



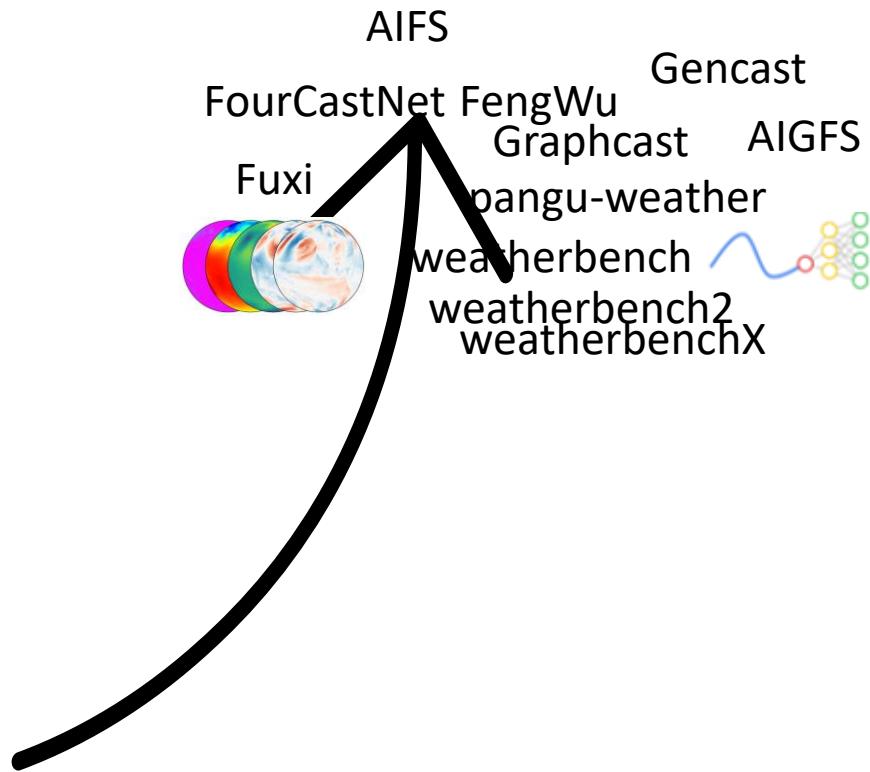
**MERCATOR
OCEAN**
INTERNATIONAL

Toward Scalable and Probabilistic Neural Ocean Forecasting

Anass El Aouni, Quentin Gaudel, Simon Van Gennip,
Yann Drillet, Marie Drevillon

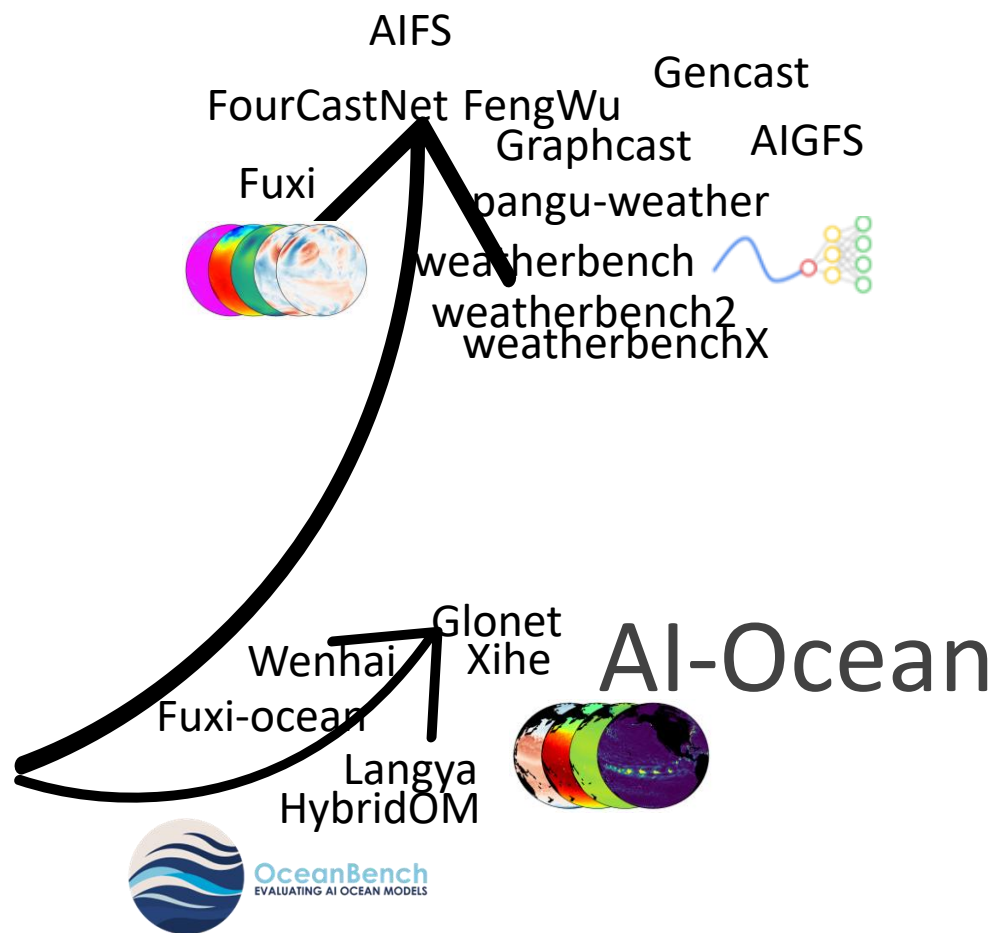
AI-Task Team workshop , Montreal, Canada, 12-13 Apr. 2026

AI-Atmosphere



- **Significant advances in ML models for weather forecasting**
- **From single deterministic forecast to forecasting mean states showing better statistics than state of the art numerical models**
- **ML probabilistic forecasting with realistic individual trajectories**
- **Inference faster than numerical models (~1min vs ~1hr)**

AI-Atmosphere



- Ocean is a complex environment
 - Ocean is not as well observed
 - ML ocean system now produce skillful forecast (possible to learn from reanalysis)
 - Inference faster than numerical models (~1min vs ~1hr)
- => ML system to run operationally and explore probabilistic approaches

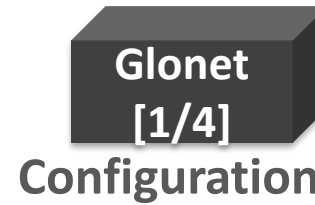
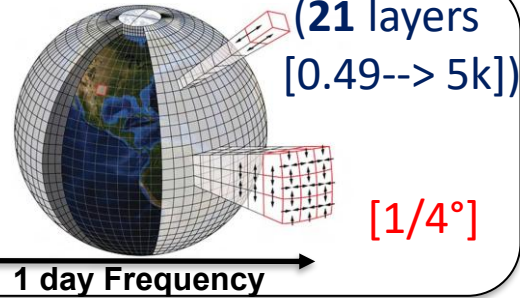
Mercator NN-Forecasting system

GLORYS12 reanalysis

- Training [1993, 2020]
- Validation [2021]
- Testing [GLO12]

Vars:

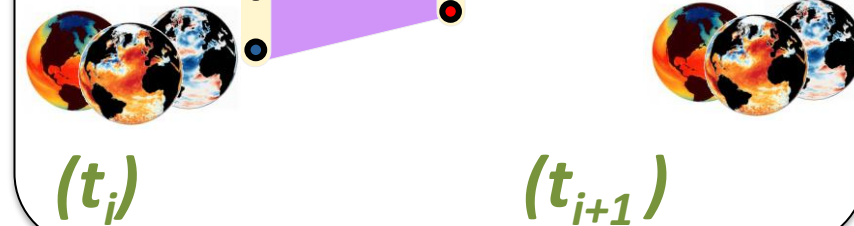
zos
[thetao,
uo,vo,
so]



Glorys12

[uo,vo,so,
zos, thetao]

overview



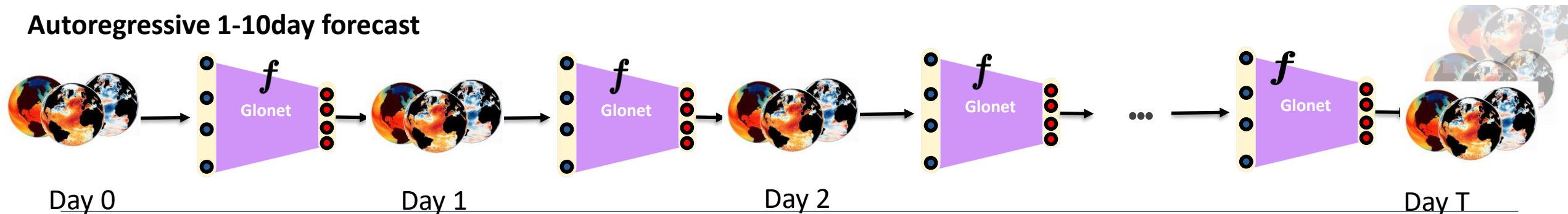
Glonet
architecture

- **Fourier neural operators** to model basin-wide patterns
- **CNN** for predicting mesoscale features
- **Encoder-decoder** design

Ressources

- ECP: 8 nodes, 32xA100 GPUs
- Several days of training

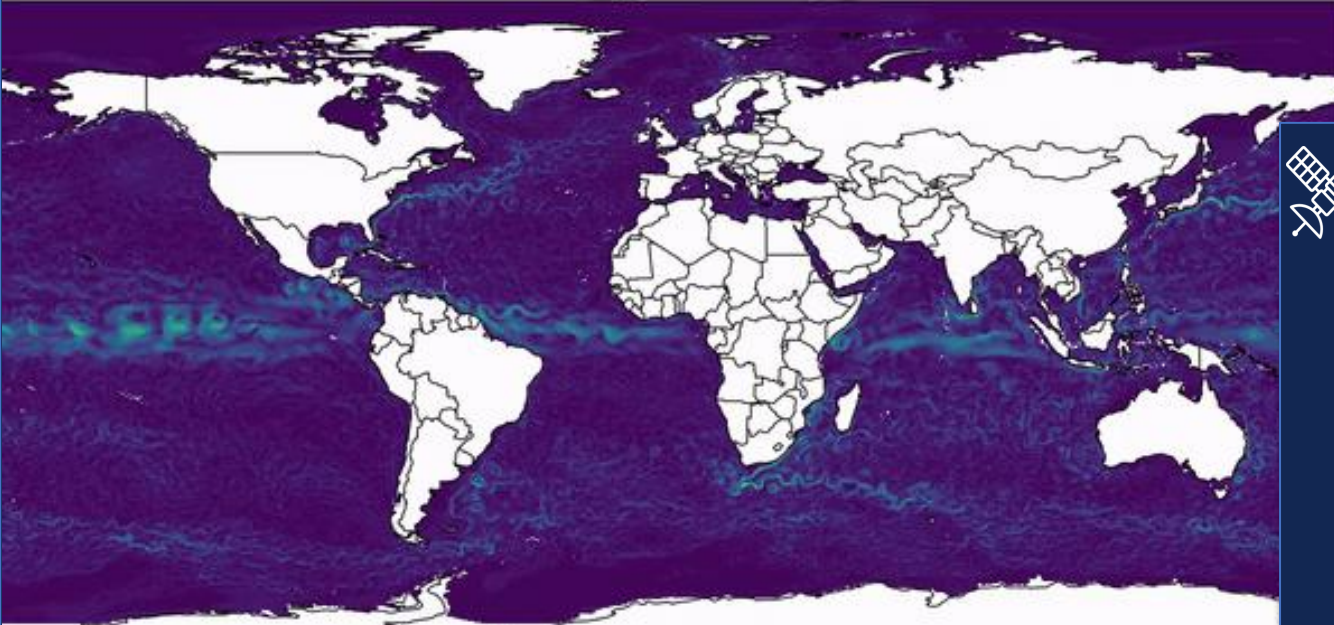
Autoregressive 1-10day forecast



GLONET

- CPU 16 cores ~ 7min
- 12G VRAM ~ 30 sec (JIT) [Nvidia]
- A100 node ~ 3 sec

currents_glonet - Day 1



365 days in 3min



<https://doi.org/10.1029/2025JH000686>

EDITO European Digital Twin Ocean

GLONET 1/4 degree resolution 2024-12-03 forecast
Catalog gathering all assets of GLONET 1/4 degree resolution 2024-12-03 forecast, from 2024-12-04 to 2024-12-13

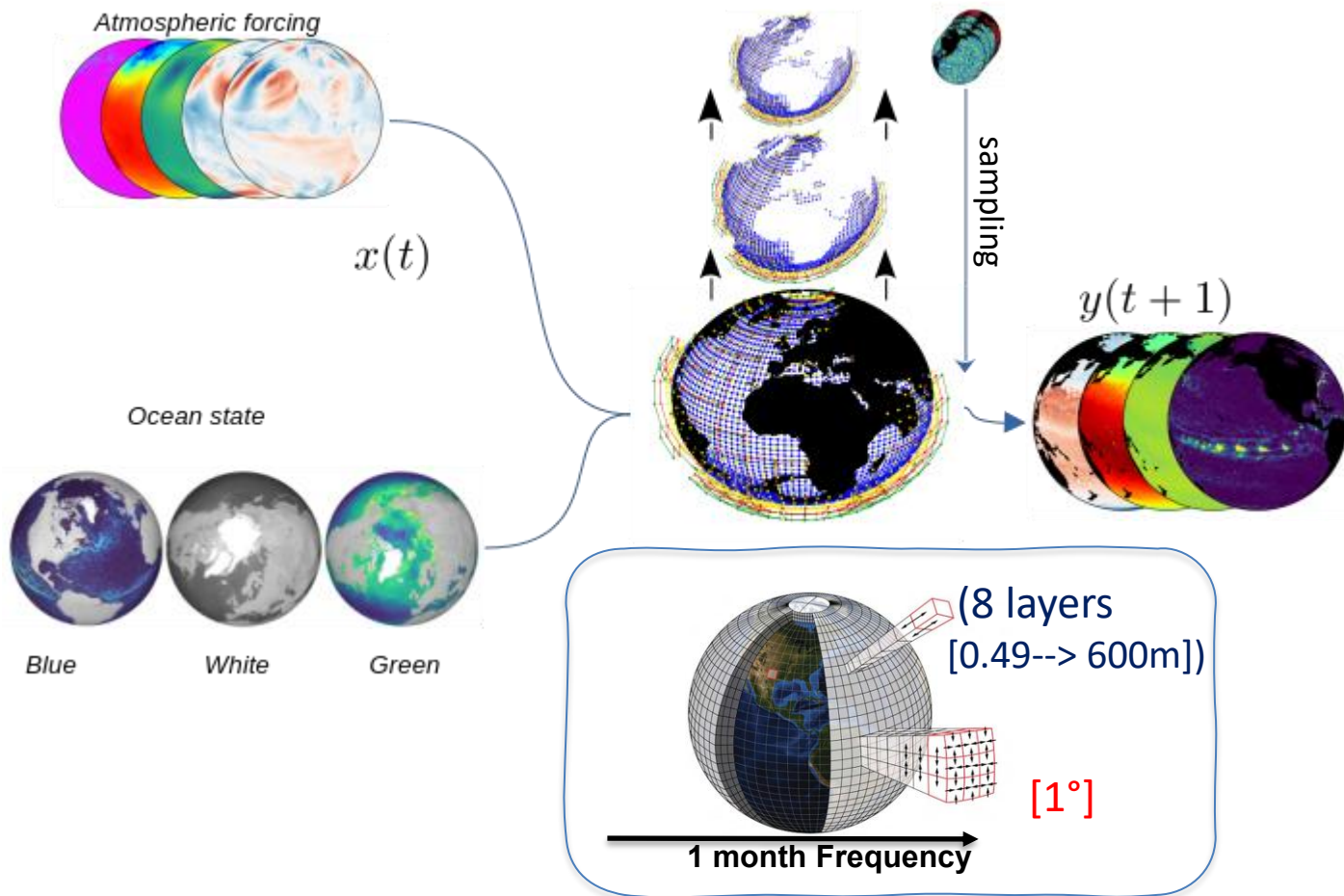
```

root
├── glonet_1_4_daily_forecast
│   └── glonet_1_4_2024-12-03_forecast
│       ├── Sea water potential temperature daily forecast of GLONET 1/4 degree resolution, from 2024-12-04 00:00 to 2024-12-13 00:00
│       ├── Eastward sea water velocity daily forecast of GLONET 1/4 degree resolution, from 2024-12-04 00:00 to 2024-12-13 00:00
│       ├── Sea water salinity daily forecast of GLONET 1/4 degree resolution, from 2024-12-04 00:00 to 2024-12-13 00:00
│       └── Sea surface height above geoid daily forecast of GLONET 1/4 degree resolution, from 2024-12-04 00:00 to 2024-12-13 00:00
    
```

Oceanbench

Temperature [0-5m]				Salinity [0-5m]							
GLONET	0.588	0.622	0.647	0.679	0.723	GLONET	0.242	0.251	0.255	0.277	0.290
WENHAI	0.549	0.719	0.833	0.898	0.928	WENHAI	0.225	0.266	0.273	0.286	0.289
XHE	0.575	0.654	0.660	0.674	0.782	XHE	0.225	0.266	0.244	0.254	0.270
Temperature [5-100m]				Salinity [5-100m]							
GLONET	0.928	0.964	0.967	1.031	1.072	GLONET	0.211	0.218	0.218	0.230	0.239
WENHAI	0.875	0.927	1.033	1.095	1.175	WENHAI	0.195	0.268	0.242	0.253	0.260
XHE	0.886	0.932	0.970	0.973	1.026	XHE	0.194	0.213	0.213	0.207	0.228
Temperature [100-300m]				Salinity [100-300m]							
GLONET	0.859	0.892	0.928	0.965	0.996	GLONET	0.148	0.152	0.157	0.161	0.165
WENHAI	0.845	0.867	0.889	0.928	0.961	WENHAI	0.141	0.141	0.153	0.155	0.155
XHE	0.815	0.848	0.879	0.893	0.953	WENHAI	0.136	0.136	0.136	0.136	0.136
XHE	0.798	0.794	0.823	0.823	0.876	XHE	0.130	0.130	0.136	0.132	0.136
Temperature [300-600m]				Salinity [300-600m]							
GLONET	0.604	0.632	0.643	0.694	0.724	GLONET	0.098	0.102	0.105	0.109	0.113
WENHAI	0.584	0.567	0.588	0.632	0.678	WENHAI	0.090	0.094	0.097	0.105	0.109
XHE	0.591	0.644	0.654	0.676	0.703	WENHAI	0.101	0.101	0.101	0.101	0.101
XHE	0.547	0.537	0.540	0.540	0.576	XHE	0.085	0.084	0.084	0.088	0.090
SST				SLA							
GLONET	0.641	0.616	0.616	0.747	0.810	GLONET	0.063	0.066	0.071	0.075	0.080
WENHAI	0.629	0.884	1.123	1.187	1.216	WENHAI	0.056	0.055	0.057	0.061	0.066
XHE	0.775	0.839	0.950	0.868	0.936	WENHAI	0.059	0.059	0.060	0.064	0.066
XHE	0.787	0.854	0.923	0.923	0.976	XHE	0.059	0.059	0.060	0.064	0.066
sw [15m]				sw [15m]							
GLONET	0.167	0.167	0.179	0.184	0.189	GLONET	0.157	0.157	0.170	0.176	0.181
WENHAI	0.163	0.165	0.166	0.171	0.175	WENHAI	0.145	0.148	0.152	0.155	0.159
XHE	0.159	0.158	0.158	0.162	0.162	XHE	0.145	0.145	0.145	0.145	0.145

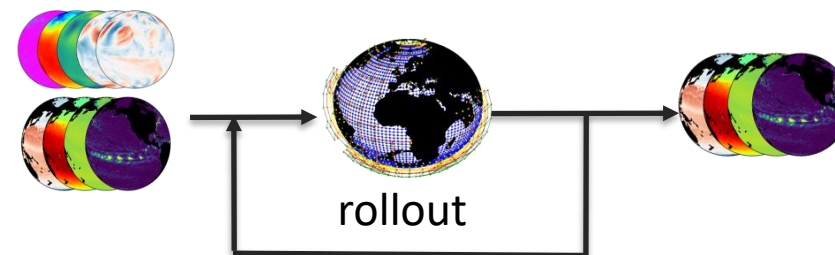
<https://openreview.net/forum?id=wZGe1Kqs8G>



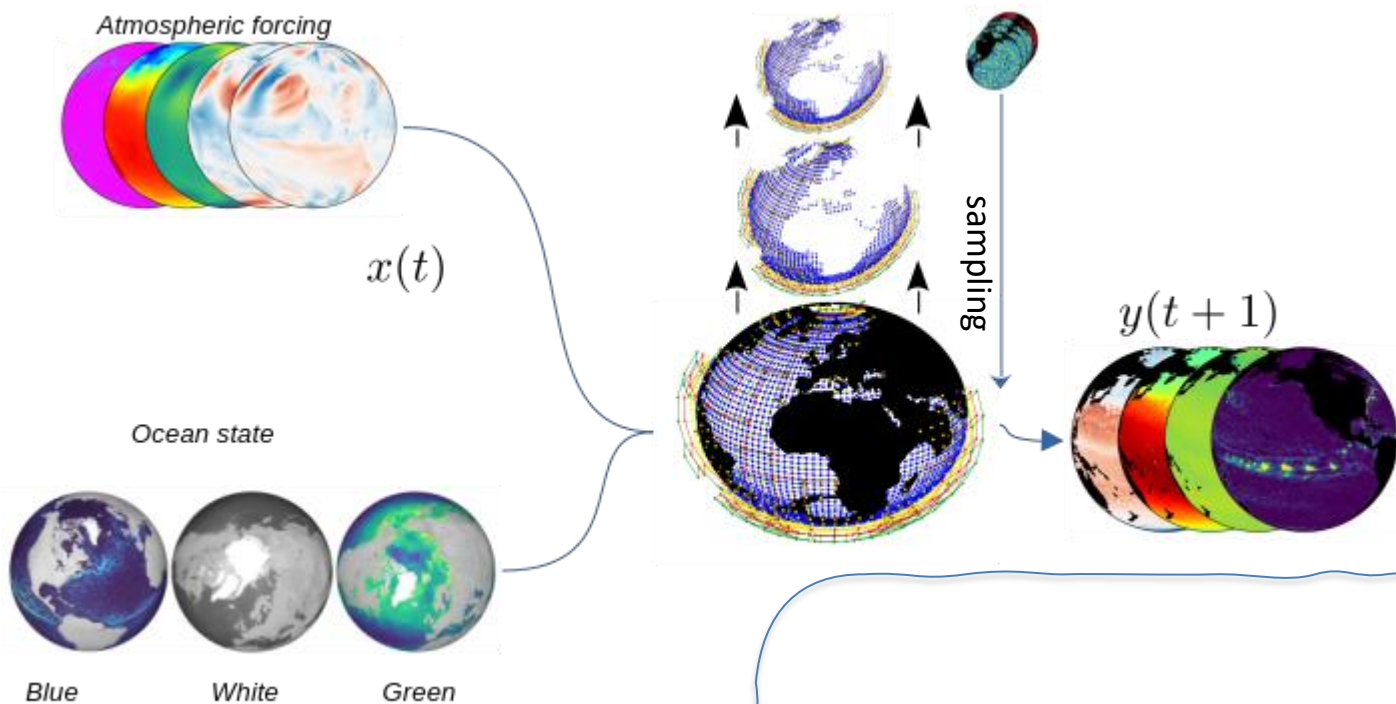
Training Dataset (1993-2020, 1°res.)

- GLORYS 12 reanalysis
 - Currents, temperature, Salinity, SSH,
 - ice velocity, thickness, fraction
- Biomer BGC hindcast
 - Chlo, Nitrate, Phosphate, primary production, dissolved o2, silicate
- ERA5 reanalysis
 - u10,v10, t2m, mslp, sp

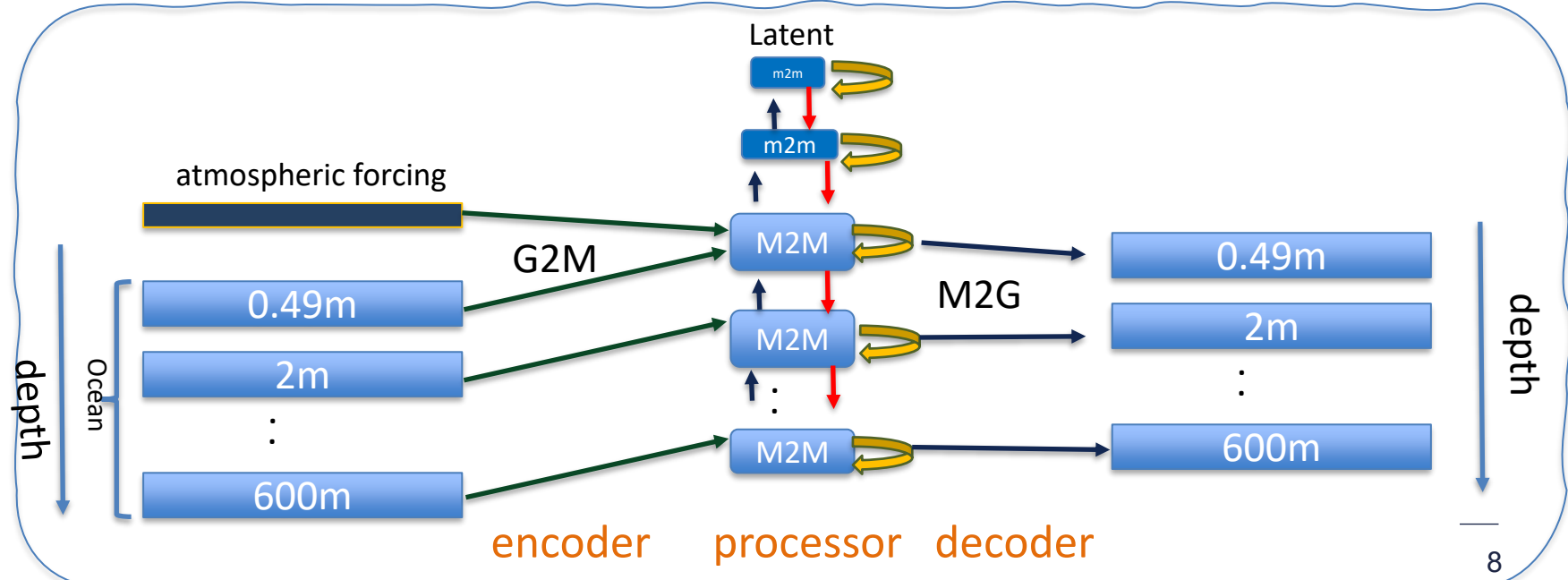
Seasonal to decadal timescales



Model design

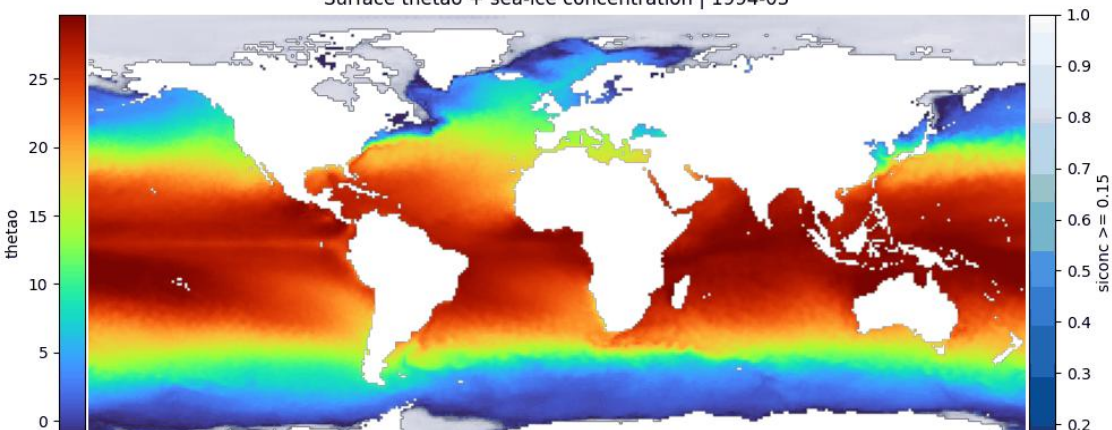


- Encoder-decoder design
 - Graph Neural network
 - Explicit representation of depth in nodes (3D information)
 - Generative ML method: latent diffusion
- Sampling in the latent space from same initial conditions to generate multiple realistic ocean state forecasts



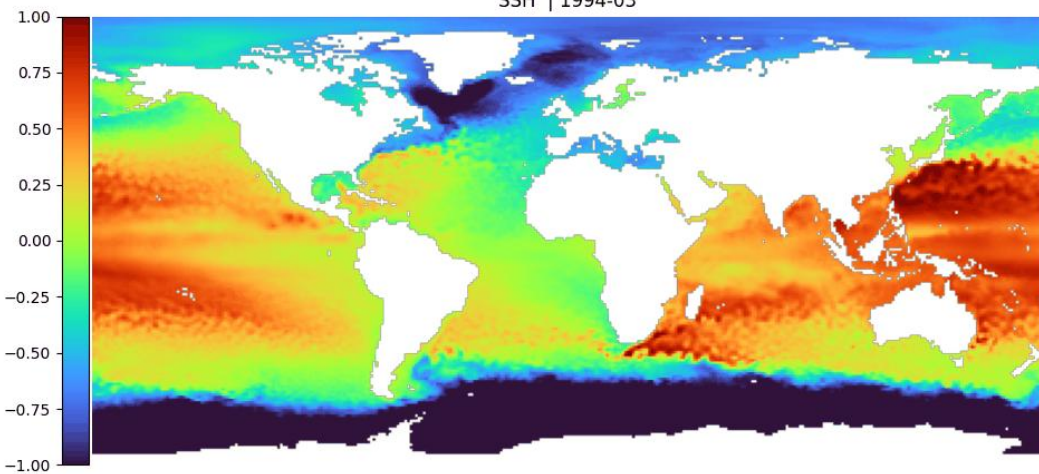
SST + [Sea Ice] (1994-2018)

Surface thetao + sea-ice concentration | 1994-03

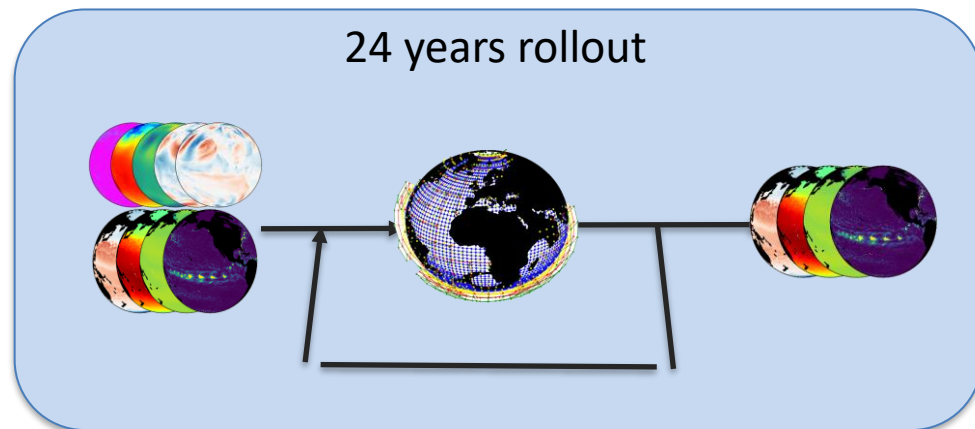


SSH

SSH | 1994-03

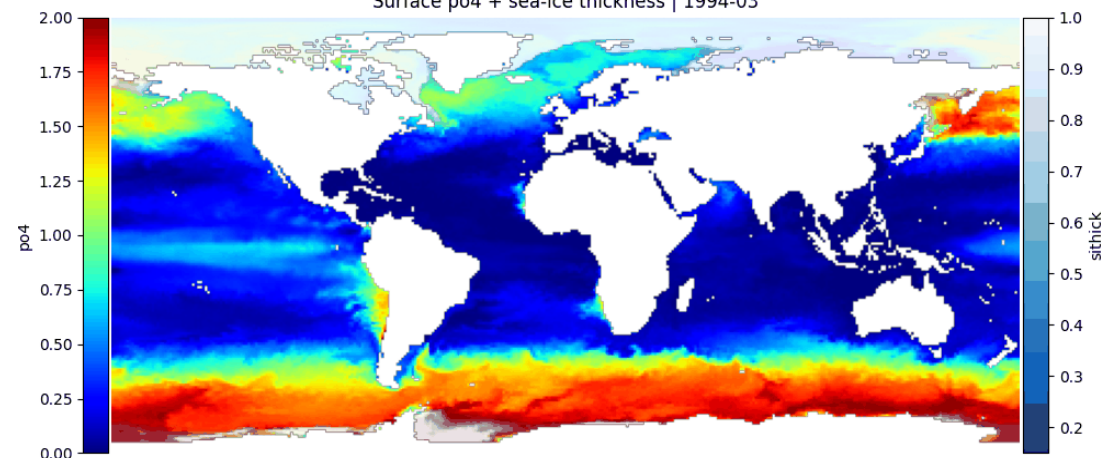


24 years rollout

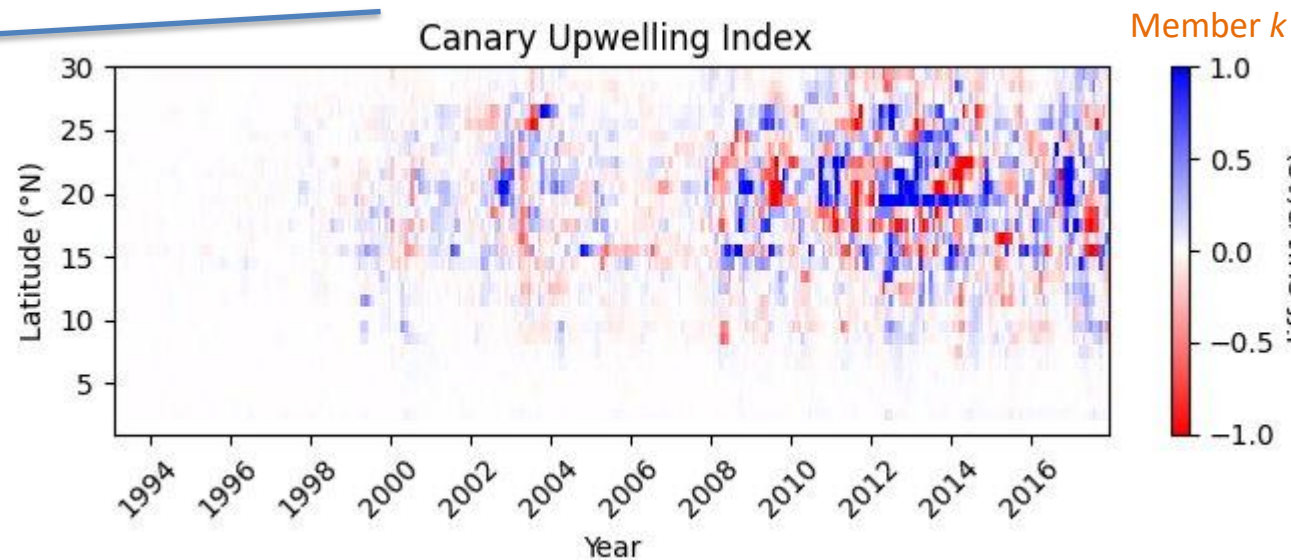
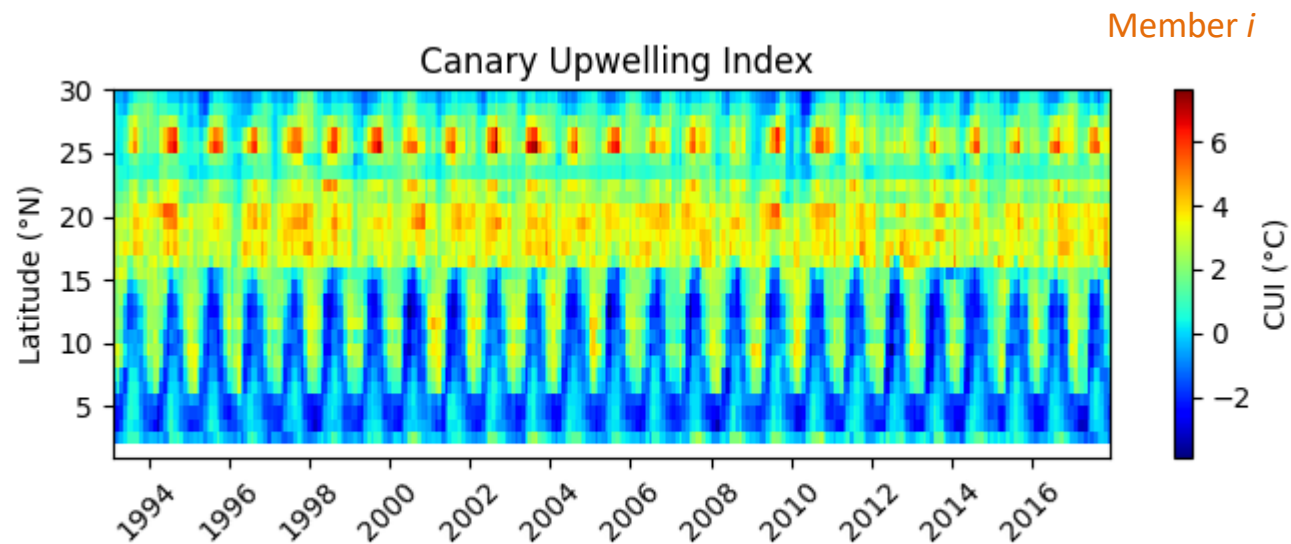
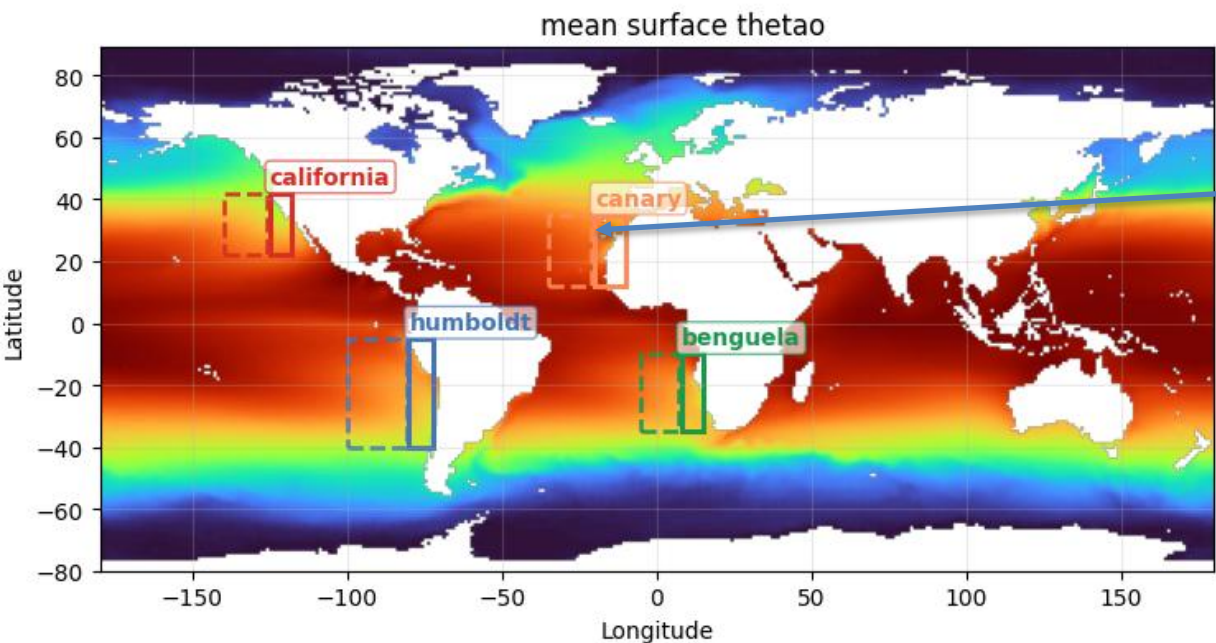


PO4

Surface po4 + sea-ice thickness | 1994-03



Evaluation over historical part [1994 2018]
 Eastern boundary currents ecosystem dynamics



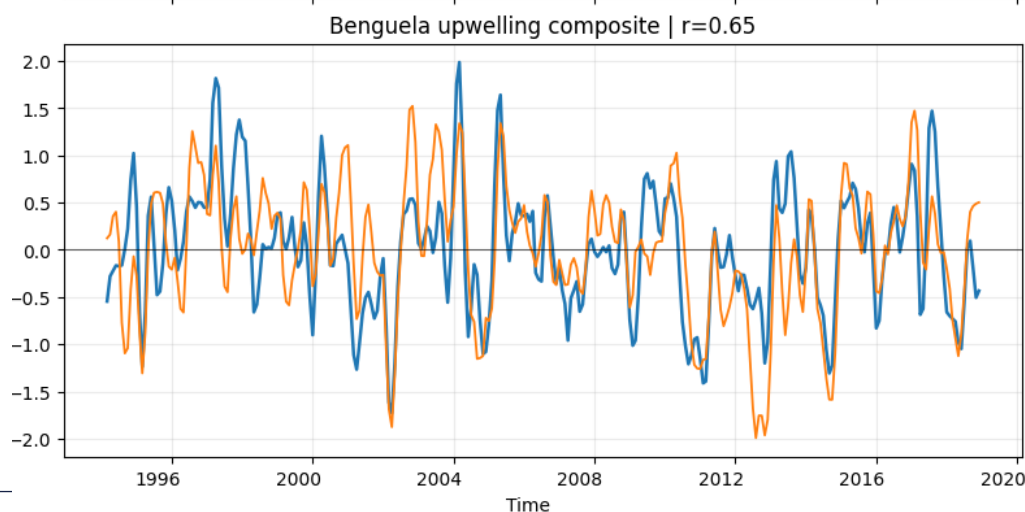
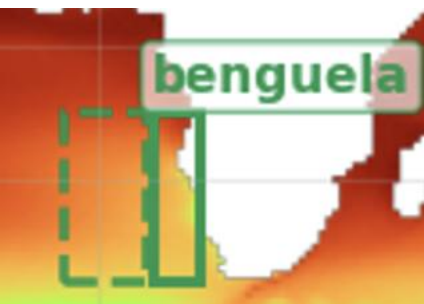
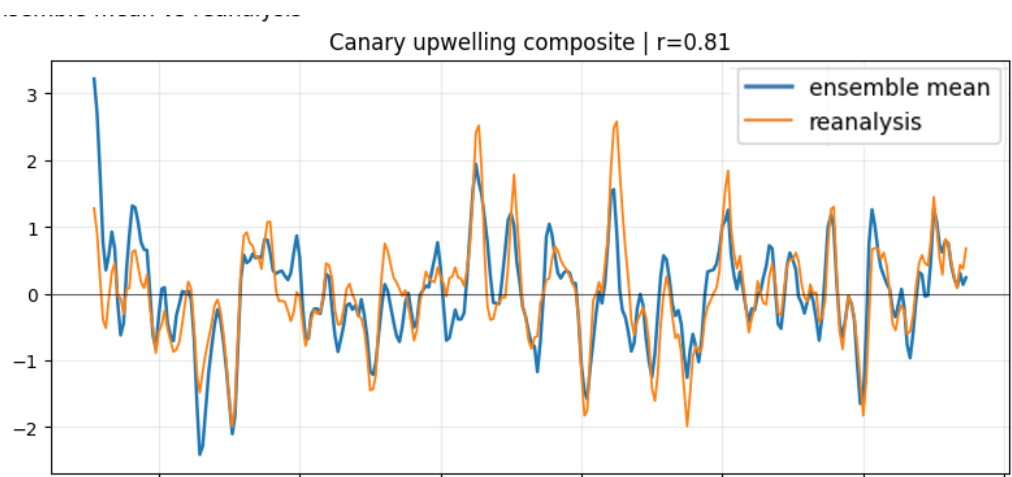
$$\text{CUI} = \text{SST}_{\text{max}}(\text{offshore}) - \text{SST}_{\text{min}}(\text{upwelling})$$

Upwelling composite metric

$sst_cooling = offshore_sst - coastal_sst$

$chl_enrichment = coastal_chl - offshore_chl$

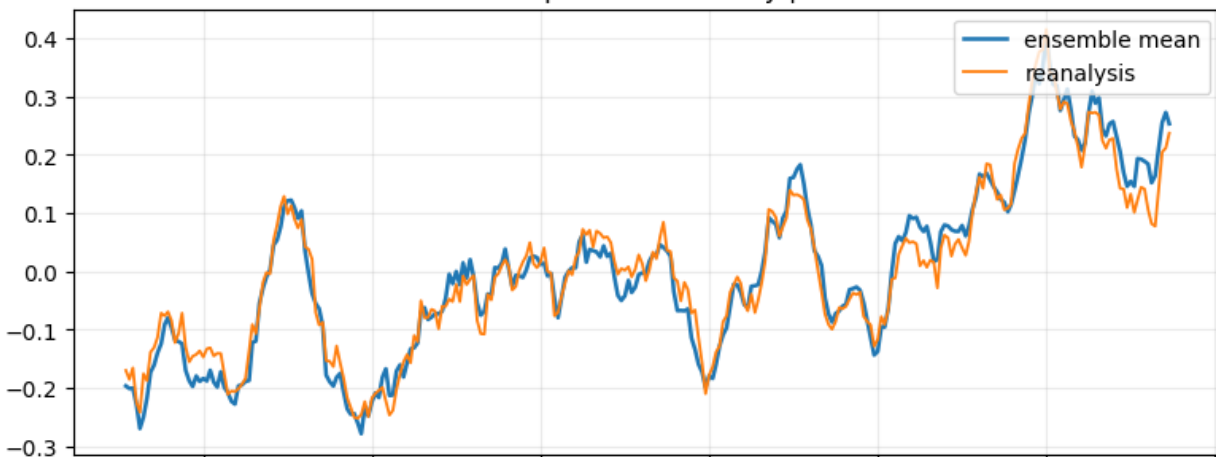
$UC = \frac{1}{2}(\text{std}(\text{ano}(sst_cooling)) + \text{std}(\text{ano}(chl_enrichment)))$



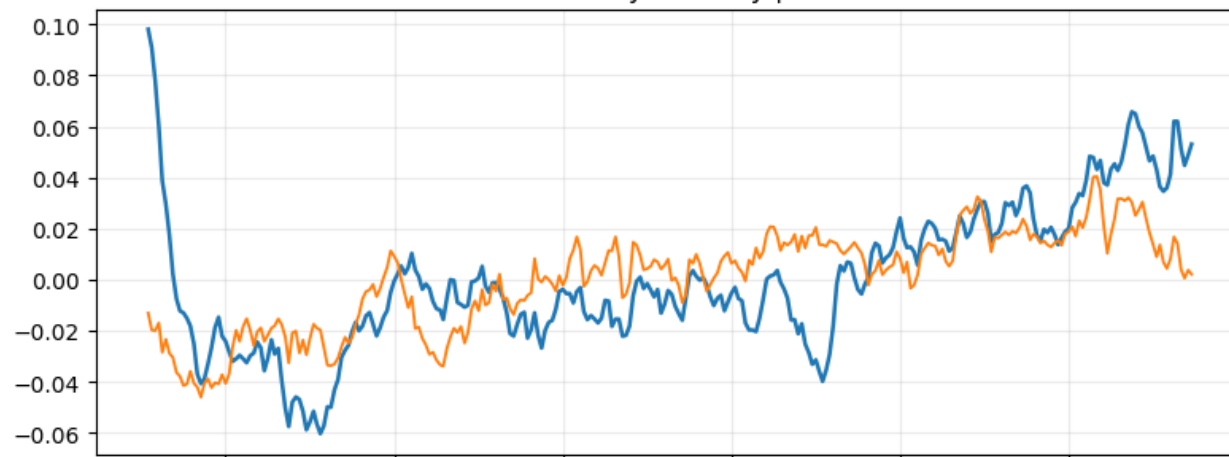
- ML model able to capture interannual variability of bio-physical metric
- Chlorophyll patterns driven by physics

Surface-variable time series: ensemble mean vs reanalysis

Global temperature anomaly | $r=0.98$



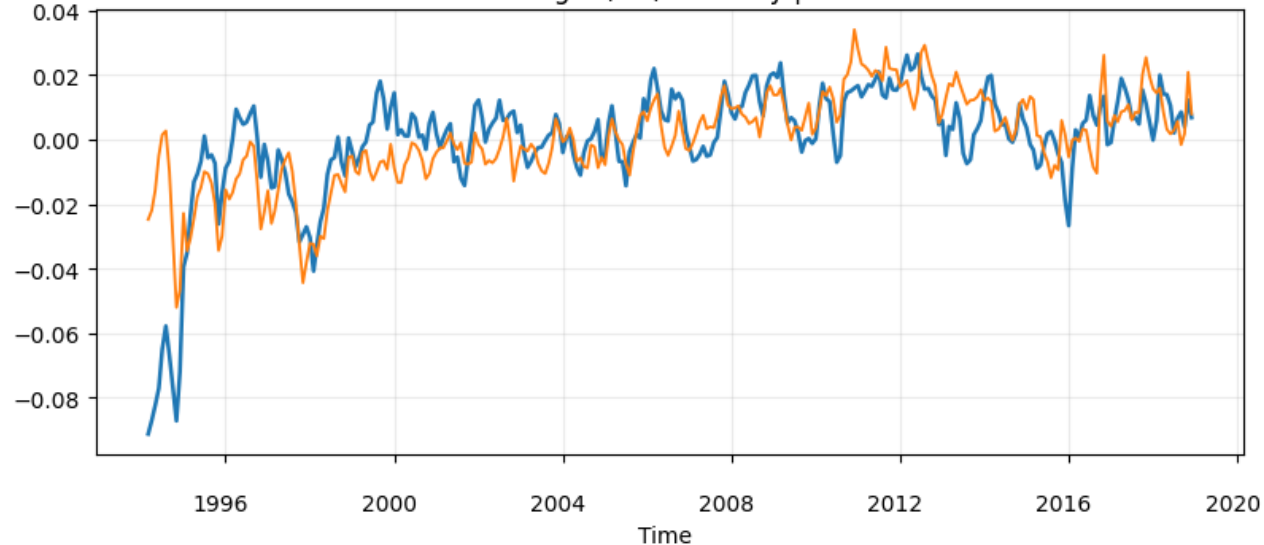
Global salinity anomaly | $r=0.57$



Global sea-surface height anomaly | $r=0.87$

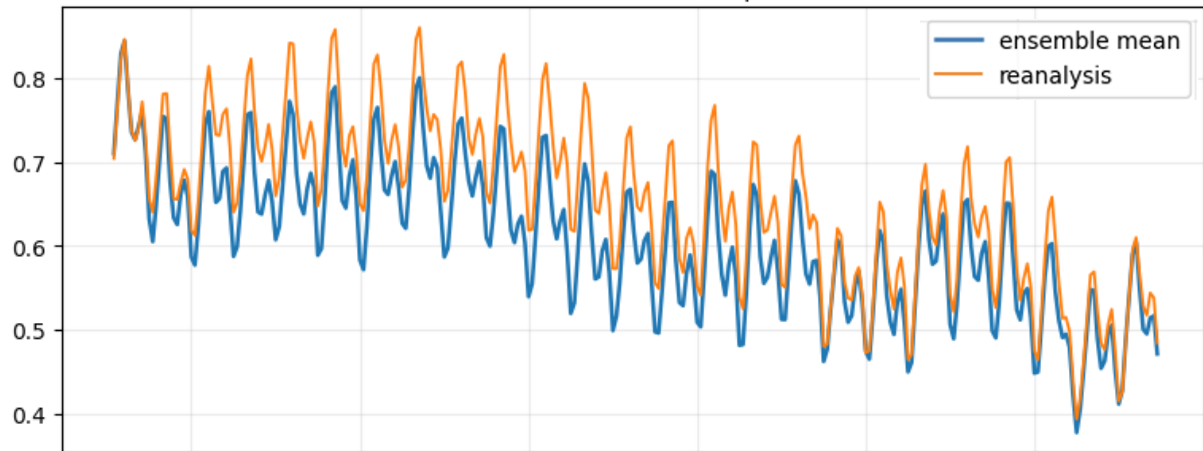


Global log10(chl) anomaly | $r=0.66$

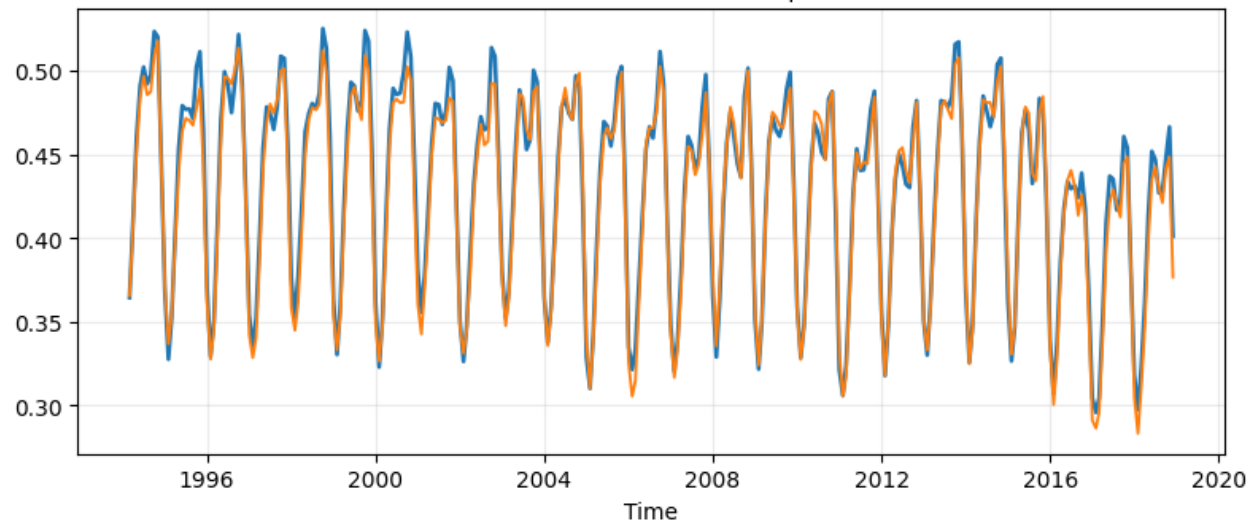


Surface-variable time series: ensemble mean vs reanalysis

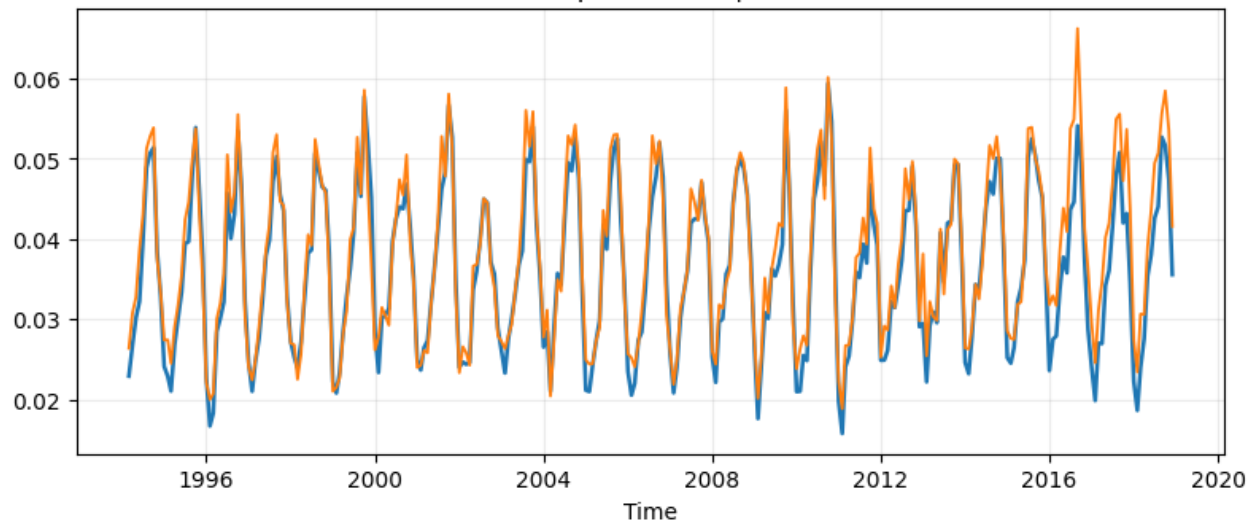
Sea-ice thickness mean | $r=0.97$



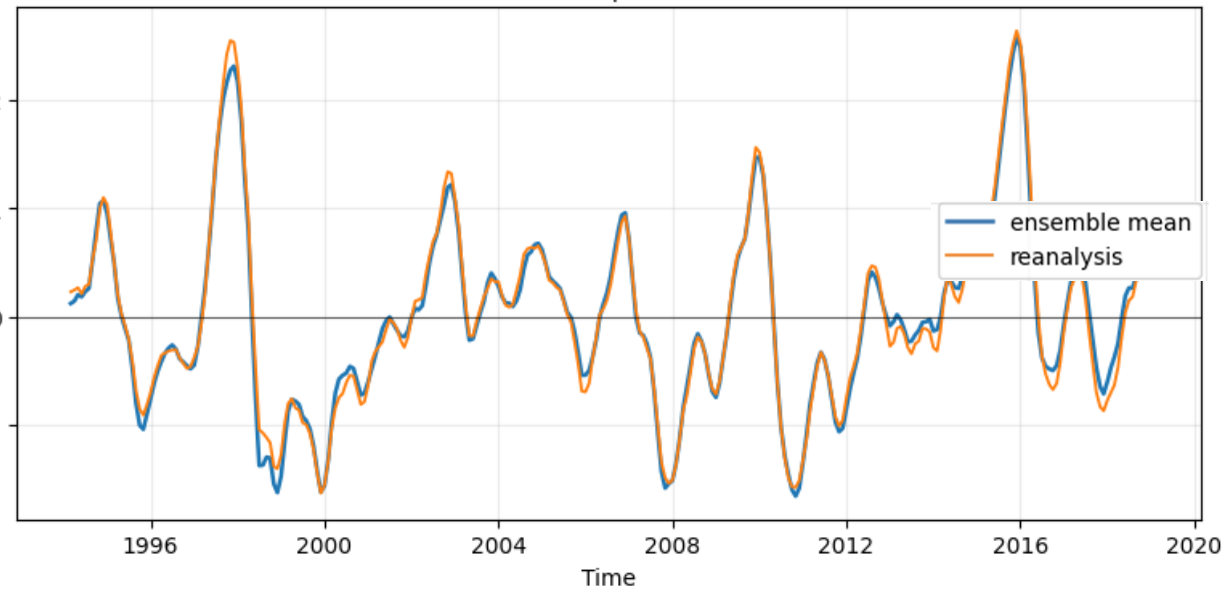
Sea-ice concentration mean | $r=0.99$



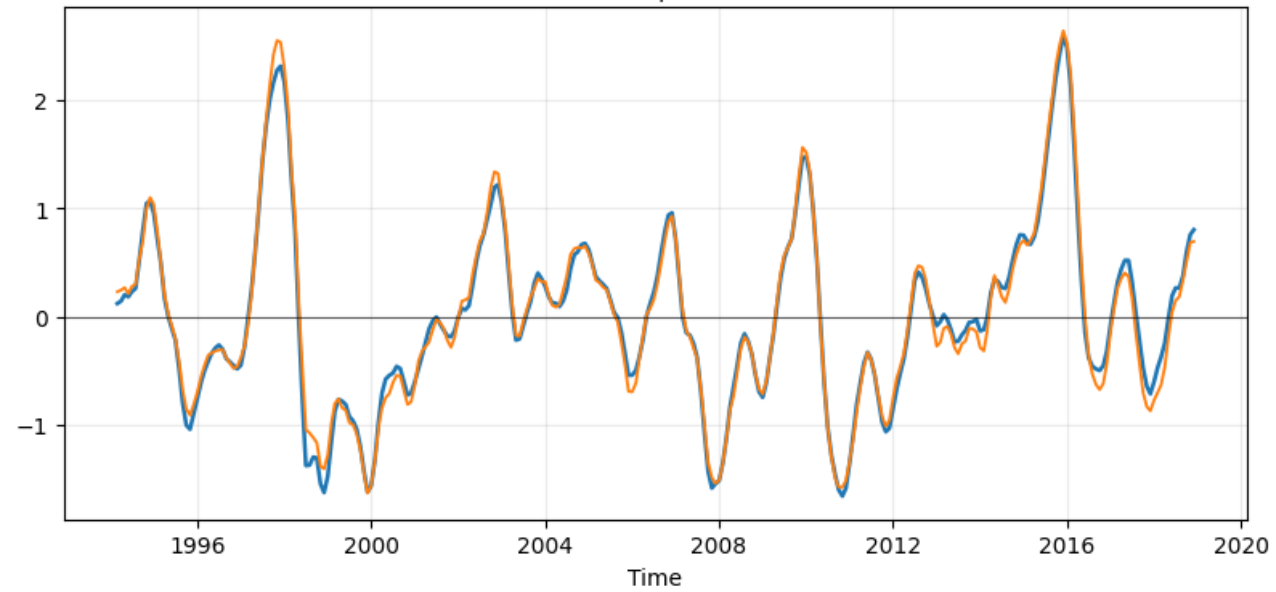
Sea-ice speed mean | $r=0.97$



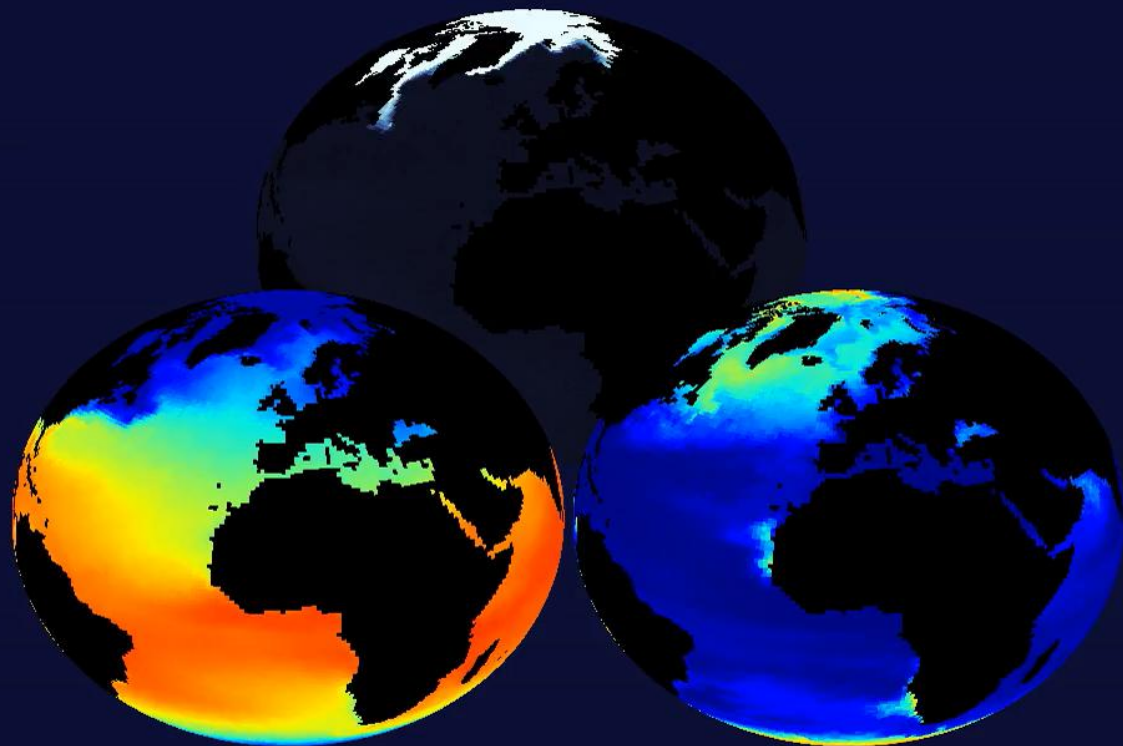
ONI-like | $r=0.99$



Nino3.4 | $r=0.99$



2025-01



Integrated Ocean Emulator

- **Next:**

- ¼ res., higher vertical sampling, daily
- proper evaluation
- Replace prior sampling with stable diffusion
- Couple with ML-atmospheric models
- IOE ensembles --> OMIP

- **Digital Twin:**

- Cheap solution for new services
- What if, MCDR..
- Long-term planning..

Thank you