvik- drought conditions)

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J. Obu et al. (2019) : Northern Hemisphere permafrost map based on TTOP modelling for 2000–2016 at 1km2 scale, Earth-Science Reviews 193, 299–316.

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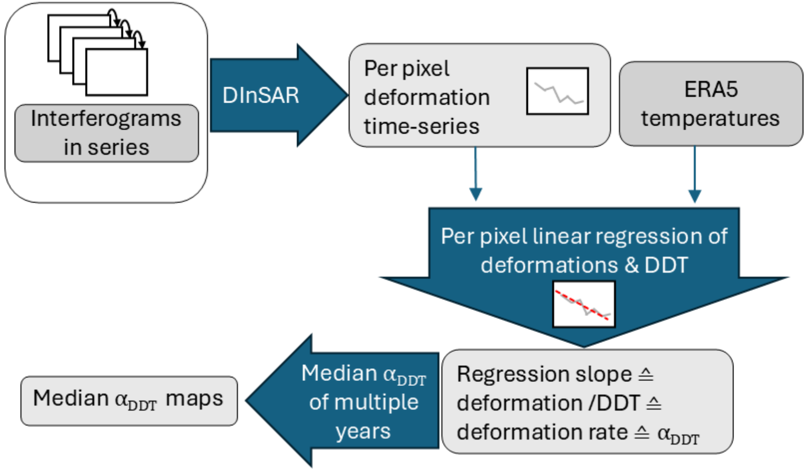
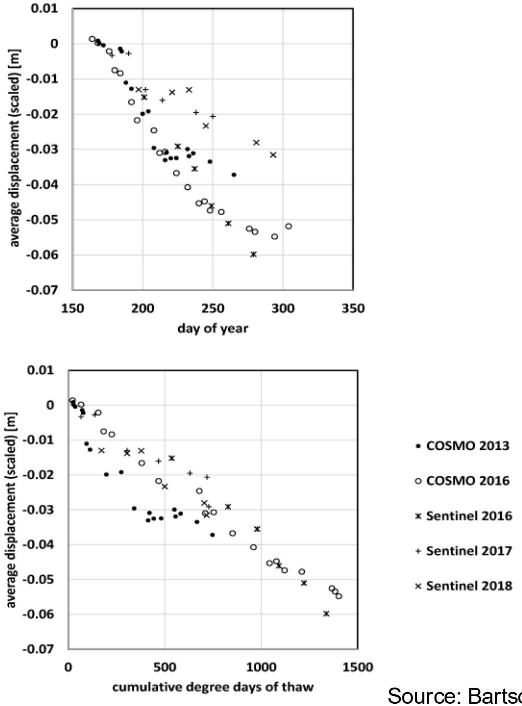
# Sentinel-1 InSAR Workflow




Relationship with cumulative Degree Day of Thaw (DDT) is similar between the years contrary to the day of year relationship

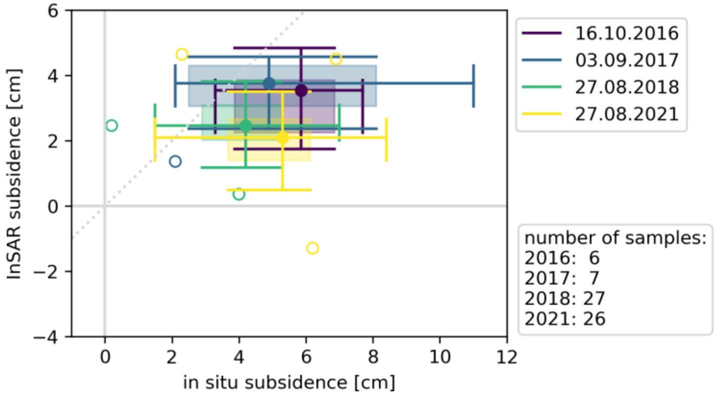



Source: Bartsch et al., 2016

Bartsch, A., Leibman, M., Strozzi, T., Khomutov, A., Widhalm, B., Babkina, E., Mullanurov, D., Ermokhina, K., Kroisleitner, C., & Bergstedt, H. (2019). Seasonal Progression of Ground Displacement Identified with Satellite Radar Interferometry and the Impact of Unusually Warm Conditions on Permafrost at the Yamal Peninsula in 2016. Remote Sensing, 11(16), 1865. https://doi.org/10.3390/rs11161865

# Comparison to in situ subsidence

CALM grid, Vaskini Dachi, Yamal:
yearly subsidence measurements (plywood plate with rod)*


InSAR subsidence corrected for onset time of thawing

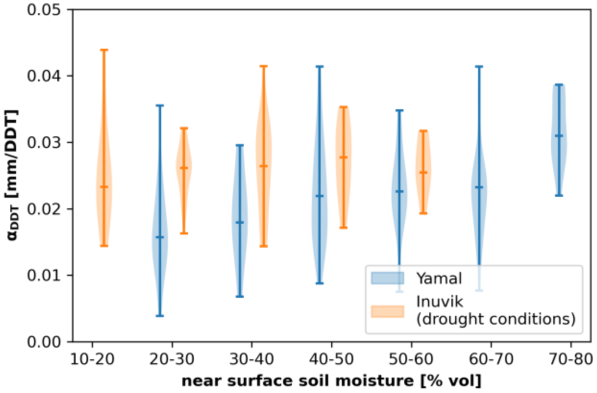
Lower InSAR subsidence compared to in situ values:

- In situ measurements are point measurements, and medium-scale InSAR measurements may therefore underestimate true displacements due to spatial averaging
- Selection of reference point
- Underestimation of subsidence values during the unmonitored beginning of the thawing season
- Soil moisture variations

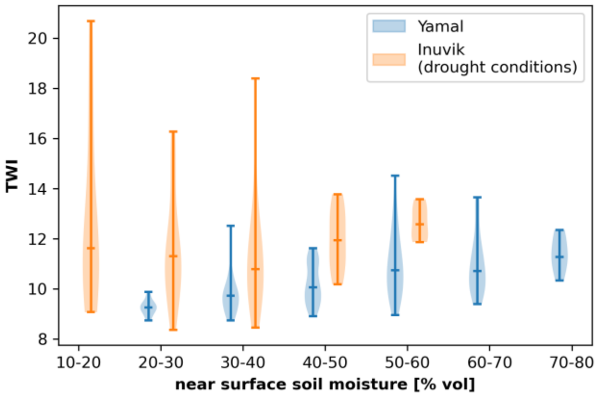
* in situ data provided by Marina Leibman, Artem Khomutov, Elena Babkina, Evgeny Babkin of the Earth Cryosphere Institute, Tyumen Scientific Centre SB RAS

# Soil moisture comparison

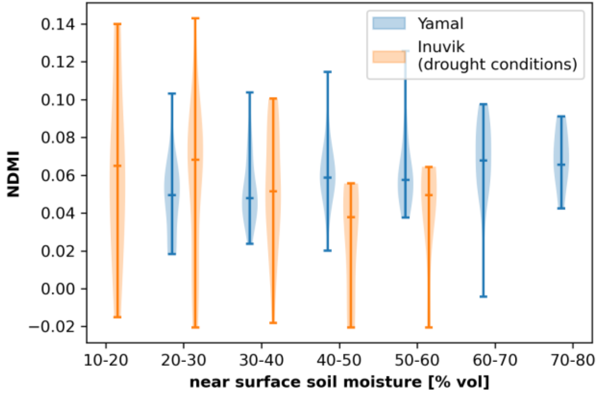
InSAR subsidence trend
($\alpha_{DDT}$, ~15m resolution)




Topographic Wetness Index
(TWI, ArcticDEM, 2m resolution)




Normalized Difference Moisture Index
(NDMI, Landsat 8, 30m resolution)



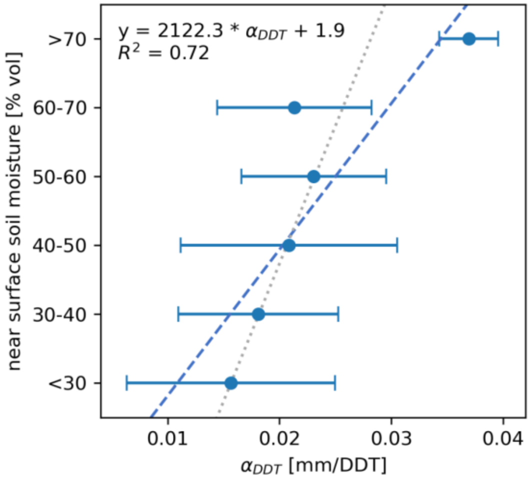

Yamal: higher soil moisture - greater subsidence
Inuvik (drought): relationship only for values below 50 % vol.

Yamal: higher soil moisture – higher TWI values
Inuvik (drought): not consistent for < 30 % vol

Yamal & Inuvik: no stringent relationship

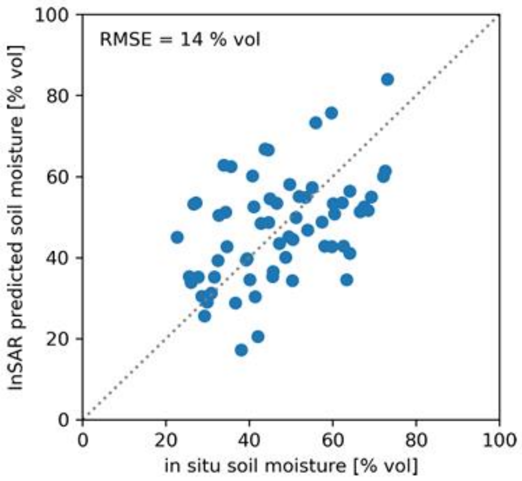
# Calibration

Yamal calibration dataset
Linear relationship derived for subsidence trends
➢ $\alpha_{DDT}$ [mm/DDT] (assuming linear relationship between seasonal subsidence and DDT)

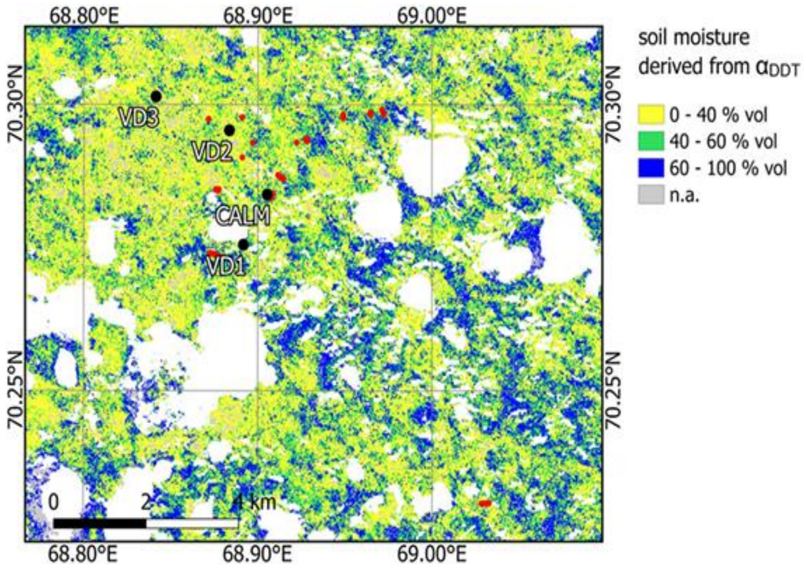


# Validation

Yamal validation dataset




Soil moisture map derived from InSAR for the Yamal study site

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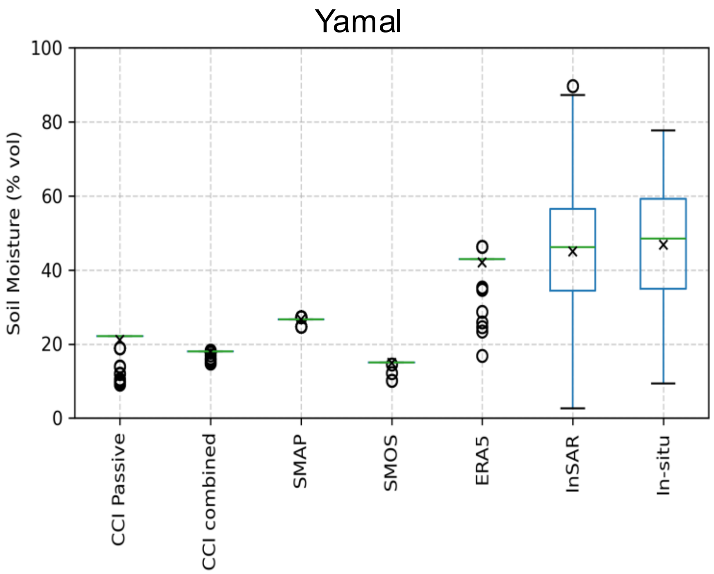
# Comparison to other remotely sensed soil moisture products

'Arctic-Boreal CO2 (ABC) flux database v2' in situ soil moisture data (Virkkala et al. 2025) additionally used for comparison




- Coarser resolution satellite products deviate form in situ measurements -> significant bias
- ERA5 soil moisture data has better agreement than coarser resolution satellite products

Virkkala et al. (2025): ABCFlux v2: Arctic–boreal CO and CH monthly flux observations and ancillary information across terrestrial and freshwater ecosystems, Earth System Science Data Discussions,2025, 1–86, https://doi.org/10.5194/essd-2025-585

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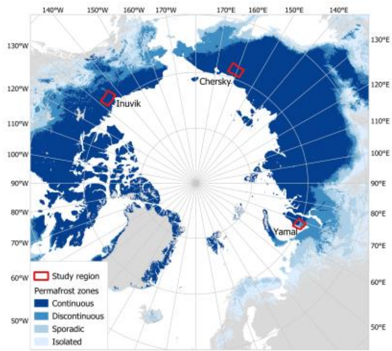


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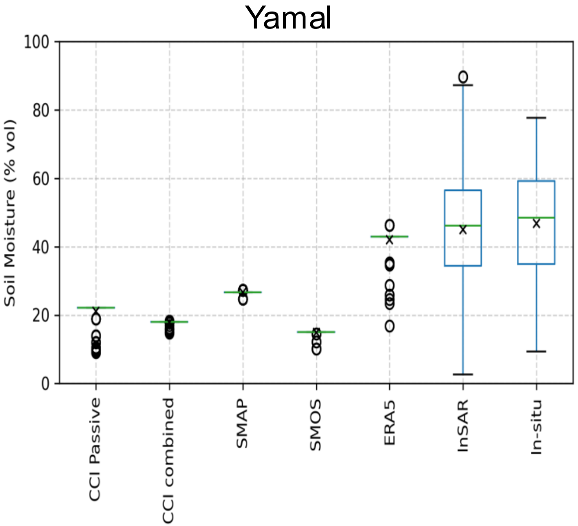
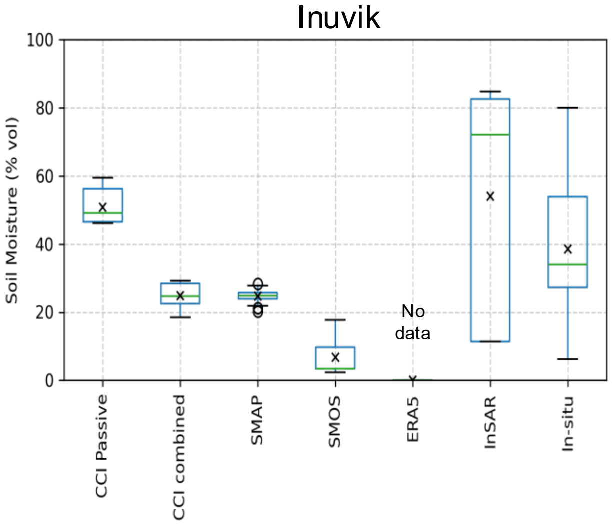
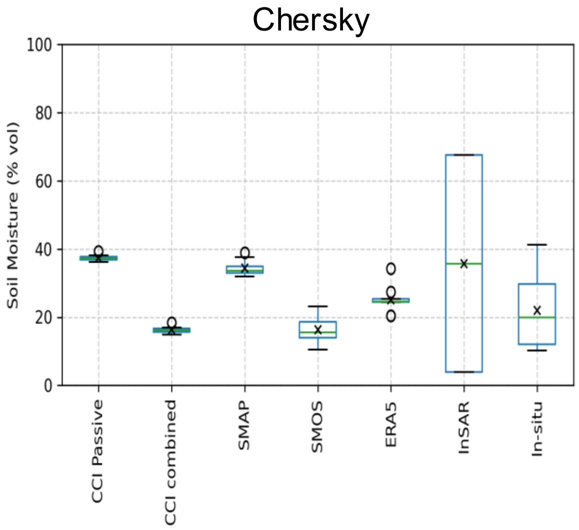


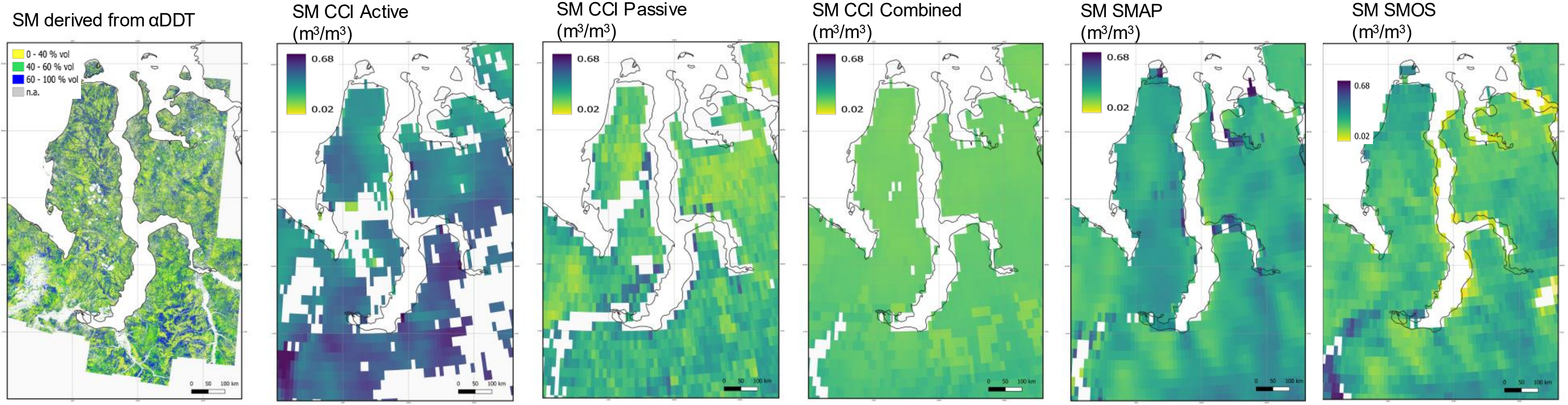




Virkkala et al. (2025): ABCFlux v2: Arctic–boreal CO and CH monthly flux observations and ancillary information across terrestrial and freshwater ecosystems, Earth System Science Data Discussions,2025, 1–86, https://doi.org/10.5194/essd-2025-585

# Spatial distribution of soil moisture from microwave remote sensing

Representation of moisture patterns for the Yamal region using
InSAR and coarse scale satellite soil moisture products (July-August average).




- ➢ InSAR as a proxy for spatial soil moisture patterns

# Applications

- Upscaling of methane fluxes (Ivanova et al. 2026)

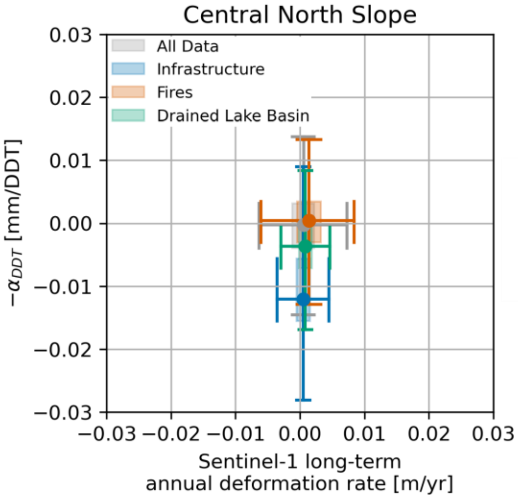
Spearman rank-correlation coefficients between July CH4 flux and environmental predictors at 1 and 10m spatial resolution (Trail Valley Creek, Western Canada)

| Group | Predictor | 1 m | 10 m | 10 m, temporal |
|---|---|---|---|---|
| Vegetation | NDVI | −0.289*** | −0.295*** | −0.082** |
| Surface wetness and soil moisture | NDWI | 0.141*** | 0.24*** | −0.013 |
| | TWI | 0.027** | 0.235*** | |
| Topography | Slope | −0.187*** | −0.238*** | |
| | Aspect | 0.14*** | 0.035*** | |
| | TPI | −0.162*** | −0.327*** | |
| Ground subsidence | Cumulative seasonal subsidence | | 0.534*** | |

Significance levels: $**$ $p < 0.01$, $***$ $p < 0.001$

- Disturbances (Bartsch et al. 2026)

Drained lake basins and the surroundings of infrastructure subside seasonally more than on average within the scenes.




Ivanova, K., Virkkala, A.-M., Brovkin, V., Stacke, T., Widhalm, B., Bartsch, A., Voigt, C., Sonnentag, O., and Göckede, M.: High-resolution remote sensing and machine-learning-based upscaling of methane fluxes: a case study in the Western Canadian tundra, Biogeosciences, 23, 233–262, 2026

Bartsch, A., Widhalm, B., Radha Krishnan,S. R., Liu, Z.: Tracking land surface deformation in lowland permafrost regions across the Arctic exploiting the first decade of Copernicus Sentinel-1, Remote Sensing of Environment, 340, 2026

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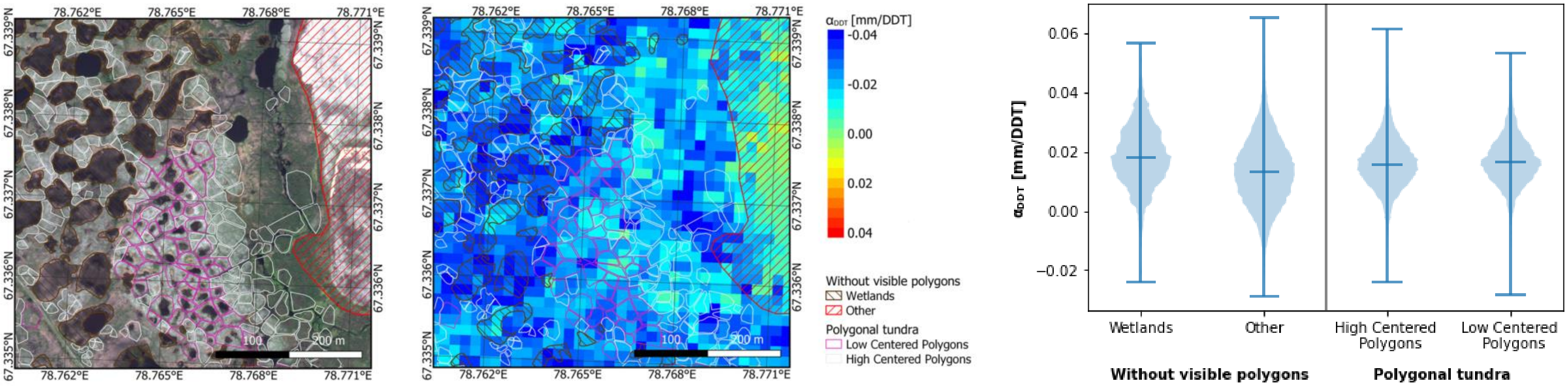
# Conclusions

- Novel approach for deriving a soil moisture index of general or predominant moisture conditions for permafrost regions based on InSAR subsidence signal rates
- Higher surface subsidence rates are found for wetter regions
- Spatial patterns of wet and dry areas can be derived, which are linked to methane fluxes
- Better match with in situ values compared to conventional coarser-scale datasets on cal/val site Yamal. However, results vary between regions

# Permafrost features characterization




- Slightly higher $\alpha_{DDT}$ and subsidence can indeed be observed for wetlands compared to other non-wetland tundra
- No visible differentiation is detectable between high-centred and low-centred polygons

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