ECMWF’s next ensemble reanalysis system for ocean and sea-ice: ORAS6

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and many others

ECMWF

Why ocean (and sea-ice) reanalyses

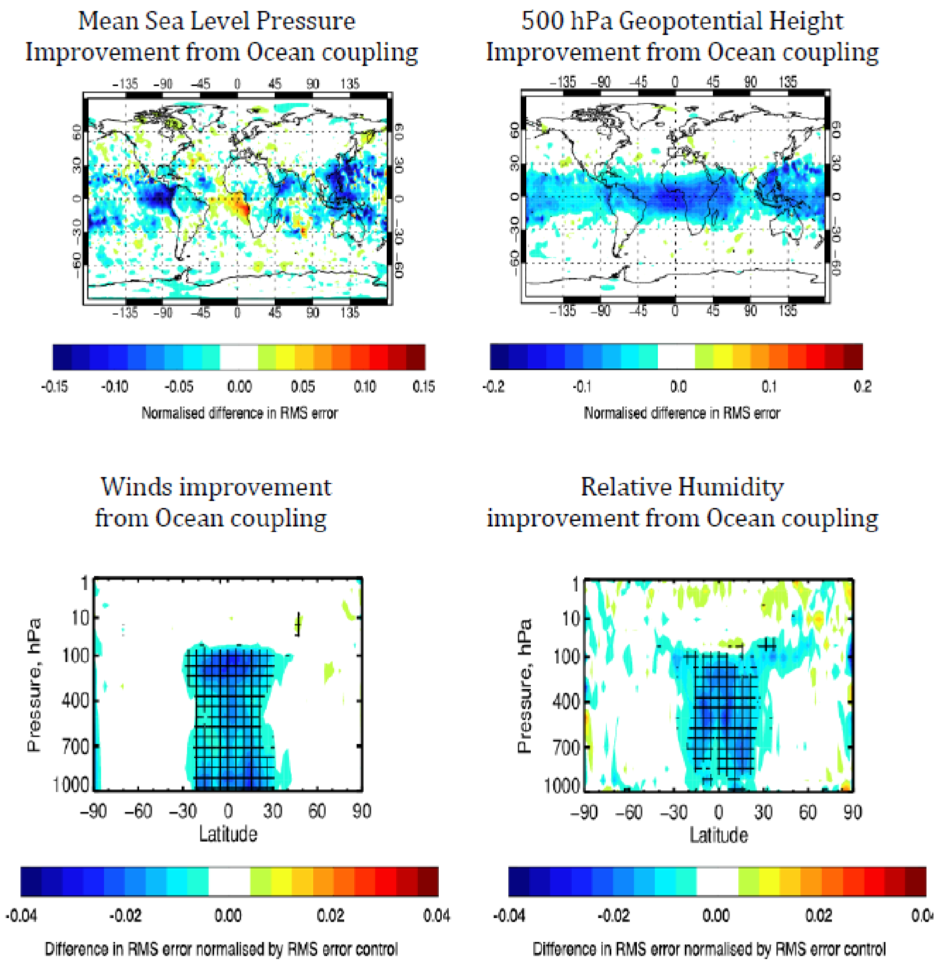
Seasonal FC → + Subseasonal FC → + Climate monitoring → + Medium-range FC → + Coupled Reanalysis ERA6

2000 | 2010 | 2020

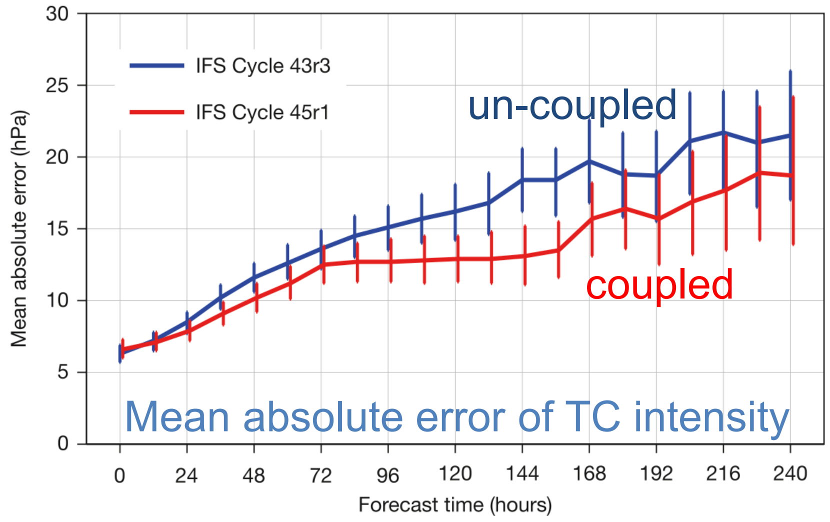
1997	2001	2007	2012	2018	2025
ORAS1	ORAS2	ORAS3	ORAS4	ORAS5	ORAS6

		ORAS1	ORAS2	ORAS3	ORAS4	ORAS5	ORAS6
Ocean		HOPE			NEMO3.0	NEMO3.4	NEMO4
Sea-ice		N/A				LIM2	SI3
Resolution		2.5-deg	1-deg			0.25-deg	
Ensemble		N/A	5				11
Forcings		ERA15		ERA40	ERA-interim		ERA5
		24hr				6hr	1hr
DA		Univariate OI		Multivar. OI	3DVar-FGAT		En-3DVar FGAT
Obs	SSH	N/A		Tropical SSH			Global SSH
	Sea-ice	N/A				L4 SIC	L3 SIC
	SST	Nudging only					SST DA
	In-situ	0-400m T only		0-2000m T/S	Full depths T/S		

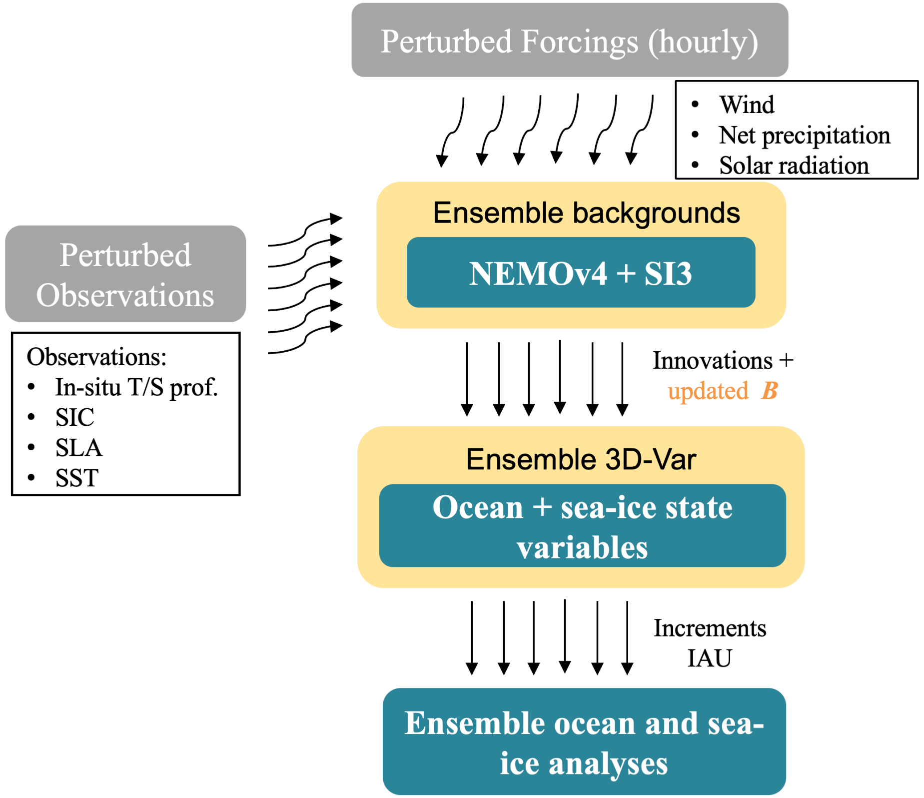
Why ocean (and sea-ice) analysis



- ECMWF forecasts became coupled for all timescales since 2018 (CY45R1) - include dynamical ocean and sea-ice components (*Mogensen et al., 2018, Buizza et al., 2018*).
- Coupling (**partial**) 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).



Key updates in ORAS6



	ORAS5	ORAS6
Forcing	ERA-interim: 24 h radiation	ERA5: hourly
Model	NEMOv3.4 + LIM2 0.25-deg	NEMOv4 + SI3 (multi-cat.) 0.25-deg
DA algorithm	Deterministic 3DVar-FGAT	Hybrid Ens 3DVar-FGAT
SST DA	Nudging	Ens 3DVar
Ensemble	4 + 1 control	10 + 1 control
Output	Netcdf	GRIB2
Data cover	1981 onwards	1950 onwards
Production	Sequential	Parallel streams

Relevant publications

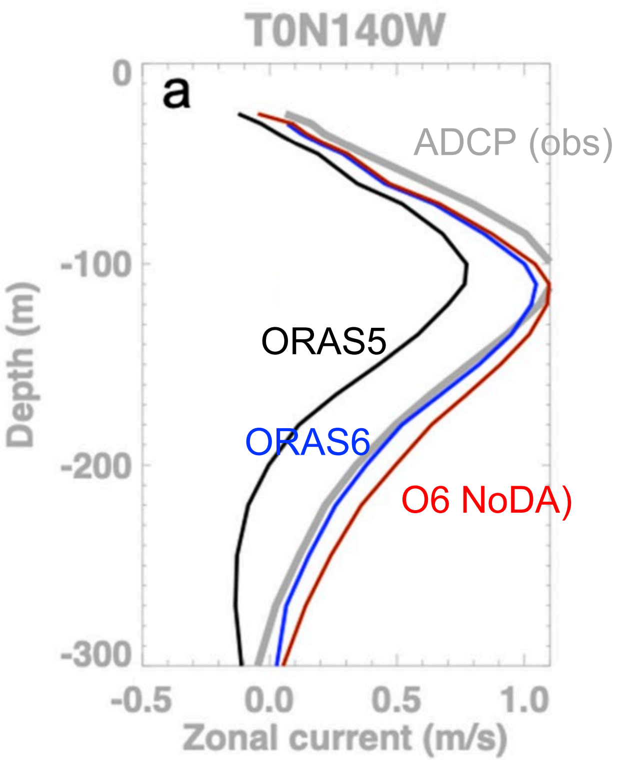
- *ORAS6 – Zuo et al., NL180, 2024*
- *GRIB2 – Sármány et al., NL178, 2024*
- *2024 SAC special paper – Zuo et al.*
- *ORAS6 system – Zuo et al., in preparation*
- *Ocean EDA – Chrust et al., 2024 QJRMS,*
- *Sea-ice DA – Browne et al., TM, in preparation*
- *Obs impact study – Mogensen et al., in preparation*

Development of ORAS6 has been partially supported by EU-funded projects: C3S-ERGO, CMEMS-GLORAN and their follow-ups.

Model/forcing upgrades - NEMOv4/SI^3 + ERA5

The ocean and sea-ice model in ORAS6 is based on NEMO4.0.6, which includes a new multicategory sea-ice model SI^3, with prognostic salinity. Atmospheric forcing comes from hourly ERA5 reanalysis and has a new bulk formulation for the computation of fluxes.

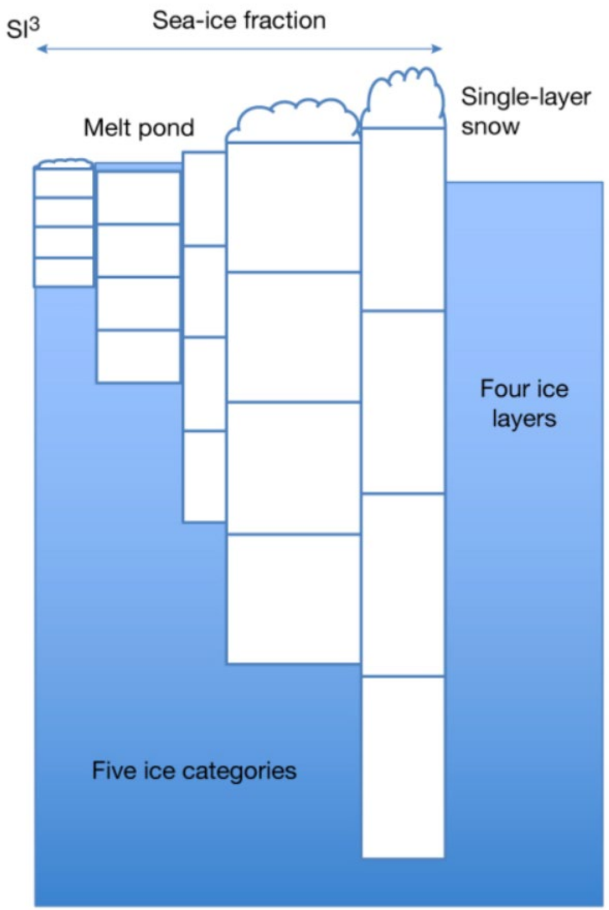
- *Large improvements on SST diurnal cycle and upper ocean currents*



2015-2020 Mean zonal current (in m/s) from TAO mooring station at equator (0N, 140W). Verified against the Acoustic Doppler Current Profilers (ADCP).

Multi-category SI^3 model

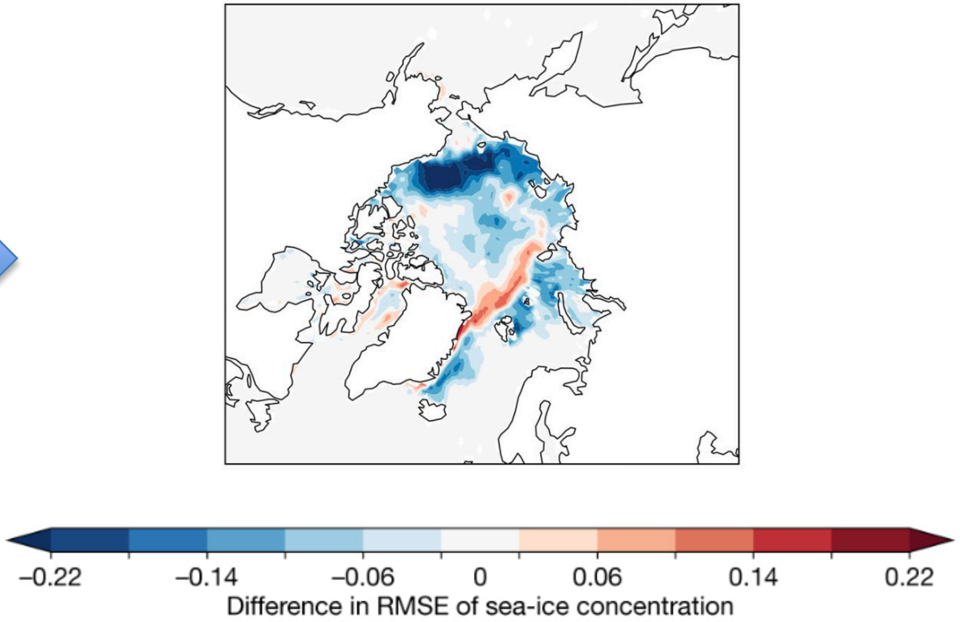
- The SI^3 has improved sea-ice concentration in marginal ice zone.
- The SI^3 model is found to have **thinner** ice on average in the Arctic.



ORAS6 uses five thickness categories, each with four thermodynamic layers and one snow layer on top.

(Keeley et al., NL180)

SIC RMSE: SI^3 – LIM2
(Sep-Nov, 1999-2019)



DA updates - En3DVar with Hybrid-B

The hybrid covariance formulation in NEMOVAR (*Thanks to EU funded C3S project – ERGO/ERGO2*)

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

$\boldsymbol{B_h}$ is the hybrid covariance matrix; $\boldsymbol{C_h}$ is the correlation matrix (using 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 std formulation

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

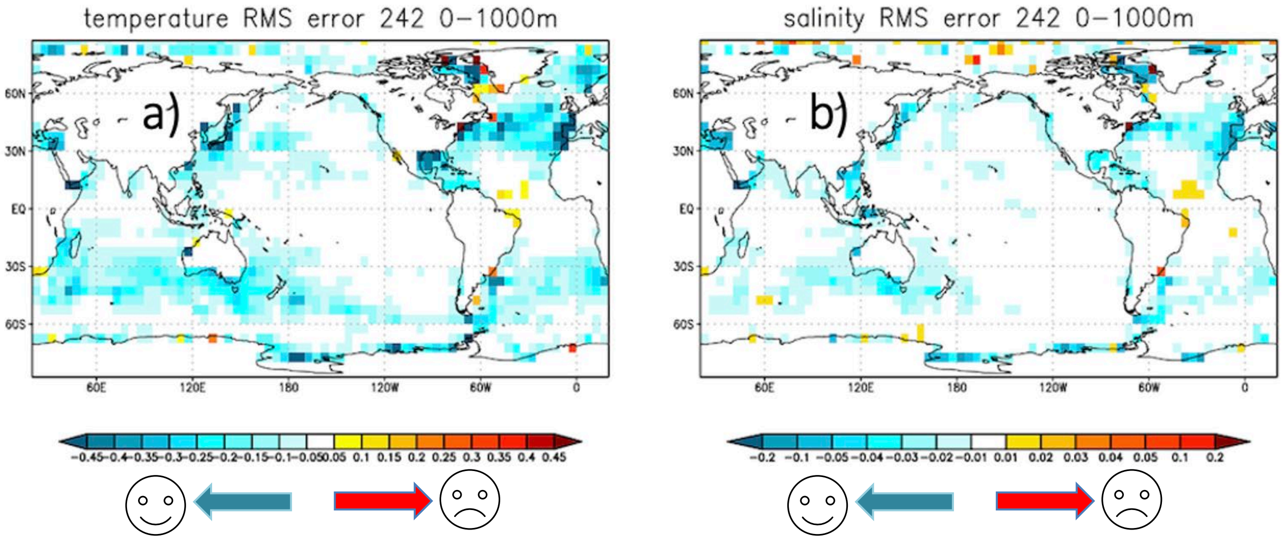
(Chrust et al., 2024 QJRMS)

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

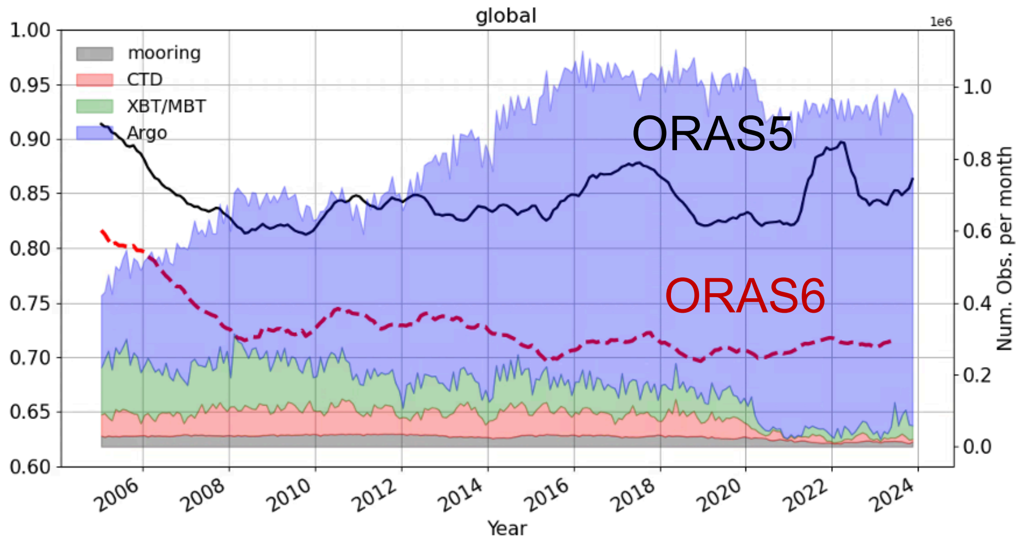
ORAS6 sub-surface performance

- Compared to ORAS5, fit-to-observations error standard deviations have been reduced by ~15% for sea-water temperature, and by ~7% for sea-water salinity.

RMSE: ORAS6 – ORAS5
(2010-2020, 0 – 1000m, against all in-situ obs)



Temperature RMSEs
(0 – 1000m, against all in-situ obs)



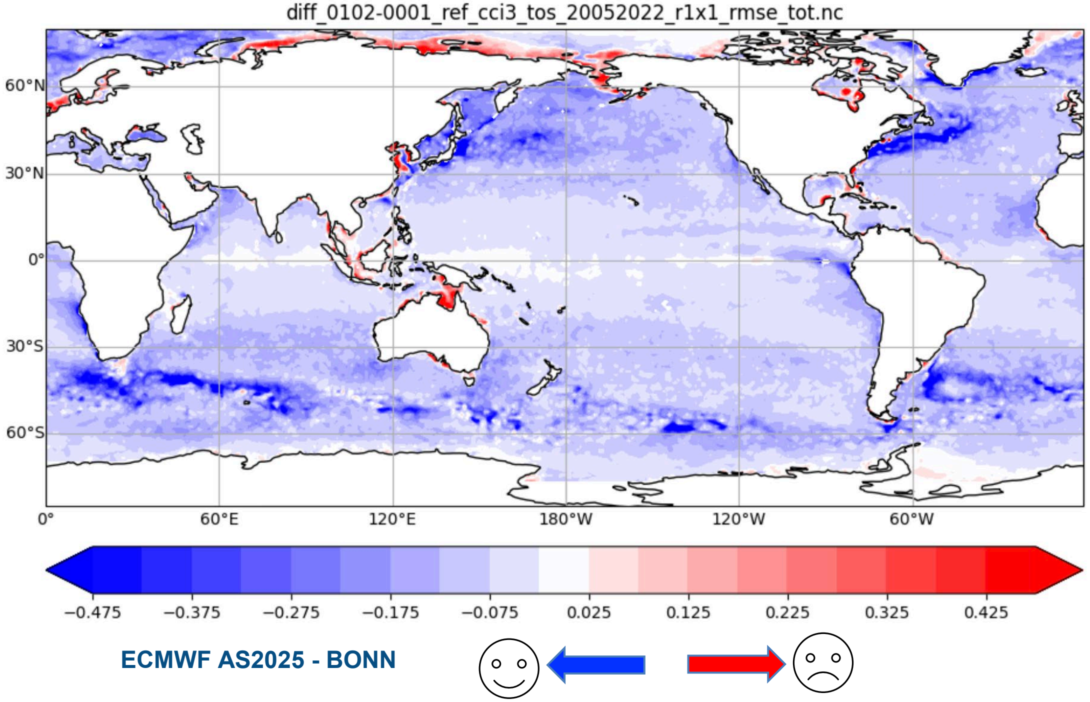
Zuo et al., 2024 NL180

SST DA with En3DVar

Direct assimilation of L4 SST data with En3DVar

- Flow-dependent correlation length-scales is essential, thanks to a novel factorized formulation of normalization factors (*Weaver et al., 2021*)
- Require careful treatment in observation operator (e.g. LST)

SST RMSE: ORAS6 – ORAS5
(2005-2022, against ESA CCIv3)

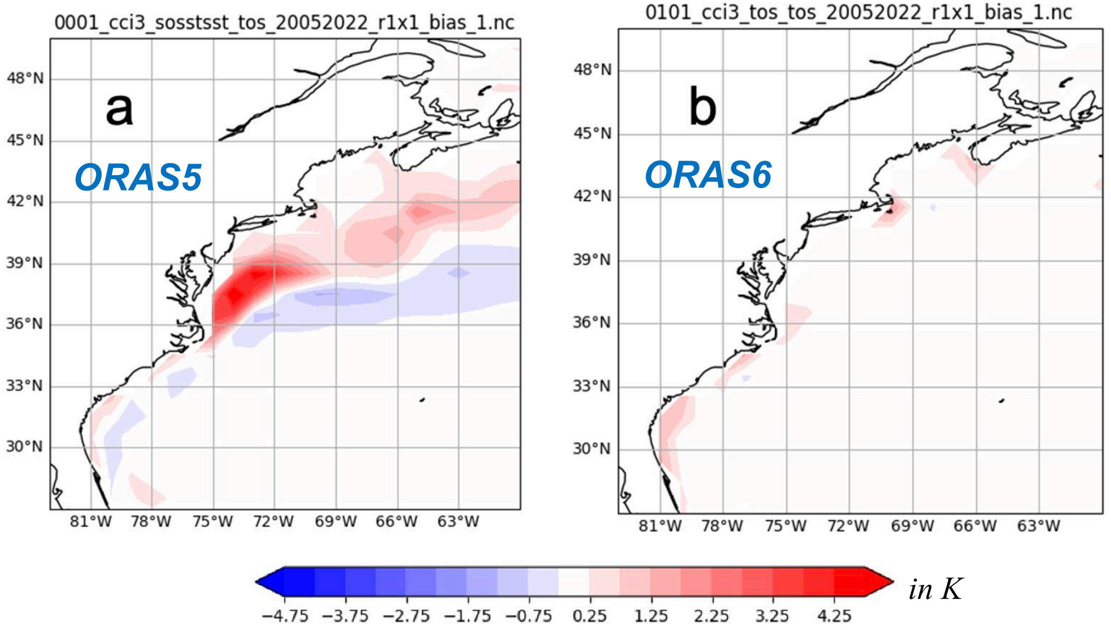


RMSE has been reduced by **~39%**

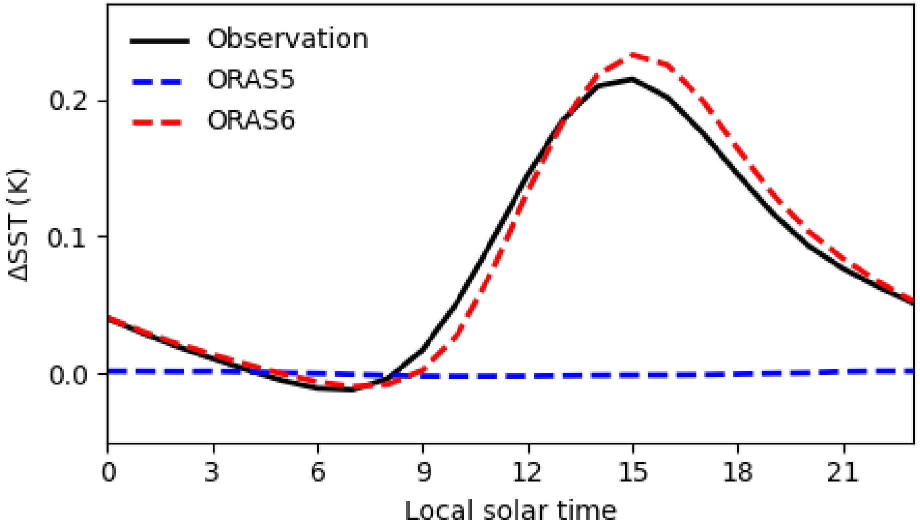
ORAS6 SST performance

- Greatly reduced SST biases in the GS regions – partial coupling no longer needed
- Good representation of SST diurnal cycle – possible for hourly coupling

SST biases in the Gulf Stream regions
(2015-2022, against CCIv3)



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



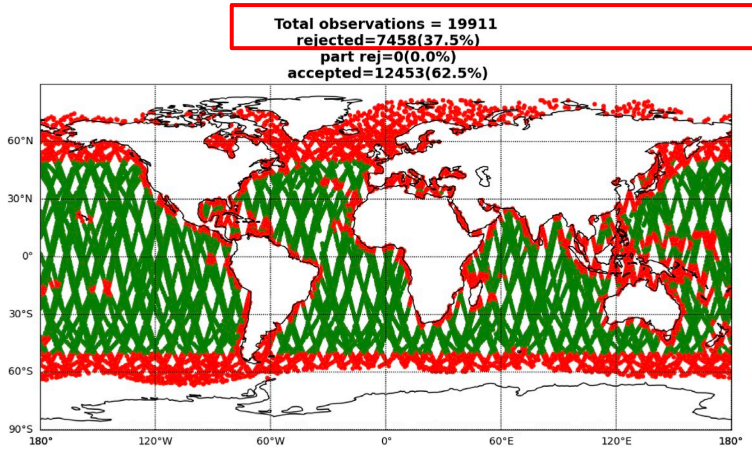
Zuo et al., 2024 NL180

Sea Surface Height DA

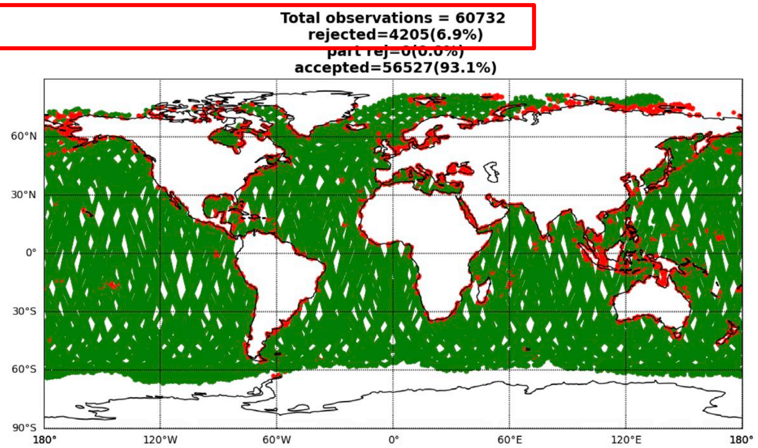
- ORAS6 now assimilates sea-level anomalies (SLA) with increased resolution and global coverage

SLA obs QC results (5-day)

ORAS5



ORAS6



red=rejected
green=accepted

- New method for MDT estimation - accounting for regional trend errors in the MDT first guess (MDT_b)

$$MDT_a = MDT_b + K\big((c_o - c_b)T\big)$$

c_b and c_o are the first guess and observed trend of SSH. The weight matrix K varies latitudinally in ORAS6; *T is the reference time period.*

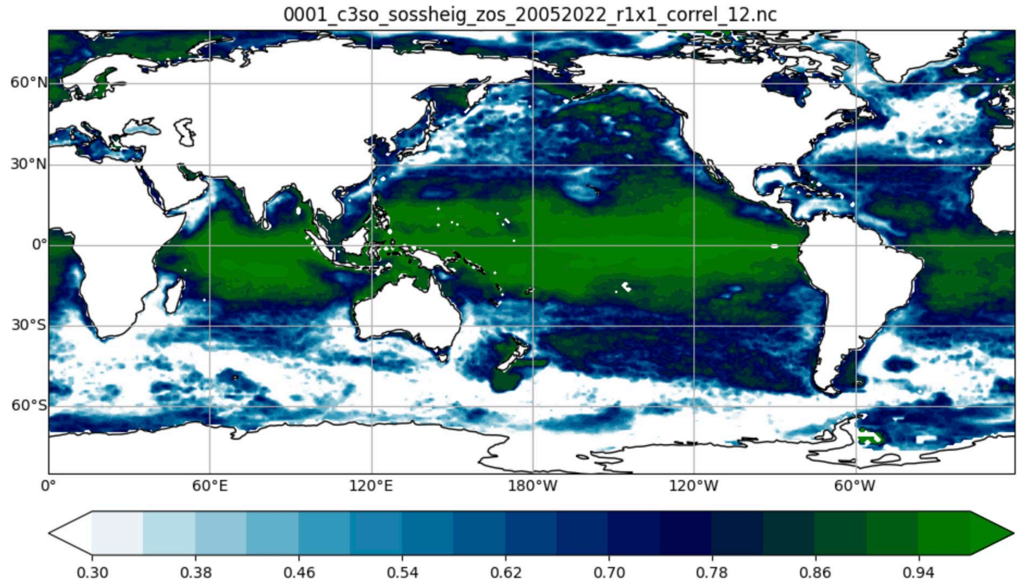
ORAS6 SSH peformance

- ACC of SLA in ORAS6 has increased by **0.15** (> **0.3** in the extra-tropics).

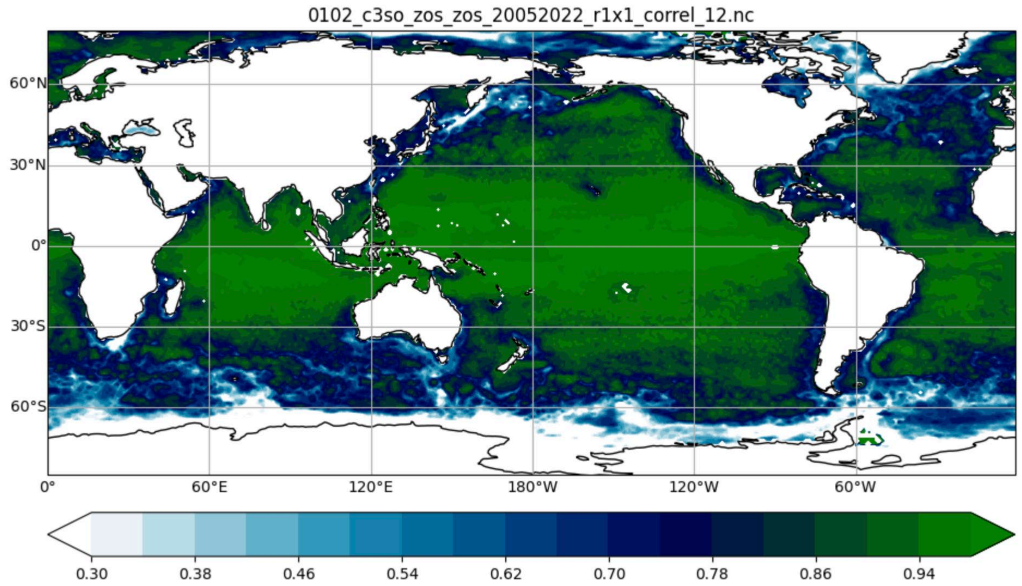
Temporal corelation between SLAs from reanalyses and observations

(2005-2022, against ESA CCIv3 sea-level data)

ORAS5



ORAS6



temporal correlations are diagnosed after removal of the seasonal cycle. Note that correlations smaller than 0.3 are shown as white.

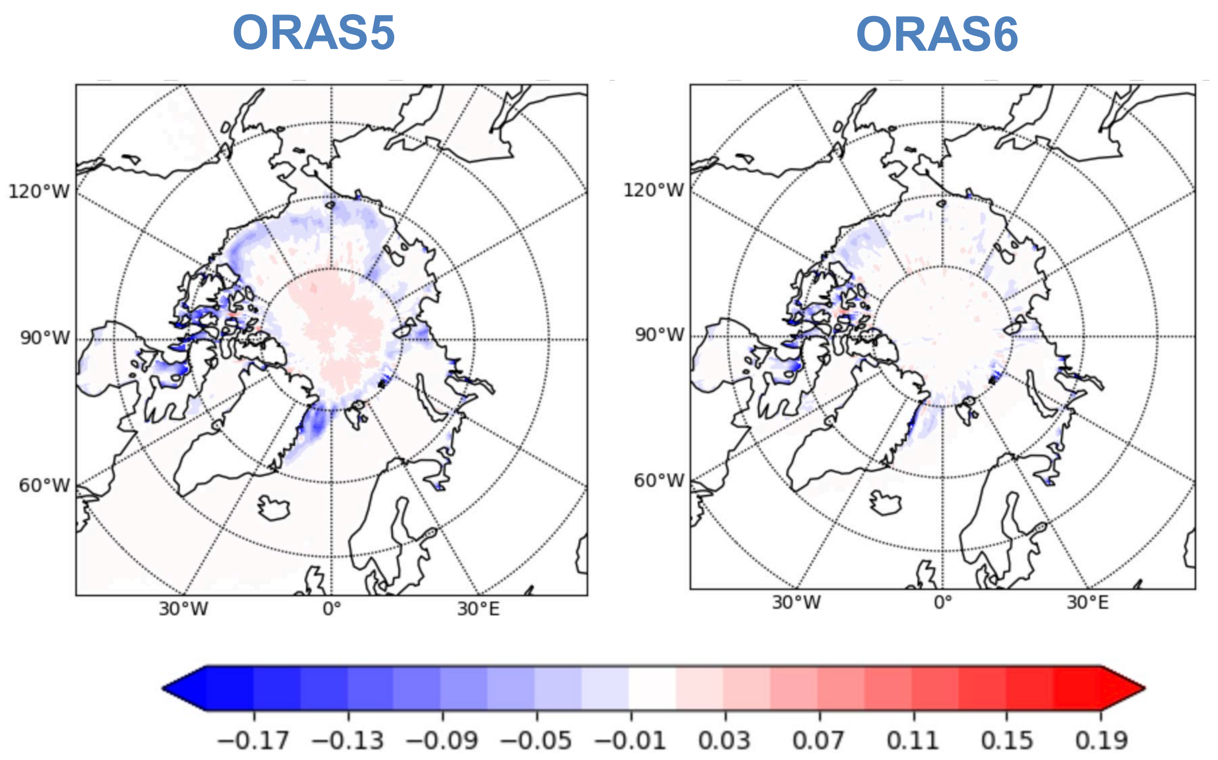
Zuo et al., in preparation

Sea-ice DA and performance

Assimilation of sea-ice concentration data with SI^3 model

- Switch to **L3 OSI SAF** data → more robust in operational service
- Distribute of total increment among different thickness categories using model **background thickness profile**
- Introduce **thermodynamic balance** between sea-ice and ocean state variables
- The thickness errors cannot be ameliorated by the analysis system as thickness is not currently assimilated

Sea-ice concentration biases
(Sep, 2005-2022, against CCIv3)

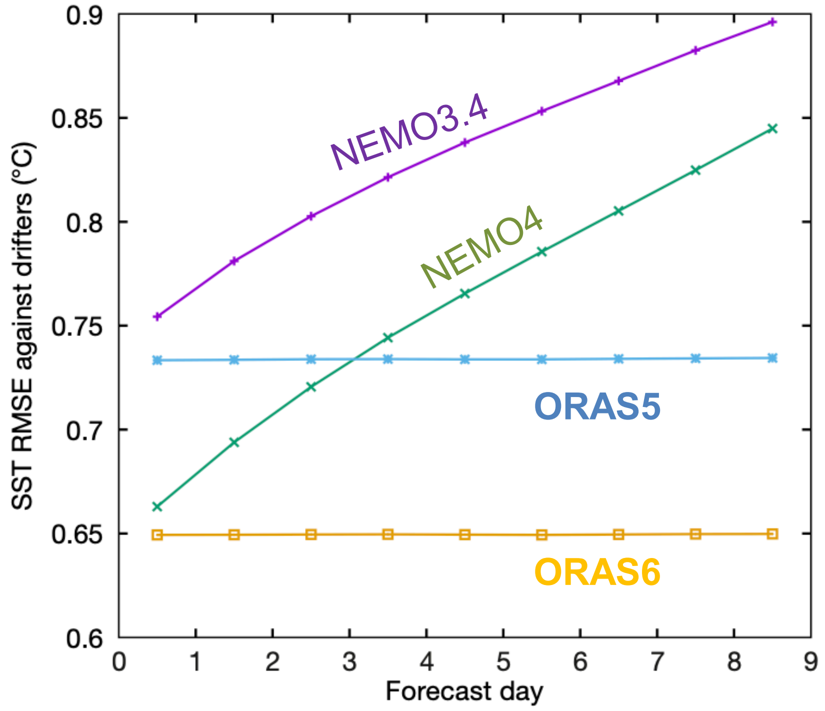


Browne et al., in preparation

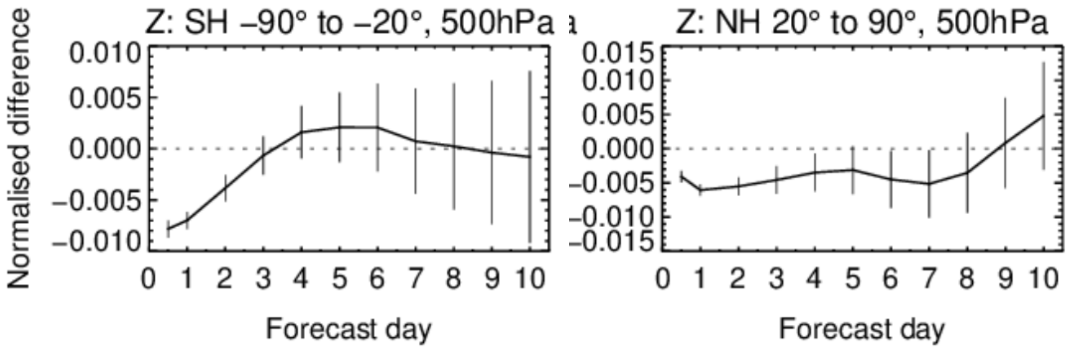
Medium-range forecasts

- Reference system (**NEMO3.4/LIM2/ORAS5**) still uses operational partial tendency SST coupling.
- The new **NEMO4/SI3/ORAS6** system uses full coupling with SST; more sea-ice fields (cover, snow and ice thickness) are also coupled with atmosphere.
- Partial coupling does not bring any benefit with the new system.

RMSE of SST forecasts
(Tco1279, 2020-2021, against drifter data)



Relative difference in RMSE: 500 hPa geopotential
(2020-2021, against 0001)



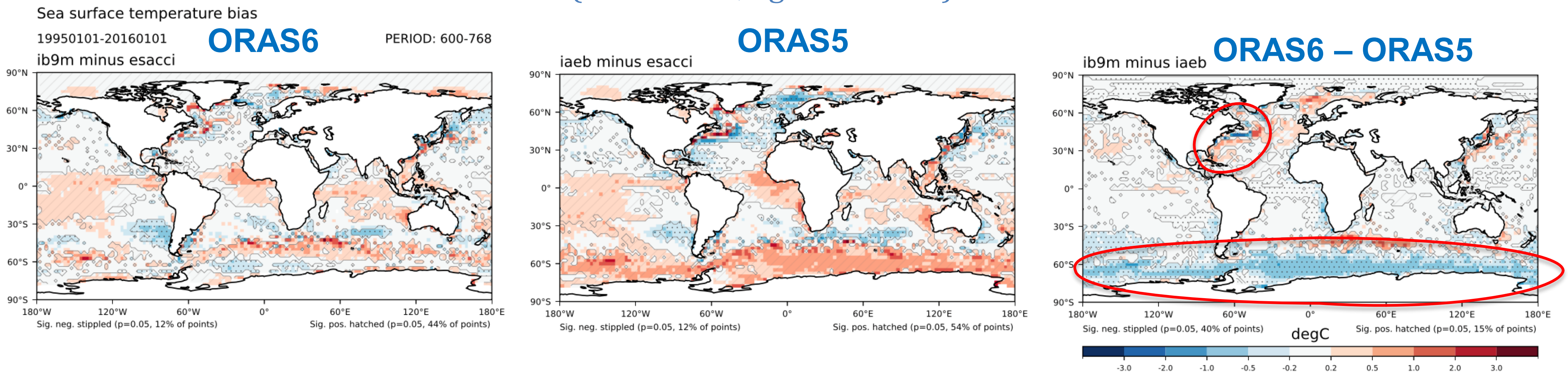
NV4/ORAS6 – NV34/ORAS5

Zuo et al., 2024 NL180

Sub-seasonal forecasts

- Use the same coupling strategies as in the medium-range forecasts.
- Sub-seasonal forecasts with NEMO4/SI³/ORAS6 provide robust improvements to SST.
- Mean state and forecasts anomalies for atmospheric fields are generally very similar to operational system – *further tunning of the coupled system is necessary (compensation of errors)*.

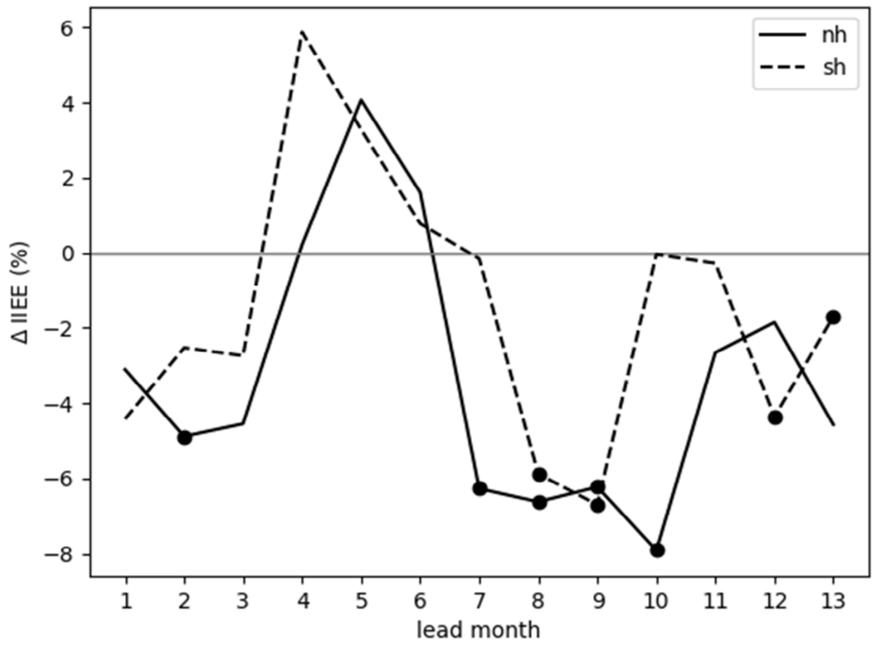
Week 4 SST forecasts biases
(1995-2016, against CCIv2)



Seasonal forecasts

- Long-range sea ice forecasts are mostly improved with the new system. However, the change in forecast performance varies strongly with region, season and lead time.
- Sea-ice thickness biases changed in ORAS6 due to lack of constraints.

Change in the integrated ice edge error (IEEE) with NV4/ORAS6 system
(May and November start, 2005-2022, against OSI-SAF 450a)

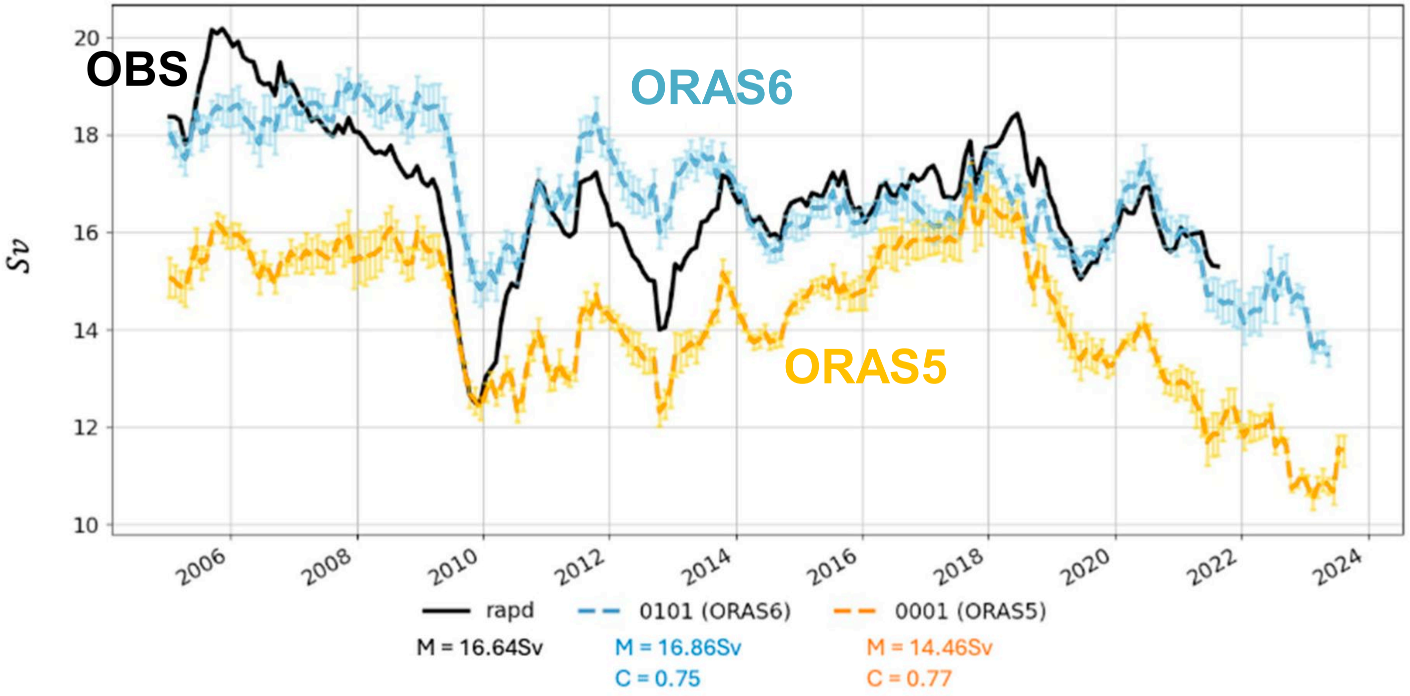


Negative value indicates that IEEE in the new system (NV4/ORAS6) is reduced compared to the reference system (NV34/ORAS5)

Climate monitoring

- ORAS6 will support climate monitoring (e.g. by contributing to C3S-ESCR).
- Robust improvements in tracking Atlantic Meridional Overturning Circulation (**AMOC**) and global sea-level changes.
- Larger uncertainties remains in the estimations of interannual variations of ocean heat content.

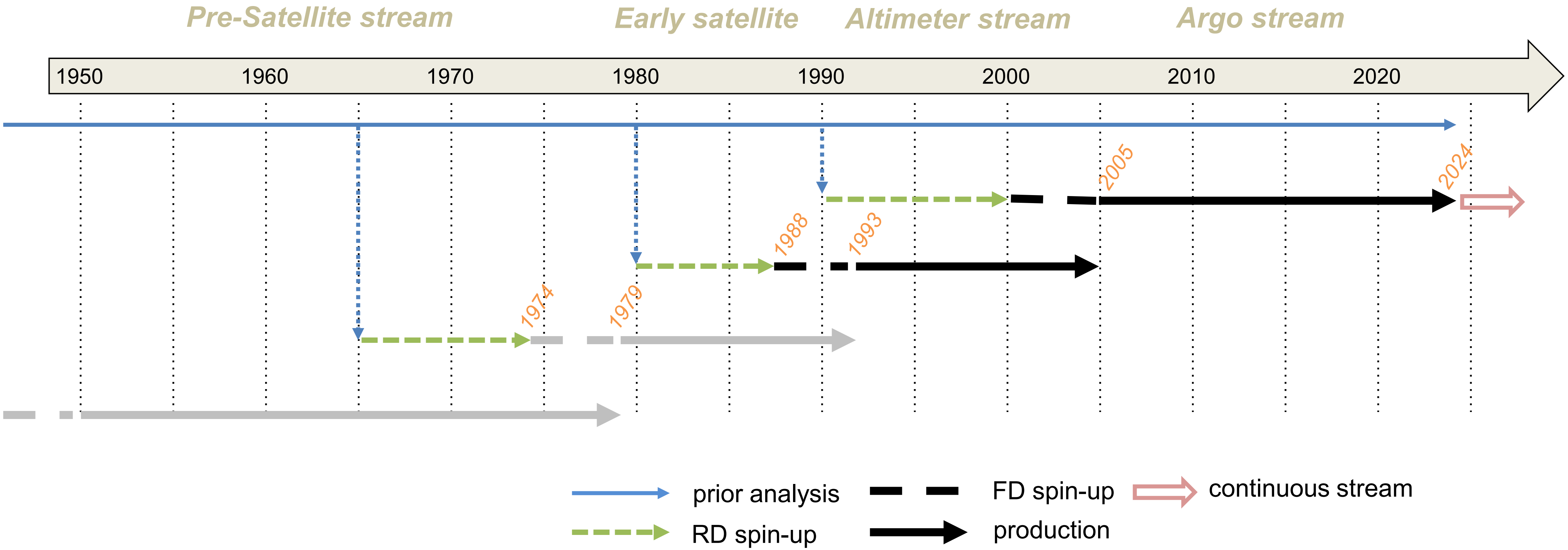
Maximum AMOC transports (in Sv) across 26.5º N
(All ensemble members, at ~1000m depth)



The M and C values stand for mean value and correlation coefficients with the RAPID measurement (in black).

ORAS6 production streams

- ORAS6 will be produced in separate parallel streams to cover from 1950-present.
- **Different EDA configurations** to account for evolving ocean in-situ observing network.
- Constraining SST and sea-ice in the pre-Satellite period remain to be challenging.



Summary and outlook

- ORAS6 will support coupled forecasting system from CY50R1 (Q4 2025). In addition, ORAS6 will also provide ocean and sea-ice conditions for ERA6.
- The performance of ORAS6 is significantly improved, especially for the estimation of the upper ocean states (e.g. SST). Initial target to remove partial coupling has been achieved.
- Medium-range forecasts (NEMO4/SI^3) initialized from ORAS6 show good performance over the entire global, with an average skill gain in the SST prediction of ~3-4 days.

Highlights of ORAS6

- *additional 8 years of RD works after ORAS5*
- *partial coupling is no longer needed in coupled forecasts*
- *providing ocean and sea-ice conditions for ERA6*
- *providing training database for AIFS-Ocean*

Summary and outlook

Challenges in ORAS6 development

- One of the main challenges in developing ORAS6 is simultaneously and accurately capturing both **high- and low-frequency** variability to meet the **diverse requirements/priorities** for different applications (*medium-range, sub-seasonal to seasonal, ERA6, Climate monitoring*).
- The sea-ice in ORAS6 can be **biased thin**. Need to introduce sea-ice thickness assimilation (DANTEX-CRISTAL)
- In the future we may consider interweaving staggered separate developments, which specifically target weather and climate (e.g. ERA6-Ocean).

What beyond ORAS6?

- Post-ORAS6 developments will be focusing on **higher spatial resolution** model, with potential **4D-Var** approaches and **coupled data assimilation**.
- Explore **ML approaches** to support enhanced observation usage, strengthen ensemble approaches (e.g. B estimation with ocean emulators) and improve bias correction in ocean reanalysis.
- Assimilation of **more interface observations**, such as drifting buoy temperatures, sea-ice thickness (including snow) and possibly ocean currents.

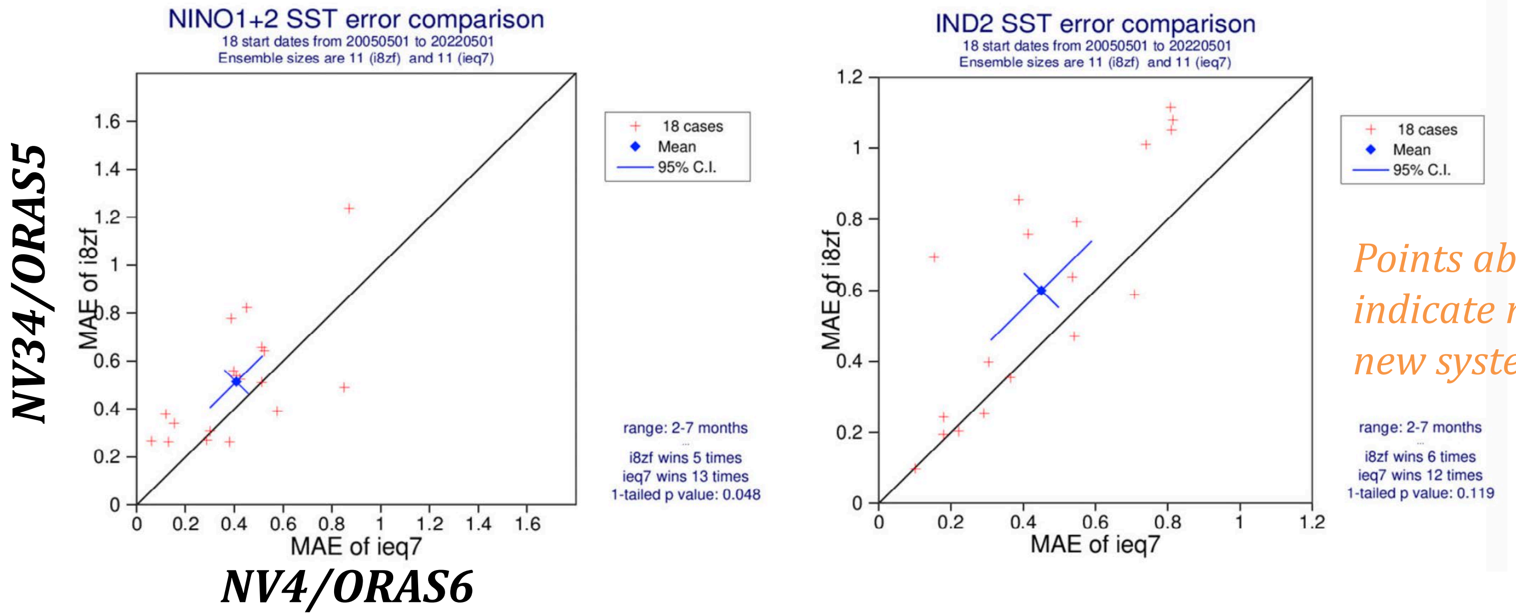
Thank you !

Extra slides

Seasonal forecasts

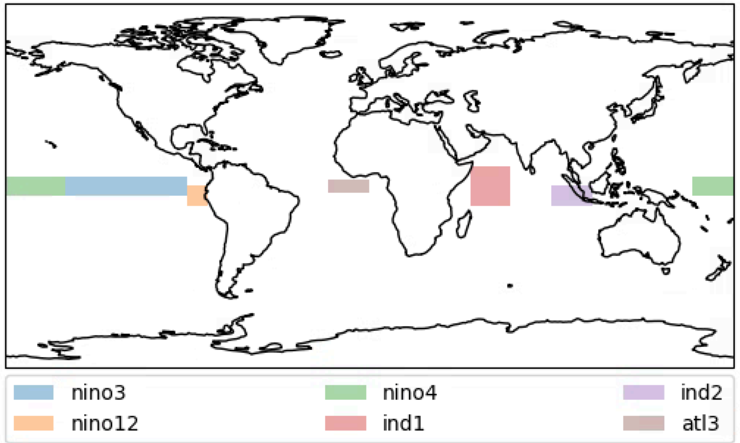
- New system has substantial impact on the mean states of ocean (e.g. SST) and atmospheric variables (e.g. humidity and precipitations), with some differences persist for several months.
- Improvements in ENSO variability in the Central Pacific (NINO3.4), in the coastal region (NINO1+2), and over the Eastern node of the Indian Ocean Dipole (IND2) in the first season.

Mean absolute error of SST reforecasts (month 2-7)
(May 1st start, 2005-2022)

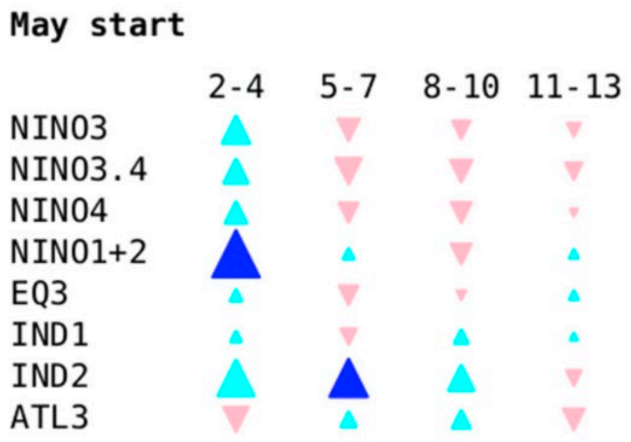


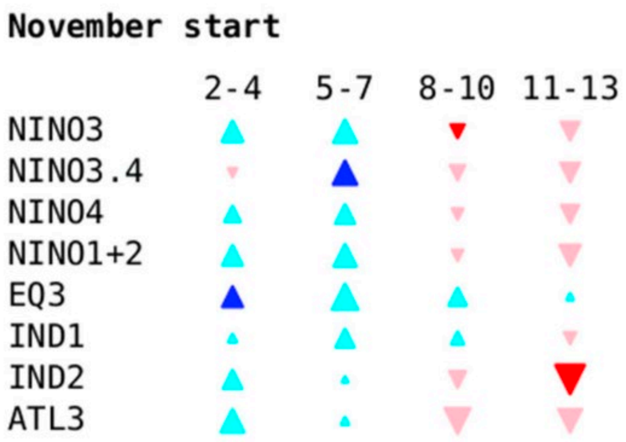
Points above the diagonal indicate reduced errors for the new system (NV4/ORAS6)

ORAS6 and seasonal forecasts



Difference in mean absolute error
NEMO4/SI^3/ORAS6 - NEMO3.4/LIM2/ORAS5

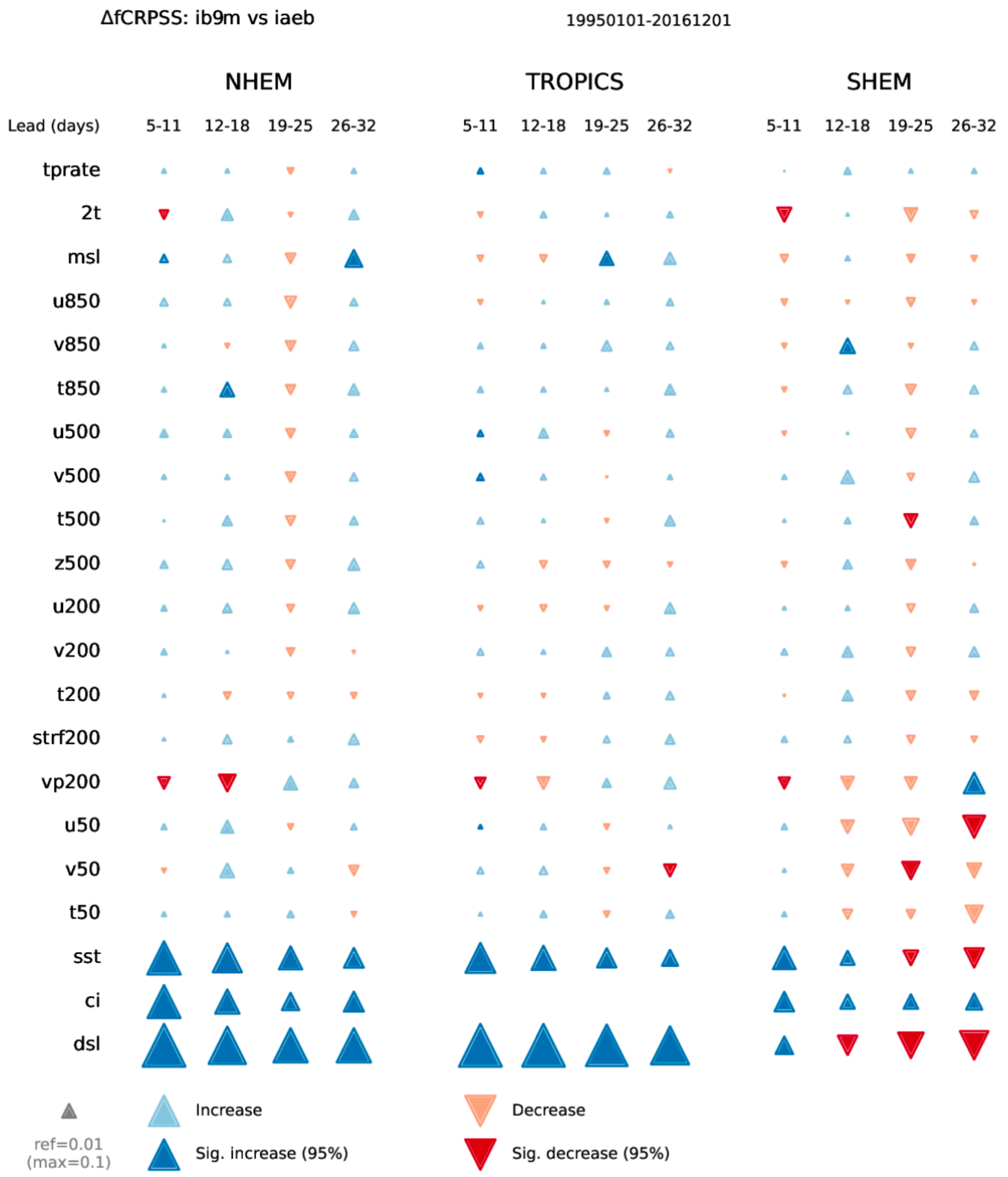




Blue/red triangles indicate an improvement/degradation when introducing NEMO4/SI^3/ORAS6. Reforecasts are initialized on 1st May and 1st Nov between 2005-2022. Seasonal (three month) means are calculated for a seven-month forecast.

- NINO1+2 is an index for the coastal El Niño by the South American Coast
- IND1 and IND2 are indices for the West/East component of the Indian ocean dipole

ORAS6 and sub-seasonal forecasts



Scorecard summarising the impact of switching from NEMO3.4/LIM2/ORAS5 to NEMO4/SI3/ORAS6 prototype on the fair version of the continuous ranked probability skill score (fCRPSS). Positive (blue) triangles indicate that fCRPSS is improved with NEMO4/SI3+ORAS6 prototype and symbol areas are proportional to the magnitude of the difference.

- total precipitation rate (tprate)
- 2m temperature (2t)
- mean sea level pressure (msl)
- temperature (t)
- zonal/meridional wind (u/v)
- geopotential height (z)
- streamfunction (strf)
- velocity potential (vp)
- sea surface temperature (sst)
- sea ice concentration (ci)
- dynamic sea level anomalies (dsl)