Njord: A Probabilistic Graph Neural Network for Ensemble Ocean Forecasting

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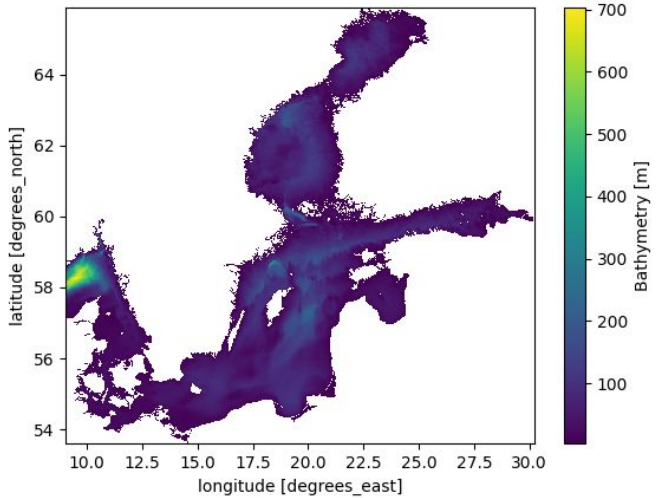
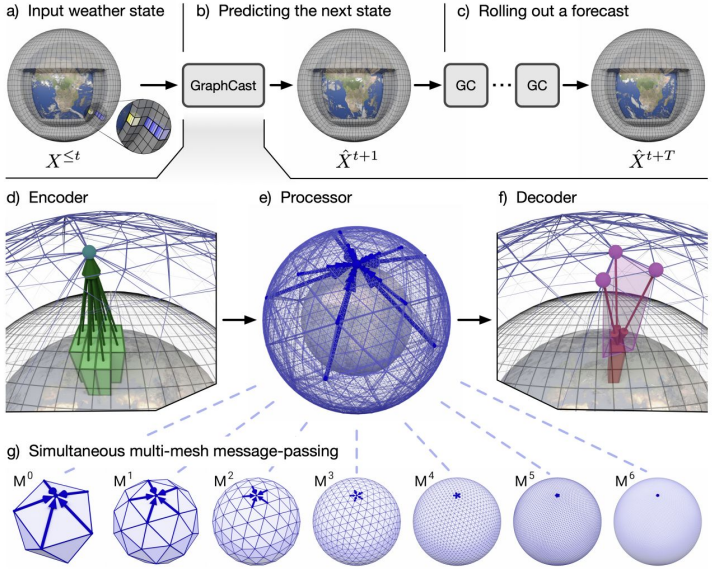
Numerical ocean models used

- Physical ocean processes such as currents, temperature, and salinity are simulated numerically using Nucleus for European Modelling of the Ocean (*NEMO*).
- Incorporates observations through variational ocean data assimilation (*OceanVar*).
- Global model (GLO12) at 1/12° resolution, we coarsen to 1/4°. Baltic Sea at 1/48° (~2km) grid.
- Baltic Sea has open boundary to the North Sea.
- Forced with surface atmospheric quantities.



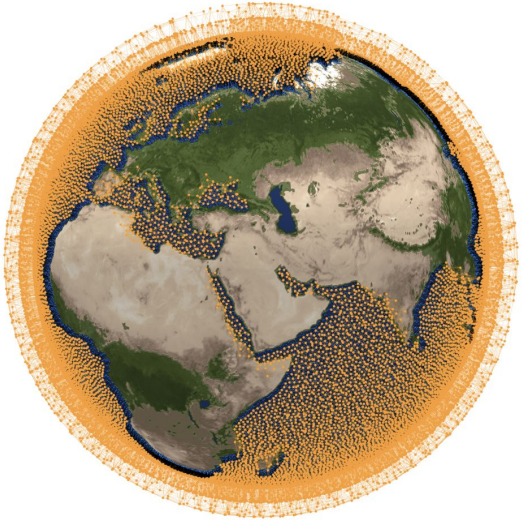
Proposed method

- Train a graph neural network (GNN) to *autoregressively* predict next simulation step.
- Produces a *cumulative error*, and smoothening as time goes on.
- However, for medium range forecasting the method works well: reasonable amount of rollout steps.
- *Large advantage in terms of prediction speed* vs numerical simulations.
- Modern generative models open the doors for fast ensemble forecasts and *uncertainty quantification*. We use a latent variable approach, inspired by the variational autoencoder trained with the ELBO + afCRPS loss.
    - Ensemble members should retain sharpness.

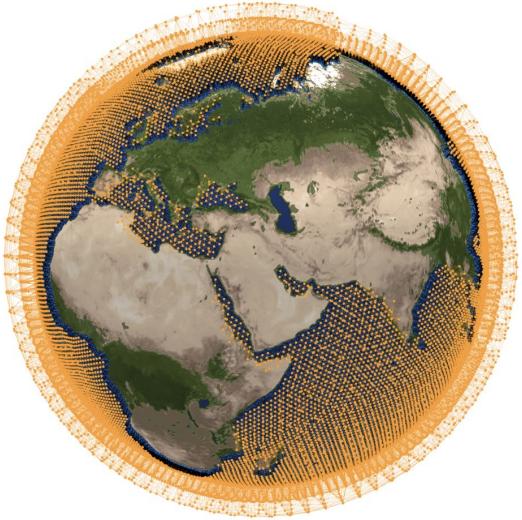


Remi Lam et al., Learning skillful medium-range global weather forecasting. Science (2023)

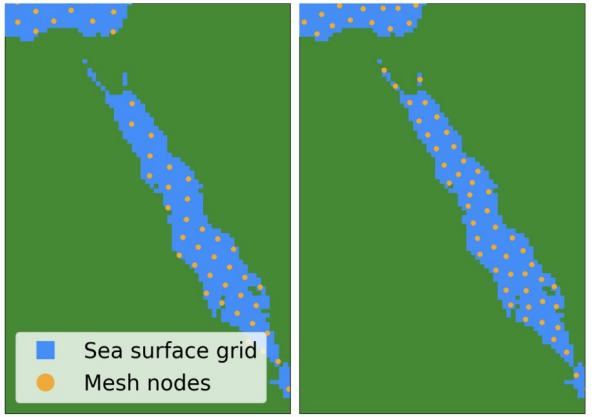
Global meshes



(a) Global cluster graph.



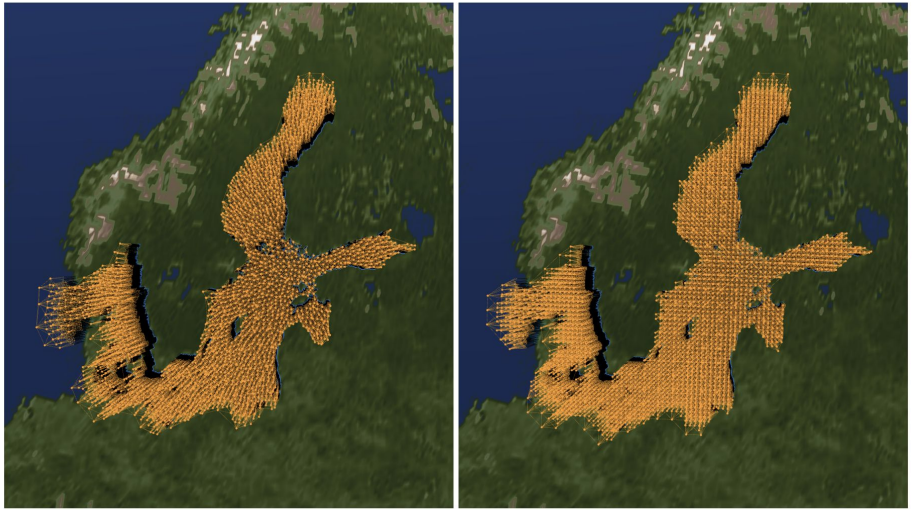
(b) Global icosahedral graph.



(a) Icosahedral (b) Cluster

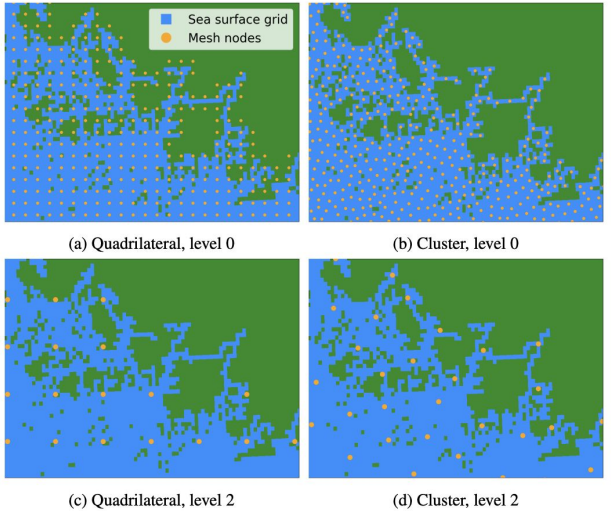
Figure 3: Example of graph node placement in the Red Sea.

Regional meshes



(a) Baltic Sea cluster graph.

(b) Baltic Sea quadrilateral graph.



(a) Quadrilateral, level 0

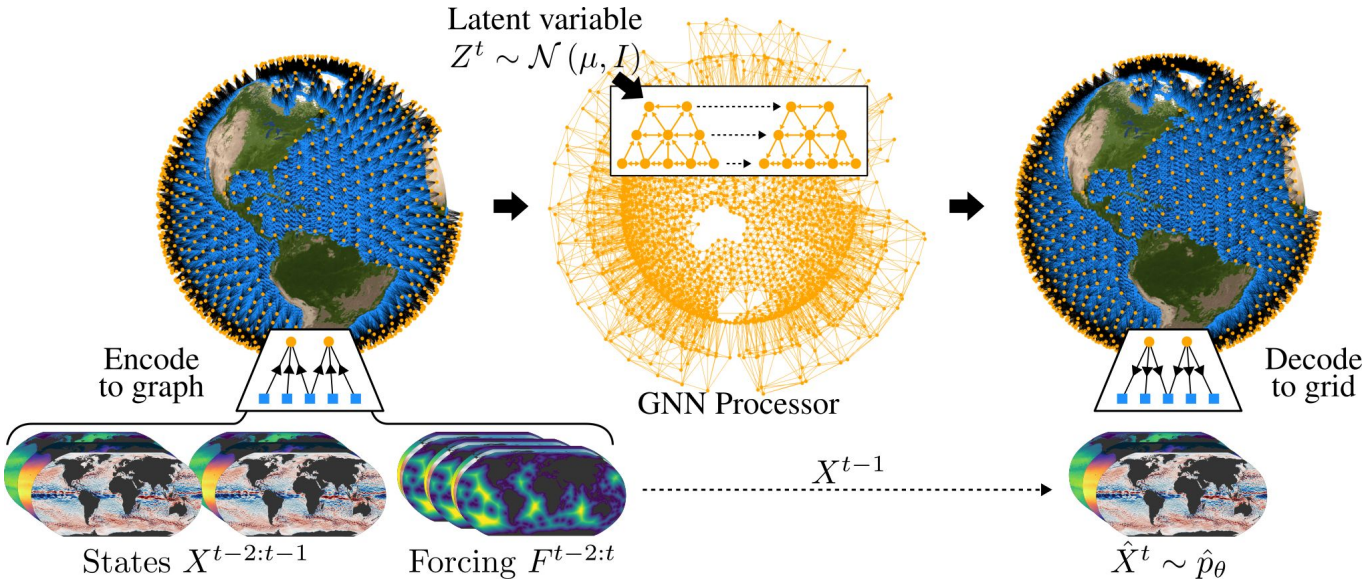
(b) Cluster, level 0

(c) Quadrilateral, level 2

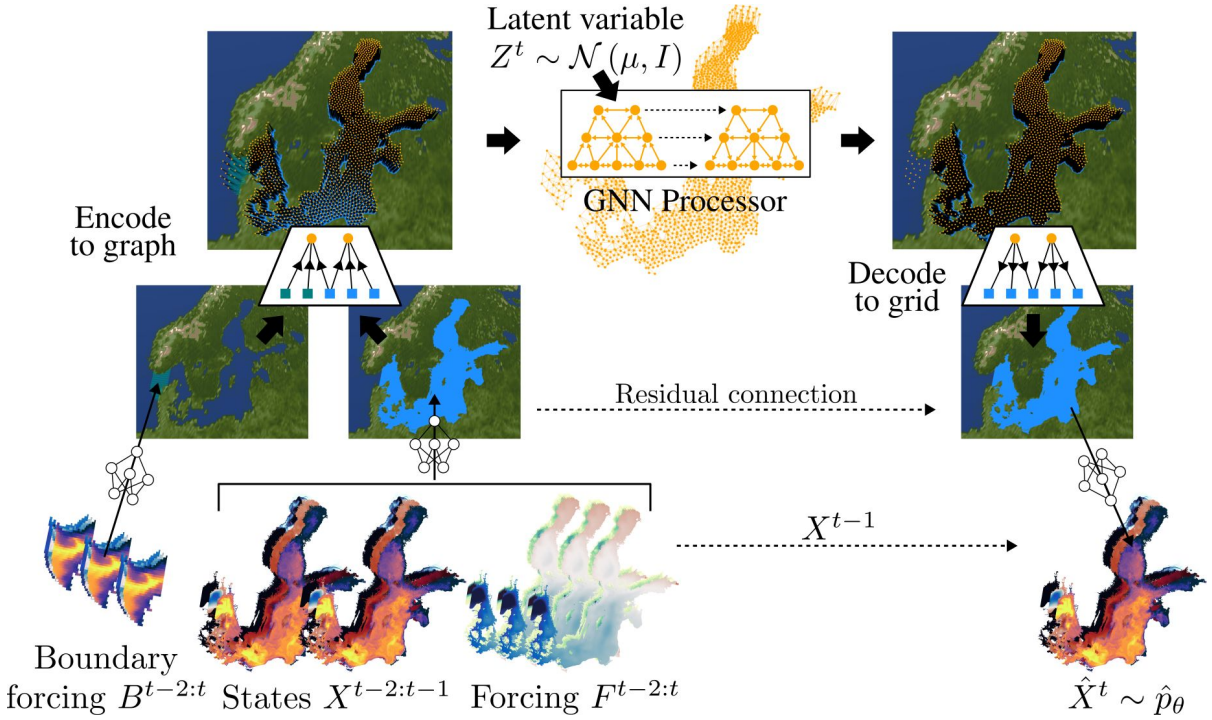
(d) Cluster, level 2

Figure 18: Example of mesh node placement in the Turku Archipelago in south-western Finland.

Global model

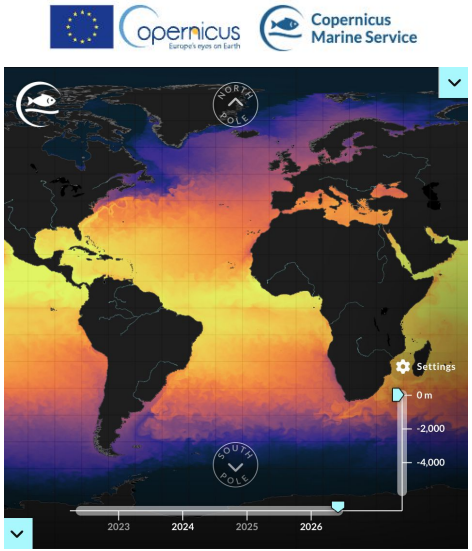


Regional model



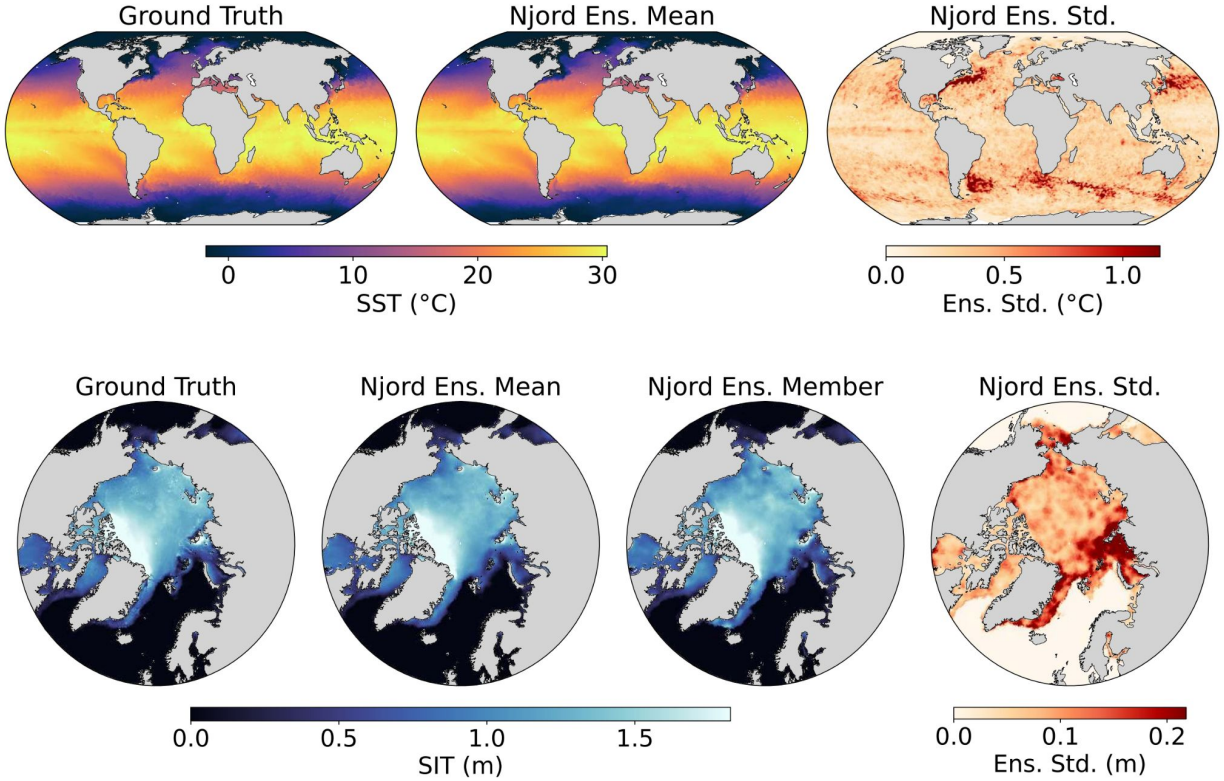
Ocean datasets

- Here we model temperature (T), salinity (S), meridional (U) and zonal (U) currents, sea surface height (SSH), sea ice concentration (SIC), sea ice thickness (SIT).
- 6 depth levels chosen as in Mercator's OceanBench.
- Atmospheric forcing: 2m temperature, 2m dewpoint, 10m wind components, shortwave / longwave radiation flux, mean sea level pressure, precipitation from ERA5 reanalysis.
- Training on reanalysis 1993–2021, with 1° pretraining and 0.25° finetuning for global model (swap G2M and M2G edge sets).
- Evaluation: weekly init. during 2024 following OceanBench.
- We put physical constraints on sea ice through activation functions and a 'density channel' derived from SIC.

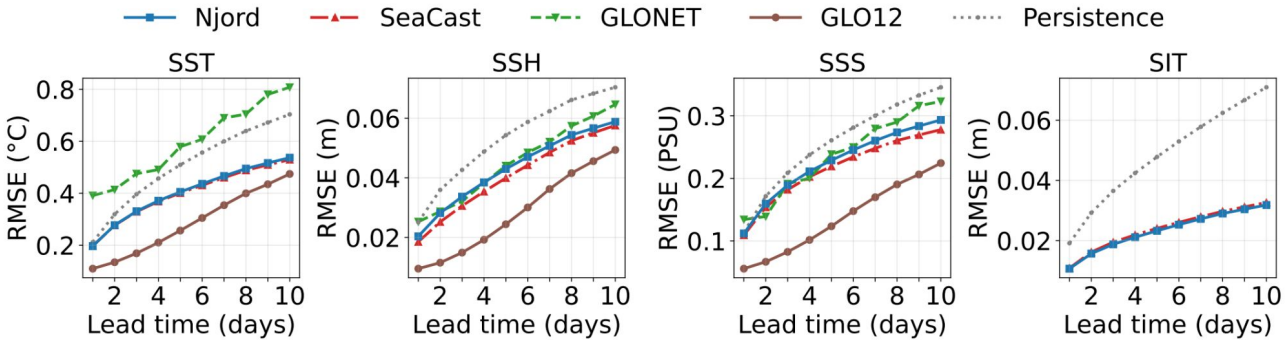


https://marine.copernicus.eu/

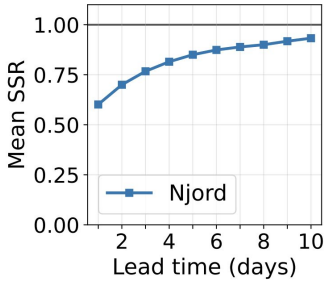
Qualitative global results



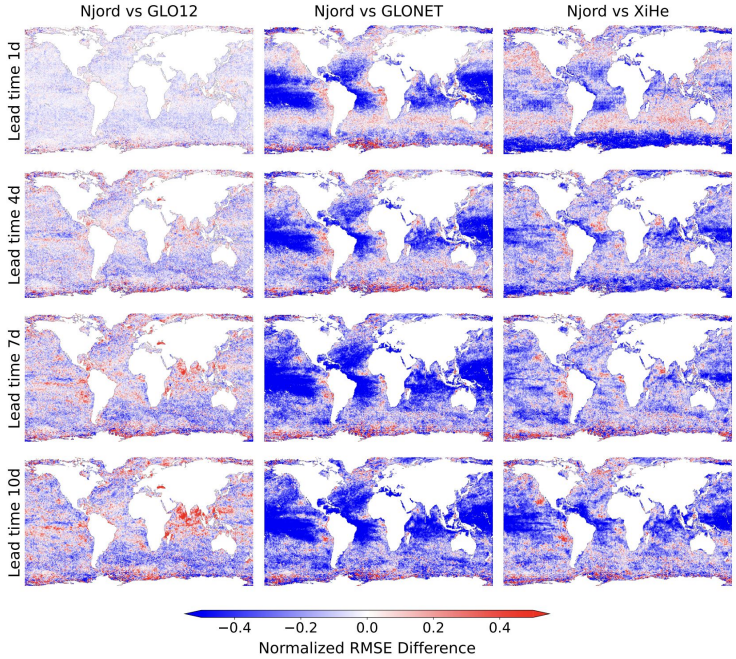
A few global metrics

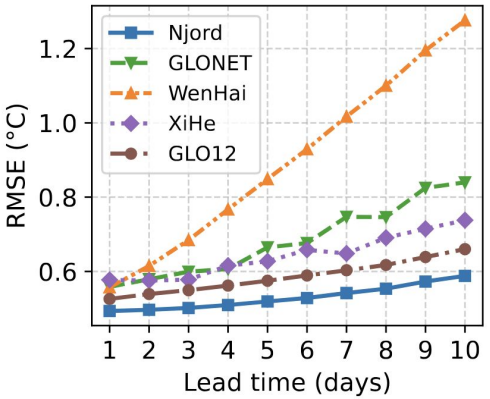


Spread-skill-ratio averaged over all variables

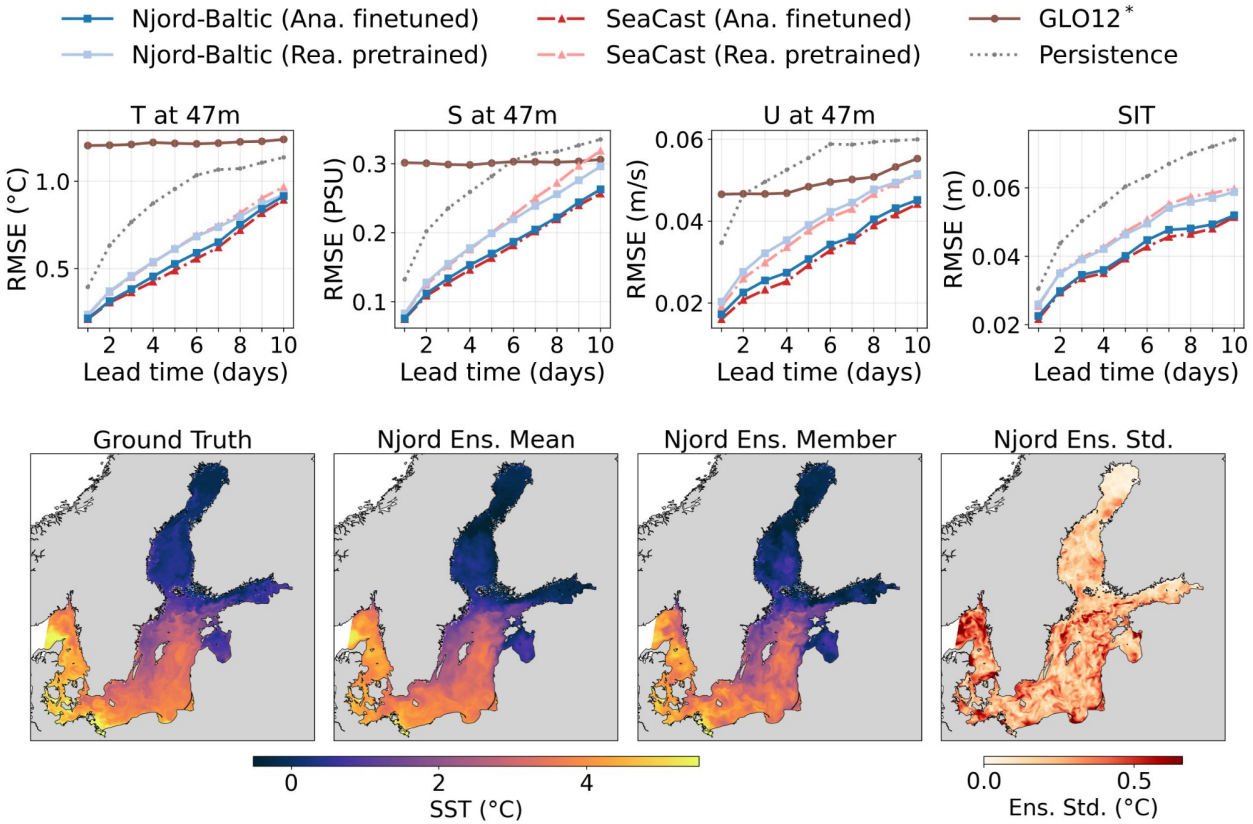


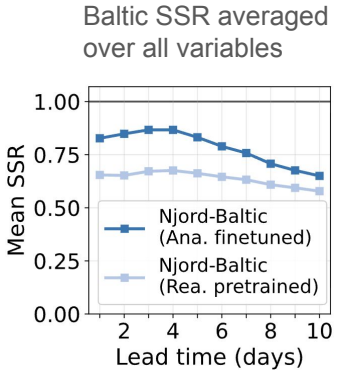
Global SST evaluation wrt L3 satellite observations





Baltic Sea results





Ideas for future work

- Probabilistic seasonal/climate scale prediction
- Include waves, biogeochemistry
- Couple with atmosphere
- Physical constraints, conservation laws
- Perhaps foundation model could be helpful (Aurora)
- Forecast from observations (Aardvark)
    - ocean more sparsely observed compared to atmosphere
- Latent space dynamics…

Thank you

Njord

https://arxiv.org/abs/2605.15470

SeaCast (Mediterranean Sea with atmospheric sensitivity analysis)

https://www.nature.com/articles/s41598-025-31177-w