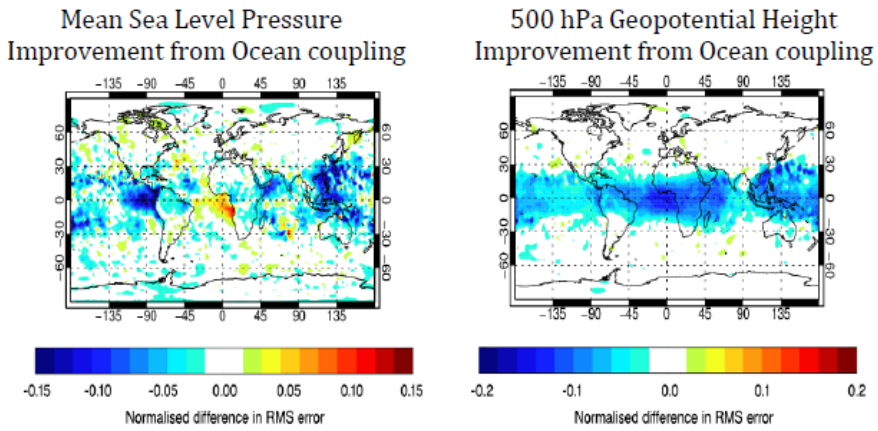
Developments in ocean data assimilation and coupling to the atmosphere

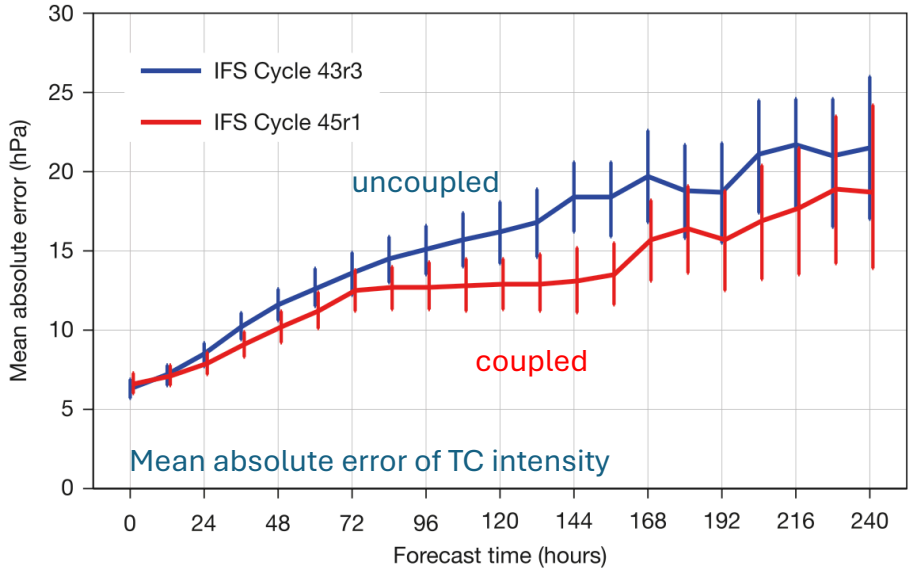
Phil Browne, Hao Zuo, Marcin Chrust, Hans Hersbach, Tracy Scanlon, Nils Risse, Alan Geer, Peter Lean, Patricia de Rosnay, Kristian Mogensen, Sarah Keeley, and many others



Why the ocean matters in weather prediction?



- ECMWF forecasts became coupled for all timescales since 2018 (CY45R1 HRES) - include dynamical ocean and sea-ice components (Mogensen et al., 2018, Buizza et al., 2018).
- Coupling with the ocean improves the weather forecast scores, with reduced RMSE (blue) in day+5.
- Coupling with ocean reduces intensity error in HRES forecasts of tropical cyclone (TC).



ORAS6 benefits from an improved data assimilation system

The hybrid covariance formulation in NEMOVAR (thanks to the EU-funded C3S ERGO/ERGO2 project)

$$B_h = \mathrm{K}_b D_h^{1/2} C_h D_h^{1/2} \mathrm{K}_b^T$$

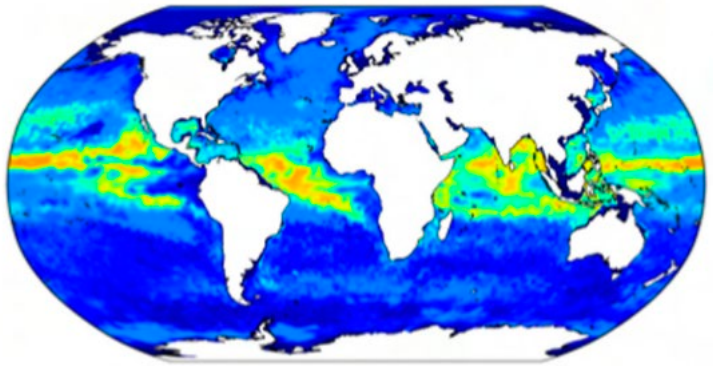
$\boldsymbol{B_h}$ is the hybrid covariance matrix; $\boldsymbol{C_h}$ is the correlation matrix (usir hybrid diffusion operator $\boldsymbol{\kappa_h}$); $\boldsymbol{D_h}$ is a block-diagonal matrix of variances (using hybrid std dev σ_h).

Hybrid background-error standard-deviation formulation

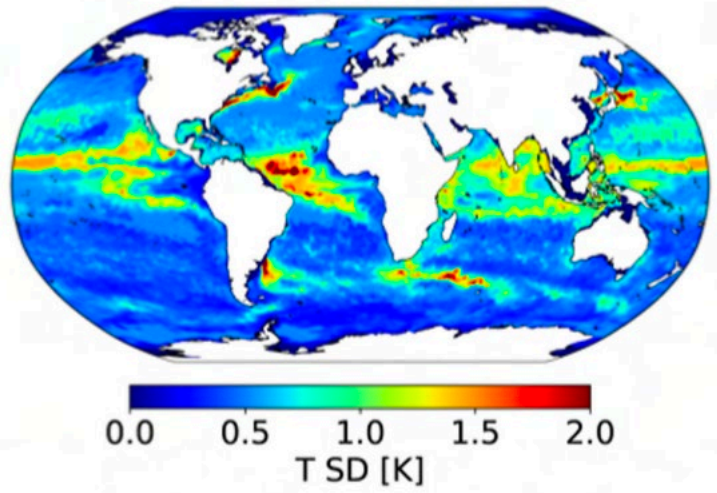
$$\sigma_h = \frac{1}{h}\log(e^{hw_m\sigma_m} + e^{hw_e\sigma_e} - 1)$$

Here w_m ,w_e are dimensionless weighting factors for *modelled/ensemble* components of standard deviations, and *h* is a hardness factor.

Parameterized σ_m



Hybrid σ_h

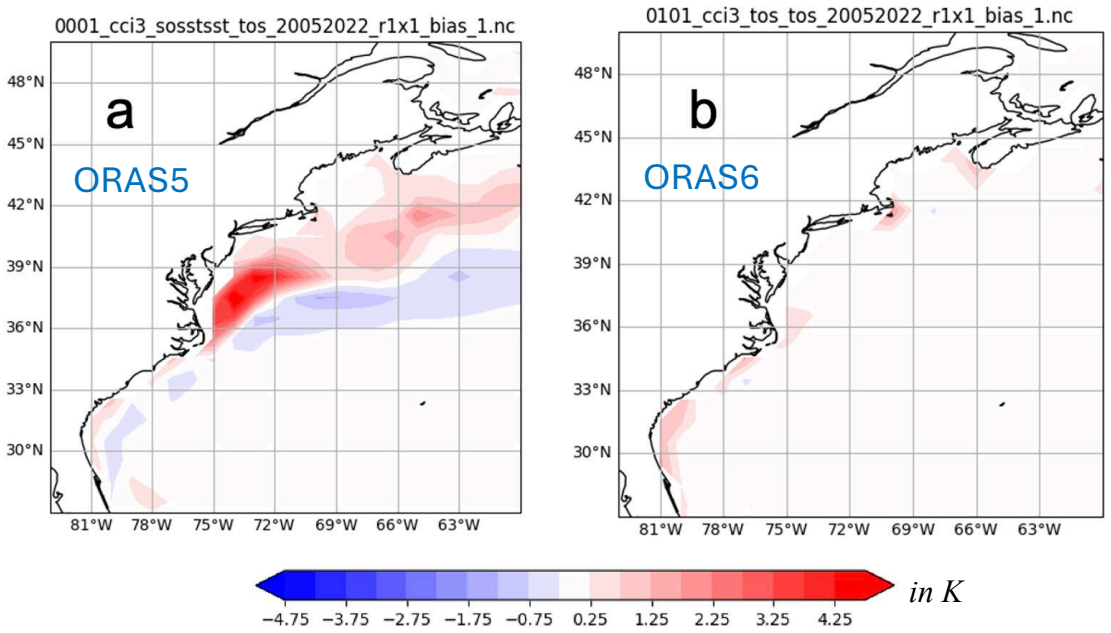


(Chrust et al., 2024, QJRMS)

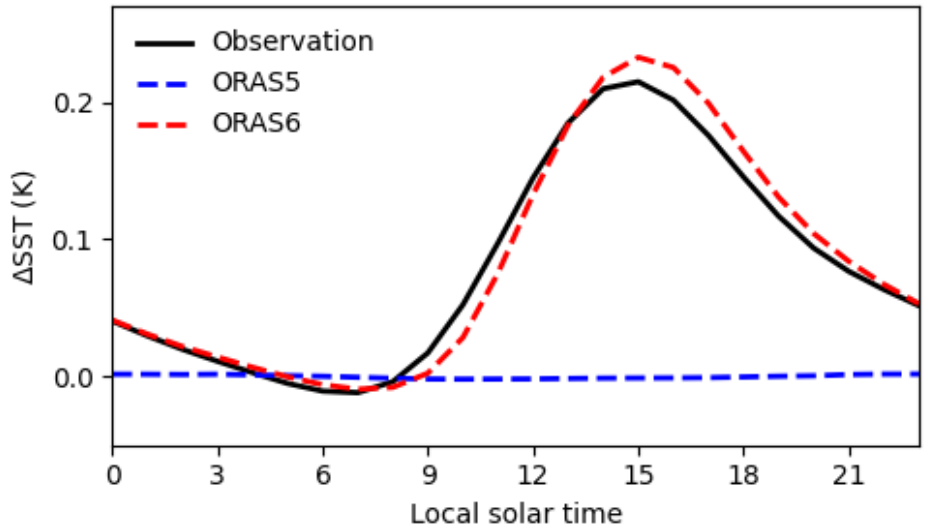
ORAS6 performance – sea surface temperature

- Greatly reduced SST biases in the GS regions – partial coupling no longer needed
- Good representation of the SST diurnal cycle – thanks to hourly forcing + SST DA

SST biases in the Gulf Stream region
(2015–2022, against CCIv3)



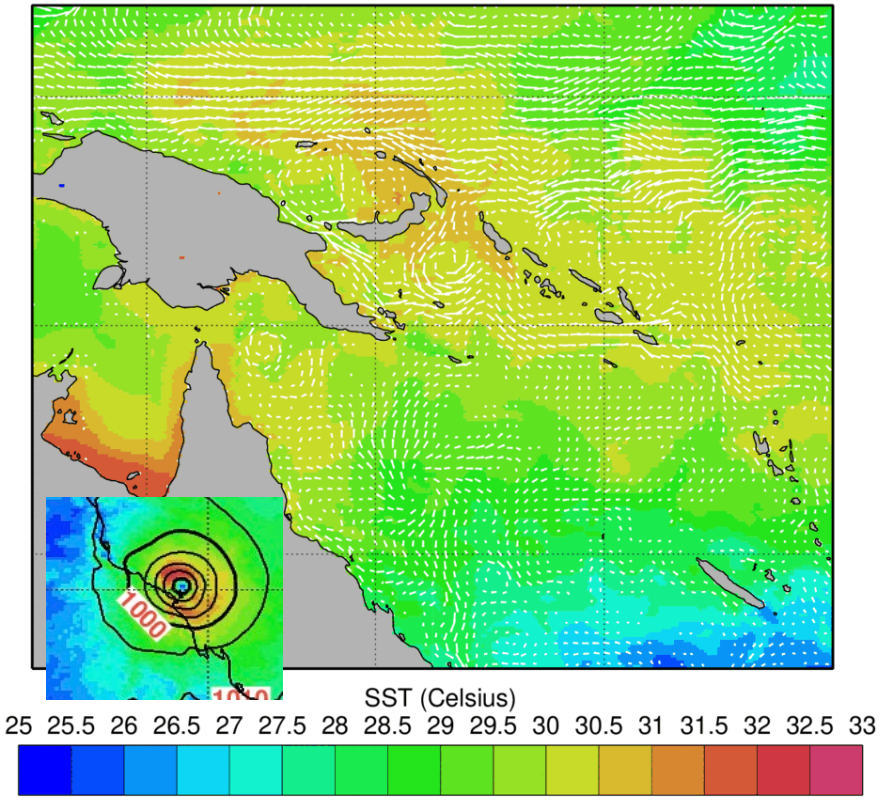
Global mean SST diurnal cycle
(2019, against drifter data)



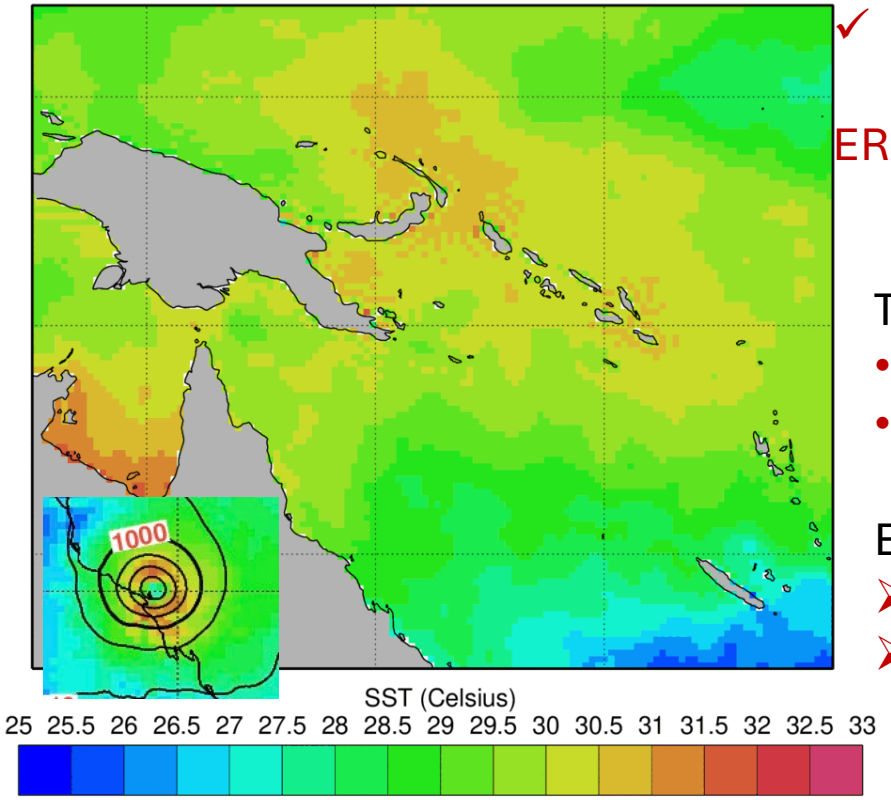
Zuo et al., 2024 NL180

More realistic ocean-atmosphere processes in ERA6 compared to ERA5

ERA6, 25 March 2017, 00 UTC



ERA5, 25 March 2017, 00 UTC



ERA6 has hourly SST + currents from its ocean component:

✓ daily cycle

ERA5: $SST_{foundation}$ only changes daily

Tropical Cyclone Debbie:

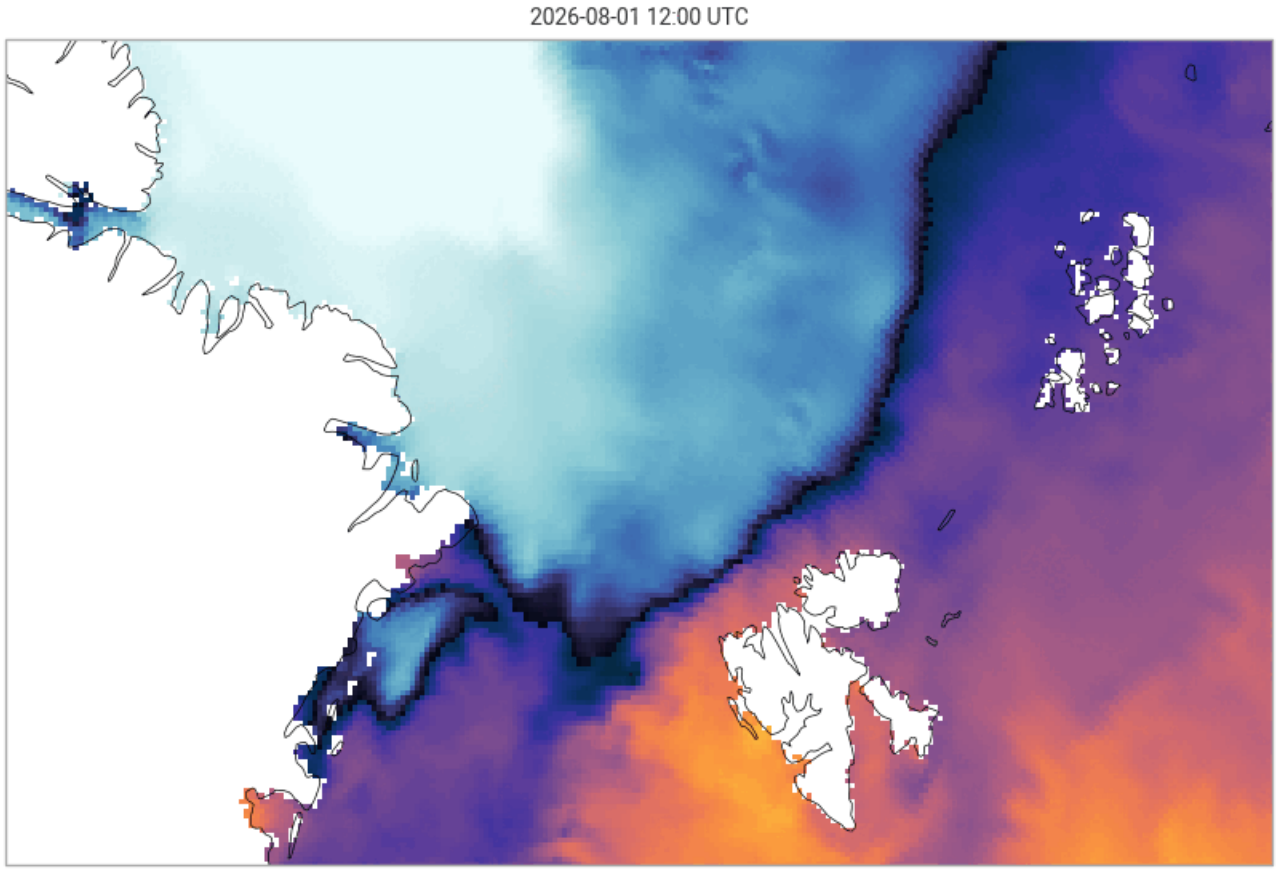
- Winds reported up to 120 mph
- Damage: ~ €2 billion

Extracts energy from the ocean:

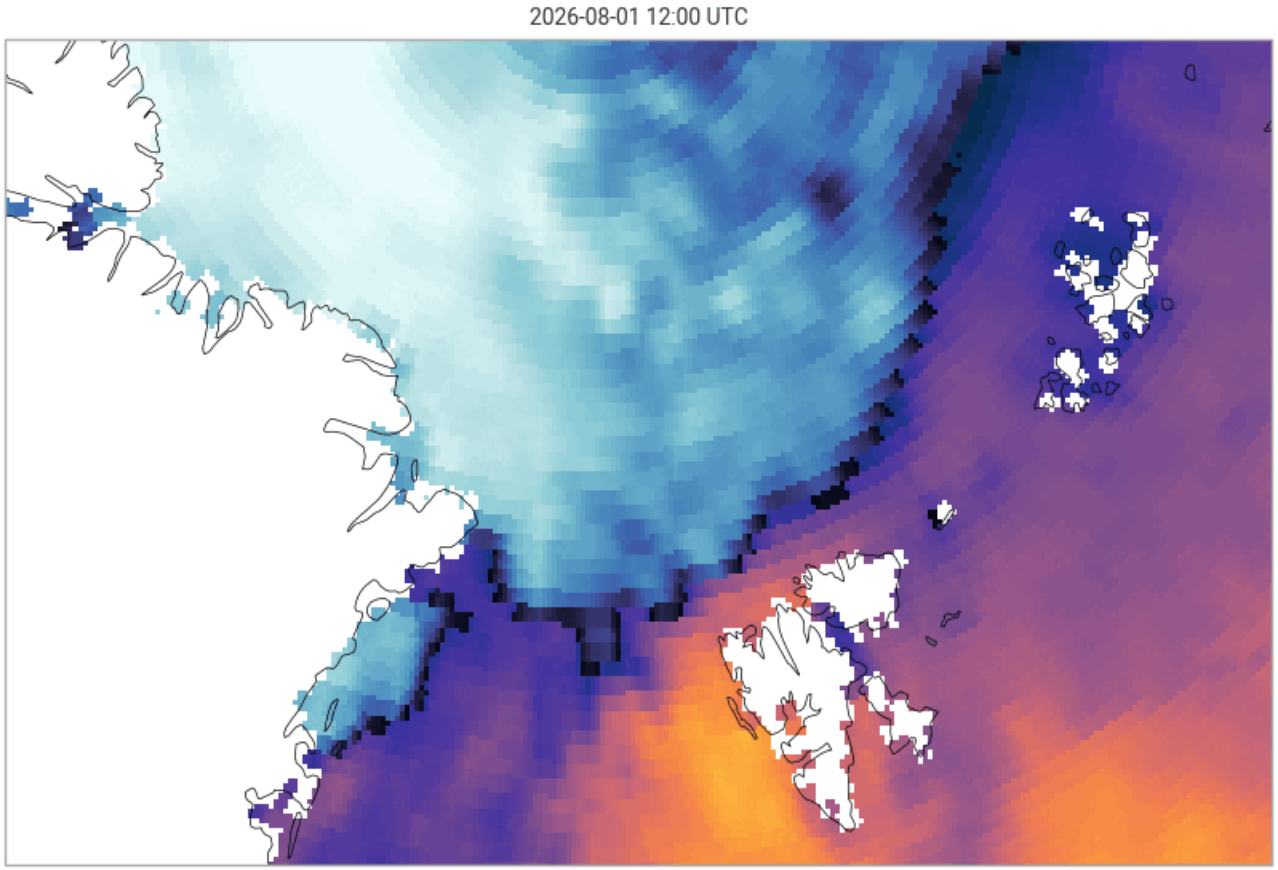
➢ Cooling of SST

➢ Induced ocean currents

Sea ice concentration and sea surface temperatures

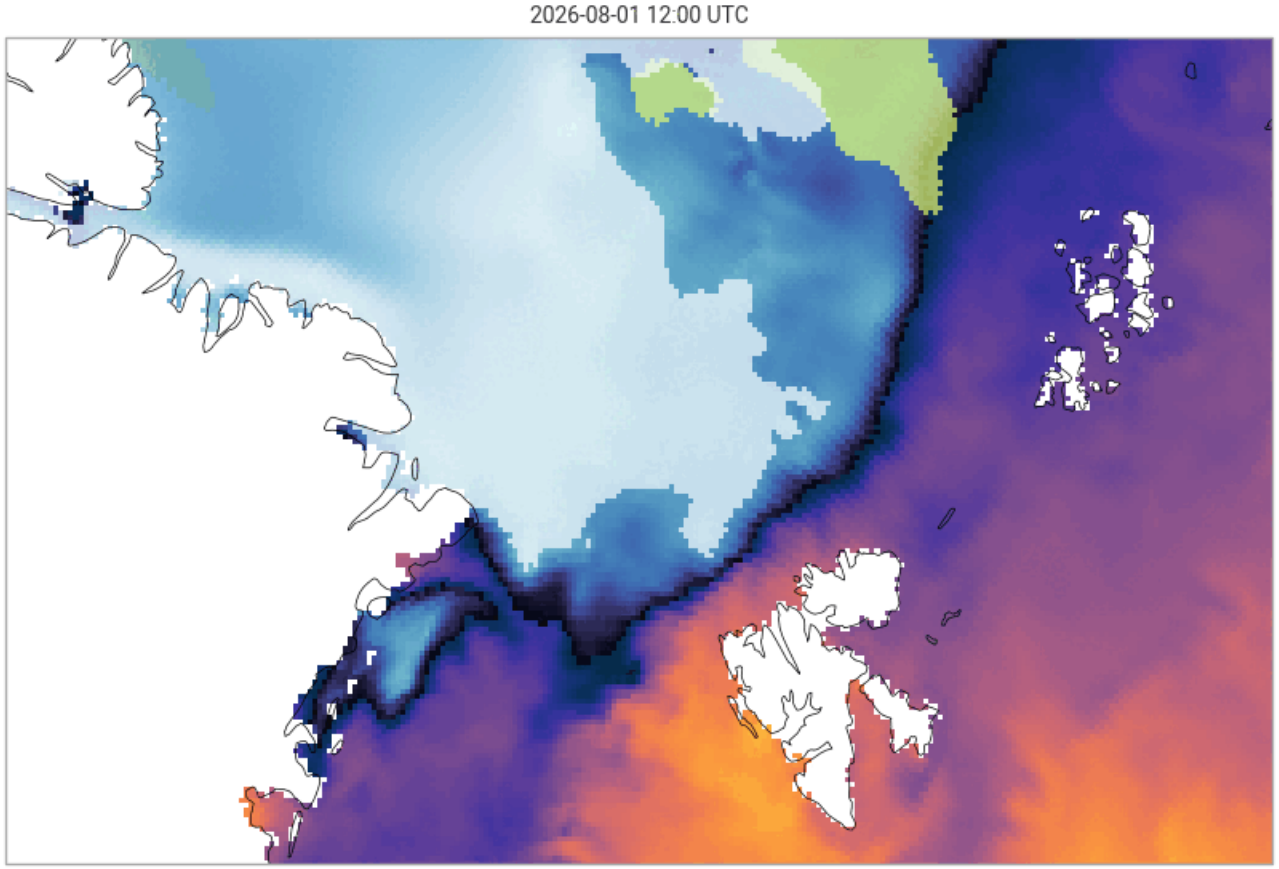


Operational IFS

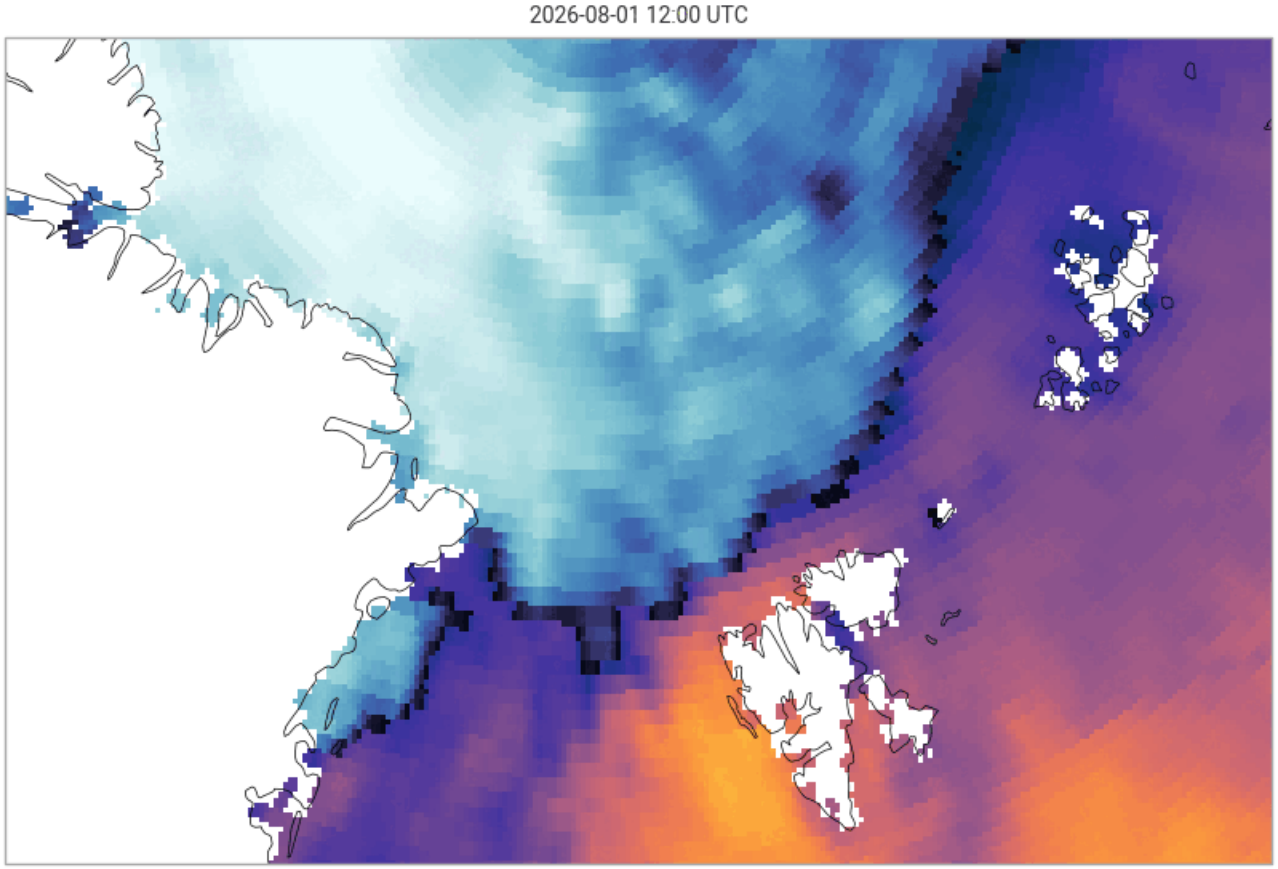


ERA5

With extra surface physics processes – meltponds and snow



Operational IFS



ERA5

meltponds

snow on ice

Working within the Variational Data Assimilation framework

- Since 1997, 4DVar has been the operational core of the ECMWF atmospheric DA

- Initial conditions are found by minimizing an objective (or cost) function

$$J(x) = \frac{1}{2}(x_b - x)^T B^{-1}(x_b - x) + \frac{1}{2}\sum_k \left(y_k - \mathcal{H}_k\left(\mathcal{M}_k(x)\right)\right)^T R^{-1}\left(y_k - \mathcal{H}_k\left(\mathcal{M}_k(x)\right)\right)$$

- This is solved by linearising to get an expression for the gradient

$$-\nabla J(x) = B^{-1}(x_b - x) + \sum_k M_k^T H_k^T R_k^{-1}\left(y_k - \mathcal{H}_k\left(\mathcal{M}_k(x)\right)\right)$$

- And finally, once the minimization has completed, we cycle the system to the next assimilation window by running a model forward in time

$$\mathrm{x}_b = \boldsymbol{\mathcal{M}}(x_a)$$

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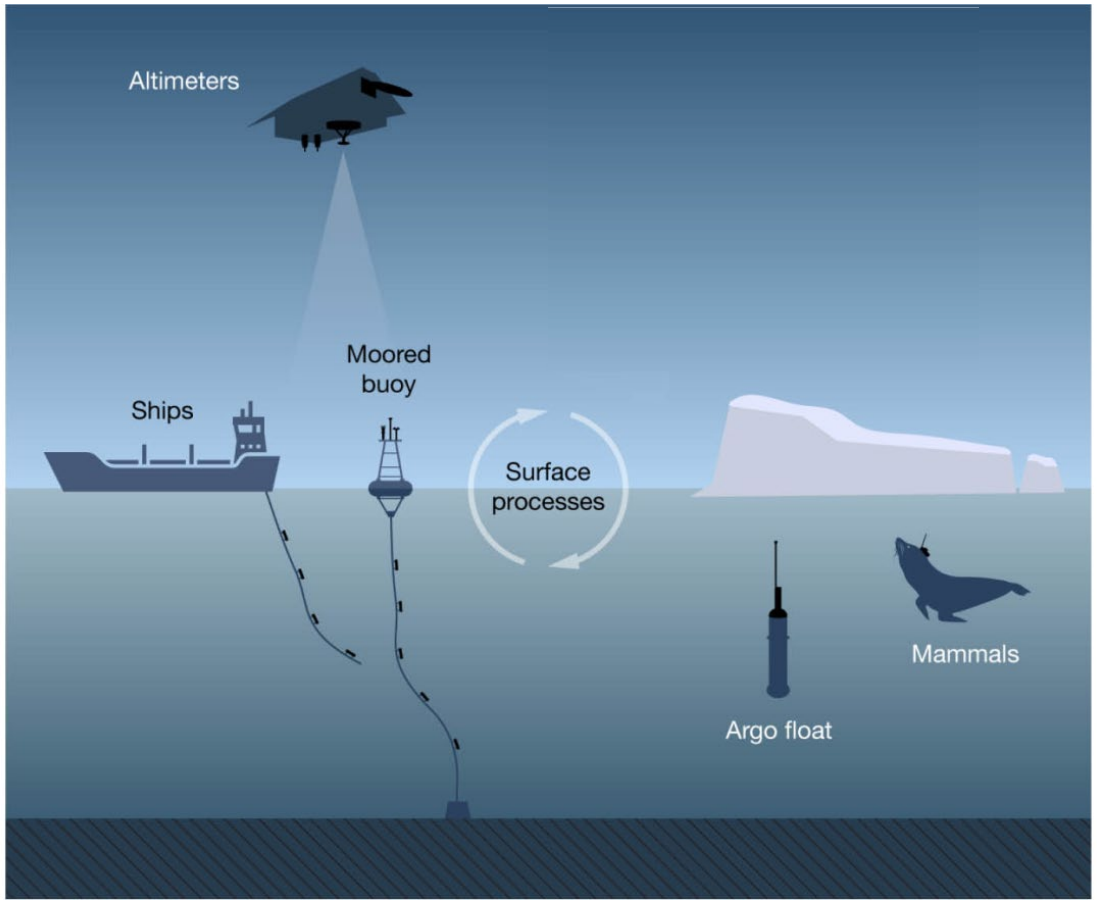
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$$\mathrm{x}_b = \boldsymbol{\mathcal{M}}(x_a)$$

Separable objective function to allow parallel minimisations

$$J(x) = J(x_1) + J(x_2)$$

Which is possible as B & M are uncoupled. Also needs H uncoupled to split observations between components.



Coupled observation operators in the ocean-sea-ice-atmosphere system

$$J^o(\mathbf{x}) = J_1^o(\mathbf{x}_1) + J_2^o(\mathbf{x}_2) + J_c^o(\mathbf{x}_1, \mathbf{x}_2)$$ ← Interface observations

$$\mathbf{x}_{\mathrm{cv}} := f(\mathbf{x}_2)$$ Extend the atmospheric control vector

$$J_1(\mathbf{x_1}, \mathbf{x}_{\mathrm{cv}}) = J_1^b + J_1^o + J_c^o$$ ← Include interface obs in the atmosphere

$$J_2(\mathbf{x_2}) = J_2^b + J_2^o + J_{\mathrm{cv}}$$ ← Add penalty term to the ocean/sea-ice

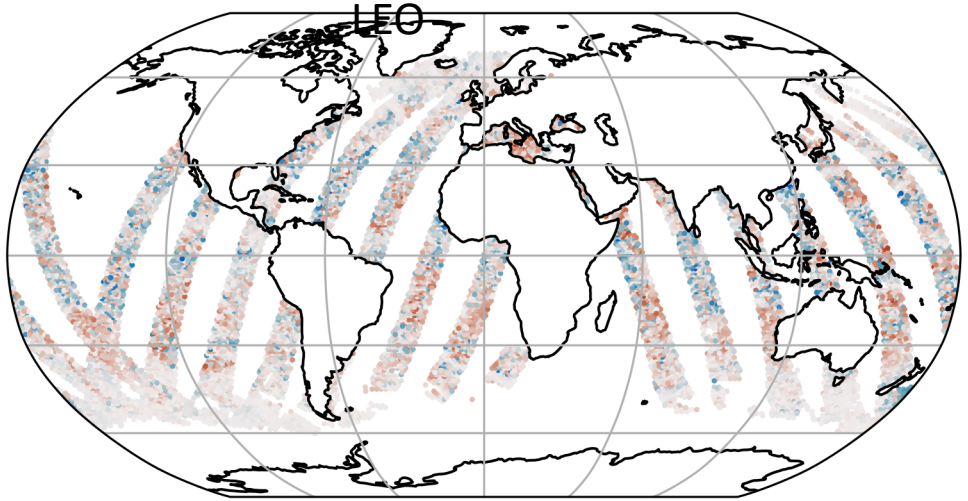
$$J_{\mathrm{cv}} = (\mathbf{x}_{\mathrm{cv}} - \mathcal{H}(\mathbf{x_2}))^T R^{-1} (\mathbf{x}_{\mathrm{cv}} - \mathcal{H}(\mathbf{x_2}))$$ Penalty term can be applied in observation space

Browne, P.A., de Rosnay, P., Geer, A.J., Quesada-Ruiz, S., Scanlon, T. & Villeneuve, E. (2026) Coupled observation-operator approximations in outer-loop coupling data assimilation. QJRMS, e70266. Available from: https://doi.org/10.1002/qj.70266

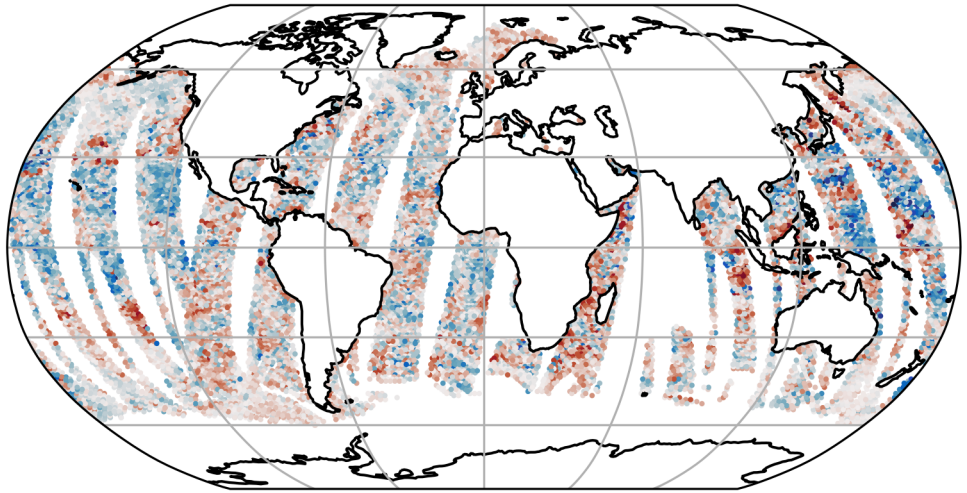
Skin temperature

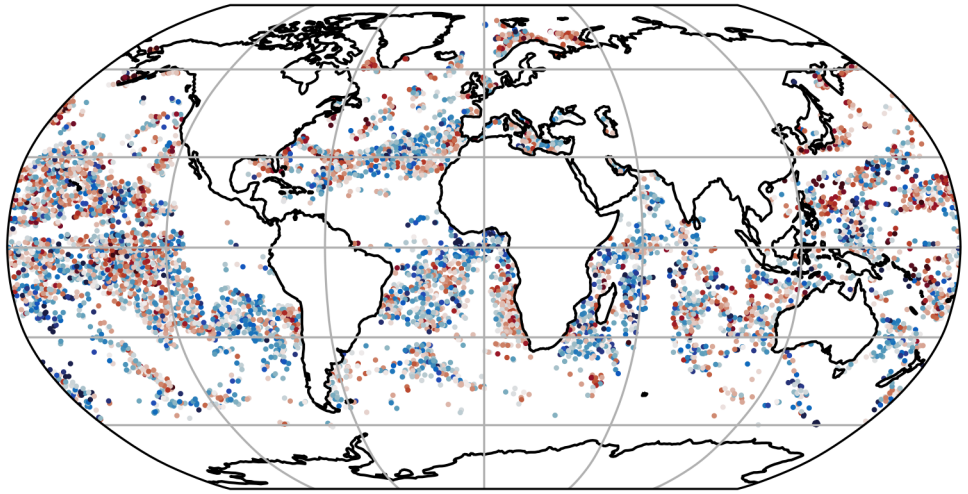
$$x_{cv} - \mathcal{H}_c(x_2)$$

GMI: MW LEO

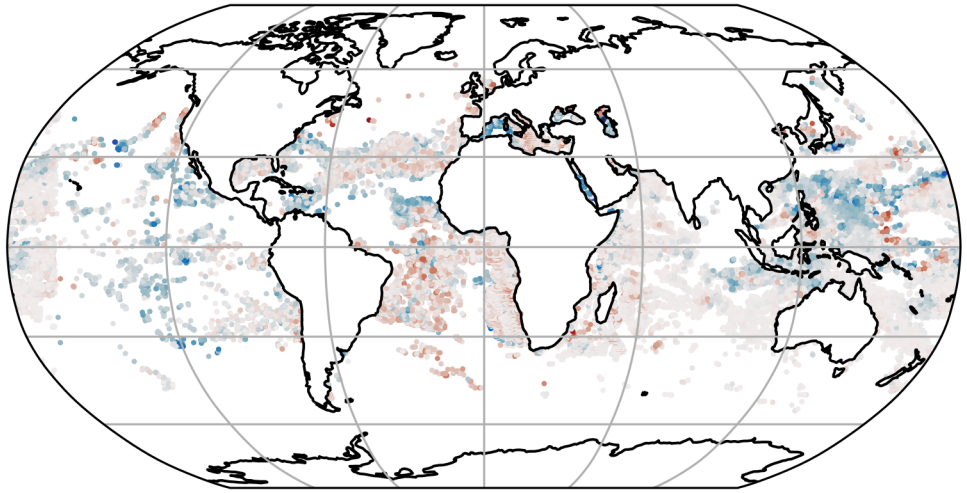


AMSR2: MW LEO





CrIS: Hyperspectral IR LEO

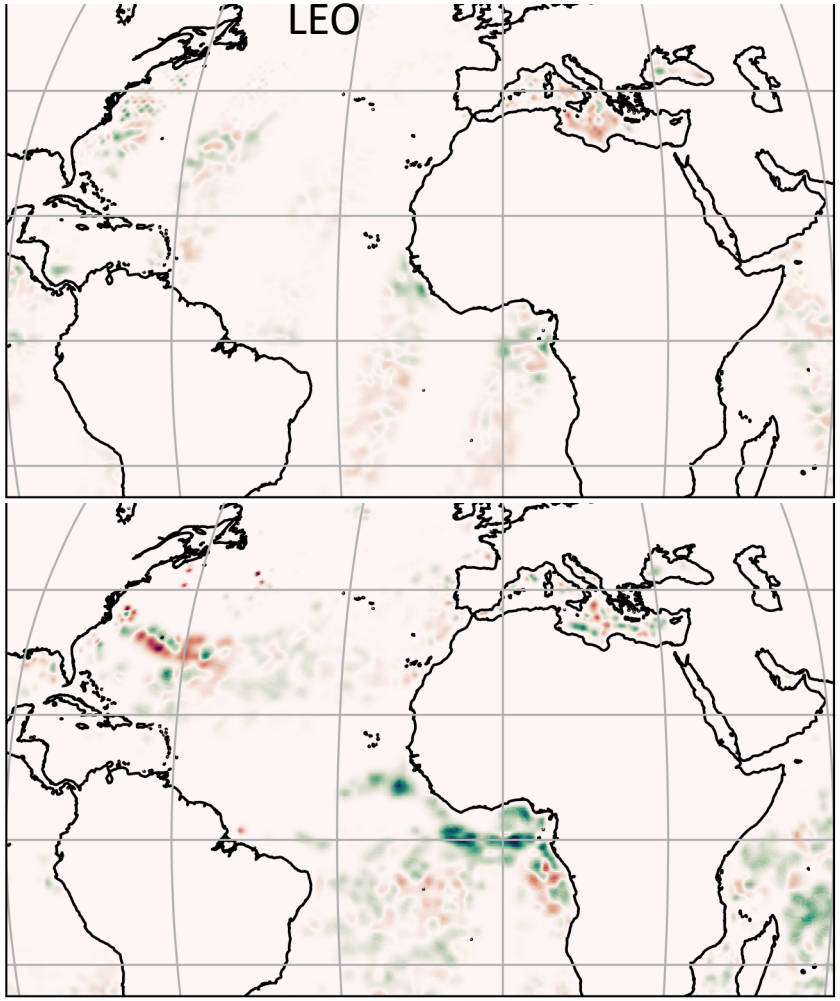


IR: GEOS Meteosat/GOES/Himawari

Skin temperature

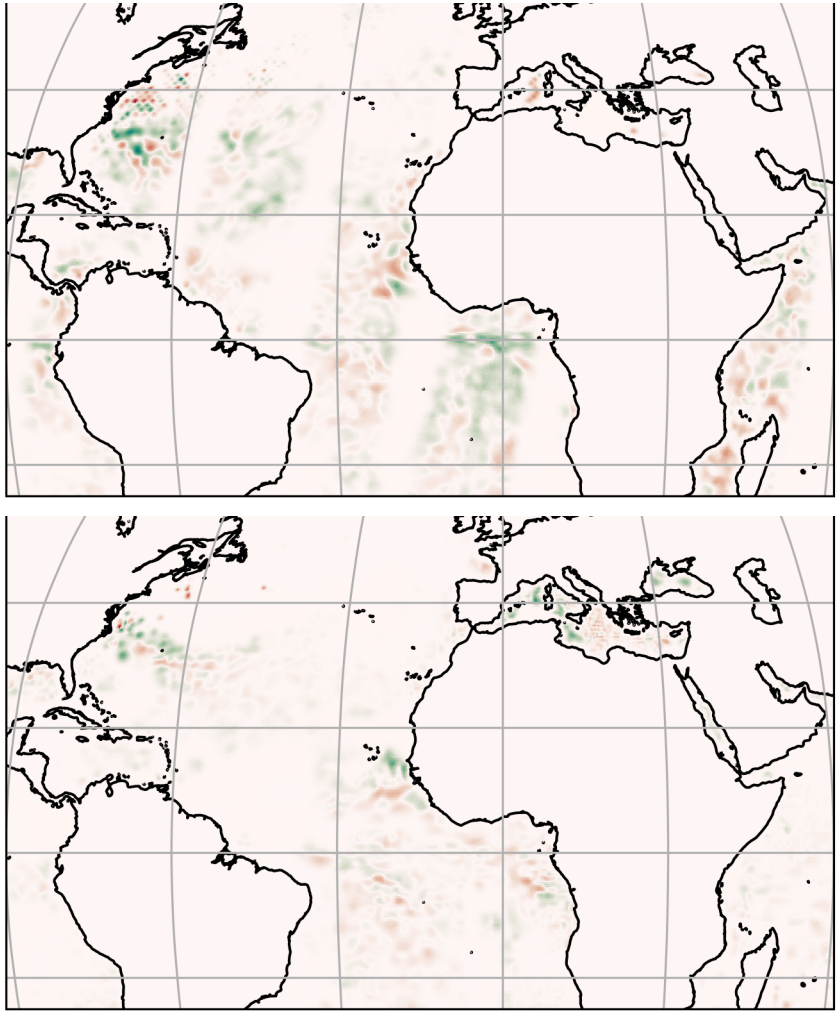
$\delta x | SSH$

GMI: MW LEO



CrIS: Hyperspectral IR LEO

AMSR2: MW LEO



IR: GEOS Meteosat/GOES/Himawari

Sea ice concentration

$$x_{cv} = SI_{eff} = SI_{conc} - MP_{conc}$$

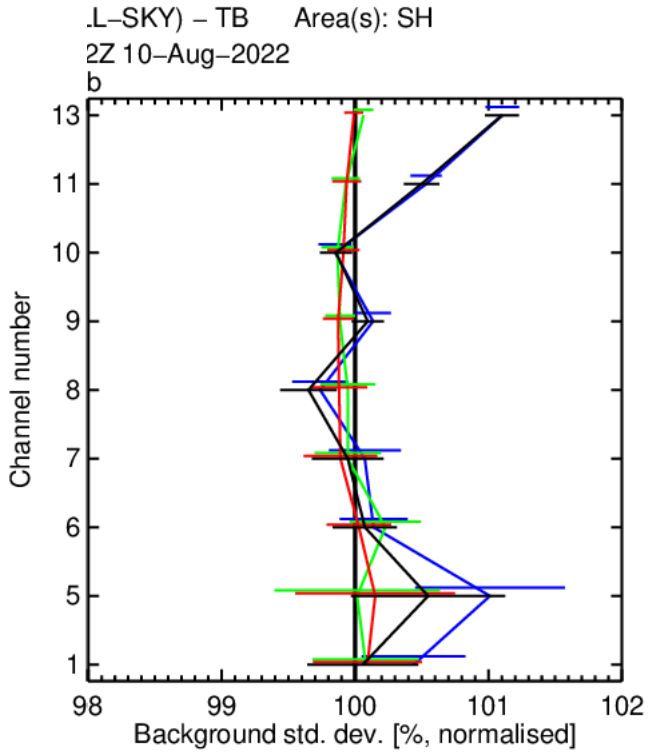


$$\frac{\partial x_{cv}}{\partial x_2} = \frac{\partial SI_{eff}}{\partial x_2} = H_{\text{sic}}$$

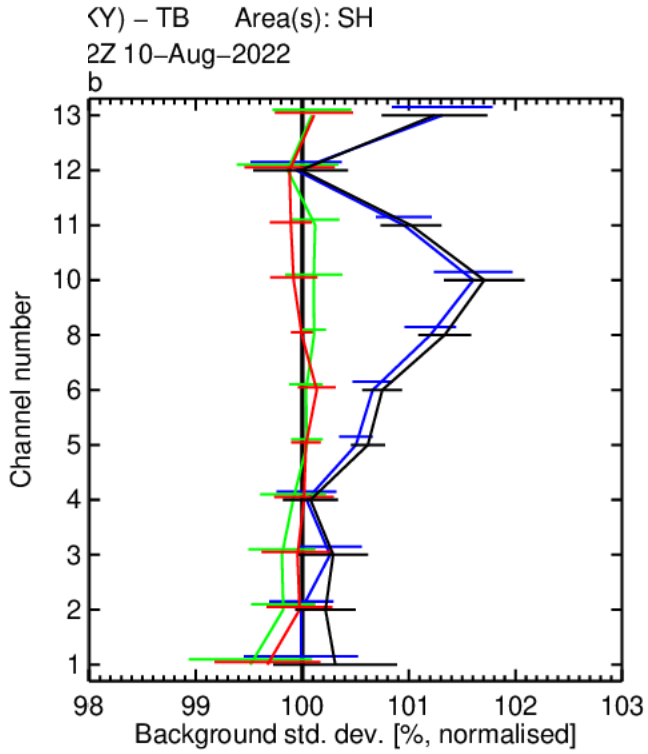
See talk by Alan Geer on Thursday for more!

Impact of coupled observation operators on satellite data usage – SH winter case

AMSR2



GMI



Blue = removal of all coupled observation operators

Black = removal of all sea ice coupled observation operator

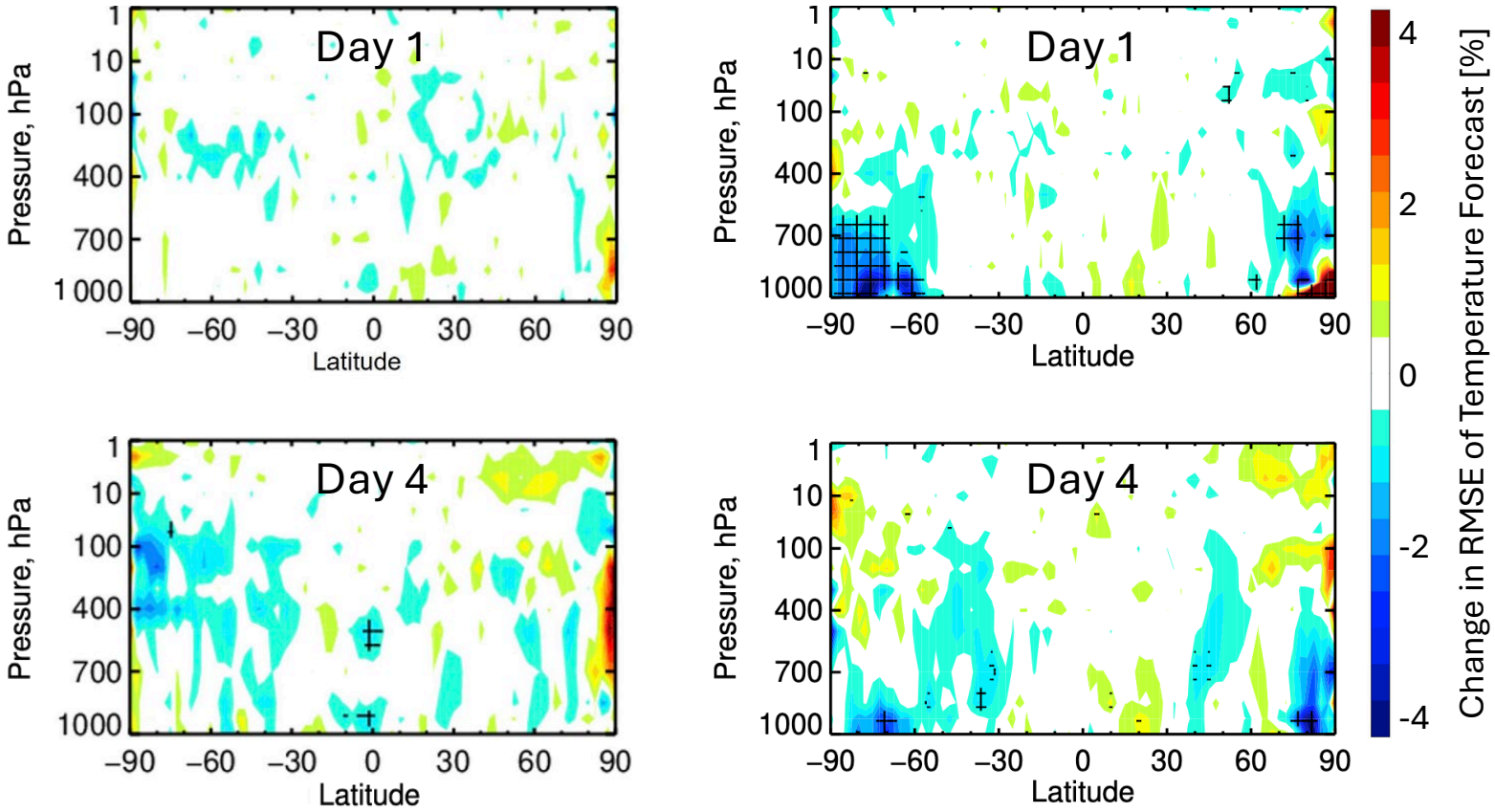
Impact of coupled data assimilation at ECMWF

- Coupled assimilation of SST+SIC in NEMOVAR improves forecast (Scanlon et al., 2026; Geer et al., 2026)

Assimilation of…

Sea surface temperature (SST)

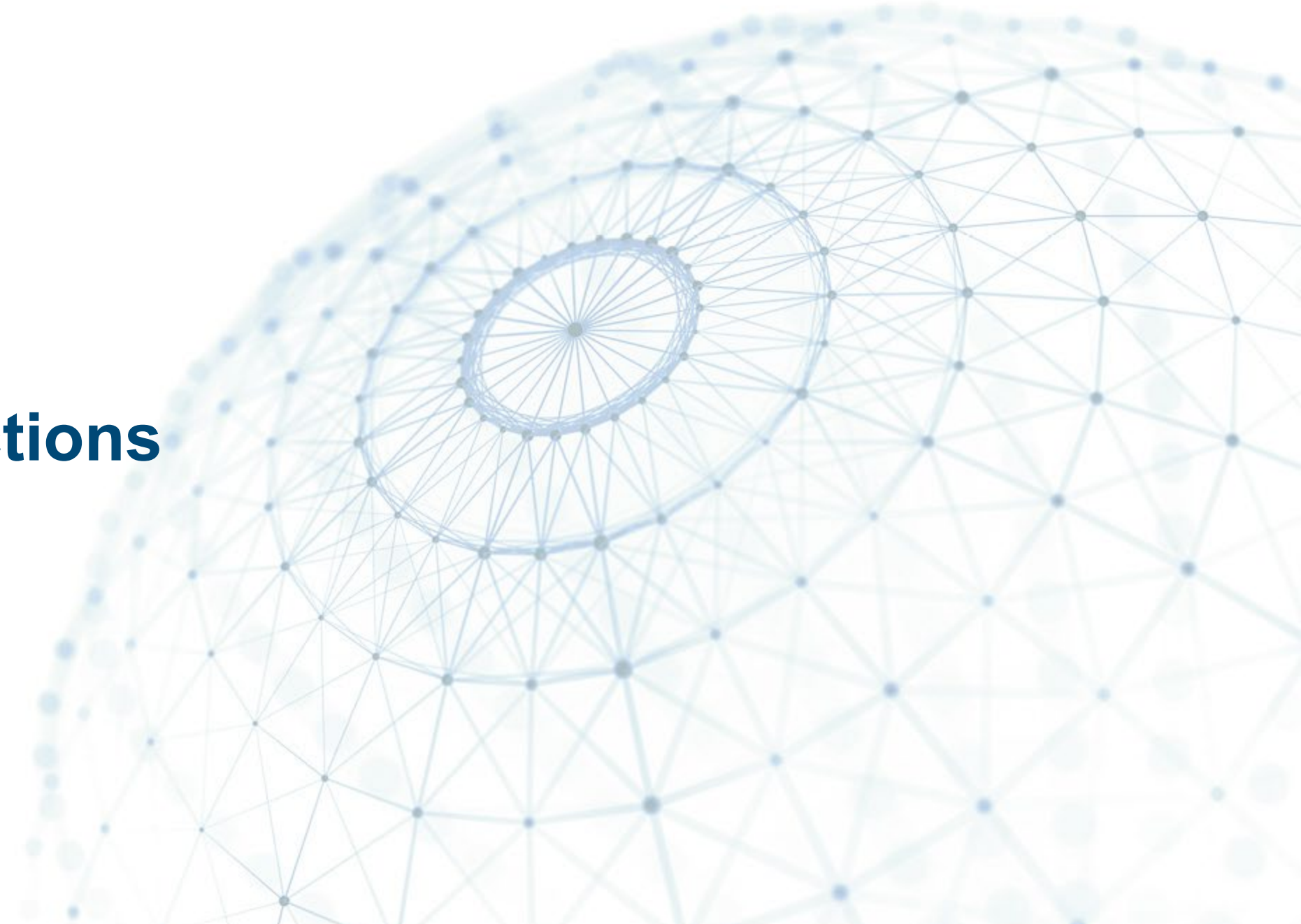
Sea ice concentration (SIC)



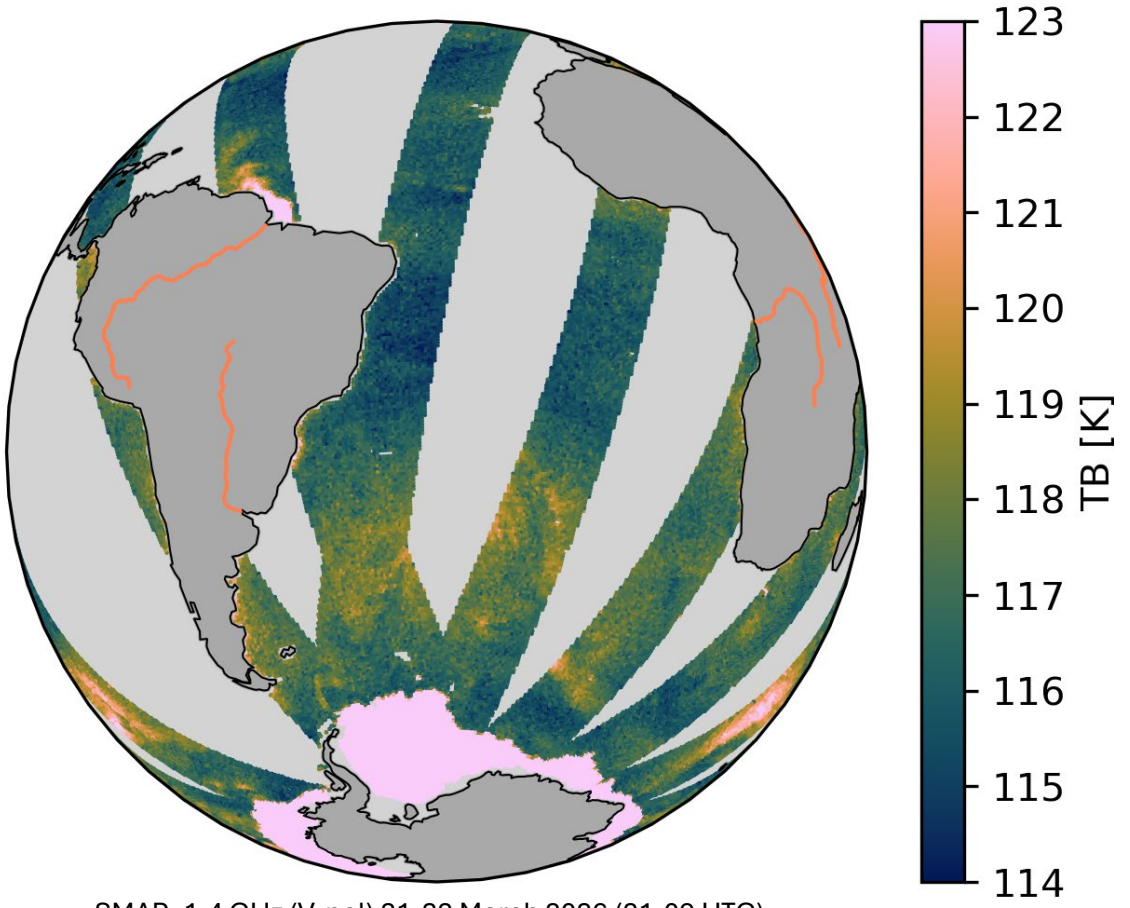
Scanlon et al. (2026)

Geer et al. (2026)

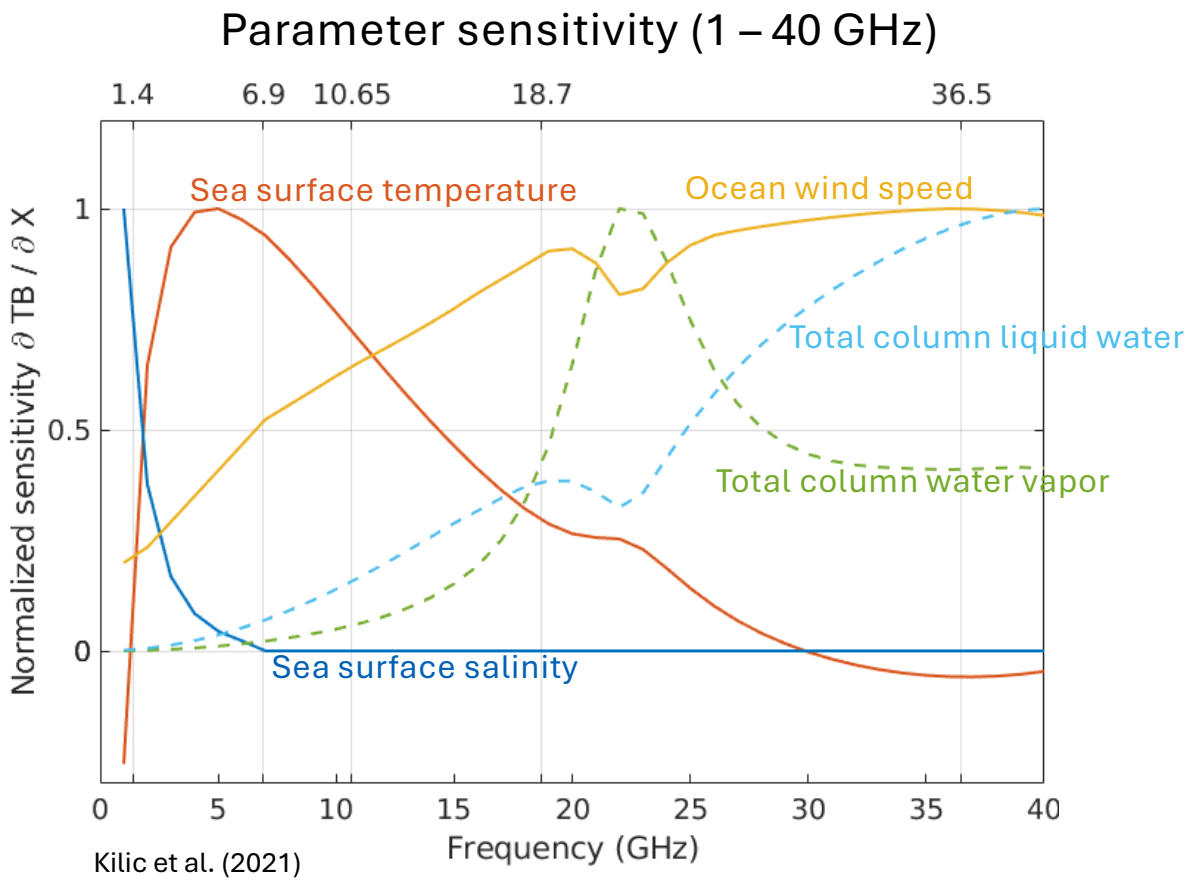
Future directions



Amazon river outflow as seen by SMAP (1.4 GHz)



SMAP, 1.4 GHz (V-pol) 21-22 March 2026 (21-09 UTC)



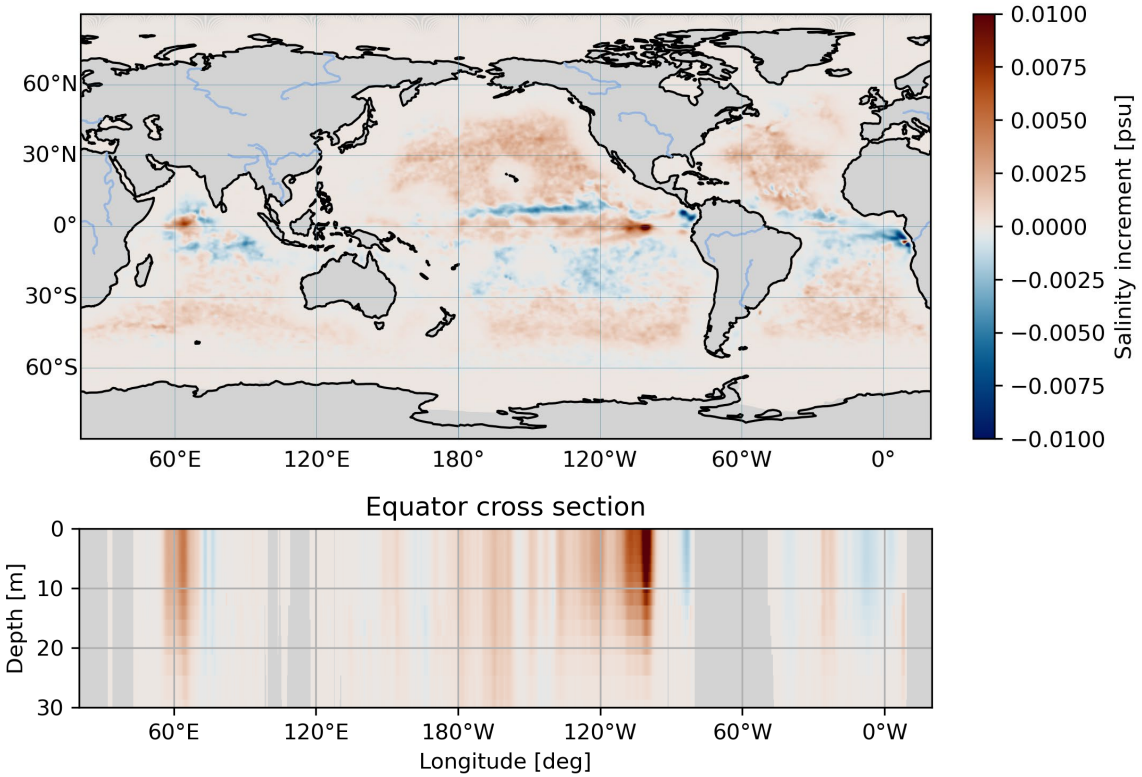
Kilic et al. (2021)

Sea surface salinity assimilation (*preliminary*)

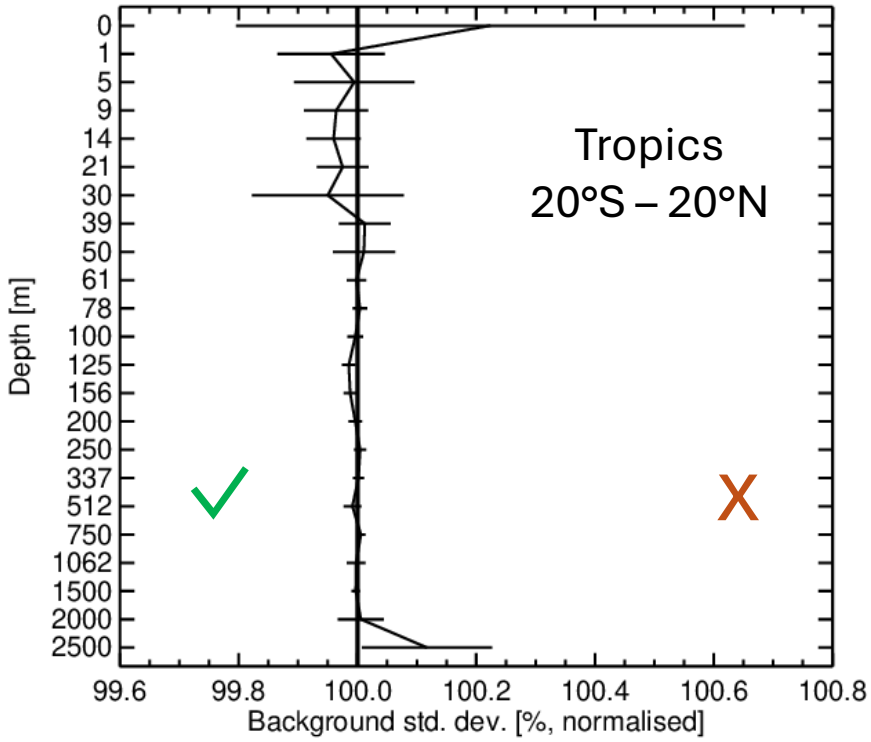
- Salinity increments are largest in the tropics, and propagate into the mixed layer (see Chrust et al., 2024)

5 Dec 2025 – 18 Jan 2026

Change of salinity increments due to SMAP



Background departure change of in situ salinity

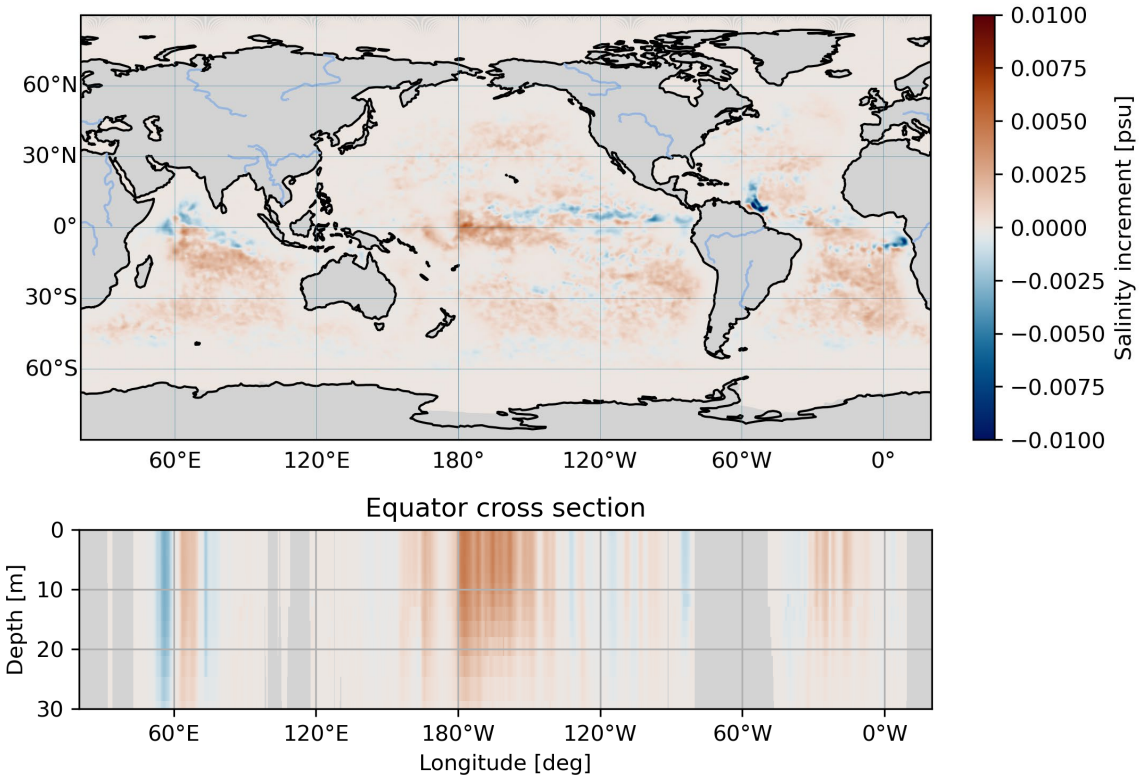


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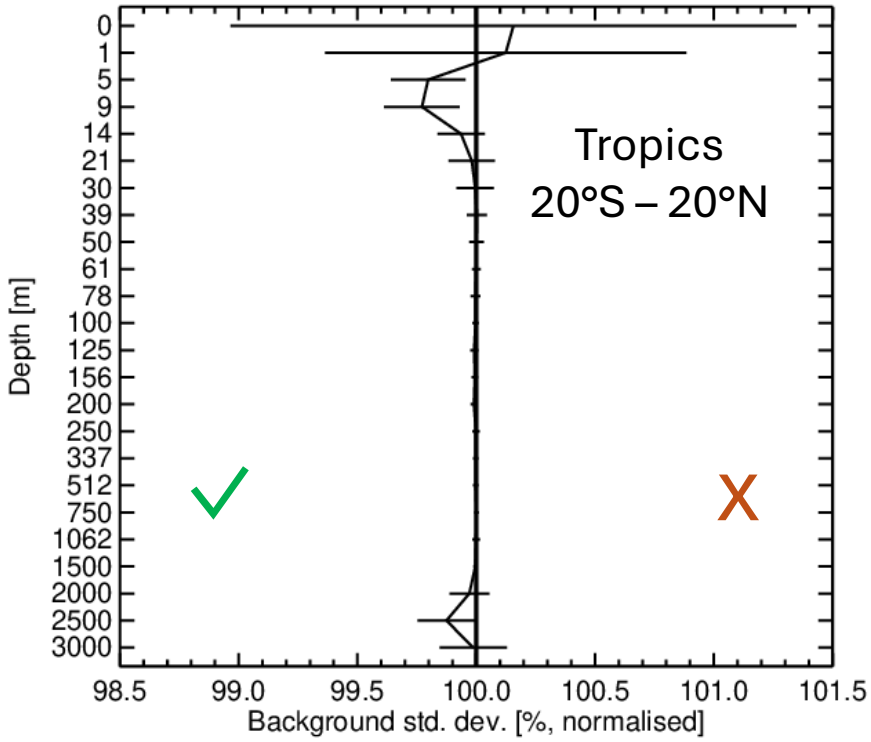
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19 May – 20 Jun 2026

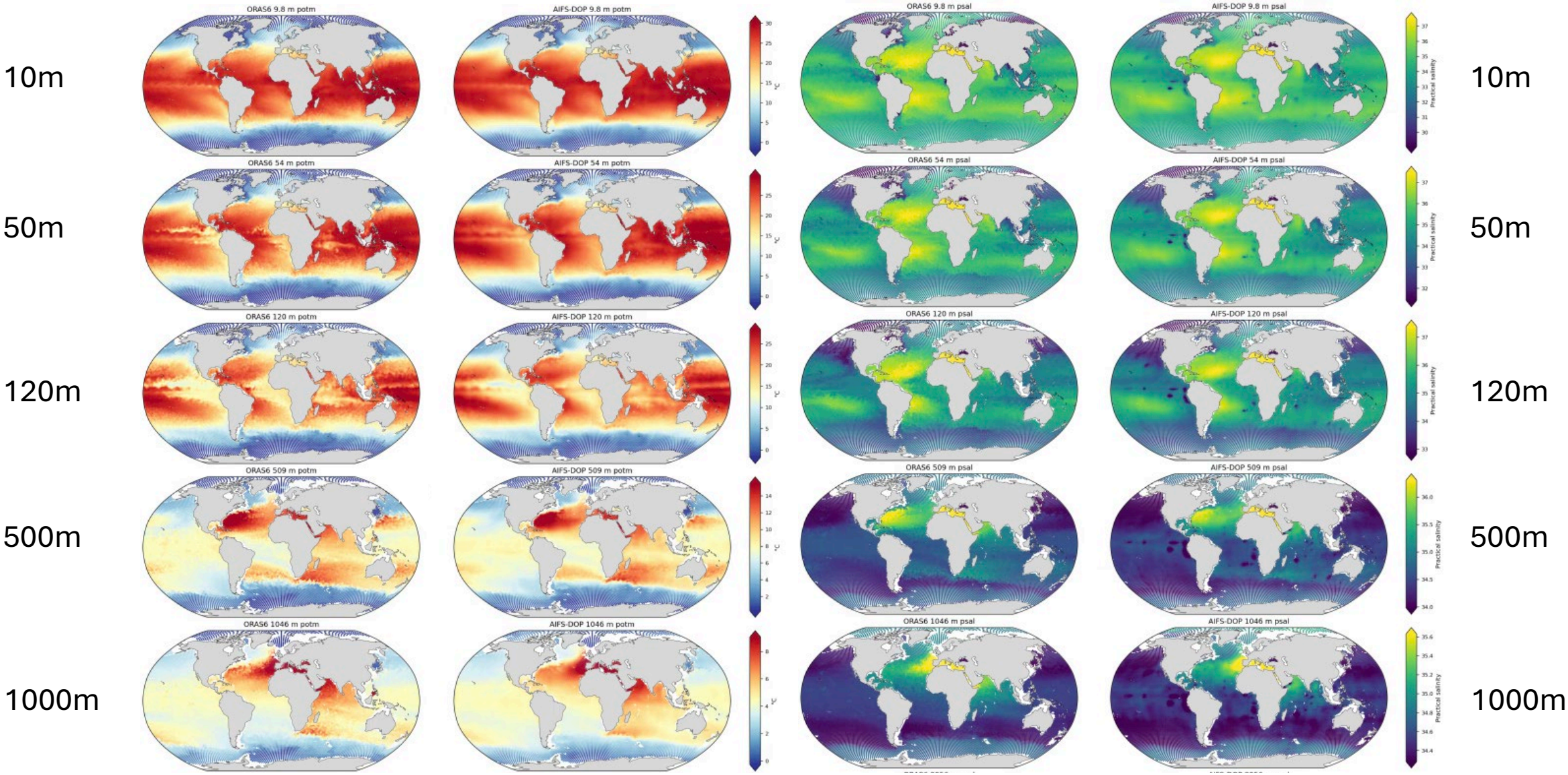
Change of salinity increments due to SMAP



Background departure change of in situ salinity



Observations are key for future ocean/coupled developments



Concluding remarks

- Ocean DA has made significant steps forward thanks to improvements to all parts of the system
- Biases are reduced so much that we can run coupled models everywhere
- Methodology developments continue with ERGO3 supported by C3S
  - Improved spread/error relationships - better **B** – 4DVar – spatially correlated **R**
- Coupled DA is now business as usual at ECMWF (more in Herbert & Massart after the break…)
- Non-coupled DA team actively develop coupled DA
- Work continues around further exploitation of observations
  - Adding observations to the coupled system that we currently only use in ocean only
  - Use of altimeters and microwave data to constrain sea ice thickness
  - Adding more existing instruments through coupled DA mechanisms
- Long term plans to have full observation operator coupling
  - Requires complex radiative transfer observation operators in non atmospheric components

Thank you



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