Long-term observations and modeling of dissolved methane from Nord Stream leaks

Publication in Review at Nature Communications

IUGC2024

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Voice of the Ocean

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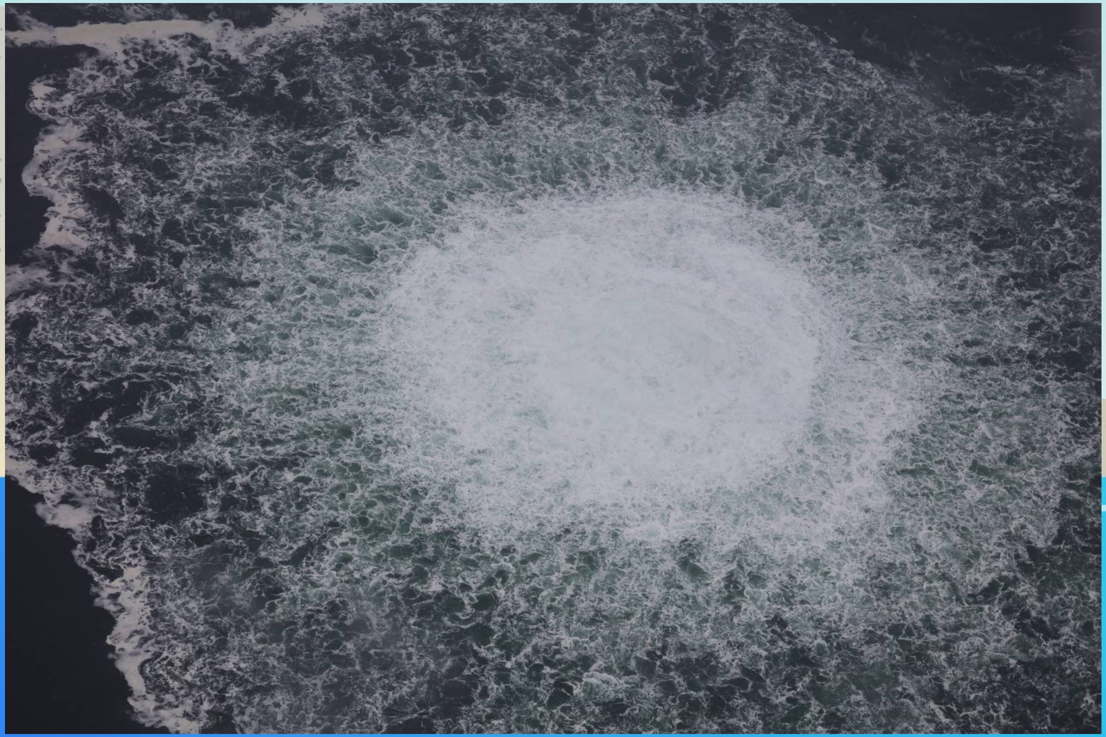
Long-term observations and modeling of dissolved methane from Nord Stream leaks



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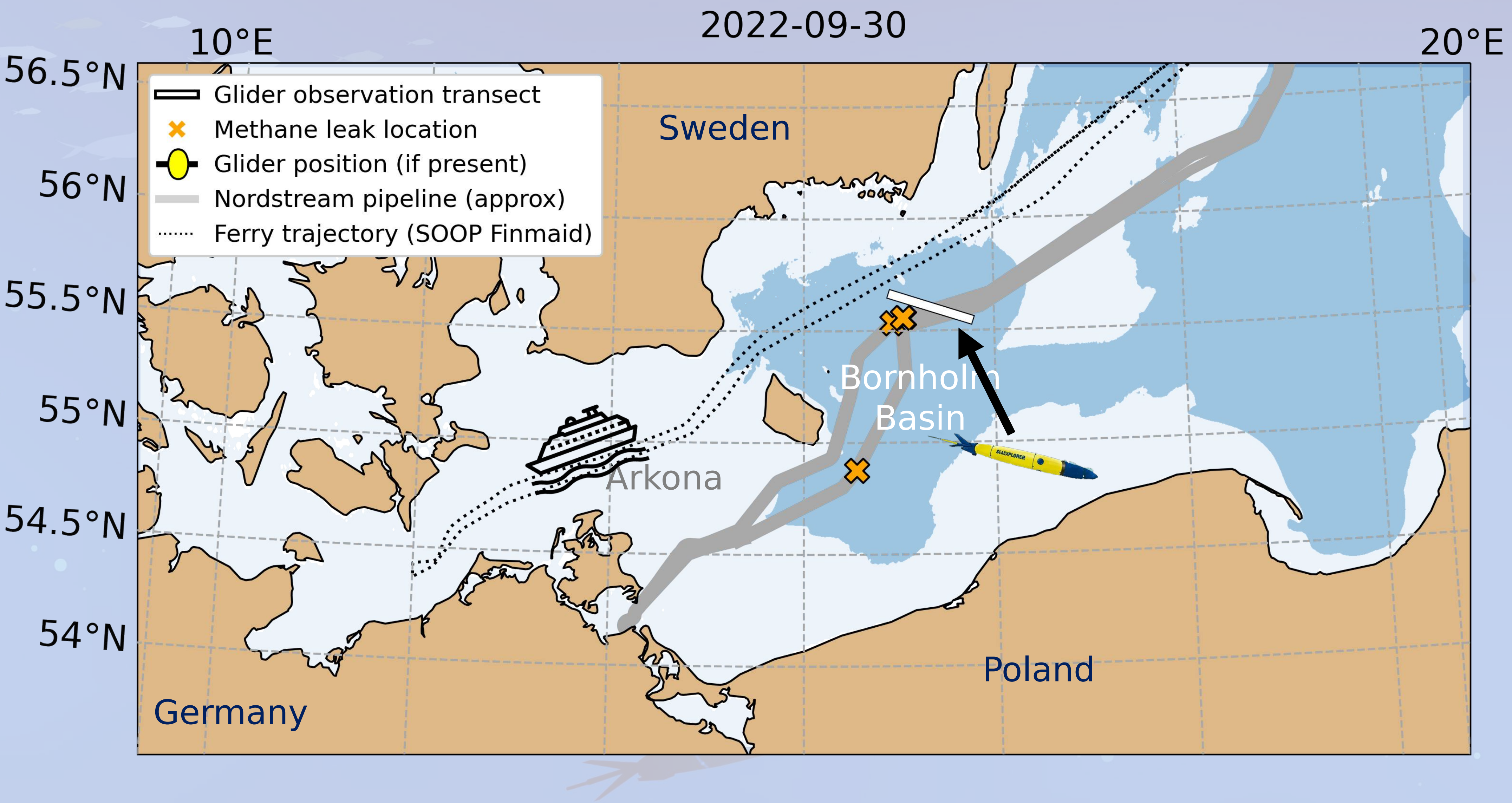
Glider Observations

- SeaExplorer Ocean Gliders with Franatec Methane Sensor
- 1 vertical profile every 15 minutes
- Measuring temperature, salinity, pressure, chlorophyll- oxygen- and methane- concentrations [and more]
- High resolution observations including depth information, but very regional

SOOP Observations

- Continuous methane monitoring from Finnmaid Ferry
- Route between Travemünde (GER) and Helsinki (FI)
- Surface measurements



2022-09-30
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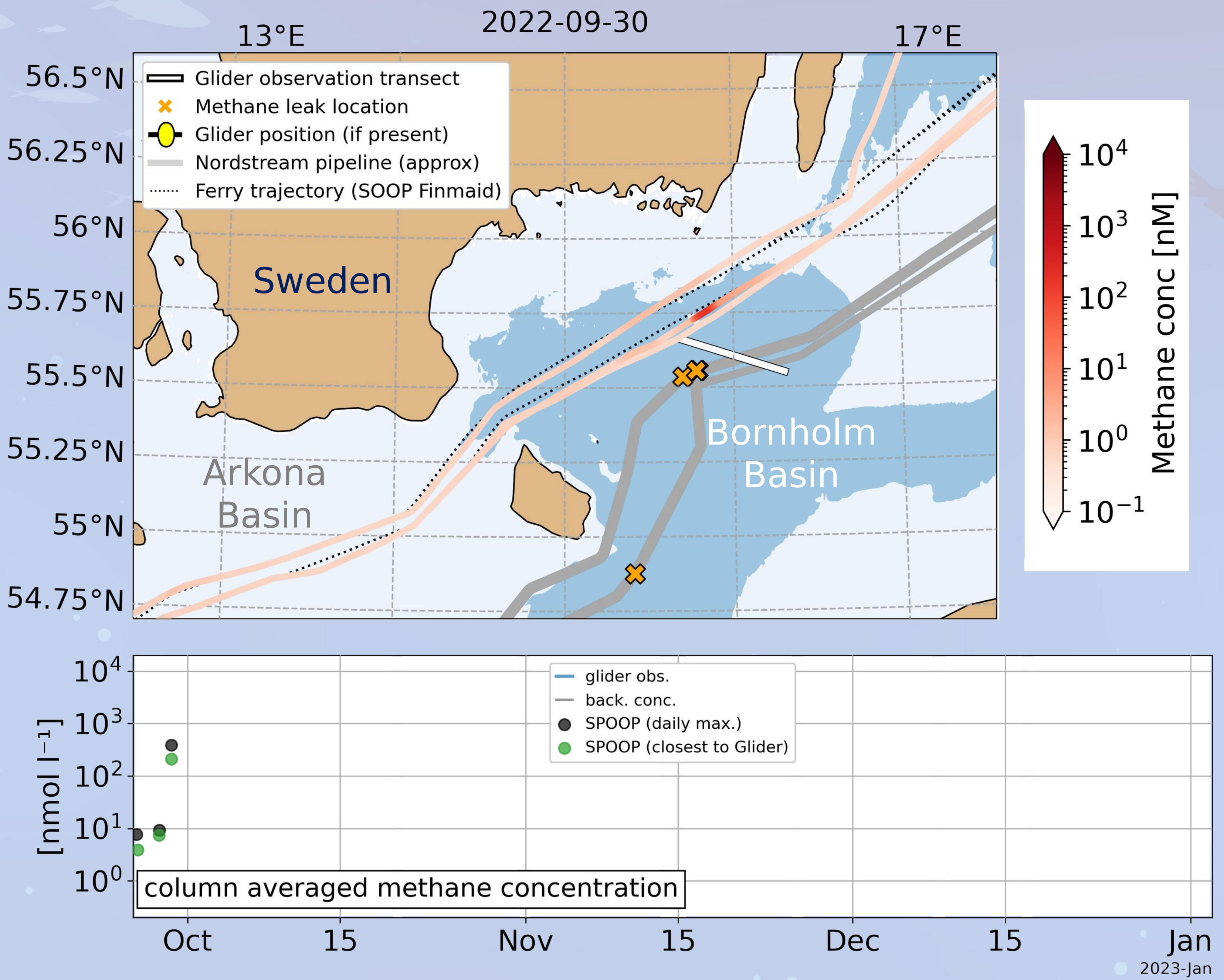
Glider observation transect
Methane leak location
Glider position (if present)
Nordstream pipeline (approx)
Ferry trajectory (SOOP Finmaid)
Sweden
Bornholm
Basin
Arkona
Poland
Germany



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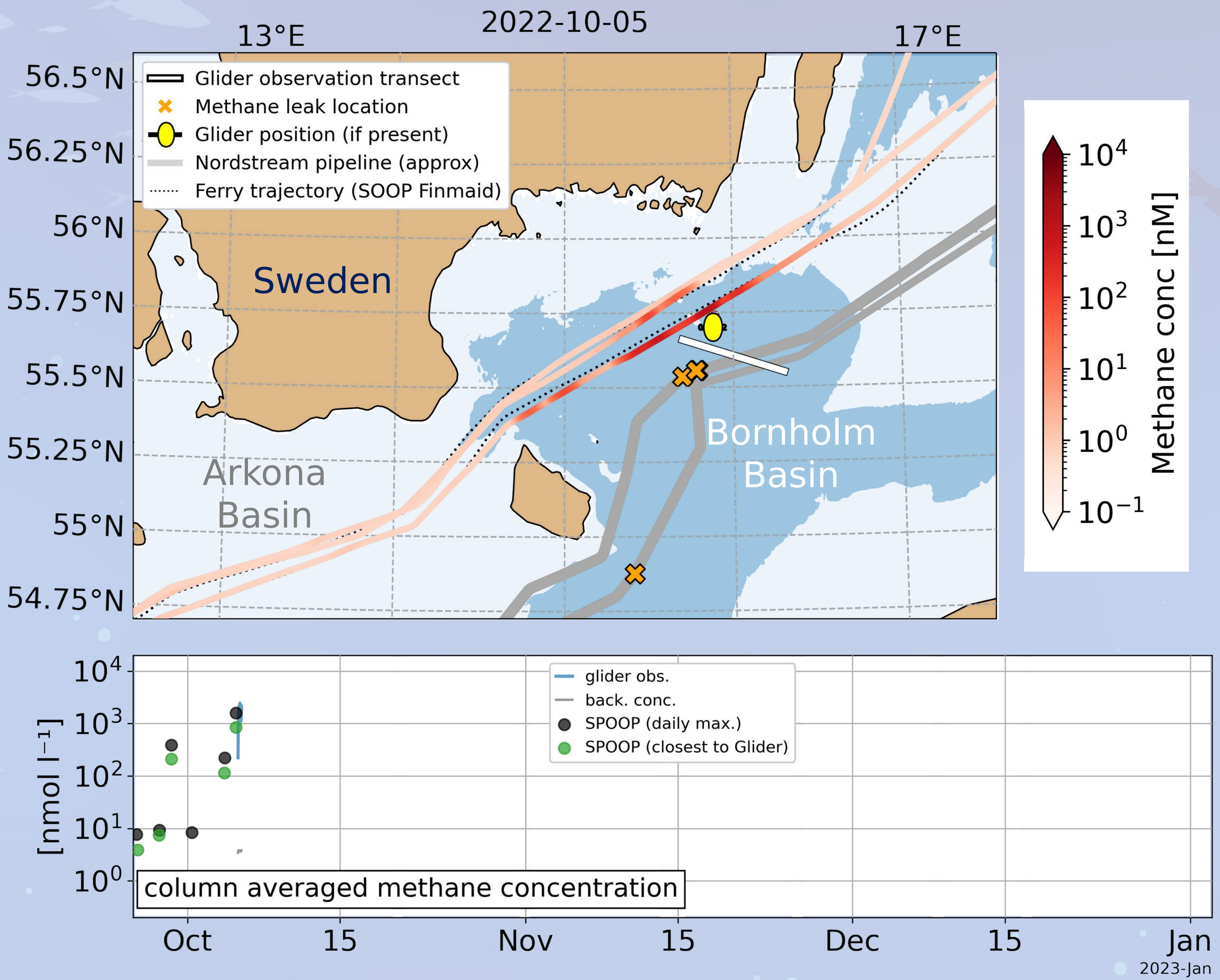
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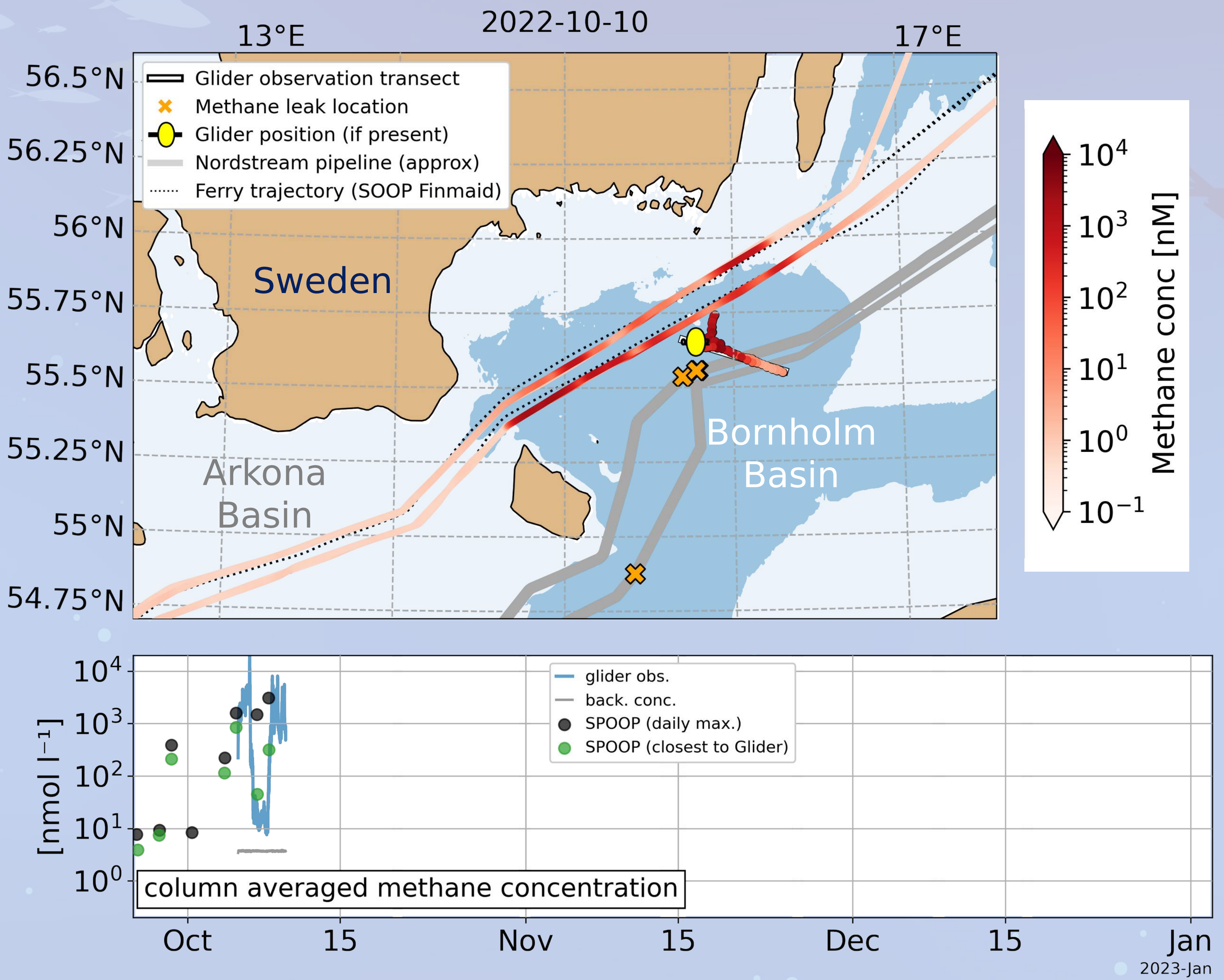

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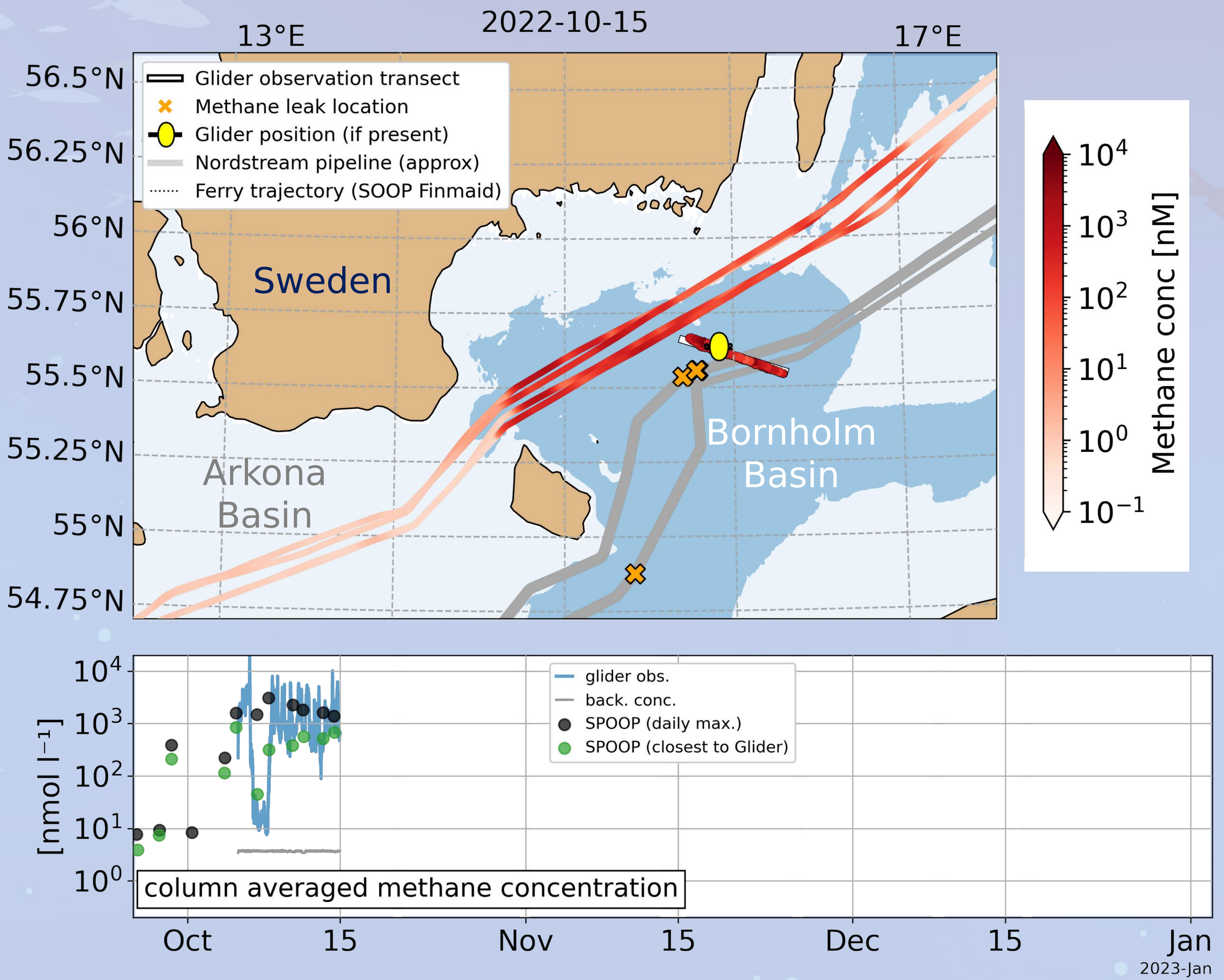

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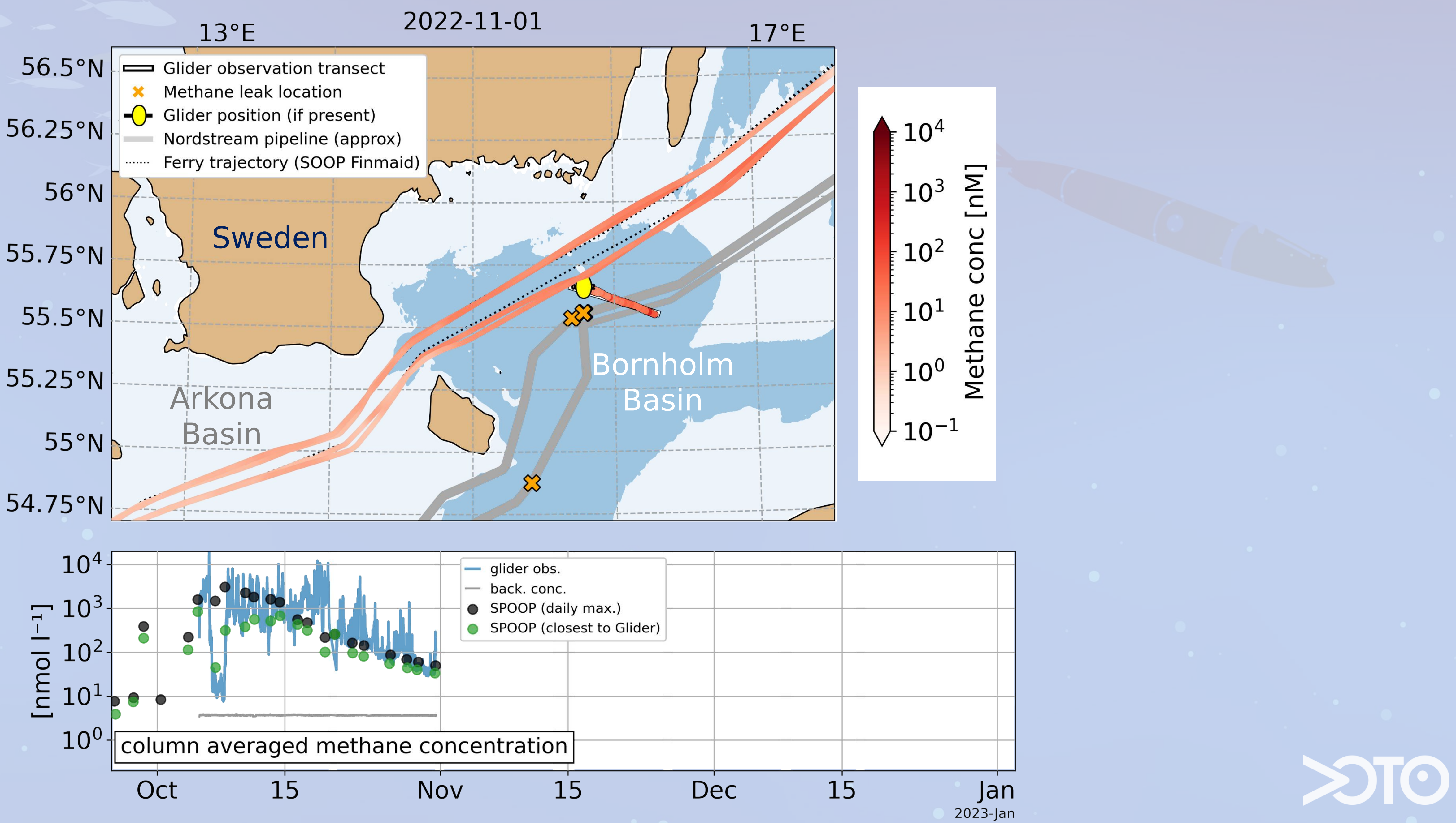
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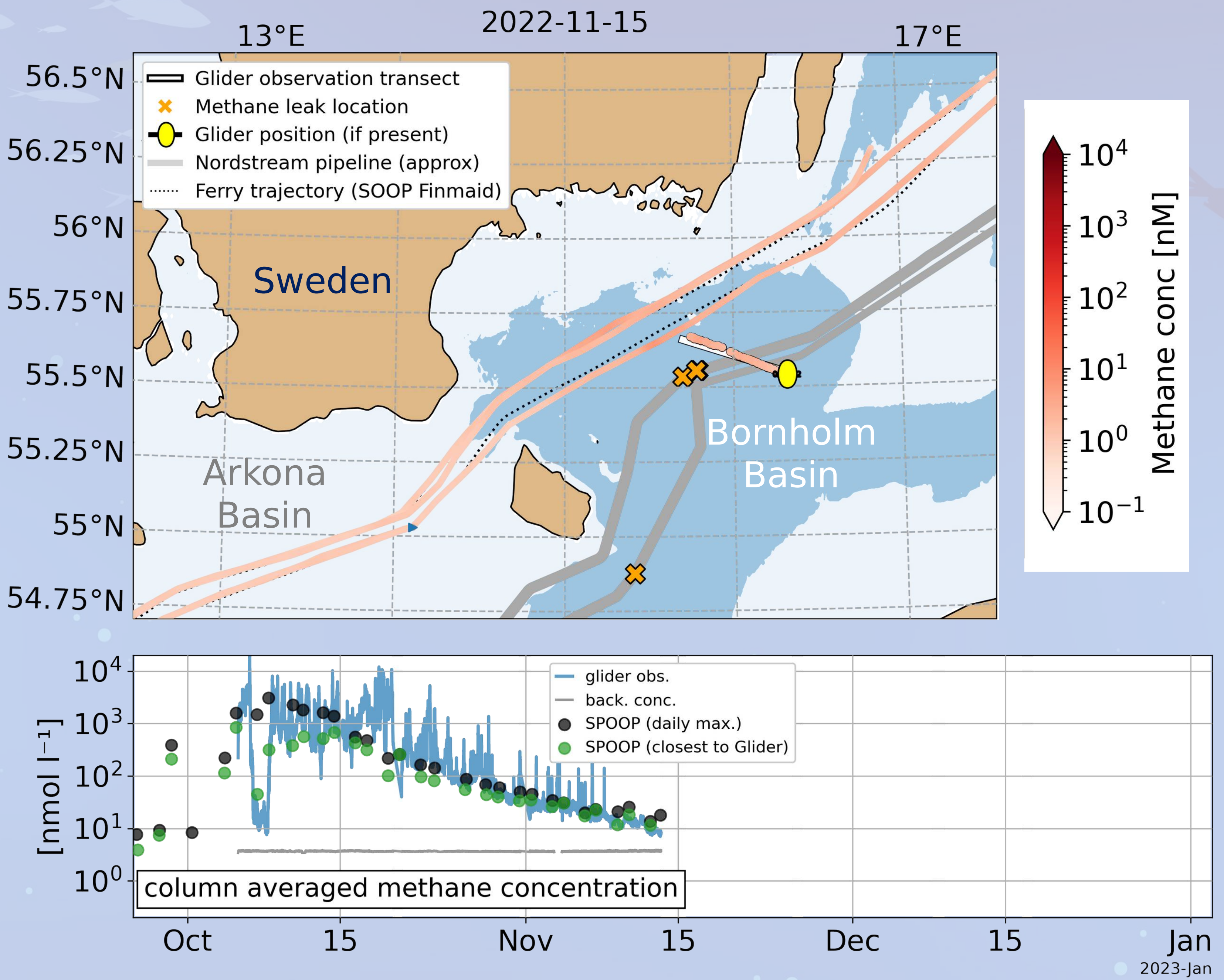
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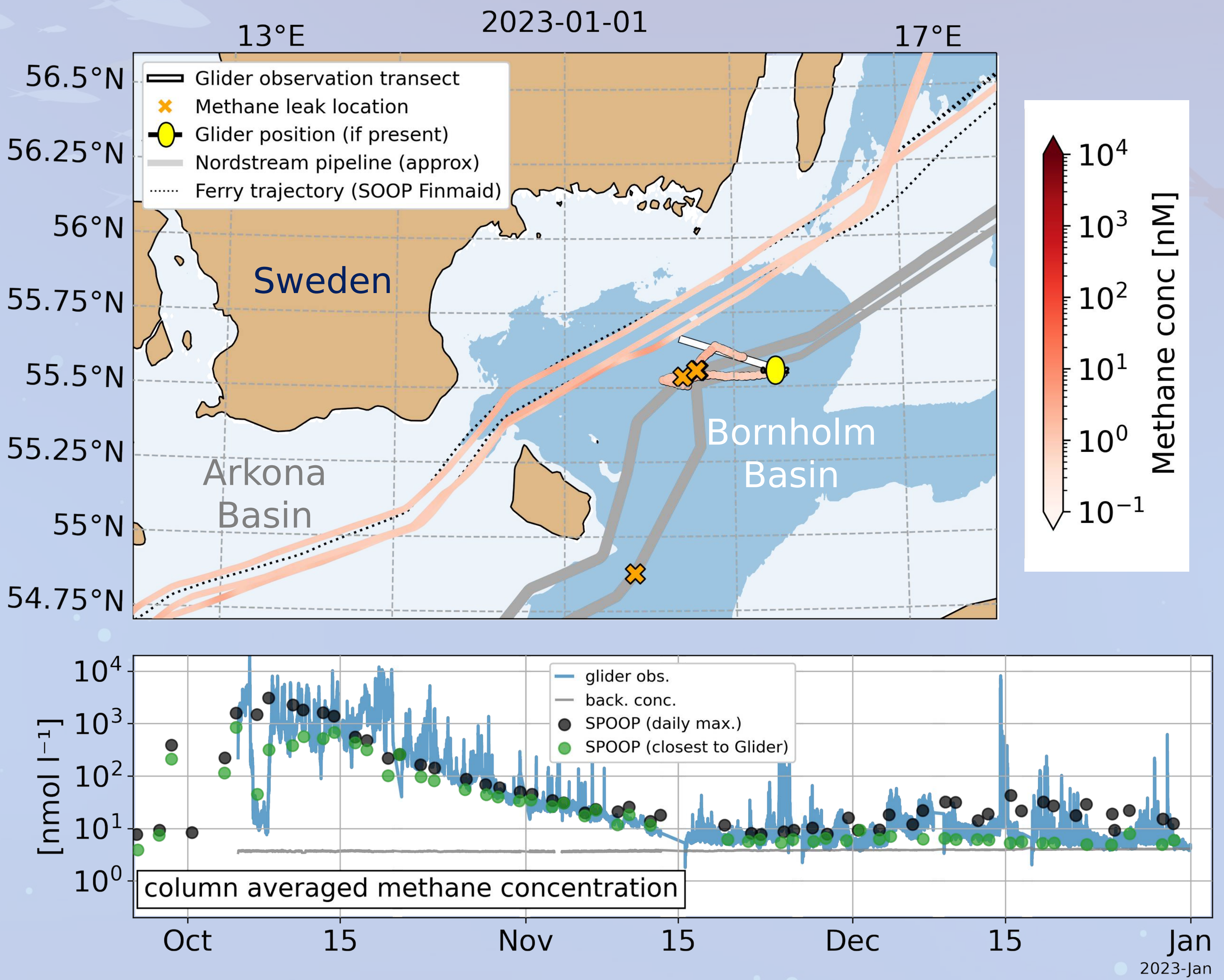
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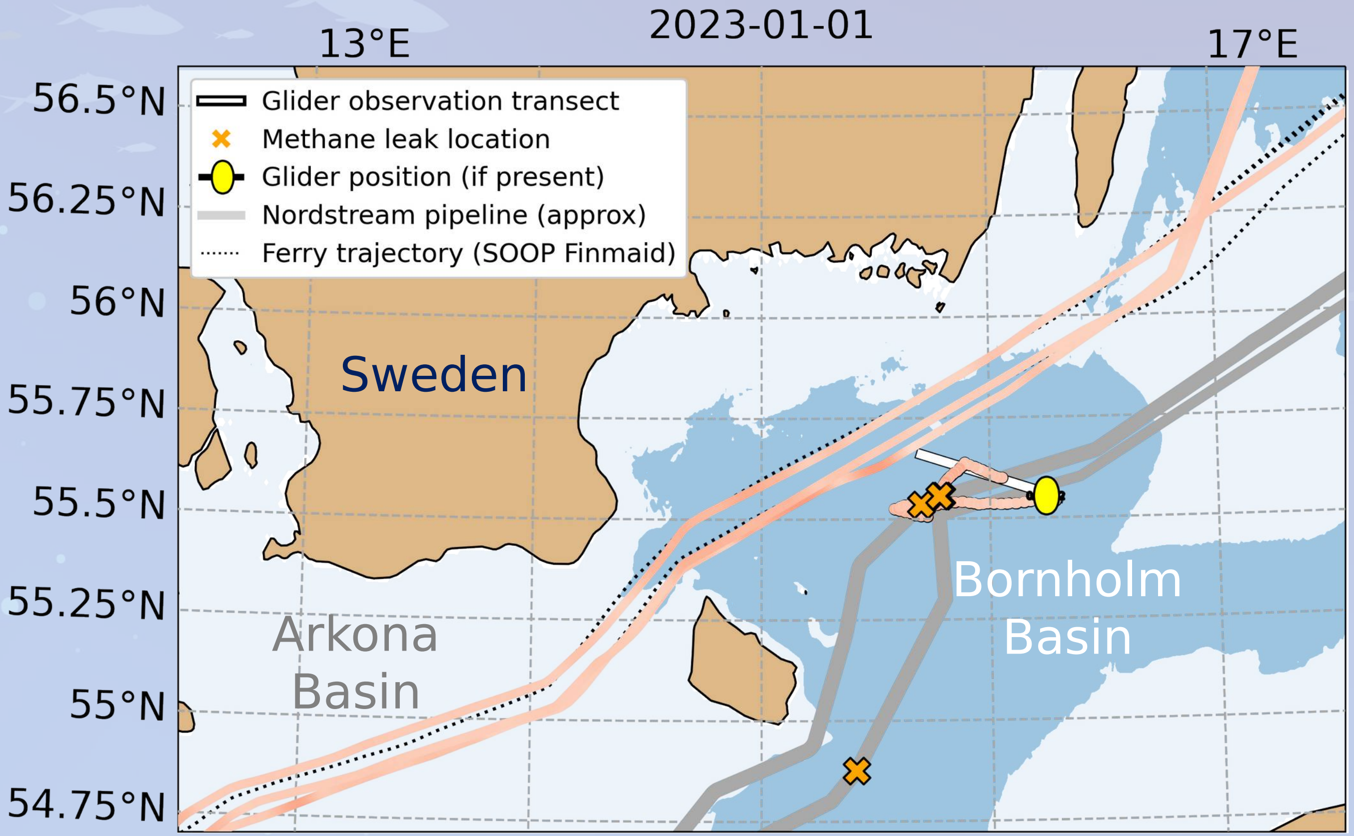
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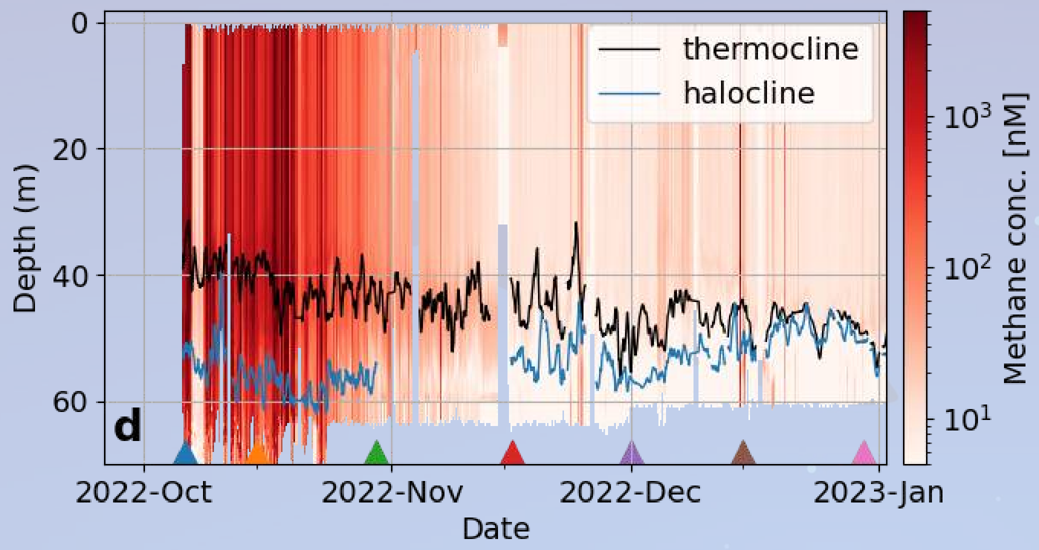
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Methane conc. [nM]
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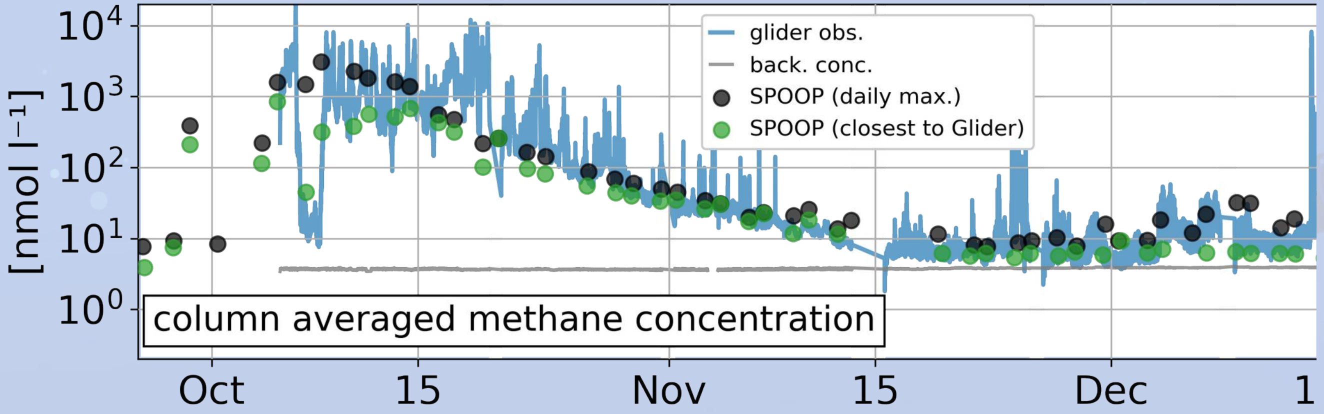
Date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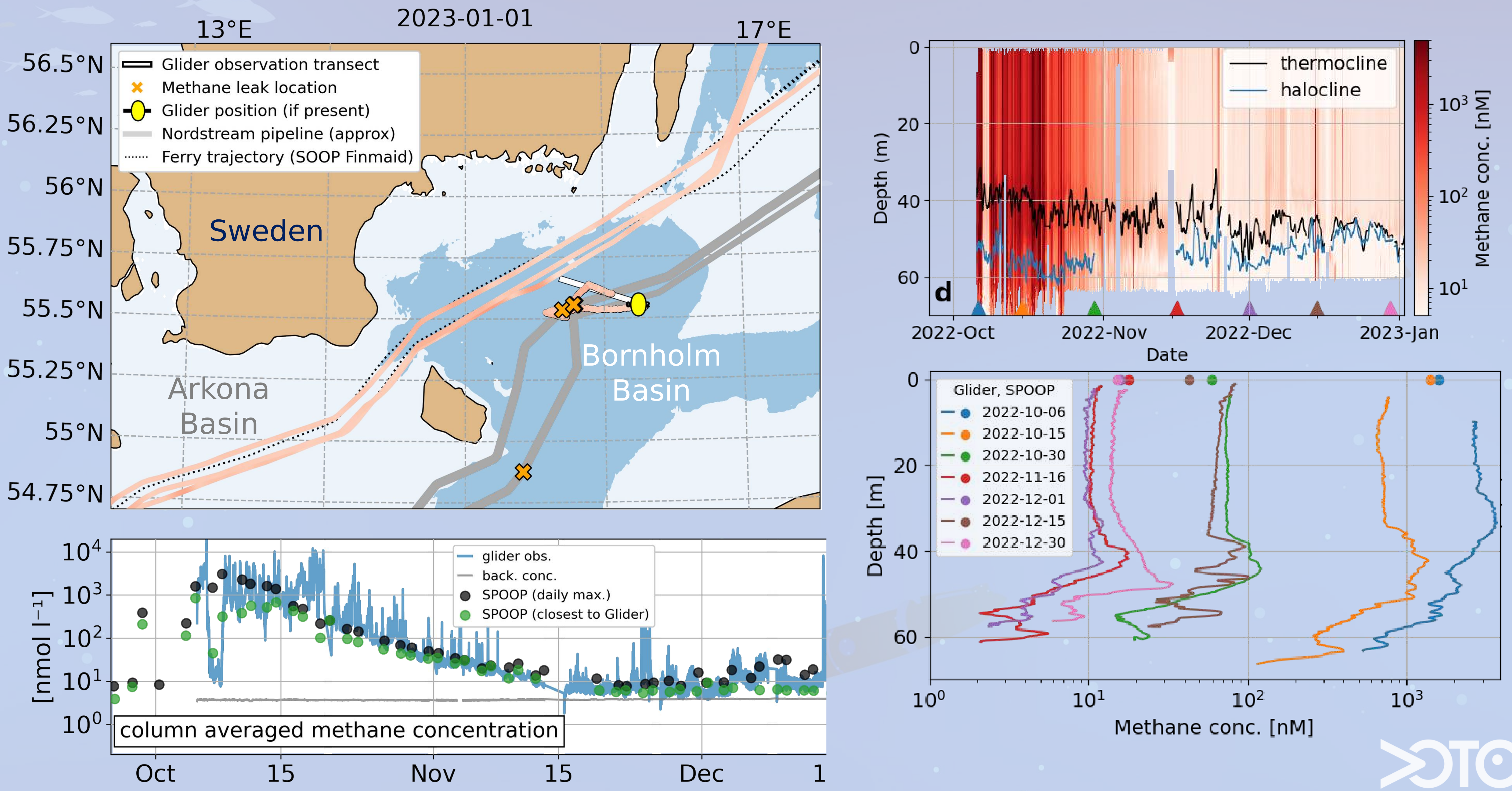

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2022-12-01
2022-12-15
2022-12-30
Depth [m]
Methane conc. [nM]

Questions:

1)Amount of dissolved methane and its pathways

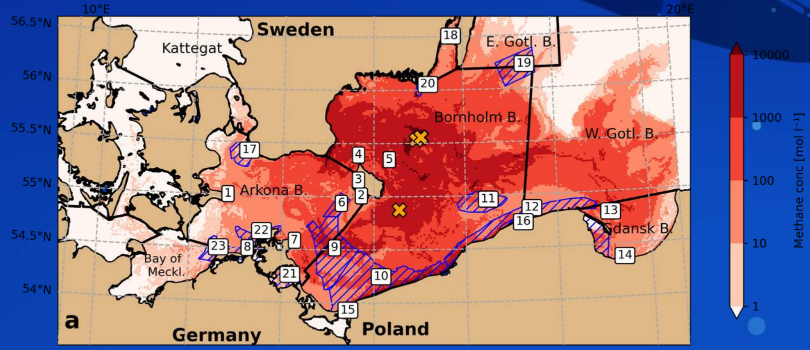
2)Spread into neighbouring basins and Marine Protected areas

3)Consequences for local ecosystem

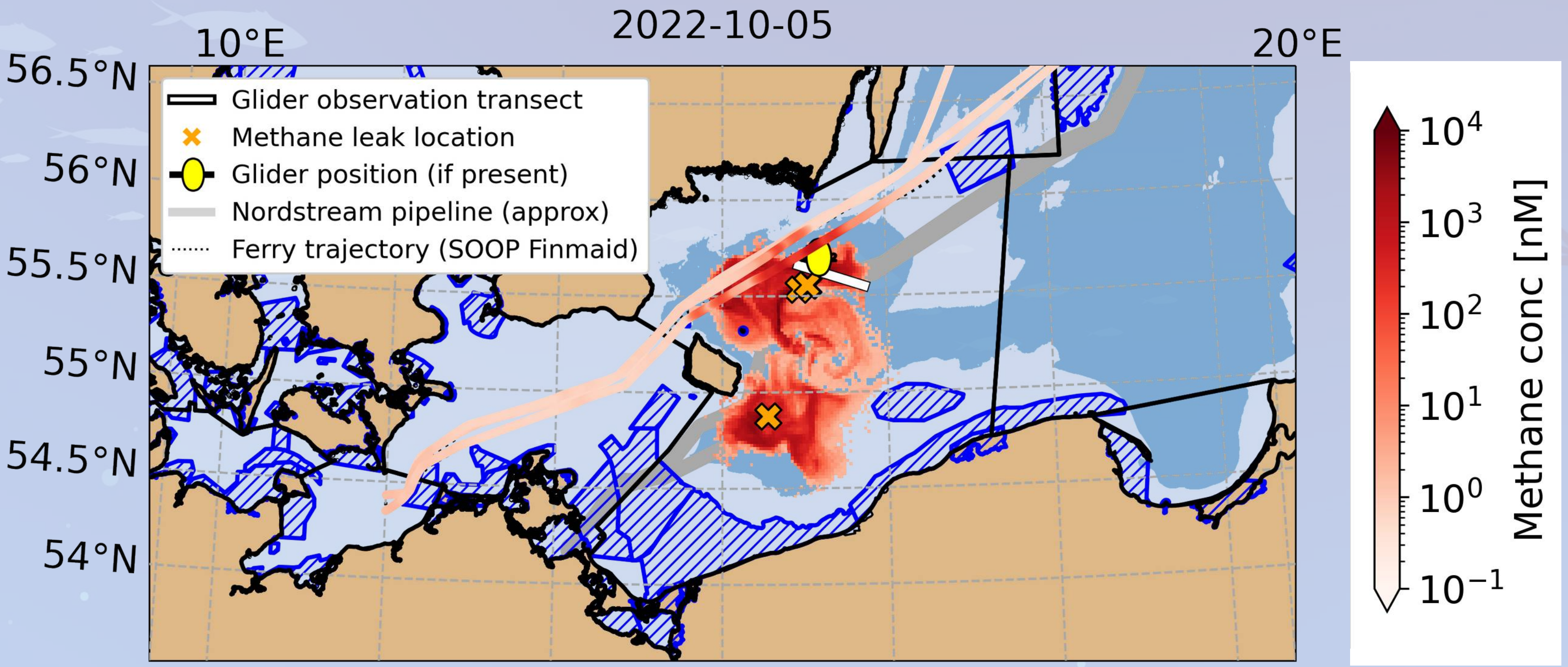
Numerical methane spread simulation

- Lagrangian chemical fate and transport model based on ChemicalDrift [8]
- Advection from Nemo Nordic 2.0 SMHI Baltic analysis model (BALTICSEA ANALYSISFORECAST PHY_003_006) [19]
- Wind from ERA5 [20]
- Simulated processes
  - Advection
  - Diffusion
  - Outgassing
- Initial conditions: methane concentrations close to saturation, equally from 70m depth to surface, initial turbulent spread ~4km from leak site, seeding rate based on engineering estimates [3]

Component	Description	Input Parameters
Advection	Euler Method [8]	u, v, w [19]
Diffusion	Random Walk Displ. Loop [8]	$D_{h,\mathrm{MLD}} = 5.0\ \mathrm{m^2 s^{-1}}$ [24], $D_{v,\mathrm{MLD}}(\tau_{\mathrm{wind}})$ [25]
Outgassing	Two Film [9]	T, S, MLD, wind [19, 20] $H^{cp} = 1.4 \times 10^{-5}\ \mathrm{mol\ m^{-3}\ Pa^{-1}}$ [23] d(ln H) /d(1/T)=1900 K [23]
Oxidation*	First Order Degradation [9]	$k =$[0.035, 0.0175, 0.0035...] $\mathrm{d^{-1}}$ [26]



[3] Harris (2024)
[8] Aghito (2023)
[19] SMHI: Baltic Sea Physics Analysis and Forecast (2022).
[20] Hersbach, H., et al.(2018)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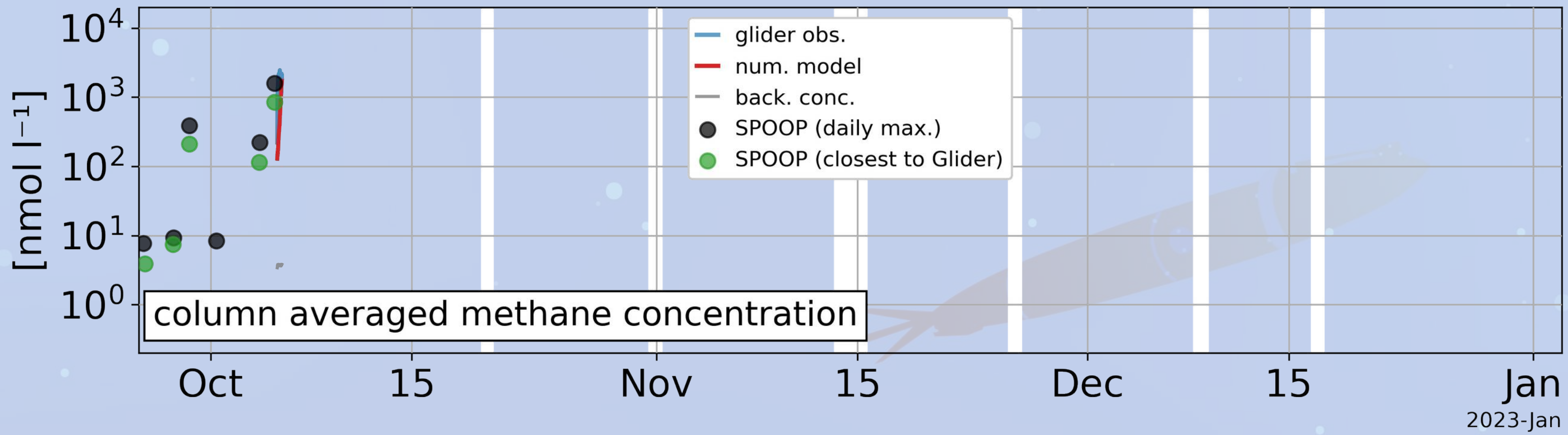
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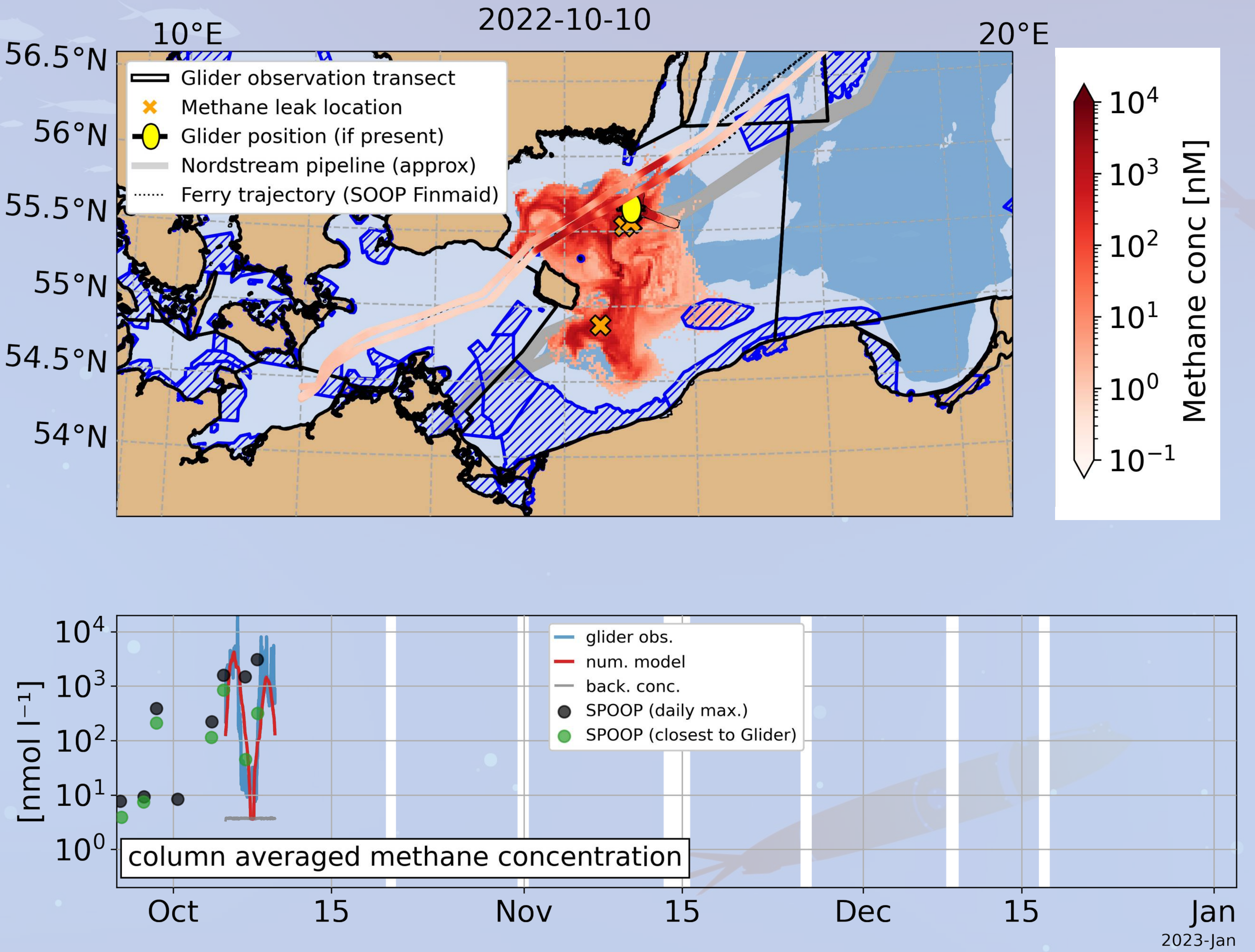

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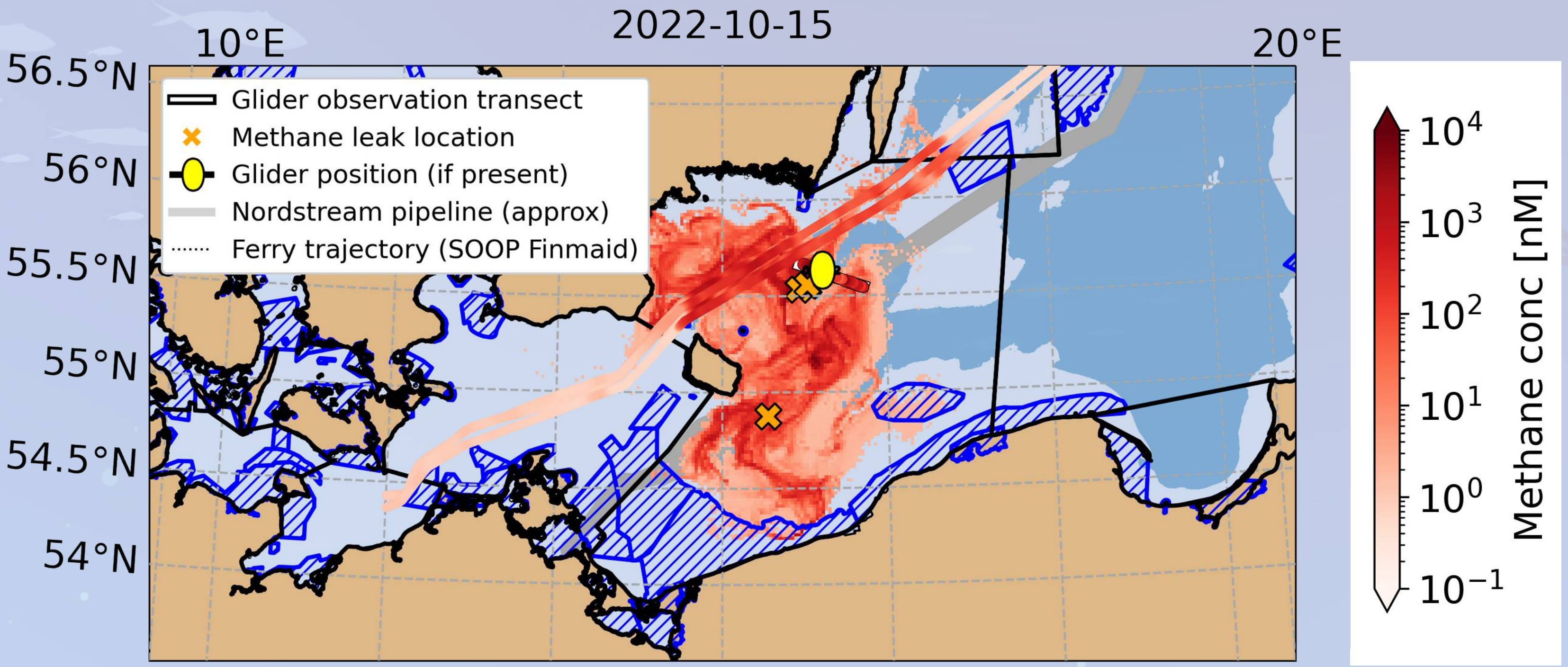
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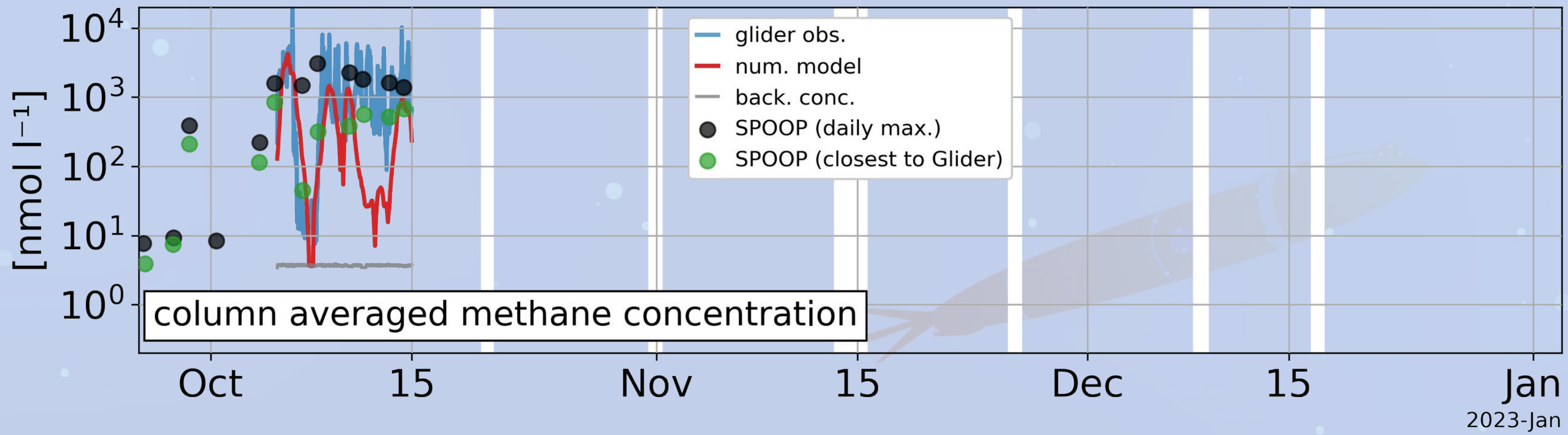
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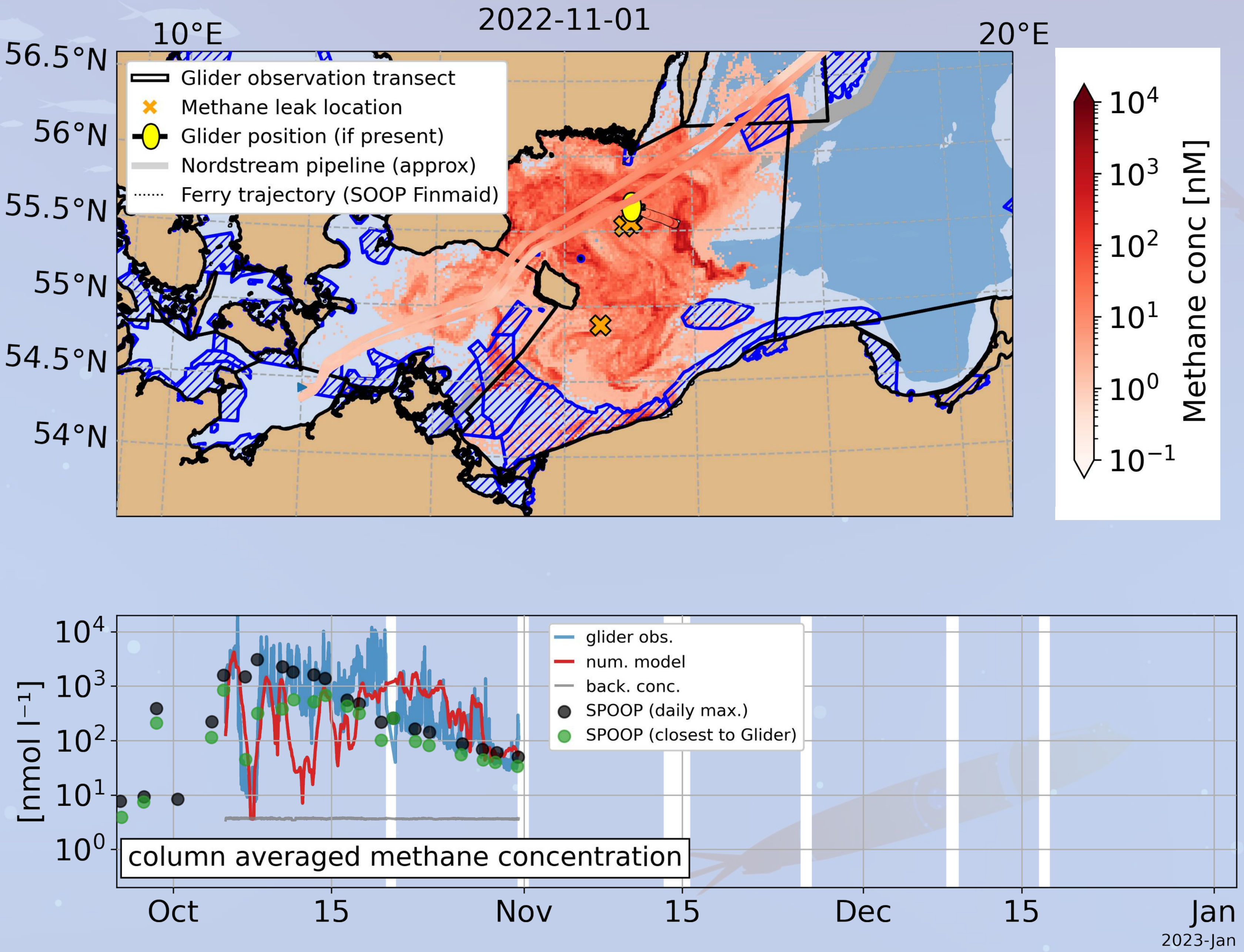
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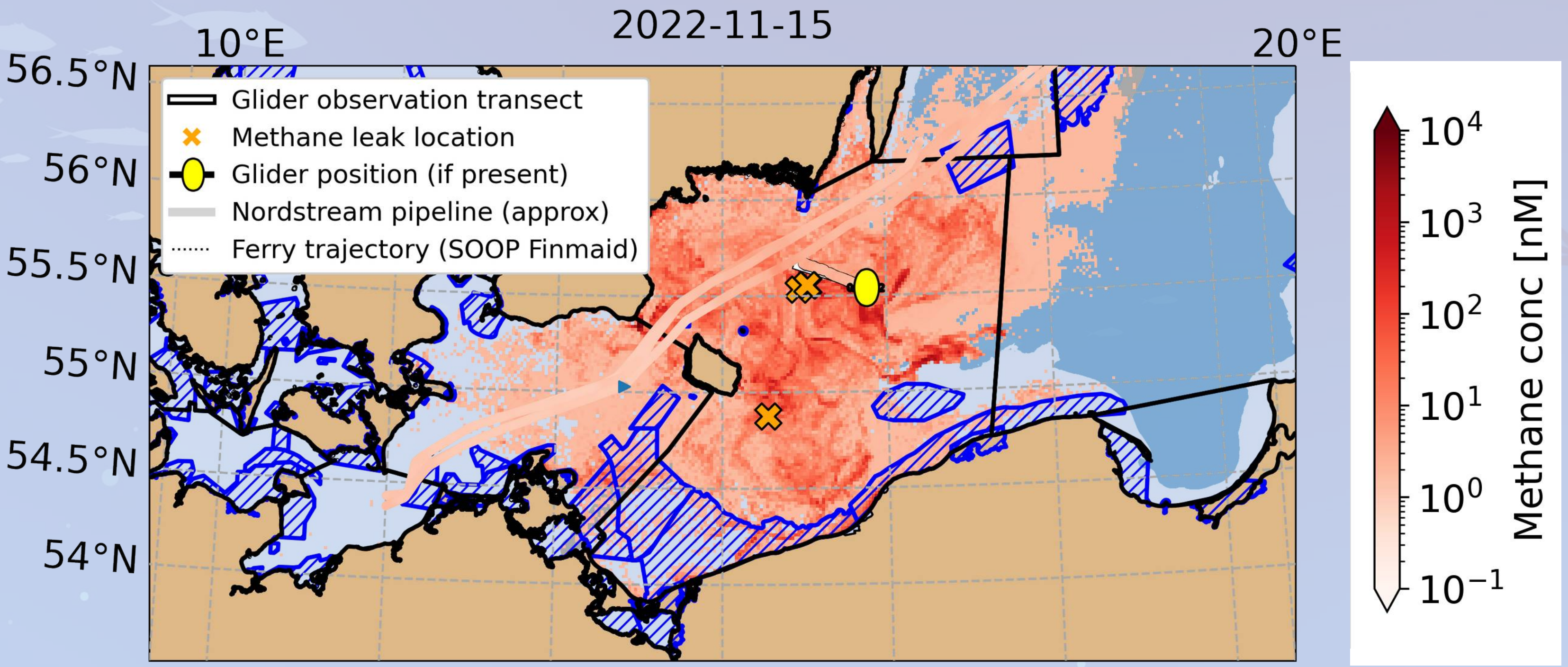
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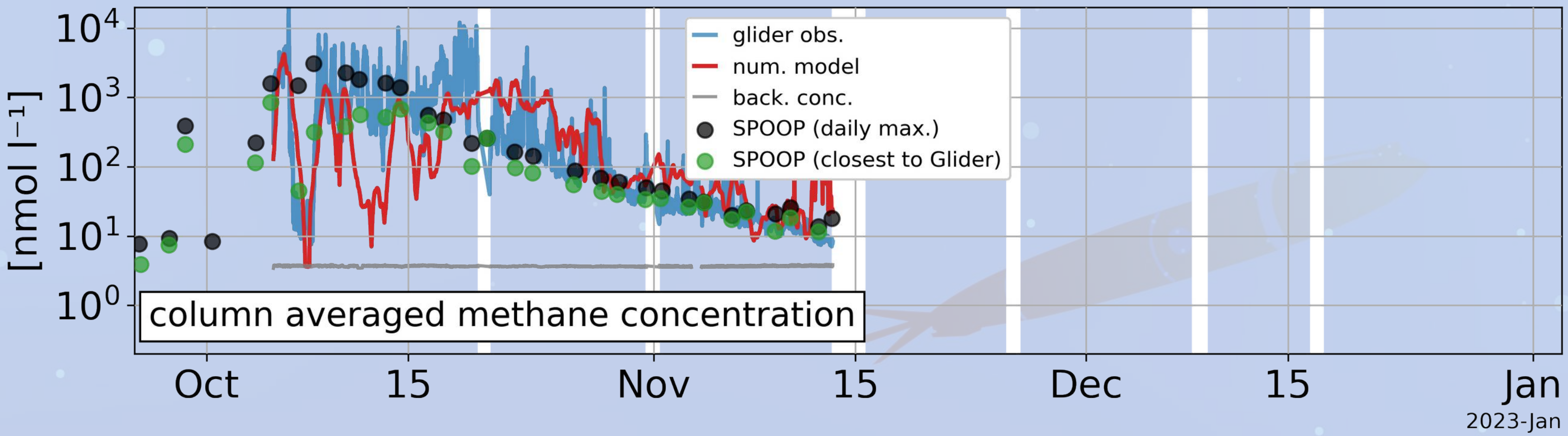
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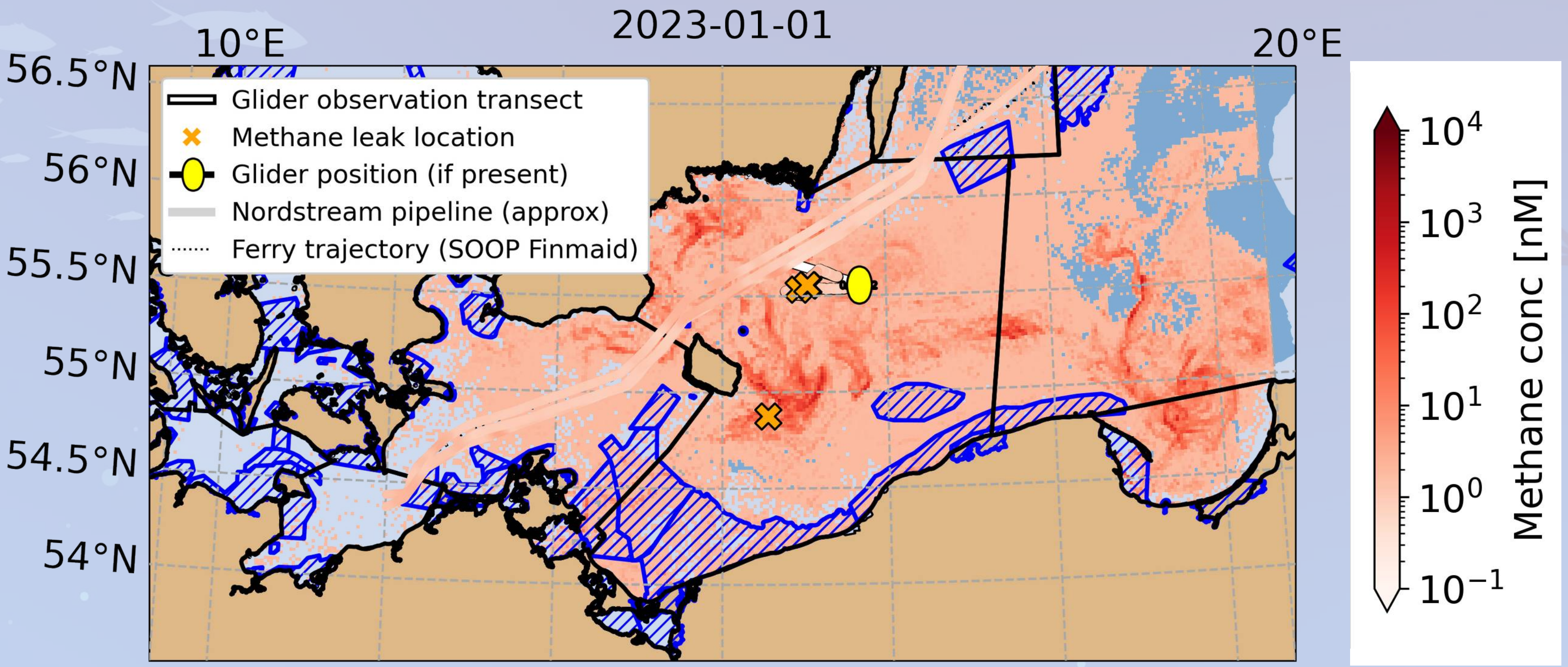
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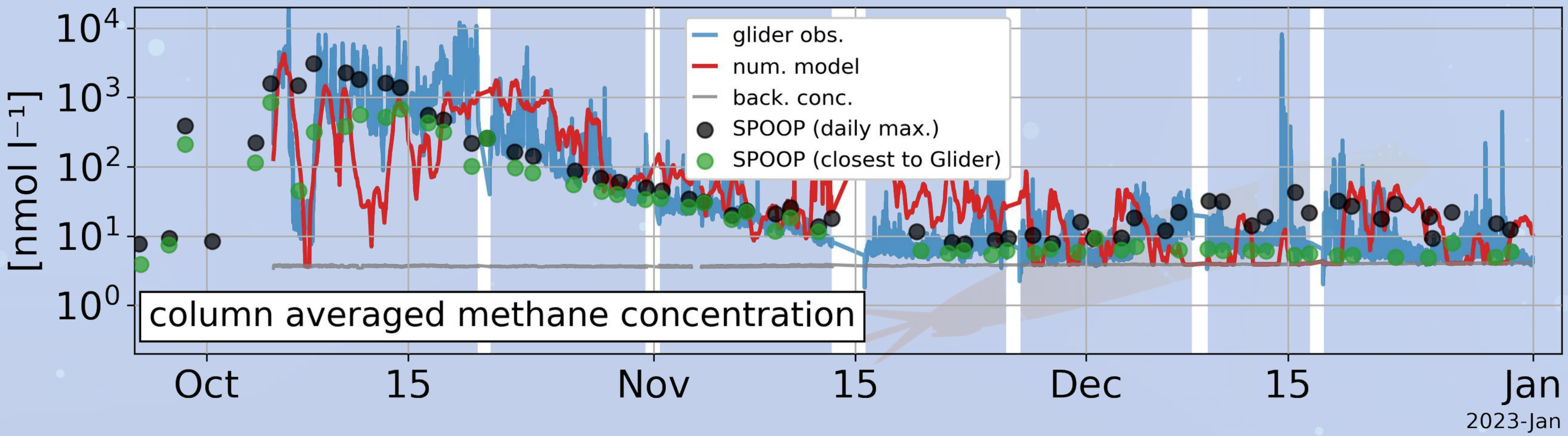
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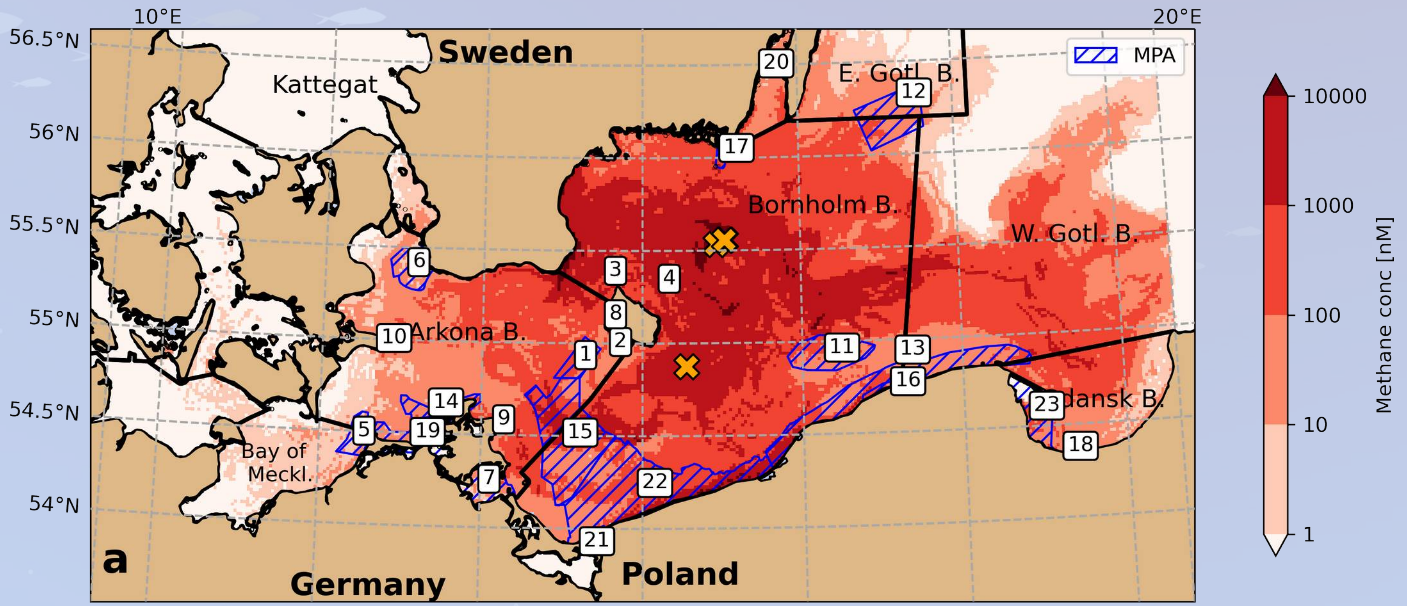
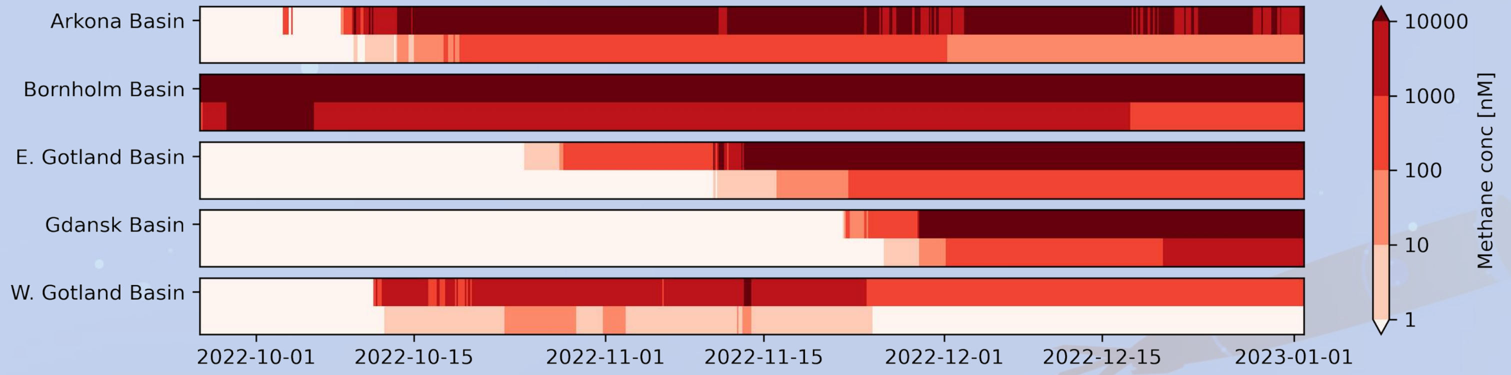
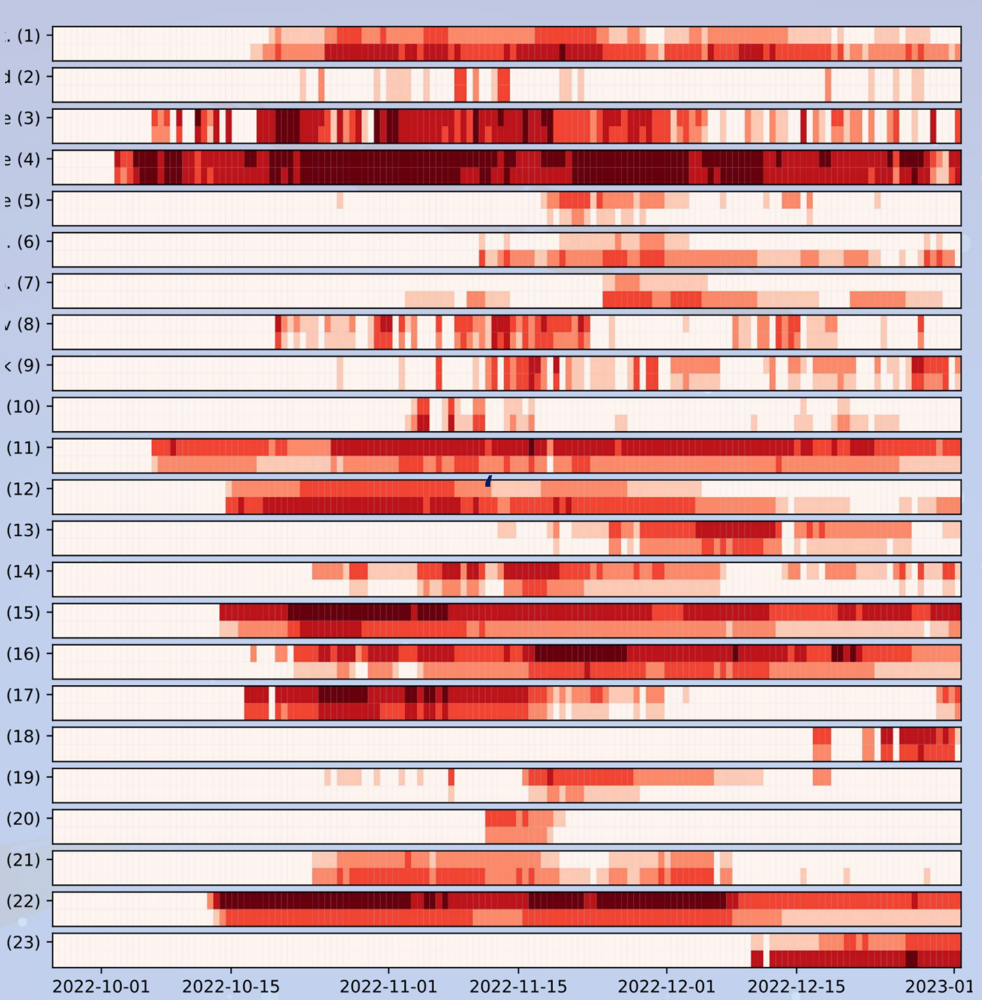
Maximum methane exposure map



Maximum/volume averaged exposure by basin



Maximum/volume averaged exposure exposure by MPA



Summary

1) About 2.5% of released methane, ~10.8 kt dissolved in the Baltic Sea, with initial concentrations of > 100 mmol/l
2) Outgassing and advection/diffusion are main processes of reducing methane concentrations
3) Dissolved methane polluted 23 MPAs in 5 Baltic basins.

Context from other studies

1)Effect of explosions and resuspended sediment is possibly greater than that of dissolved gas [8]
2) aerial outgassing observations (5 October) [10] ~10% larger than our model output (distance of confidence intervals)
3) Plume modeling [9] resulted in 11 kt dissolved methane

[7] Chen, X. L., and T. J. Zhou, 2023
[8] Sanderson (2023).
[9] A. L. Dissanayake (2023)
[10] Reum et al. (submitted to Nature communications in 2024)

Thank you!

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Prof. Gregor Rehder
gregor.rehder@iow.de


Dr. Henry Bittig
henry.bittig@iow.de

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Advection: Euler method

$$P_{t+1}^{x}=P_{t}^{x}+\Delta t\,u(x,t)$$

Diffusion: Random walk with normal distributed particle velocities
→ derived from Fick's law of diffusion

$$P_{t+1}^{x}=P_{t}^{x}+\sqrt{\frac{2D}{\Delta t}}\,random\left(\frac{1}{\sigma\sqrt{2\pi}}e^{-1/2\left(\frac{x-\mu}{\sigma}\right)^2}\right)\Delta t$$

Dagestad et al. (2018)
Horizontal diffusivity of mixed layer:
5 m^2s^{-1} Kärnä et al. (2021) NEMO Nordic documentation
Vertical mixed layer diffusion wind based
after Lange et al. (1994)

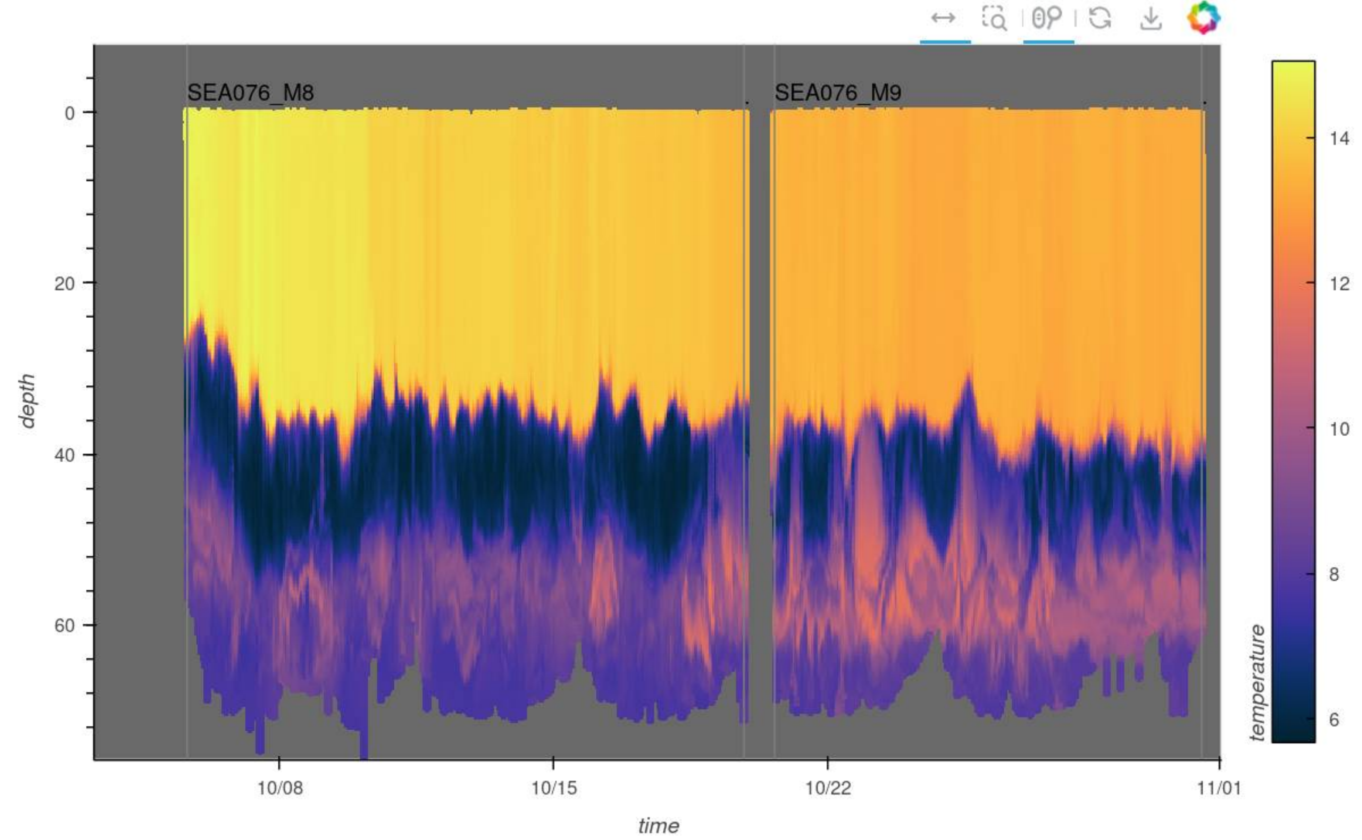
Outgassing:

$$F = k(C_w - \cancel{\alpha C_a})M \times 2.4 \times 10^{-4}$$

Lundevall-Zara et al. (2021)

$$\mathrm{k} = 0.251{U_{10}}^2 \times \left(\frac{Sch}{660}\right)^{-\frac{1}{2}}$$

$$Sch_{balticsea} = \frac{(Sch_{seawater}-Sch_{freshwater})\times S_{balticsea}}{35} + Sch_{freshwater}$$


SEA076_M8
SEA076_M9
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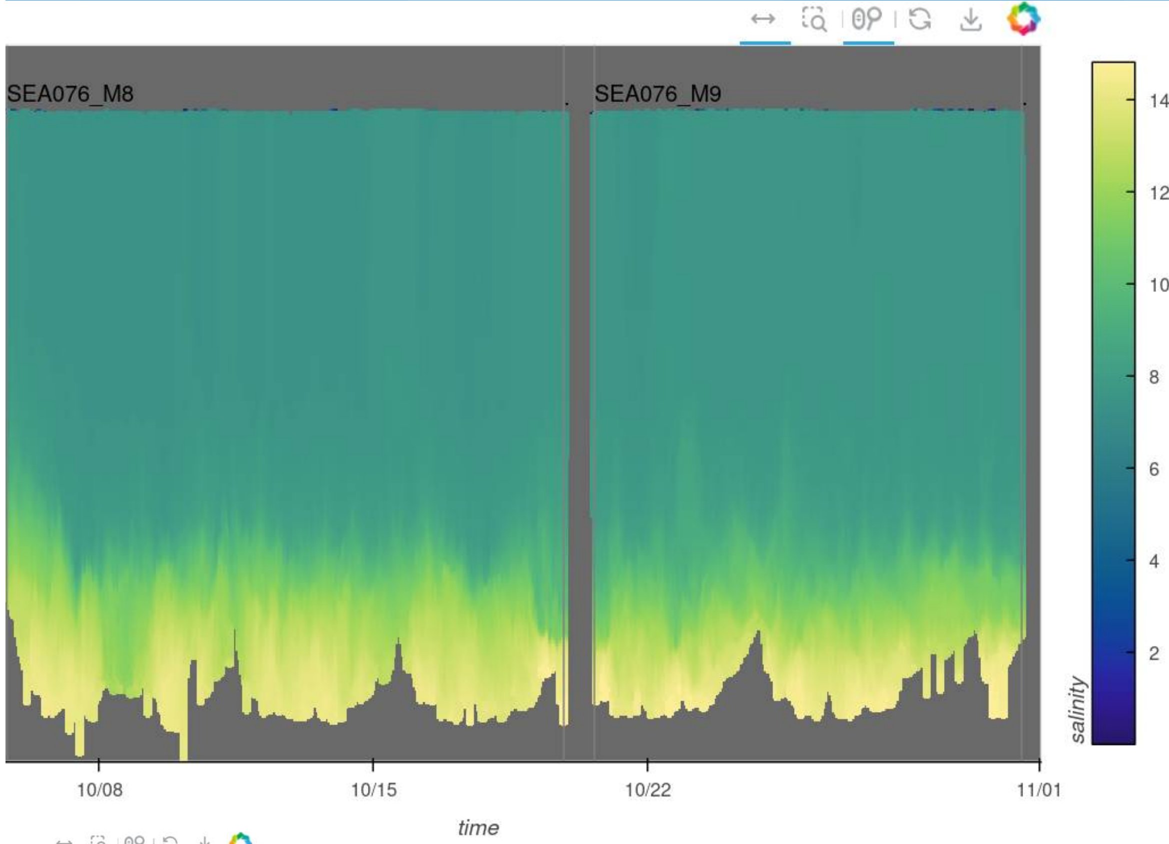
40
60
10/08
10/15
10/22
11/01
time
temperature
14
12
10
8
6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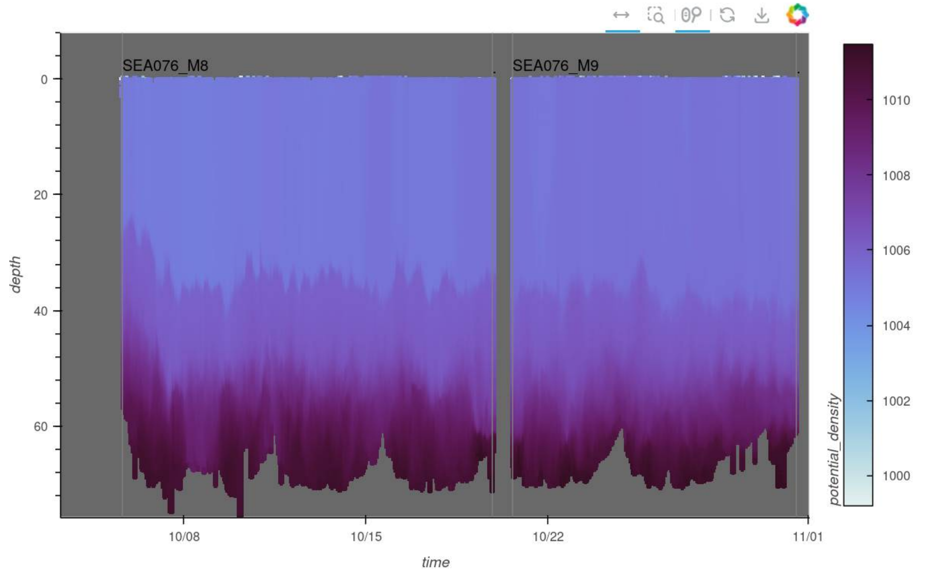
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20
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10/15
10/22
11/01
time
potential_density
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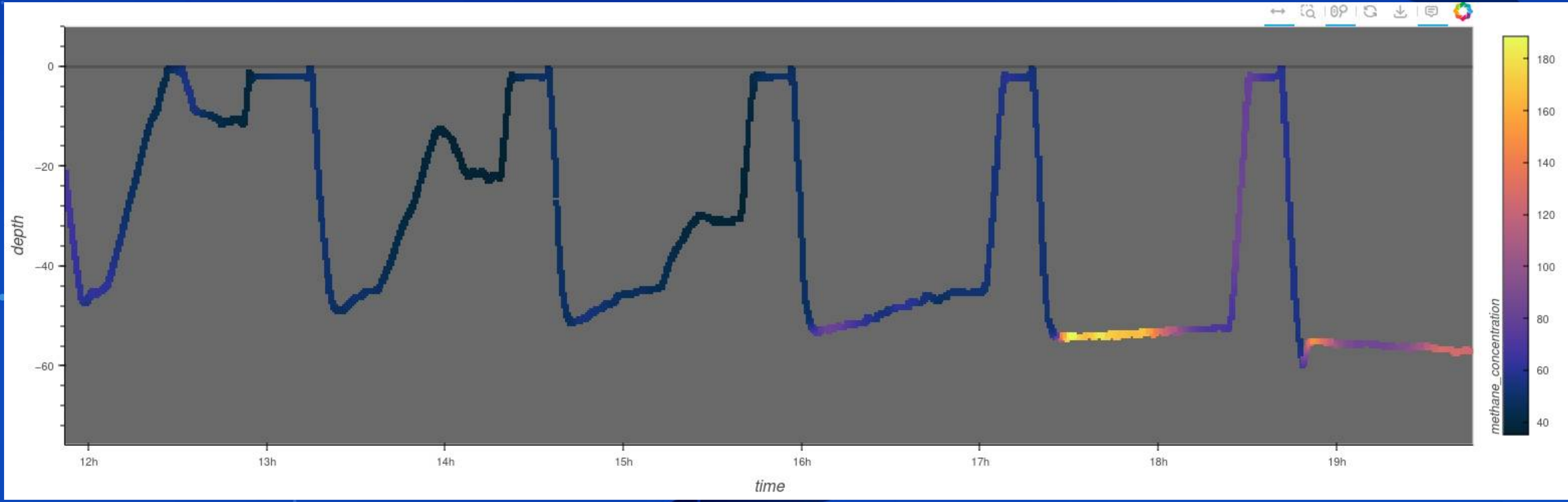
1006
1004
1002
1000



depth
time
methane_concentration
0
−20
−40
−60
12h
13h
14h
15h
16h
17h
18h
19h
180
160
140
120
100
80
60
40