Exploring salinity and density flux variability in the Nordic Seas through new satellite products: Insights from ESA Polar Science Cluster ARCTIC-FLOW project

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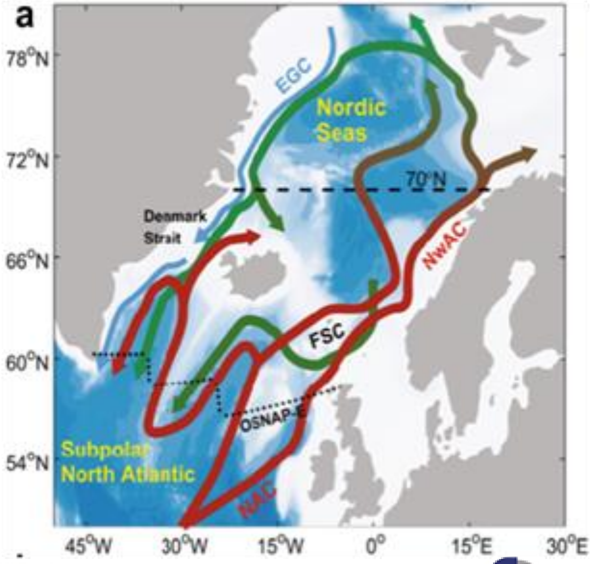
ARCTIC-FLOW: MOTIVATION

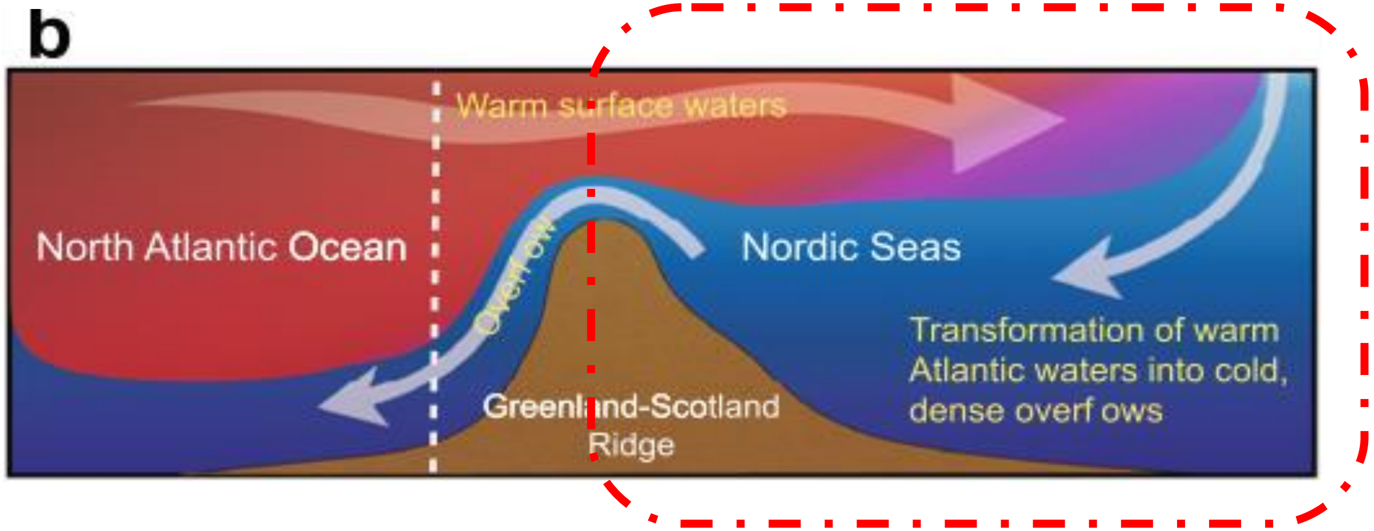
Improve our understanding of water mass transformation and overturning processes in the Nordic Seas.

The Atlantic Meridional Overturning Circulation carries warm surface waters northward, which cool and sink, returning southward at depth.

Especially in this regions all the processes under investigation are strongly modulated by salinity.

Pathways and transformation of Atlantic water (red) into cold dense overflows (green)





(Årthun et al., 2023)

ARCTIC-FLOW: GOAL

Generation of 15 year time series of satellite salinity and density fluxes at 25km and daily resolutions for latitudes higher than 50º N

Use this new data set together with in situ and model data for better understand processes of water mas formation and convection in nordic seas

YEAR 1				YEAR 2			
Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4

K0: NOV 2024

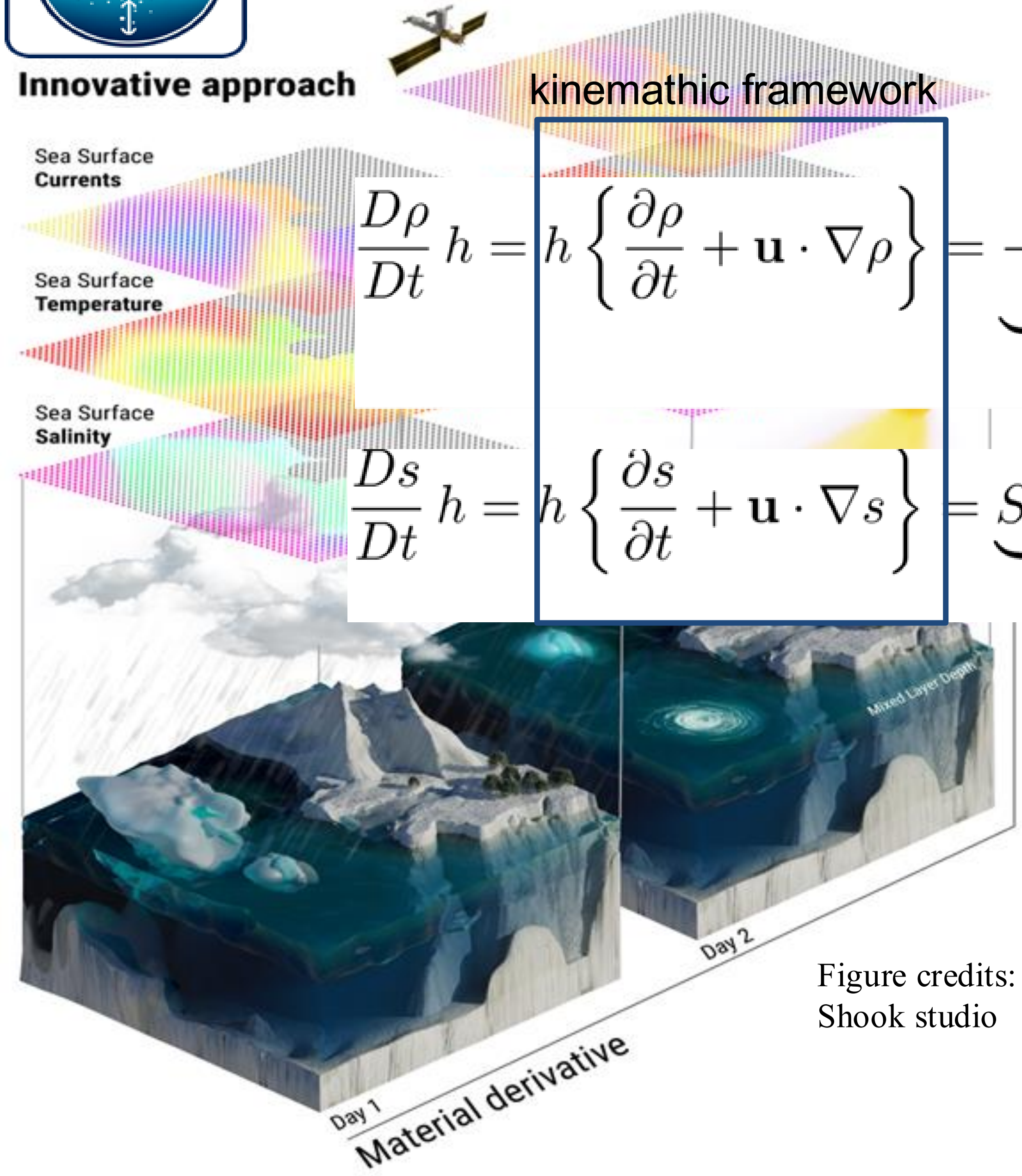
JUL 2025 ***Delivery of the product v1***

FEB 2027 ***Delivery of the product v2***

Integrate the user's feedback and improve scheme of derivation

ARCTIC-FLOW approach

Innovative approach



kinemathic framework

$$\frac{D\rho}{Dt}h = h\left\{\frac{\partial\rho}{\partial t} + \mathbf{u}\cdot\nabla\rho\right\} = \underbrace{-\alpha\frac{Q_{net}}{C_p} + \beta\,\rho_s\, s\,\varepsilon}_{f_\rho} + \underbrace{\kappa\nabla^2\rho}_{d_\rho} + \underbrace{(\rho_0-\rho_{-h})\left(\frac{Dh}{Dt}+w_{-h}\right)}_{h_\rho}$$

$$\frac{Ds}{Dt}h = h\left\{\frac{\partial s}{\partial t} + \mathbf{u}\cdot\nabla s\right\} = \underbrace{S\cdot(E-P-R-I)}_{f_s} + \underbrace{\kappa\nabla^2 s}_{d_s} + \underbrace{(s_0-s_{-h})\left(\frac{Dh}{Dt}+w_{-h}\right)}_{}$$

Figure credits: Shook studio

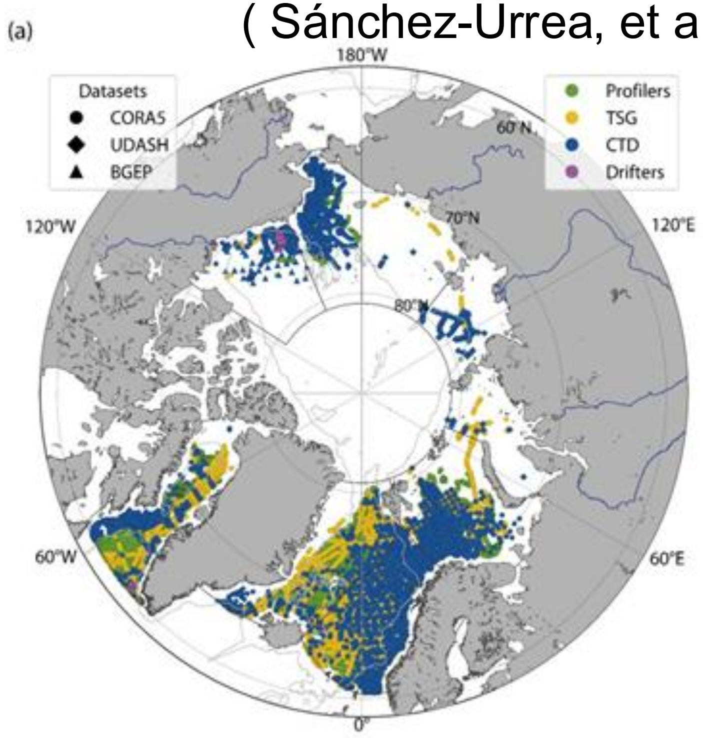
Satellite data provide us sea surface salinity, sea surface temperature, sea surface currents

In situ derived product provide us mixed layer depth estimates

Generation of the product

INPUT DATA	Dataset	Res.
SSS	BECv4 (Level 3)	25km/9-day running mean
SST	OSTIA (Level 4)	0.05º/daily
SSC	AVISO	25km-3days
MLD	CORA	0.5º-Monthly

(Sánchez-Urrea, et al. 2026)



ARCTIC-FLOW PRODUCT v1:

Dataset	Description	Level	Satellite only	Temporal resolution	Spatial grid	Spatial coverage	Temporal coverage
DF	Density Flux	L4	NO	9 days	EASE-NL 25 km	50°N-90°N	2011-2021
SF	Salinity Flux	L4	NO	9 days	EASE-NL 25 km	50°N-90°N	2011-2021

Quality assessment of fluxes

1) Generation of 15-year time series of salinity and density fluxes
2) Monthly, seasonal and interannual comparison with air-sea fluxes from FESOM2 and ERA5 and fluxes from ORAS5

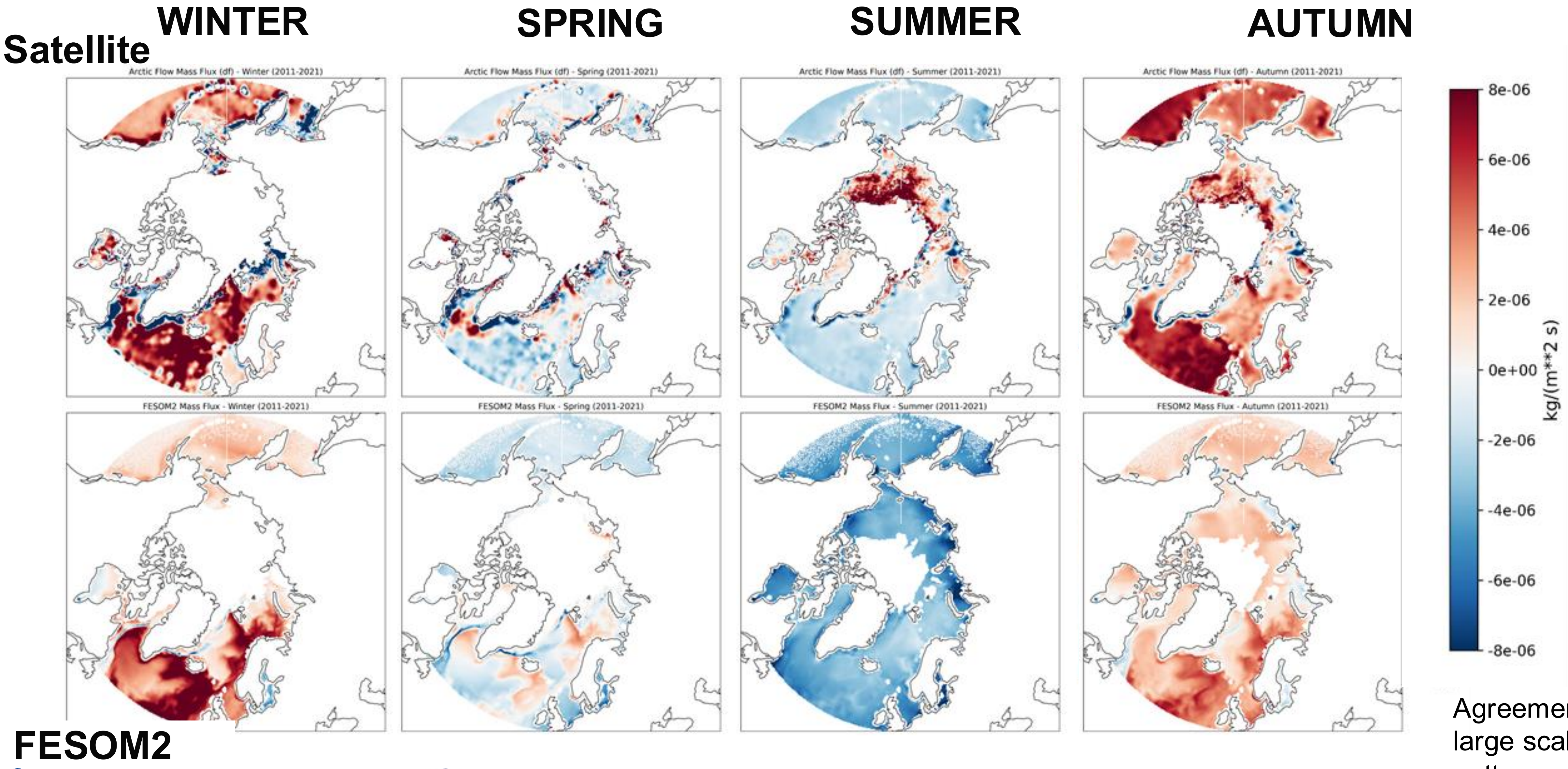
$$\frac{D\rho}{Dt}h = h\left\{\frac{\partial\rho}{\partial t} + \mathbf{u}\cdot\nabla\rho\right\} = \underbrace{-\alpha\frac{Q_{net}}{C_p} + \beta\,\rho_s\,s\,\varepsilon}_{f_\rho} + \underbrace{\kappa\,\nabla^2\rho}_{d_\rho} + \underbrace{(\rho_0 - \rho_{-h})\left(\frac{Dh}{Dt} + w_{-h}\right)}_{h_\rho}$$

$$\frac{Ds}{Dt}h = h\left\{\frac{\partial s}{\partial t} + \mathbf{u}\cdot\nabla s\right\} = \underbrace{S\cdot(E - P - R - I)}_{f_s} + \underbrace{\kappa\,\nabla^2 s}_{d_s} + \underbrace{(s_0 - s_{-h})\left(\frac{Dh}{Dt} + w_{-h}\right)}$$

Satellite products
ORAS5 fluxes

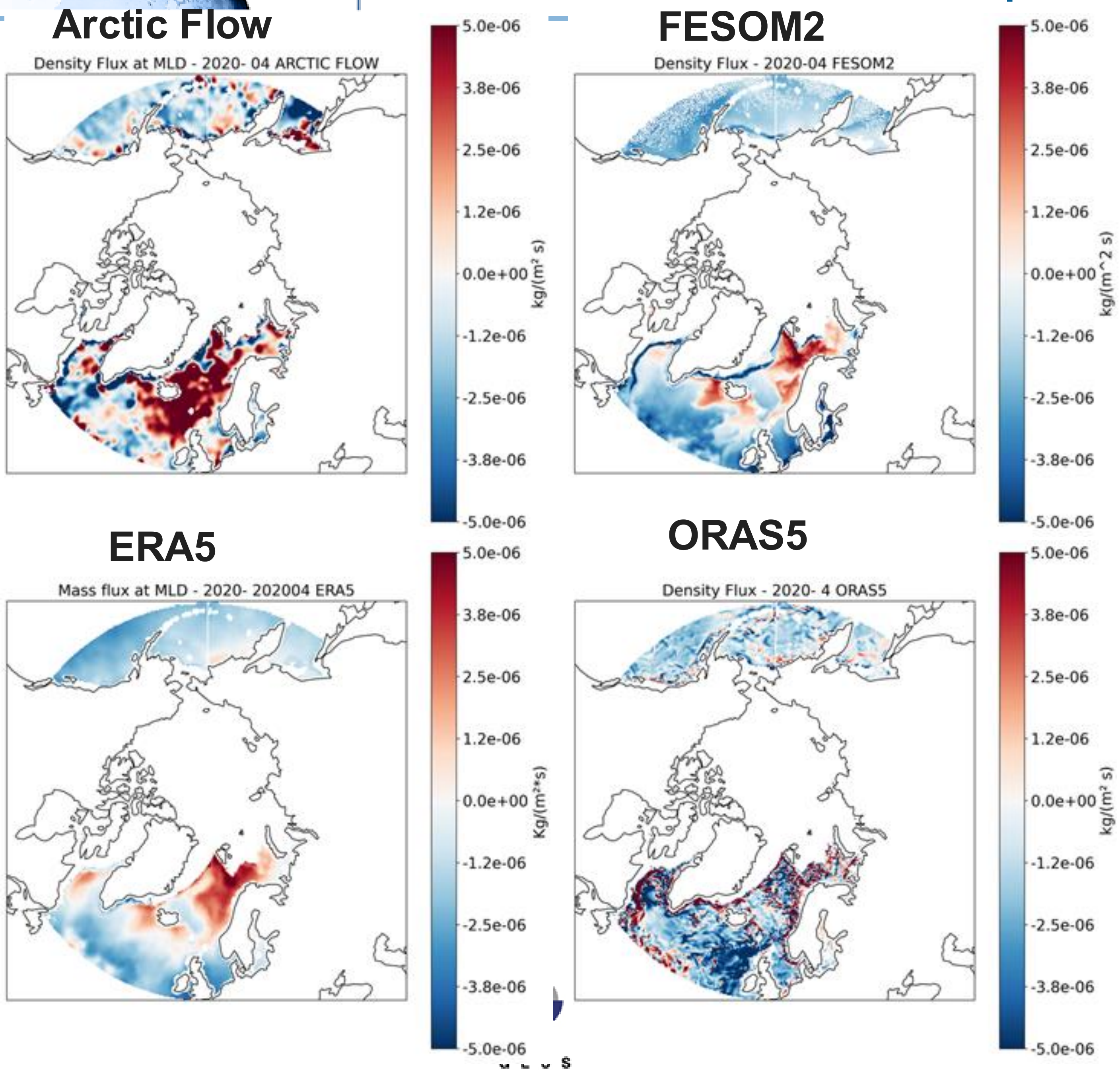
FESOM2 and ERA5
air-sea fluxes

Density fluxes: Seasonal comparison



Agreement in large scale patterns

Density flux: Monthly comparison, April

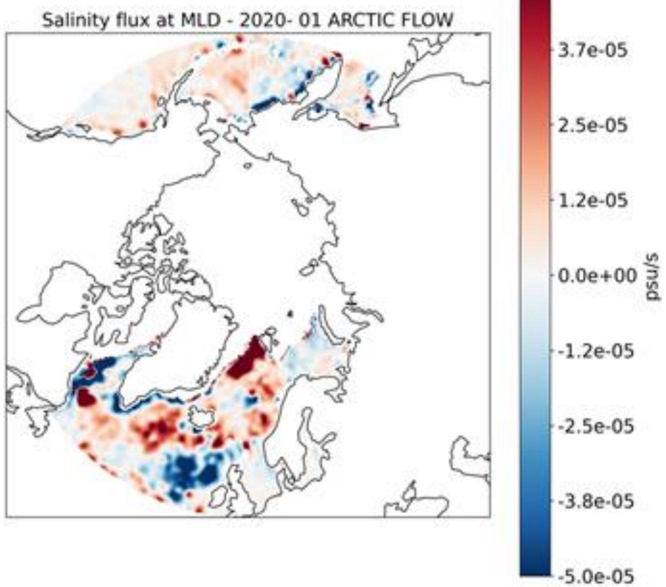


Density fluxes:

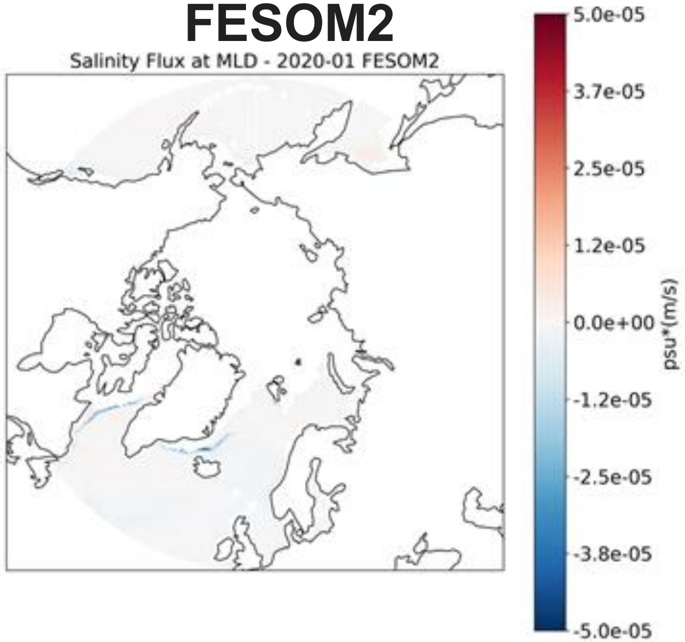
Consistent with model air–sea fluxes, capturing patterns not represented in ocean analyses.

Salinity flux: Monthly comparison, January

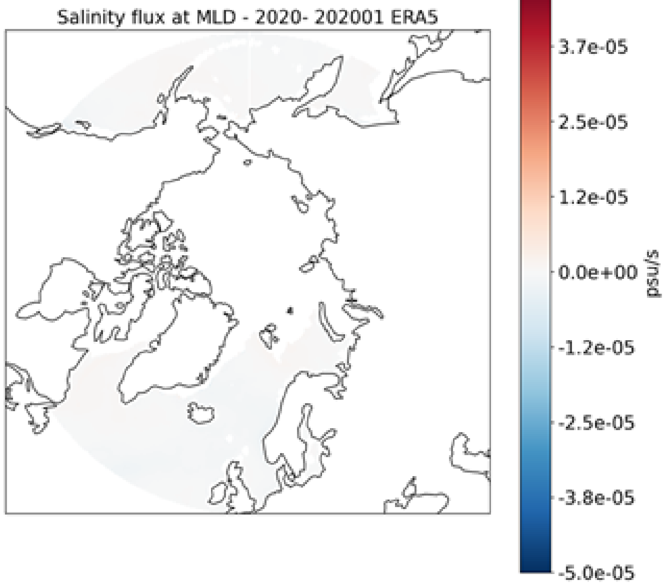
Arctic Flow



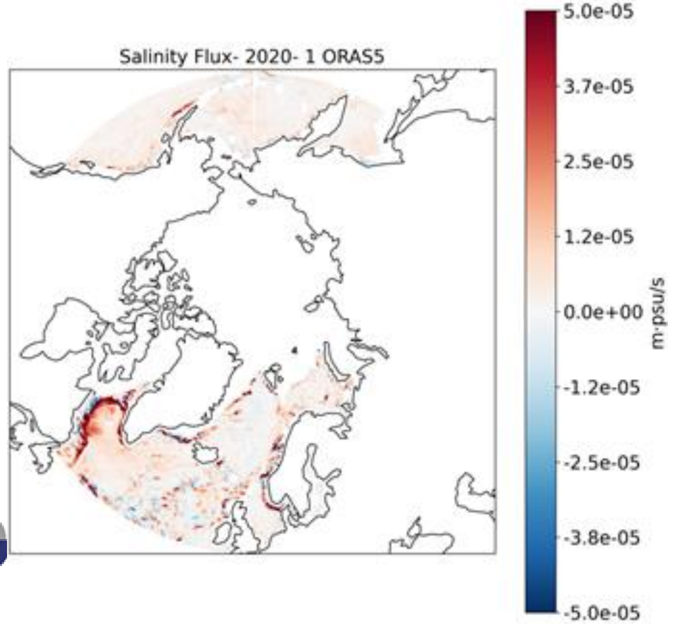
FESOM2



ERA5



ORAS5

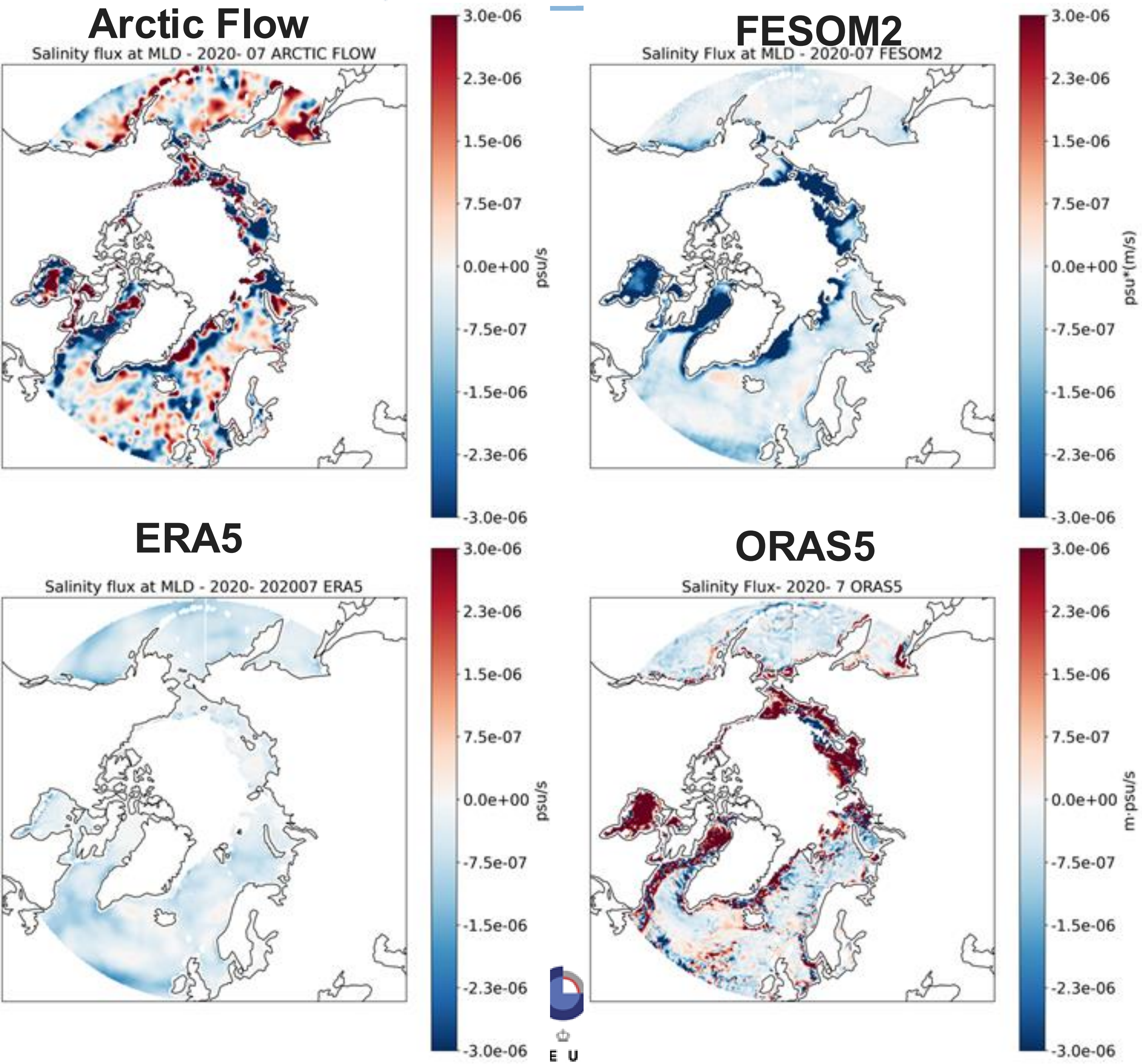


GEU

Salinity fluxes:

In winter, satellite fluxes larger than air-sea model and ocean reanalysis

Salinity flux: Monthly comparison, July



Salinity fluxes:

In summer, magnitude more comparable.

- Differences can be associated to uncertainties in satellite measurements, but also high-frequency geophysical processes like wind forcing that are not well represented in model observations

Before addressing scientific questions…

1. What does the satellite-derived estimate truly represent?

    a. Which term dominates in the material derivative: advection or eulerian?
    b. Relative contributions of salinity and temperature in the density flux

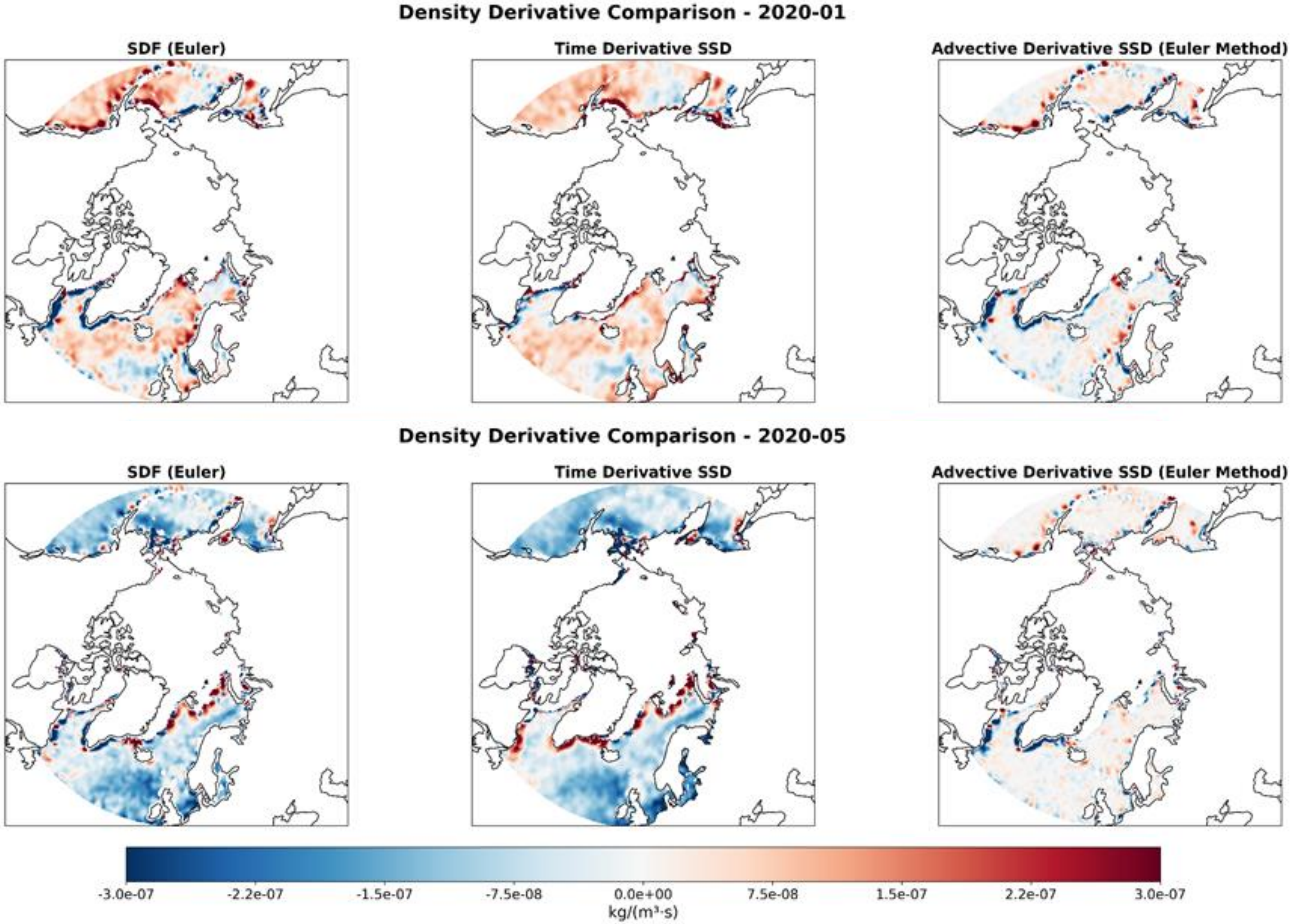
1. Which is the expected uncertainty in satellite products?

Advective term vs time derivative importance

$$\underbrace{\frac{D\rho}{Dt}}_{sdf} = \underbrace{\frac{\partial \rho}{\partial t}}_{time} + \underbrace{\mathbf{u} \cdot \nabla \rho}_{advection}$$

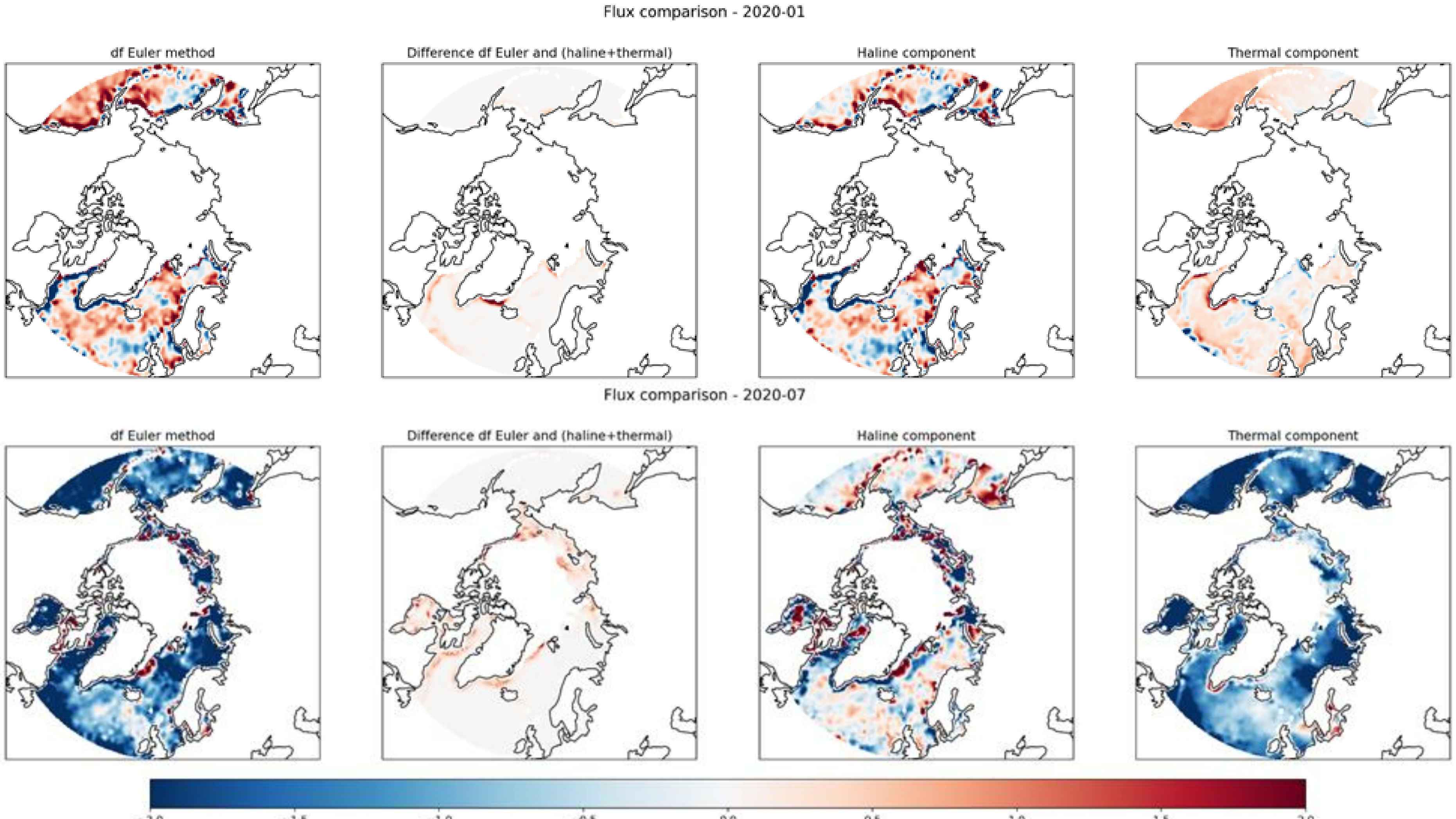
Time derivative is the major contributor to the material derivative.

Advective term has a significant contribution in strong current regions (close to the coast).



Salinity vs Temperature importance

$$\underbrace{\frac{D\rho}{Dt}}_{sdf} = \left\{\frac{\partial\rho}{\partial t} + \mathbf{u}\cdot\nabla\rho\right\} = \underbrace{-\rho\,\alpha\,\frac{D(sst)}{Dt}}_{thermal} + \underbrace{\rho\,\beta\,\frac{D(sss)}{Dt}}_{haline}$$



In winter haline pattern dominates

In summer temperature has a larger contribution, but still many patterns are haline-driven

Which is the expected noise in density flux due to SSS and SST undertainty?

$$
\begin{aligned}
u\left(h\frac{D\rho}{Dt}\right) &\approx h\cdot\left\{u\left(\rho\alpha\frac{Dsst}{Dt}\right)+u\left(\rho\beta\frac{Dsss}{Dt}\right)\right\}\\
&\approx h\cdot\left\{\rho\alpha u\left(\frac{Dsst}{Dt}\right)+\rho\beta u\left(\frac{Dsss}{Dt}\right)\right\}\\
&\approx h\cdot\left\{\rho\alpha u\left(\frac{sst_1-sst_0}{t_1-t_0}\right)+\rho\beta u\left(\frac{sss_1-sss_0}{t_1-t_0}\right)\right\}\\
&\approx h\cdot\left\{\rho\alpha\frac{u(sst)\sqrt{2}}{t_1-t_0}+\rho\beta\frac{u(sss)\sqrt{2}}{t_1-t_0}\right\}
\end{aligned}
$$

By asuming u(sss)~0.3 psu, u(sst)~0.25K, h~100 m, density~ 1000 kg/m³ , \alpha~ 10^{-4} K^{-1}, \beta~7x 10^{-4} g/kg $^{-1}$

- Haline contribution to uncertainty ~ 3x10^{-4} kg/(m^2s)
- Thermal contribution to uncertainty ~4x10^{-5} kg/(m^2s)

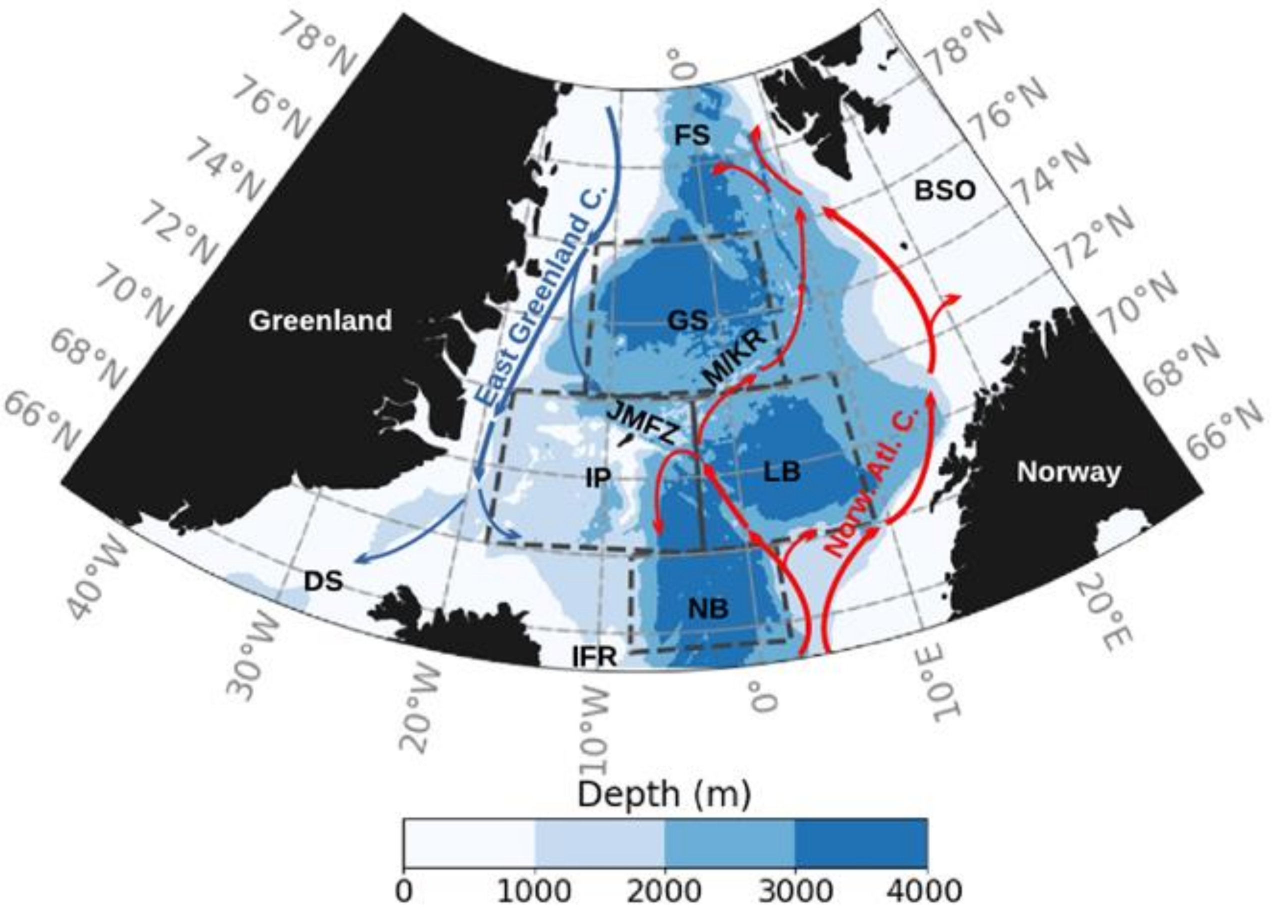
Uncertainty in density flux is dominated by salinity

Uncertainty is larger than the magnitude of the flux at daily and 25km scales. Uncertainties in the input data are the principal limitation.

When averaging in time and spatially smoothing (applying a low-pass filter) the error decreases and the results become significant.

We are working in the v2 of the product that will be focus on the reduction of the noise at daily scale.

Next step: Addressing scientific cases



Almeida et al., 2025

Assessing the monthly evolution of the density and salinity fluxes in these regions

Estimating ratios of water mass formation in the region following approach described in (Piracha et al. 2023)

$$\int_{MLD}^{0} \frac{D\rho_l}{Dt} dz = \sum_{i}^{i=n} \frac{D\rho_l}{Dt}(\lambda, \phi, i) \cdot \Delta z \prod (z \leq MLD)$$

Thank you for your attention !

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Photo from A. Beszczynska-Möller