Methane profile and gradient studies in Arctic Space Centre, Sodankylä, Finland

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Finnish Meteorological Institute operates a Bruker IFS125HR Fourier transform spectrometer and two portable EM27/SUN spectrometers, from which the other one is on loan from Karlsruhe Institute of Technology, at Arctic Space Centre in Sodankylä, Finland. After measuring side-by-side from 2022 until 2024 the other one was moved to a wetland site 1 km away for a XCH_4 gradient study. Methane concentrations and fluxes have also been monitored on the wetland with other methods. Vertical profiles and horizontal variability have been measured in several campaigns using drone-based active AirCore instrument, and the fluxes are continuously monitored using the eddy covariance method.

For studying vertical profiles up to stratosphere, Arctic Space Centre performs balloon-borne sampling using AirCore samplers. FMI has also developed a retrieval software, called Swirlab, that uses a prior reduction method to extract vertical information from high resolution (TCCON standard 0.02 cm^{-1}) spectra within a short spectral window at 6000 -- 6005 cm^{-1}.

EM27/SUN time series and the first results of the gradient study

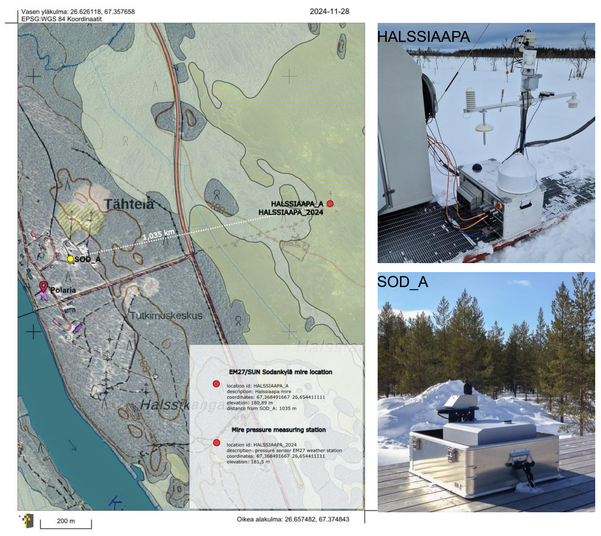


Figure 1. FMI-owned EM27/SUN SN122 measured on top of a container at location marked SOD_A 2020-2023 and was moved to a wetland site at Halssiaapa. KIT-owned EM27/SUN SN81 measured on a trolley at the foot of the container at SOD_A 2022-2023 and was relocated to the top of the container 2024 for easier operation.
SN122 data is automatically synced to a local server, where a processing pipeline is run every evening to process data from the previous day.
SN122 is enclosed in an automated weather shelter (see top right). The enclosure is based on design by Technical University of Munich (TUM). The measurements are initiated whenever weather and solar elevation angle allows which enhances the temporal coverage of measurements.

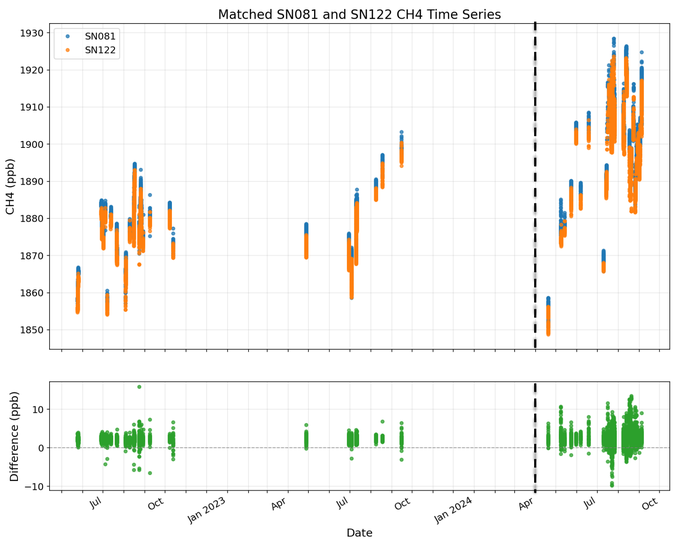
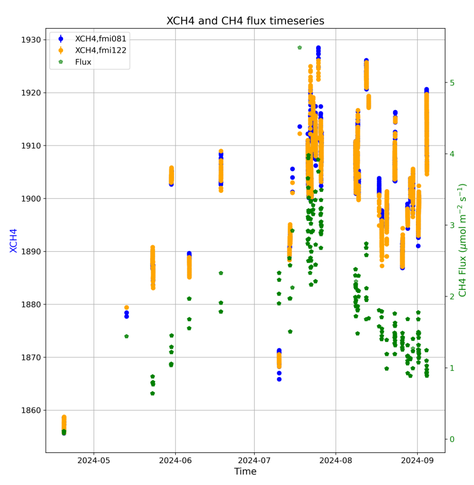


Figure 2. Timeseries of EM27/SUN XCH_4 measurements at FMI-ARC. The dashed line marks the date when SN122 was moved to the wetland site and measurements were automated with the help of the new enclosure. SN81 was moved to the top of the container allowing more frequent measurements.
On average, the difference (bottom panel) between the instruments was 2.24 ppb (SN081 – SN122) before the transfer and 2.43 ppb after. The standard deviation of differences increased from 0.7 to 1.7 ppb.



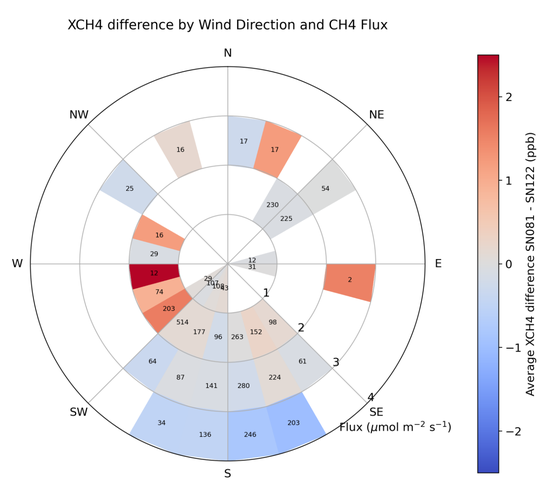
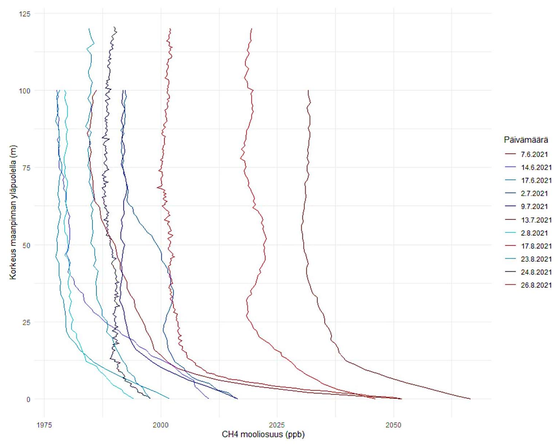


Figure 3 and 4. Wetland site is equipped with eddy covariance flux measurements. The left side shows the timeseries of each EM27/SUN instrument and the flux from eddy covariance for 2024. On the right the radial axis represents the 30-minute average flux (in µg/m2/s) at the wetland, and the polar angle represents the wind direction. The differences of the two instruments binned in 15 degree bins in wind direction and 1 in µg/m2/s bins in methane flux. The color scale depicts the average difference for each bin.The scale of the differences has been offset by the average difference (2.48 ppb) during low flux (<0.2 µg/m2/s) conditions. The binned averages of the differences are largest during the largest fluxes (> 3 µg/m2/s), suggesting there could be a weak but detectable enhancement from the wetland flux. The EM27/SUN measuring next to TCCON station has larger column values when wind direction is from the wetland towards the station.

Drone-based AirCore measurements of vertical profiles



Figure 5. Drone operator ready to take off on the wetland with an active AirCore onboard. The drone-AirCore pumps ambient air into a thin tube. Mixing in the tube is slow and by analyzing the gas soon after the flight the concentrations can be georeferenced. The volume of the tube allows for about 10-minute sample. Measurements are performed on a campaign basis.



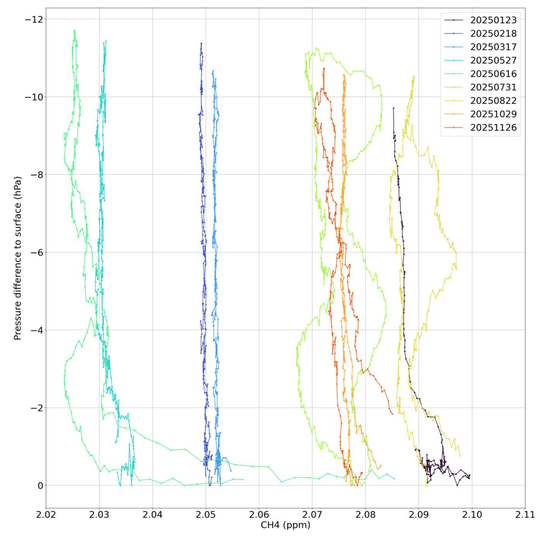


Figure 6 and 7. On the left (figure by Aatu Perkiö): drone-AirCore profiles measured at the wetland during summer 2021. Usually, an enhancement can be seen close to surface confined within the first 25 meters. On the right (figure by Marika Honkanen): Monthly measurements of methane profiles on the wetland in 2025. Profiles from April and December were left out due to technical issues during the flight or analysis. The summer profiles show more vertical variability than winter profiles. Occasionally, winter profiles contain some enhancement in the lower part which could be caused by disturbance to the snowpack by the people performing the measurement

SWIRLAB profile retrieval

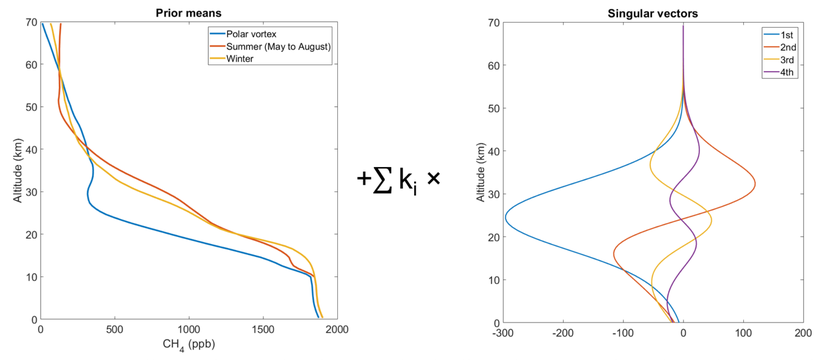


Figure 8. Schematic of the SWIRLAB methane profile retrieval

We use a dimension reduction method, directly truncating the prior covariance matrix. A Gaussian prior $\mathbf{X} \sim \mathcal{N}(\mathbf{x}_0, \mathbf{C})$, where $\mathbf{x}_0 \in \mathbb{R}^n$ is the prior mean and $\mathbf{C} \in \mathbb{R}^{n \times n}$ covariance which can be factorized using eigenvalue decomposition, or with SVD,

$$\mathbf{C} = \mathbf{USU}^T \approx \sum_{i=1}^{k} \sigma_i \mathbf{u}_i \mathbf{u}_i^T = \mathbf{P}_k \mathbf{P}_k^T, \tag{1}$$

where $\mathbf{P}_k = [\sqrt{\sigma_1}\mathbf{u}_1, \ldots, \sqrt{\sigma_k}\mathbf{u}_k]$, σ are the (sorted) eigenvalues, and $\mathbf{u}$ are the corresponding eigenvectors. Then the profiles are parameterized $\mathbf{x} = \mathbf{P}_k\alpha + \mathbf{x}_0$, where $\alpha \sim \mathcal{N}(0, \mathbf{I}_k)$. In the FTS inverse problem, the number of layers is $n \approx 70$, but the number of unknowns is $k = 3$ which approximately corresponds the actual information content of the measurement. Then the posterior distribution becomes

$$\pi(\alpha|\mathbf{y}) \propto \exp\left(-\frac{1}{2}\left(\|\mathbf{y} - f(\mathbf{P}_k\alpha + \mathbf{x}_0)\|^2_{\mathbf{C}_y} + \|\alpha\|^2_{\mathbf{I}_k}\right)\right), \tag{2}$$

where $\mathbf{y} \in \mathbb{R}^m$ is the measured spectrum, $f : \mathbb{R}^n \to \mathbb{R}^m$ is the forward model, $\mathbf{C}_y \in \mathbb{R}^{m \times m}$ is the measurement error covariance, and $\mathbf{I}_k \in \mathbb{R}^{k \times k}$ is a diagonal unit matrix.

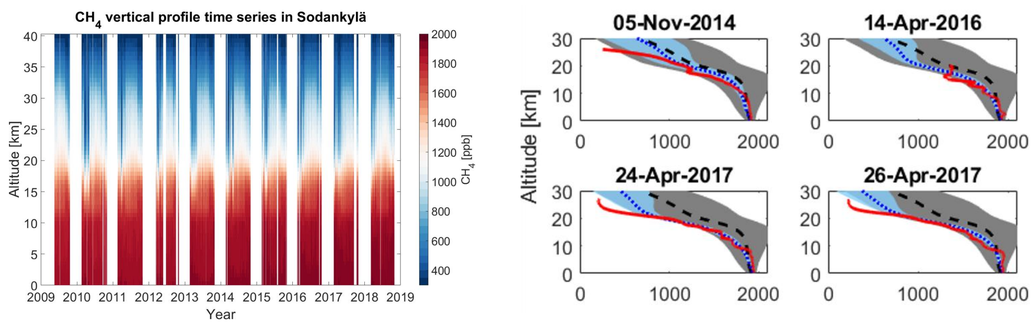


Figure 9 and 10. Left: Methane profile timeseries retrieved by using the SWIRLAB retrieval code. Right: Comparison of SWIRLAB profiles to a set of AirCore profiles. Black line and grey shading show prior mean and uncertainty whereas blue line and shading show posterior mean and uncertainty. Red line depicts AirCore measurement.

References

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