ECMWF OCEAN & SEA-ICE REANALYSIS

ORAS6 – A Framework for Assessing and Designing the Global Ocean Observing Network

Hao Zuo, Kristian Mogensen, Magdalena Alonso Balmaseda, Eric de Boisseson, Philip Browne, Marcin Chrust, Alison Cobb, Sarah Keeley, Patricia de Rosnay

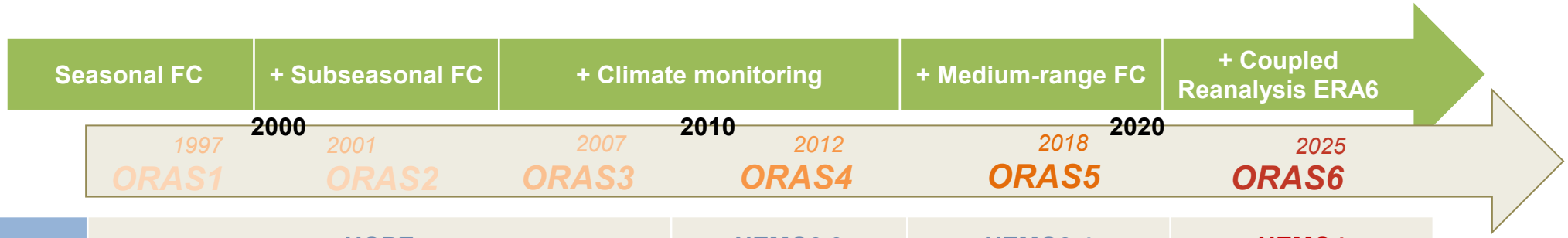
European Centre for Medium-Range Weather Forecasts

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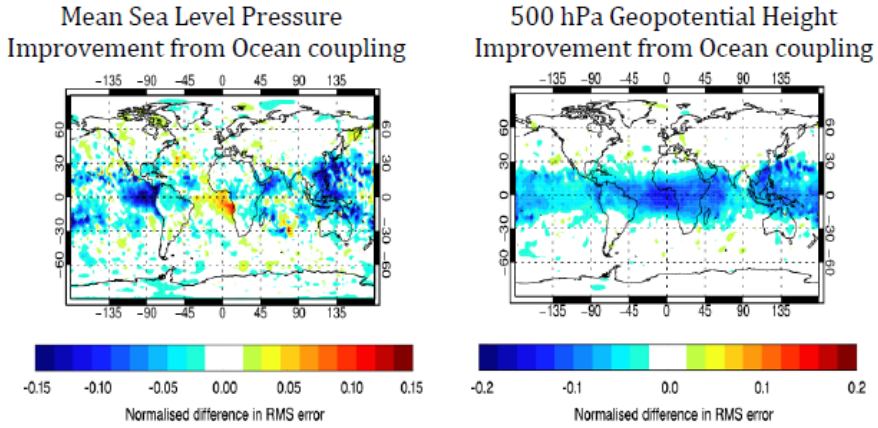
SynObs & Ocean Observing Co-design International Workshop
August 24, 2026, Mustu, Japan

ECMWF ocean (and sea-ice) reanalyses

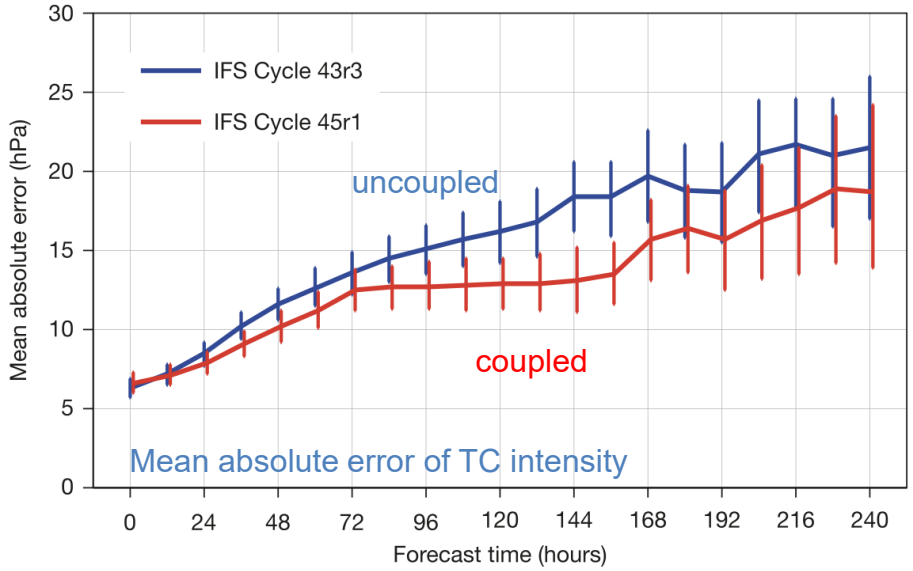


Ocean		HOPE		NEMO3.0	NEMO3.4	NEMO4
Sea-ice		N/A			LIM2	SI3
Resolution		2.5-deg	1-deg		0.25-deg	
Ensemble		N/A	5			11
Forcings		ERA15	ERA40	ERA-interim		ERA5
		24hr			6hr	1hr
DA		Univariate OI	Multivar. OI	3DVar-FGAT		En-3DVar FGAT
Obs	SSH	N/A	Tropical SSH			Global SSH
	Sea-ice	N/A			L4 SIC	L3 SIC
	SST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

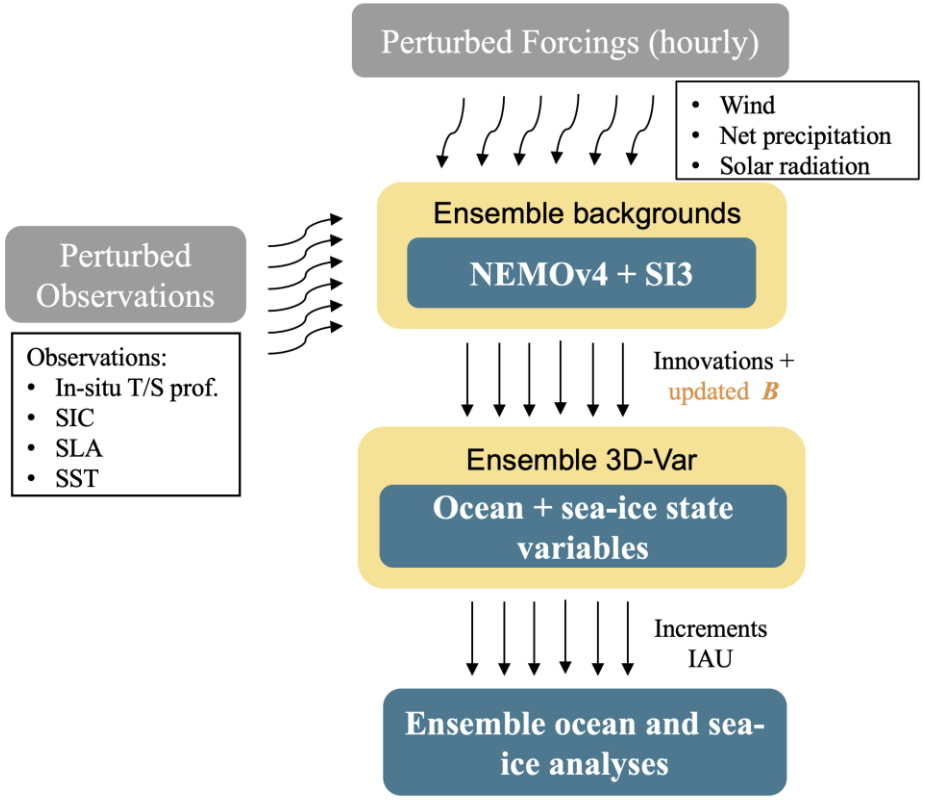
Why ocean matters in weather prediction?



- 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).



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*
- *Ocean EDA – Chrust et al., 2024*
- *Sea-ice DA – Browne et al., 2026*
- *ORAS6 system – Zuo et al., in preparation*
- *NEMO v4 + SI3 – Keeley et al., in preparation*
- *Obs impact study – Mogensen et al., in preparation*
- *Coupling between the atmosphere and ocean*

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

ECMWF

ORAS6 benefits from an improved data assimilation system

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

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

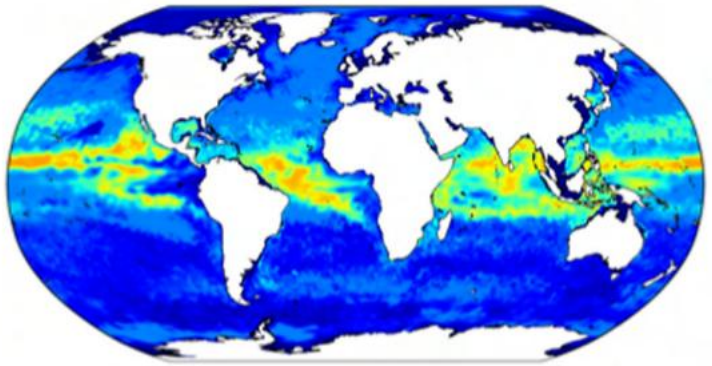
$\boldsymbol{B_h}$ is the hybrid covariance matrix; $\boldsymbol{C_h}$ is the correlation matrix (using hybrid diffusion operator $\boldsymbol{\kappa_h}$); $\boldsymbol{D_h}$ is a block-diagonal matrix of variances (using hybrid std dev σ_h).

Hybrid background-error standard-deviation formulation

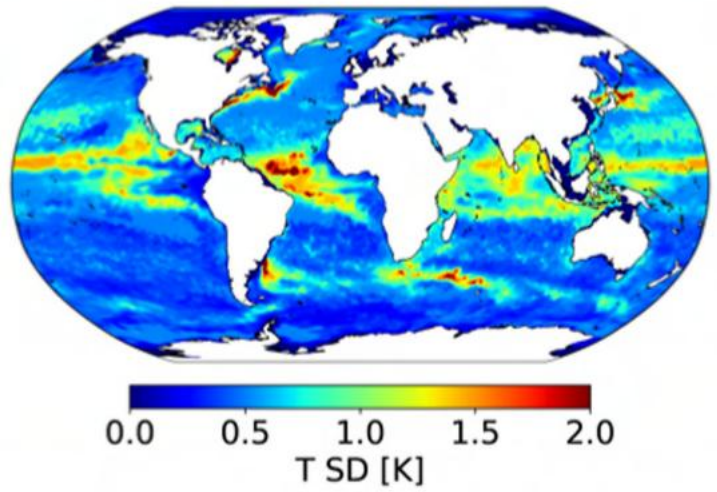
$$\sigma_h = \frac{1}{h}\log(e^{hw_m\sigma_m} + e^{hw_e\sigma_e} - 1)$$

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



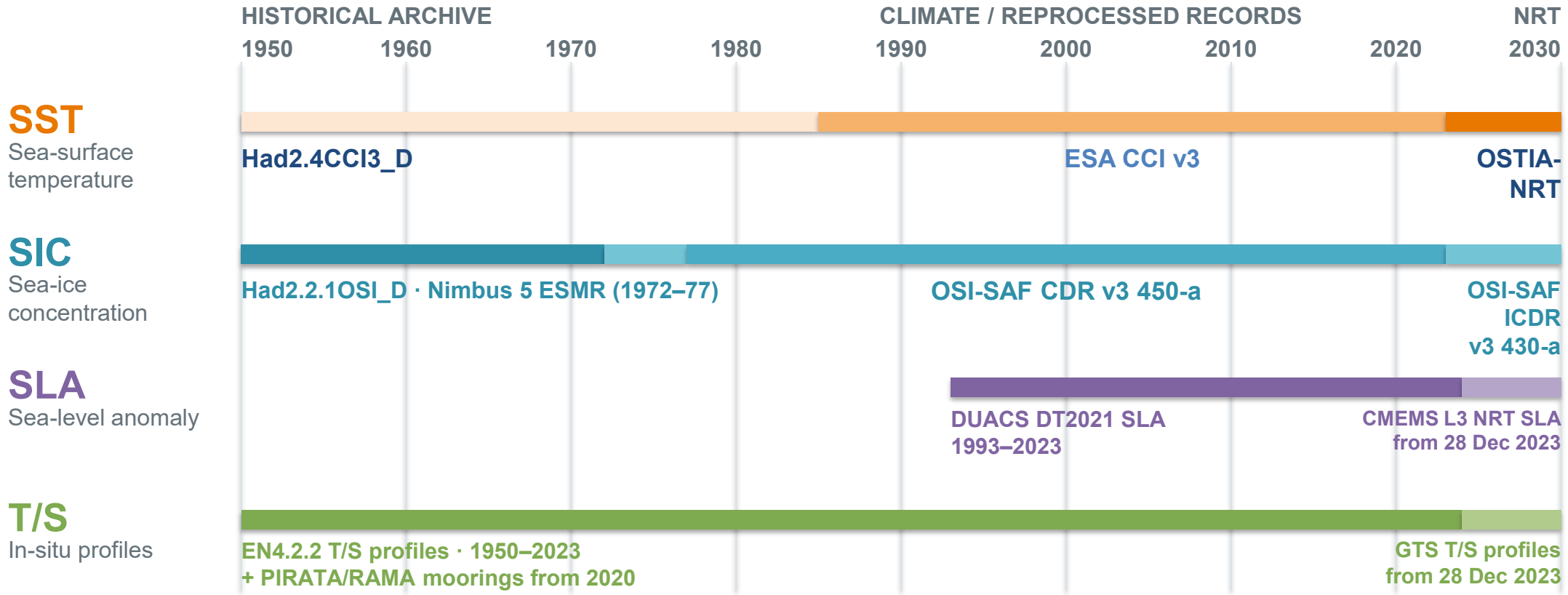
Hybrid σ_h



(Chrust et al., 2024, QJRMS)

ORAS6 draws on four complementary observation systems

Long historical records are combined with satellite-era and operational data streams



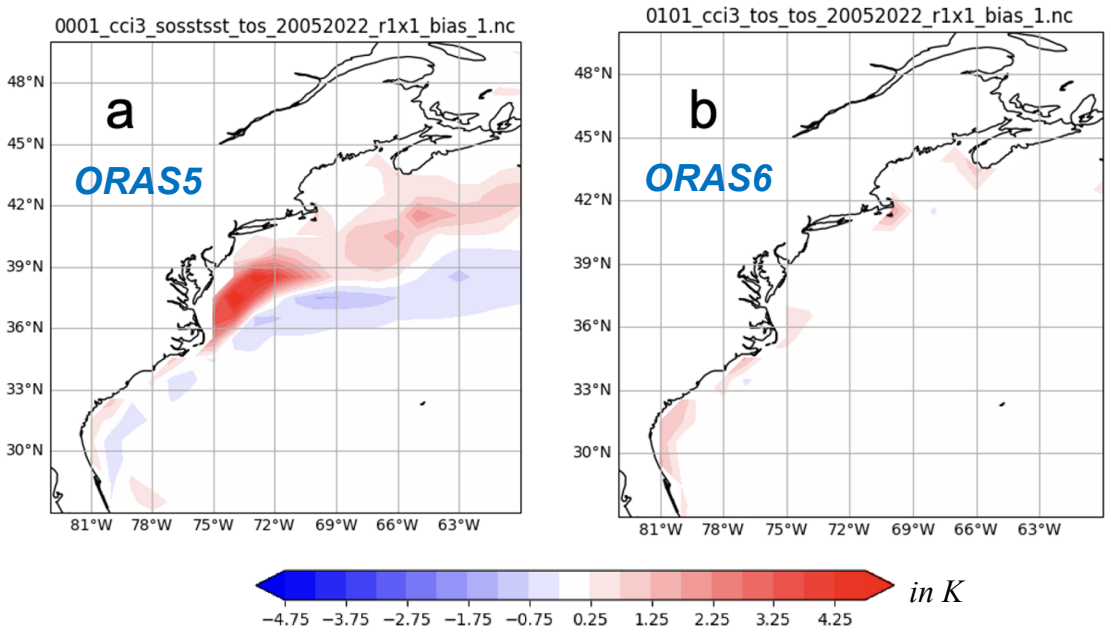
Reprocessed DT2021 and EN4.2.2 records transition to operational SLA and GTS profile feeds.

Source: ECMWF Confluence — Observations used by ORAS6 production (13 Aug 2026).

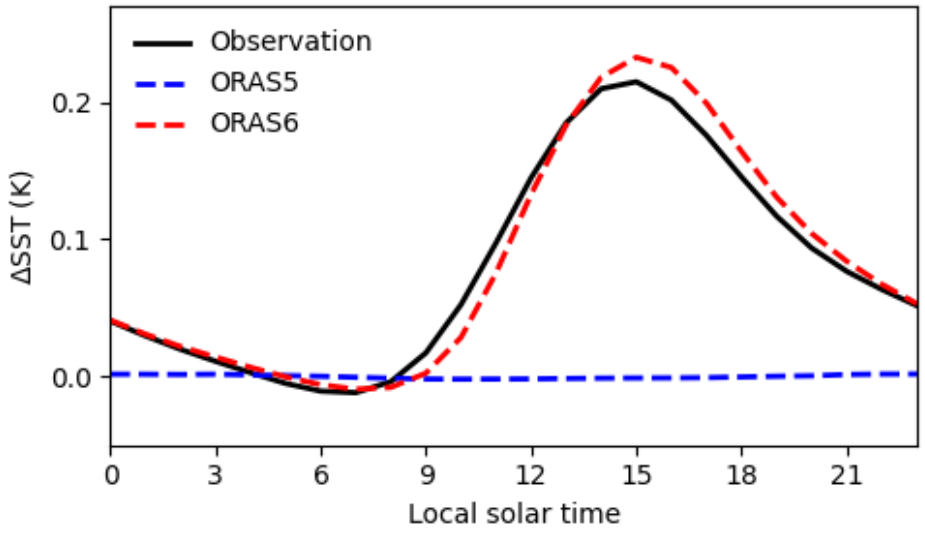
ORAS6 performance – sea surface temperature

- 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

ECMWF OCEAN & SEA-ICE REANALYSIS

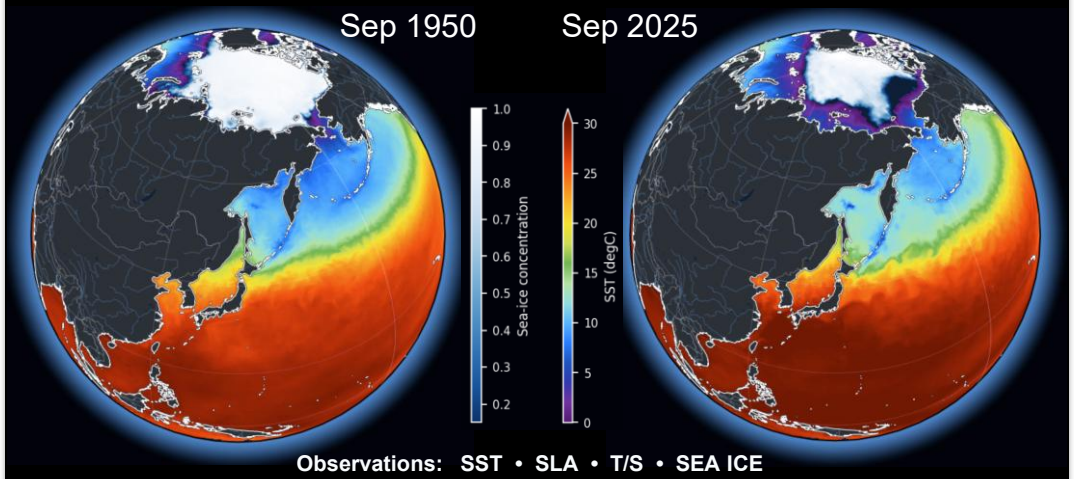
ORAS6 REANALYSIS

A new ocean foundation for forecasts and climate

6TH GENERATION

1950–PRESENT	11 MEMBERS	¼° × 75 levels	HOURLY 2D Daily 3D
continuous global record	ensemble reanalysis	global ocean grid	

SST and sea-ice September concentration



Observations: SST • SLA • T/S • SEA ICE

~30%	~15%	3–4 DAYS
lower SST RMS error	lower temperature fit error	SST forecast skill gain

POWERS FORECASTS • SUPPORTS ERA6 • CLIMATE MONITORING • TRAINS AIFS

Production complete · archive consolidation underway

Sources: ECMWF Newsletter 180 (2024); ECMWF News (Jun 2026); SAC update (Aug 2026).

APPLICATIONS

Initialise forecasts (CY50R1)

Ocean and sea-ice states from medium range to seasonal outlooks

Support climate/real-time monitoring

The ocean and sea-ice foundation for ERA6

Train data-driven models (AIFS marine)

Extend machine-learning systems to more components of the Earth system

PRESENTATION FOCUS

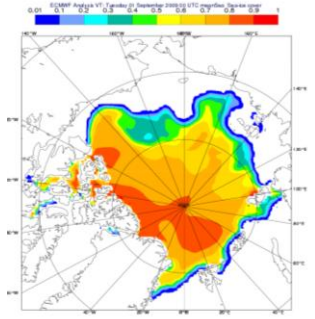
Design the observing network

Assess existing/new observations for forecasting and real-time monitoring

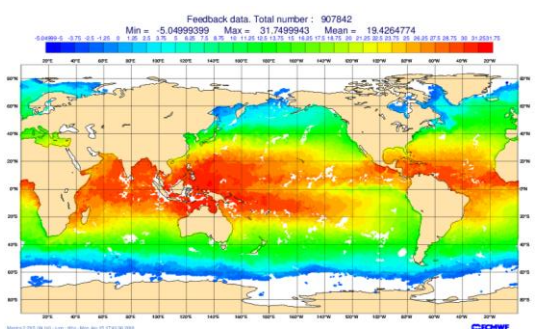
What observations are used by ORAS6 ?

Satellite data

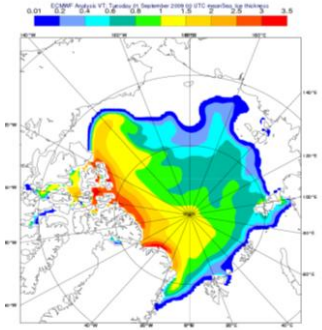
Sea-ice concentration



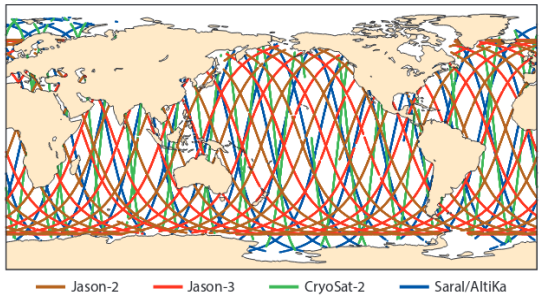
SST (IR, PMW)



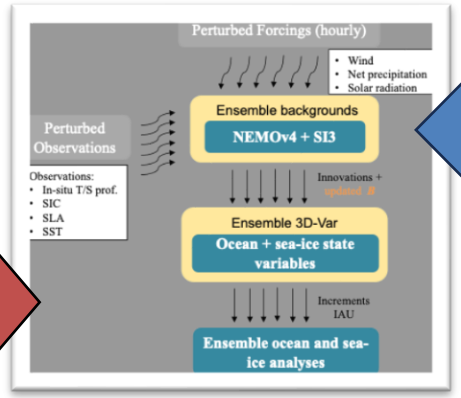
Sea-ice thickness - FB (under-development)



Sea-Level Anomaly (Altimeter)

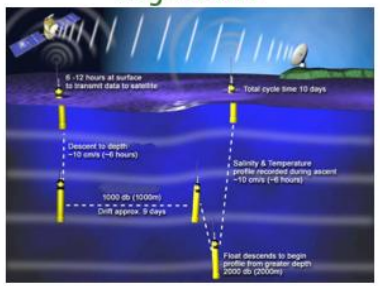


ORAS6



Ocean in situ data

Argo floats



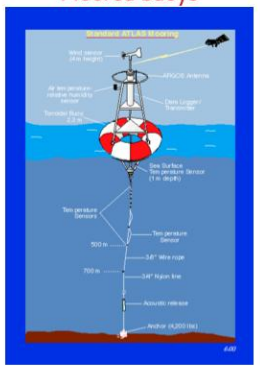
Argo operational cycle.
[Argo 2018]

Mammals!



[MEOP et al. 2015]

Moored buoys



[PMEL 2018]

Ship based observations





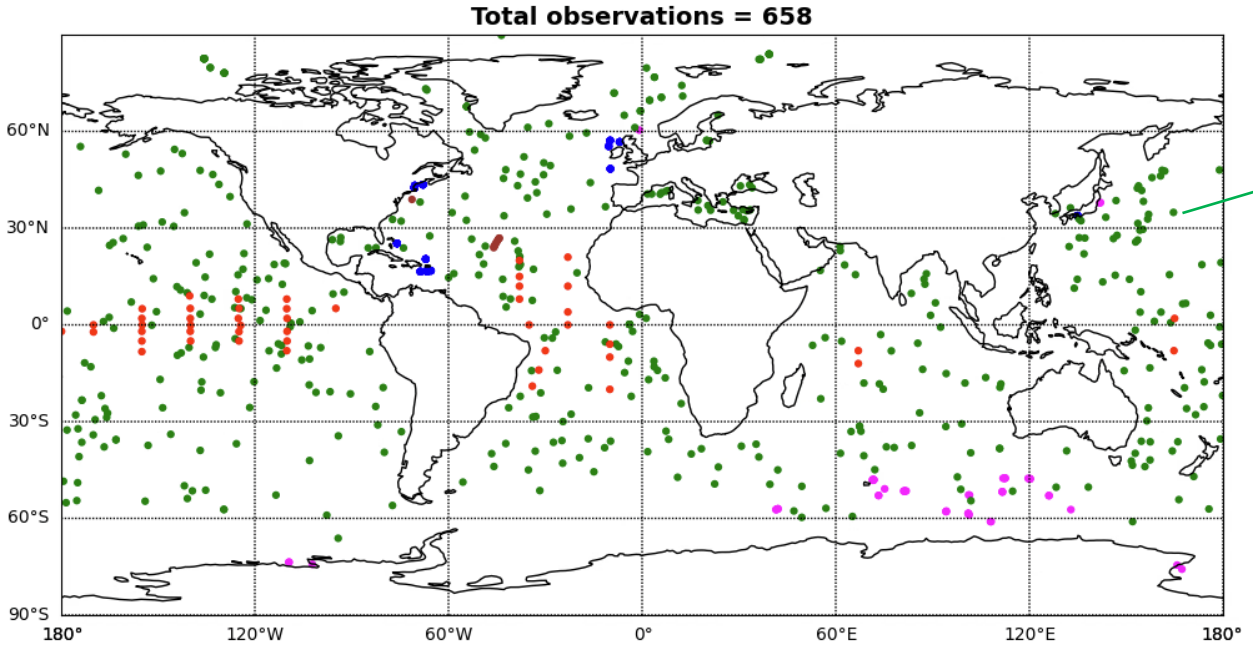
[CSIRO 2001]

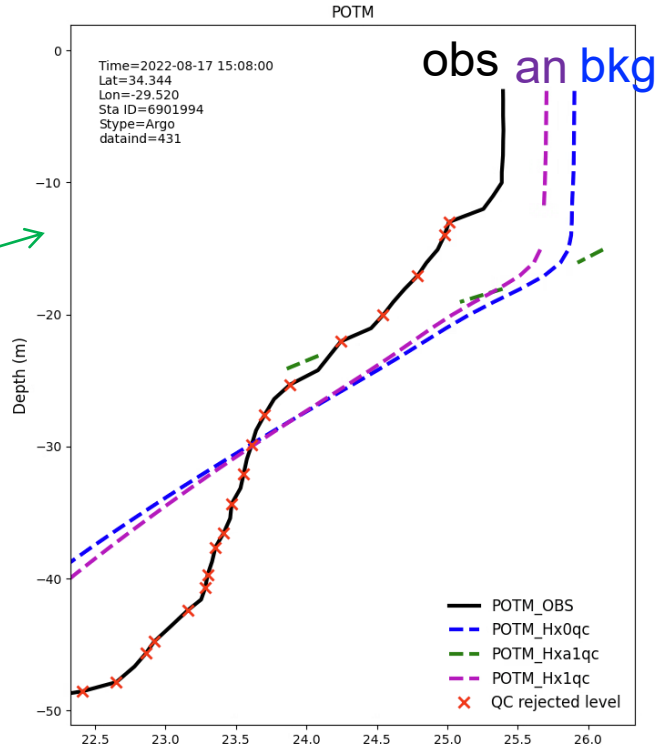
+ Experimental platforms
- ALAMO/AXBT, Saildrone, gliders, ice-tethered profilers

Daily ingestion of ocean in-situ observations

- Use in situ profiles to 6,000 m (including Deep Argo), with vertical thinning; excessive vertical levels in BUFR data are rejected.
- Only temperature and salinity are used; BGC variables are not included.

Available ocean in-situ observations on 17 August 2022

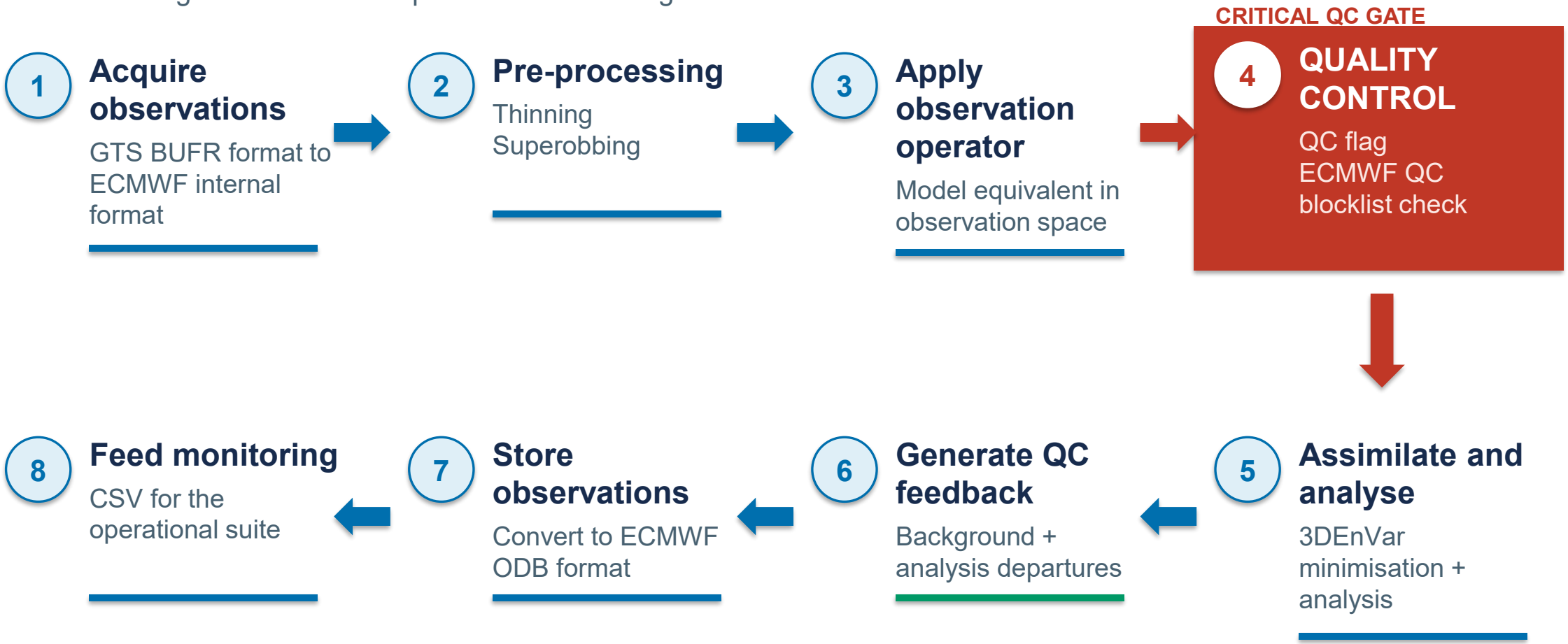




XBT:10 hres CTD:0 Mooring:48 Argo:451 DRB:0
APB:0 UOR:0 CTD:94 Mammals:55 Seaglider:0

Observation processing and quality control system

From incoming observations to operational monitoring



Quality control of in-situ data

A layered QC gate turns raw profiles into analysis-ready observations

1 Incoming profiles
GTS BUFR reports or reprocessed data

2 Pre-screening
QC flag
Manual exclusions

3 ECMWF QC checks
Automatic checks + ECMWF rules

4 Decision & feedback
Accept / reject / monitor
QC feedback file

ECMWF QC checks

PROFILE INTEGRITY	OCEAN CONTEXT	ADDITIONAL SAFEGUARDS
Range + profile checks	Bathymetry + land–sea mask	Consistency + duplication
stability + waterfall checks	Shallow-water + coast-distance	Ad-hoc regional blocklists
Measurement-depth check	Background	

Based on Ingleby and Huddleston (2007) and Good et al. (2013).

Design of OSEs – following the SynObs framework

All OSEs are carried out with a prototype ORAS6 system

Core experiments isolate the contribution of each observing-system component

OSE	SST	Argo	Mooring	Other in-situ types	Altimetry	Sea ice
CNTL	Included	80%	Included	Included	Included	Included
→ **NoInsitu**	Included	—	—	—	Included	Included
→ **NoArgo**	Included	—	Included	Included	Included	Included
HalfArgo	Included	50%	Included	Included	Included	Included
NoMoor	Included	80%	—	Included	Included	Included
→ **NoSST**	—	80%	Included	Included	Included	Included
→ **NoAlt**	Included	80%	Included	Included	—	Included
NoIce	Included	80%	Included	Included	Included	—
Oper	Included	100%	Included	Included	Included	Included

Legend: "—" indicates the observation type is withheld

Localised OSE additions

OSE	Baseline	Observations
FVON	CNTL	Add observations from FVON network
Animal-borne	CNTL	Removal of Animal-borne profiles

ECMWF

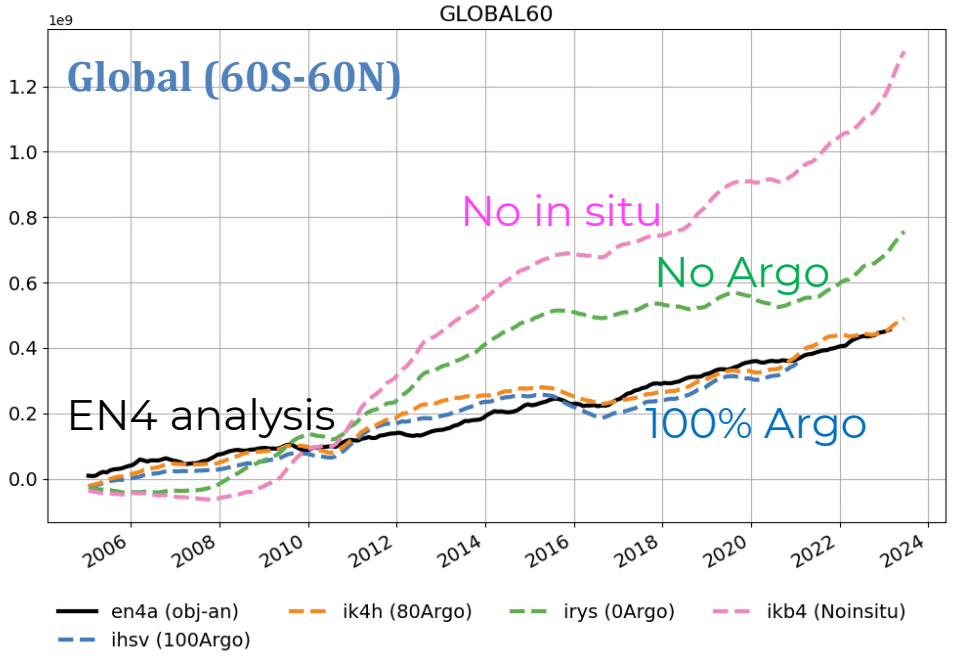
Impact on climate monitoring – ocean heat content

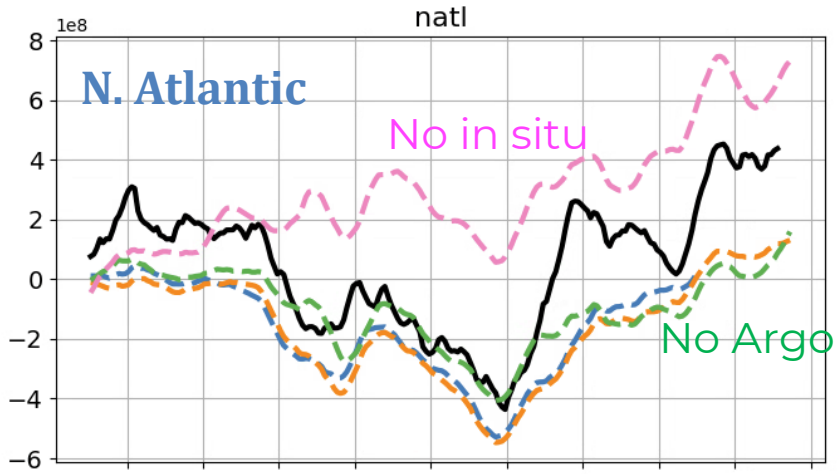
Argo observations play a critical role in monitoring ocean heat content changes, but **their impact varies considerably by region**.

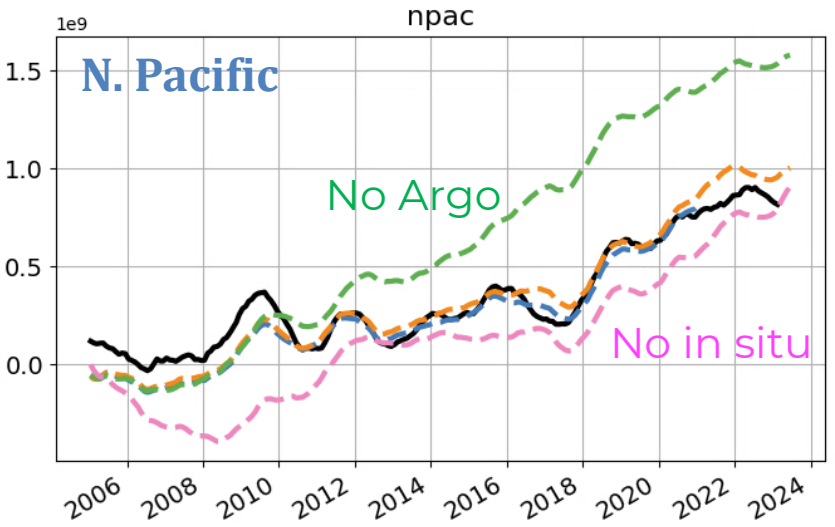
- Removing Argo data degrades ocean heat-content monitoring.
- The impact is smaller in the North Atlantic than in the North Pacific.

More results on climate signals in Magdalena's talk at 13:40 today!

Anomalies of global ocean heat content (0–700 m, in J/m²)







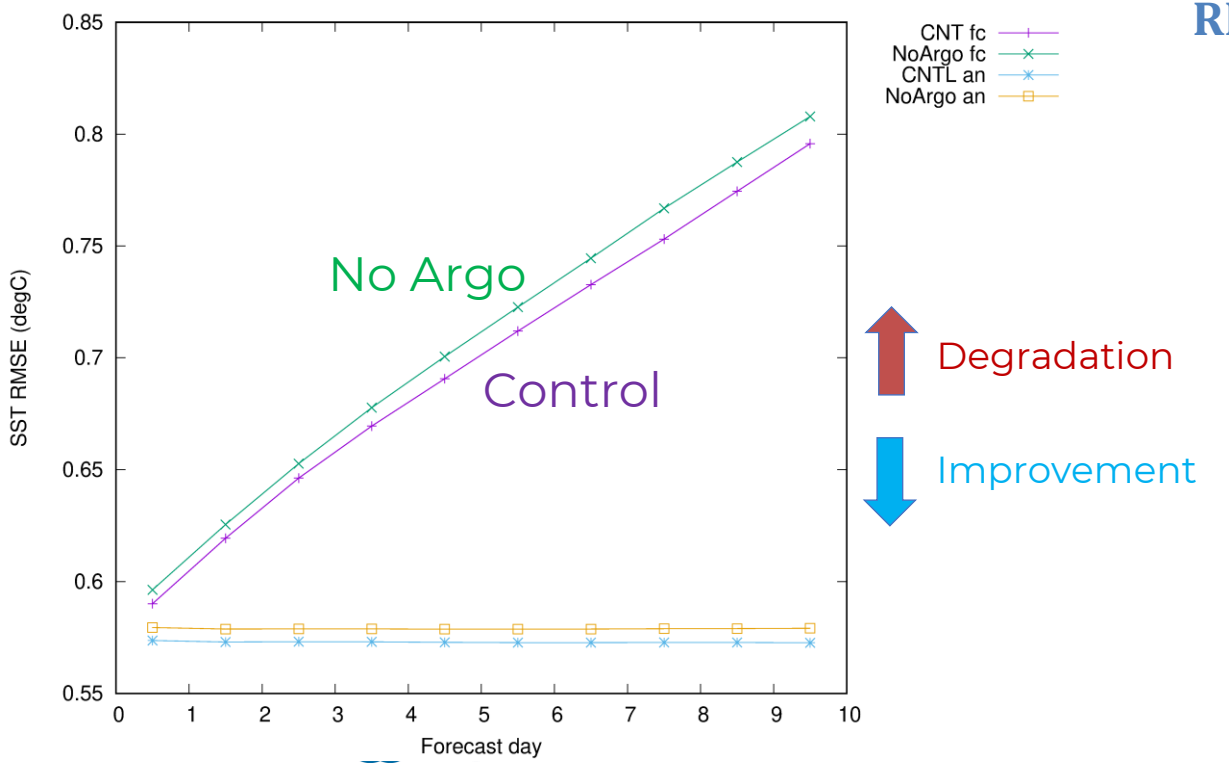
Impact on medium-range forecasts – Argo

Prototype forecasting system

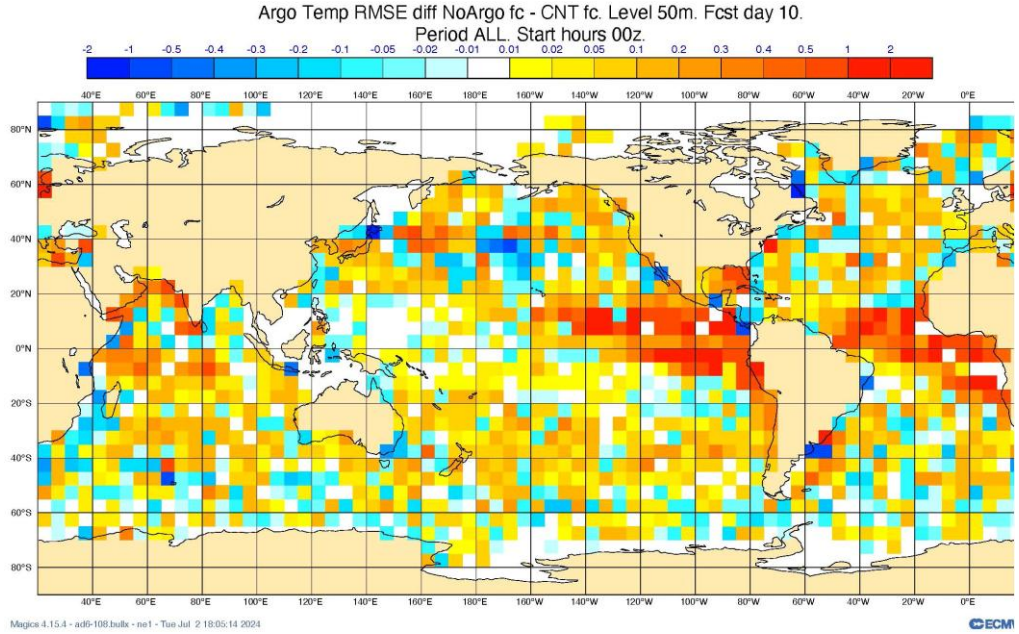
Forecasting period	Two years (Jun 2021–Jun 2023) · daily 00Z
Forecast config.	10 days · TCo1279 atmosphere
Ocean model	eORCA025 · NEMO v4
Initializations	From ORAS6-FP OSEs

- Removing Argo data degrades **SST forecasts** through day 10**.**
- Removing Argo data degrades **subsurface-temperature forecasts** through day 10.

SST forecast errors



RMSE of subsurface temperature (50 m) at day 10

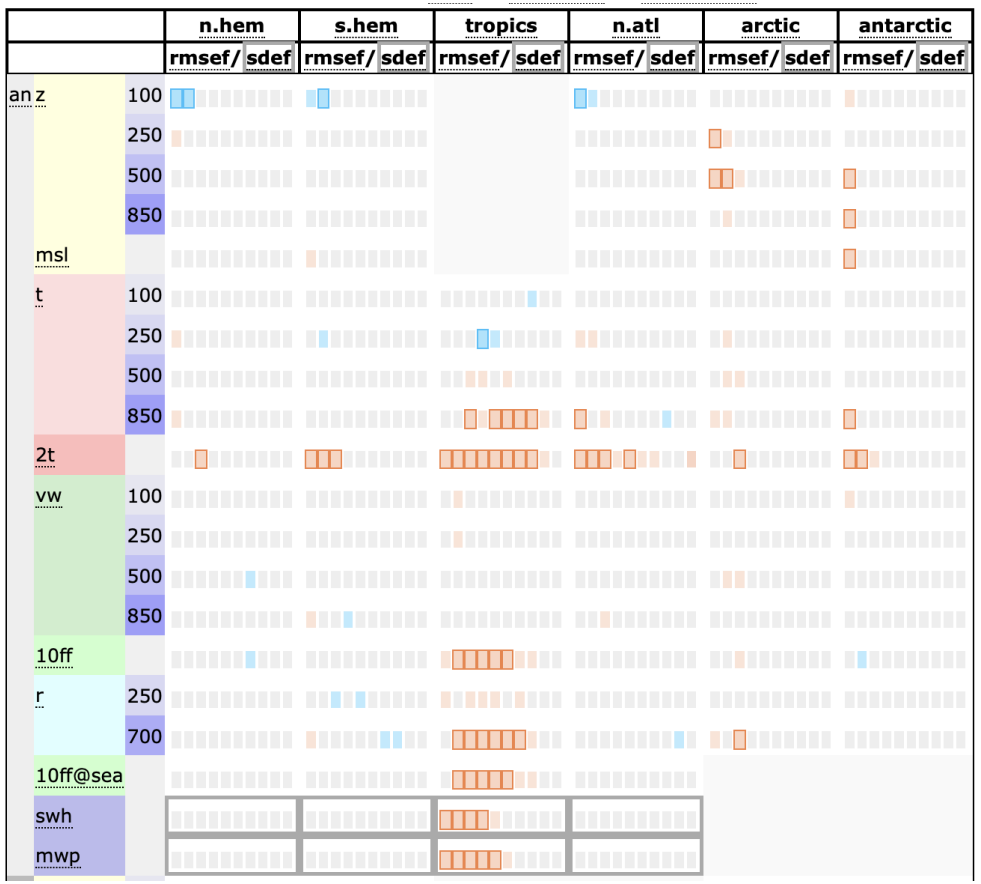


Thierry et al., 2025

Impact on medium-range forecasts – Argo

- There are small but significant degradations in forecast atmospheric fields (**2 m temperature, 10 m wind, significant wave height**, etc.).
- The impact of removing Argo data is **comparable to that of atmospheric model changes** in a typical ECMWF IFS cycle upgrade.

Changes in atmospheric forecast errors
NoArgo - Control



KEY TAKEAWAY

Argo removal degrades forecasts in both ocean and atmosphere

- *2 m temperature (2t)*
- *mean sea level pressure (msl)*
- *temperature (t)*
- *geopotential height (z)*
- *vector wind (vw)*
- *10 m wind speed (10ff)*
- *relative humidity (r)*
- *significant wave height (swh)*
- *mean wave period (mwp)*

Degradation

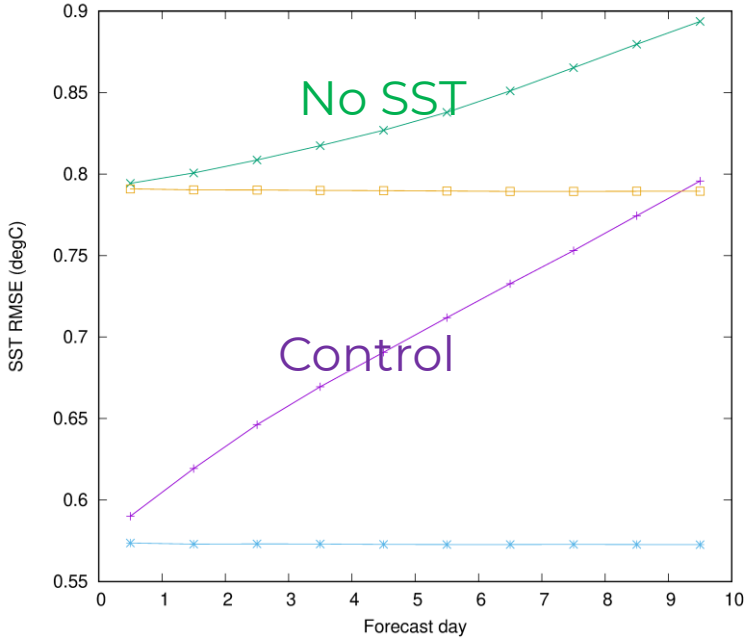
Improvement

ECMWF

Impact on medium-range forecasts – SST data

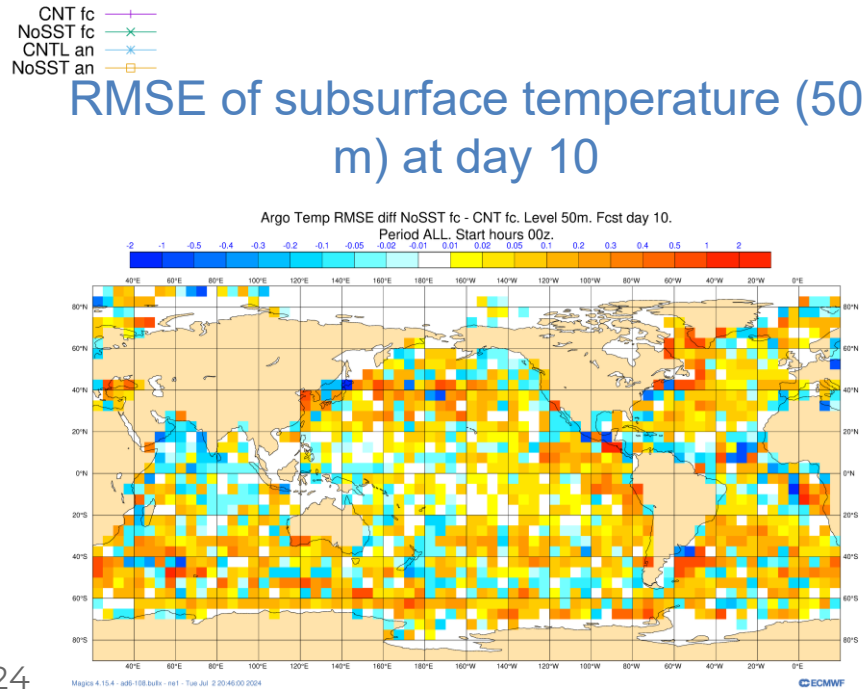
- **Withholding SST observations** strongly degrades SST forecast accuracy through day 10.
- The day-10 ocean-temperature forecast at 50 m also degrades, while atmospheric fields show a substantial negative impact.

SST forecast error through day 10



Source: Kristian Mogensen, OceanPredict24

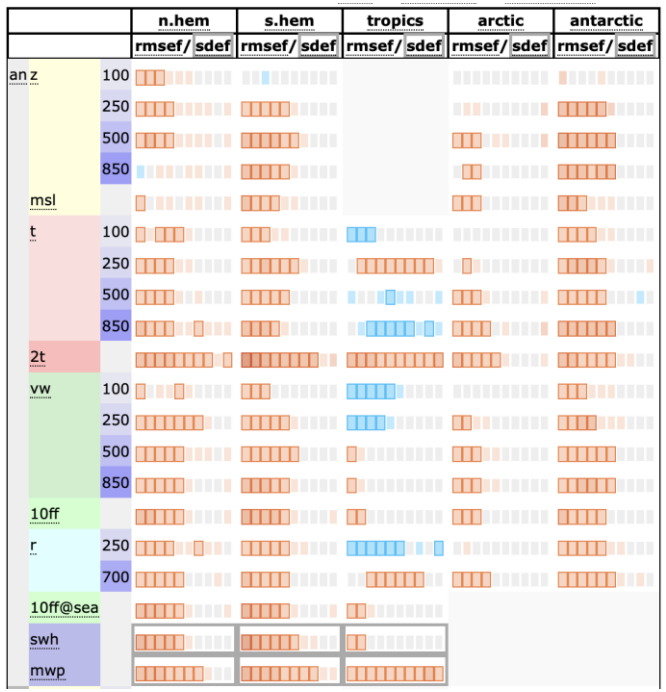
RMSE of subsurface temperature (50 m) at day 10



KEY TAKEAWAY

Largest impact among the OSEs performed

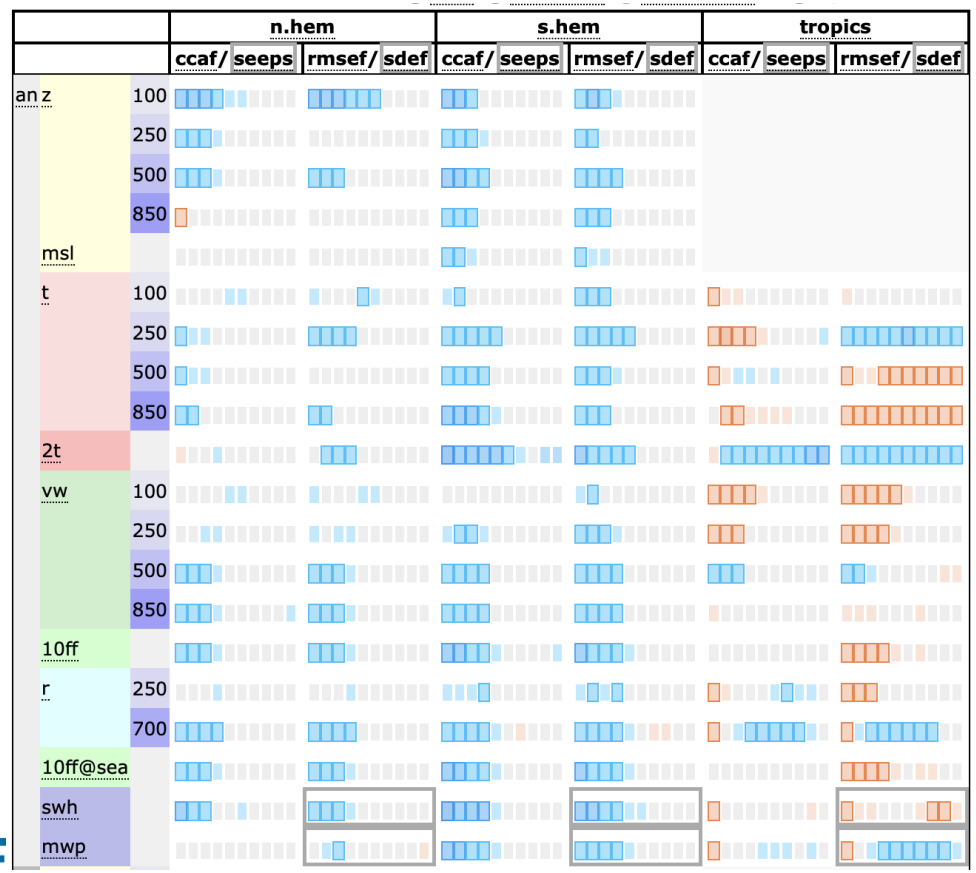
Atmospheric forecast errors NoSST – Control



Impact on medium-range forecasts – SST data

- Compared with SST nudging, **assimilating** the same SST data with **En3DVar** in ORAS6 improves both initial states and medium-range forecast scores.

Atmospheric forecast errors:
SST DA – SST nudging



Red indicates worse performance than the control.

Blue indicates better performance than the control.

Colour intensity is proportional to the normalised difference.

Outlined cells are significant at 99.7%; differences below 95% significance are masked in light grey.

KEY TAKEAWAY

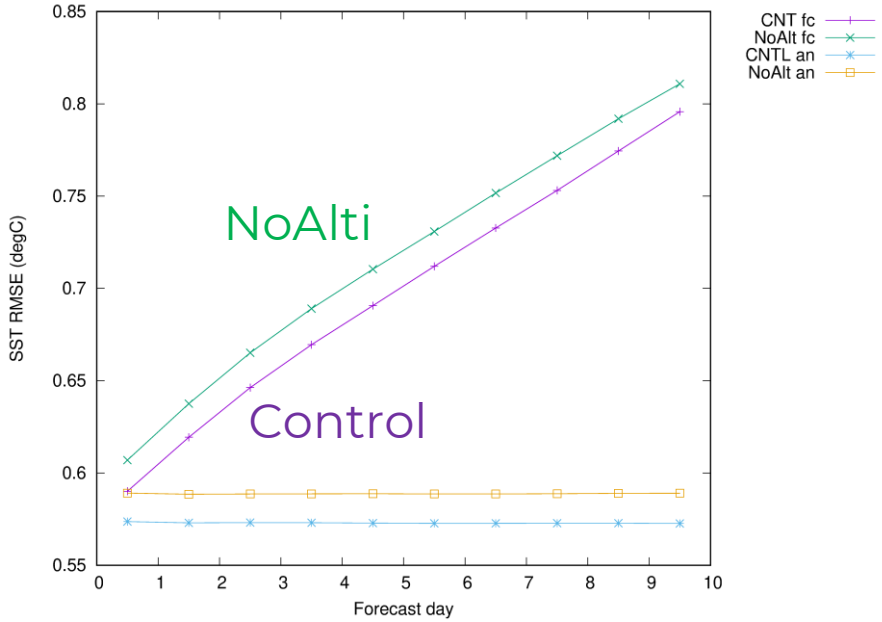
Better usage of existing observations is equally important

Better ocean initial conditions can be achieved not only by improving observation networks, but also by making better use of existing observations in operational ocean data assimilation systems.

Impact on medium-range forecasts – Altimeter data

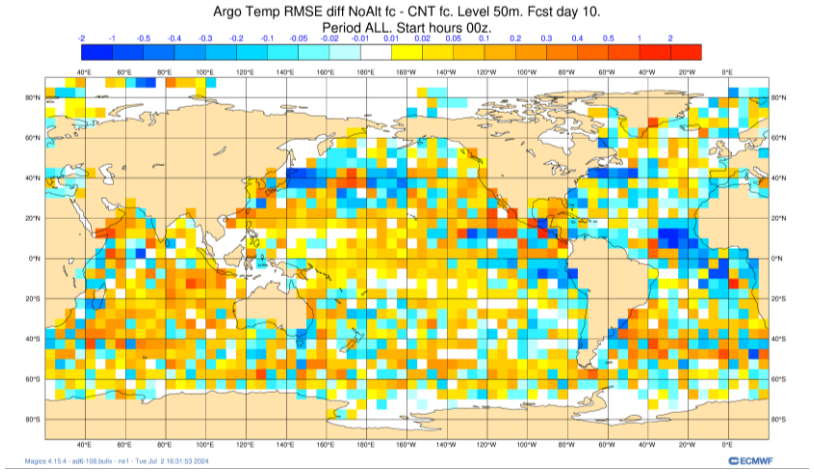
- **Withholding altimeter observations** degrades SST and subsurface-temperature forecast performance.
- Atmospheric fields show a small but significant degradation, comparable in scale to changes in a typical IFS cycle upgrade.

SST forecast error through day 10



Source: Kristian Mogensen, OceanPredict24

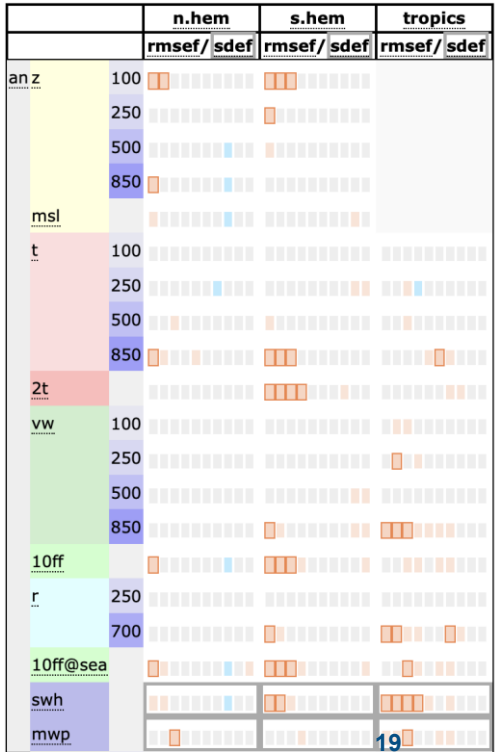
RMSE of subsurface temperature (50 m) at day 10



ATMOSPHERIC SIGNAL

Small but significant cycle-scale impact

Atmospheric forecast errors NoAlti – Control



Impact on medium-range forecasts – all in-situ data

ADD OBSERVATIONS

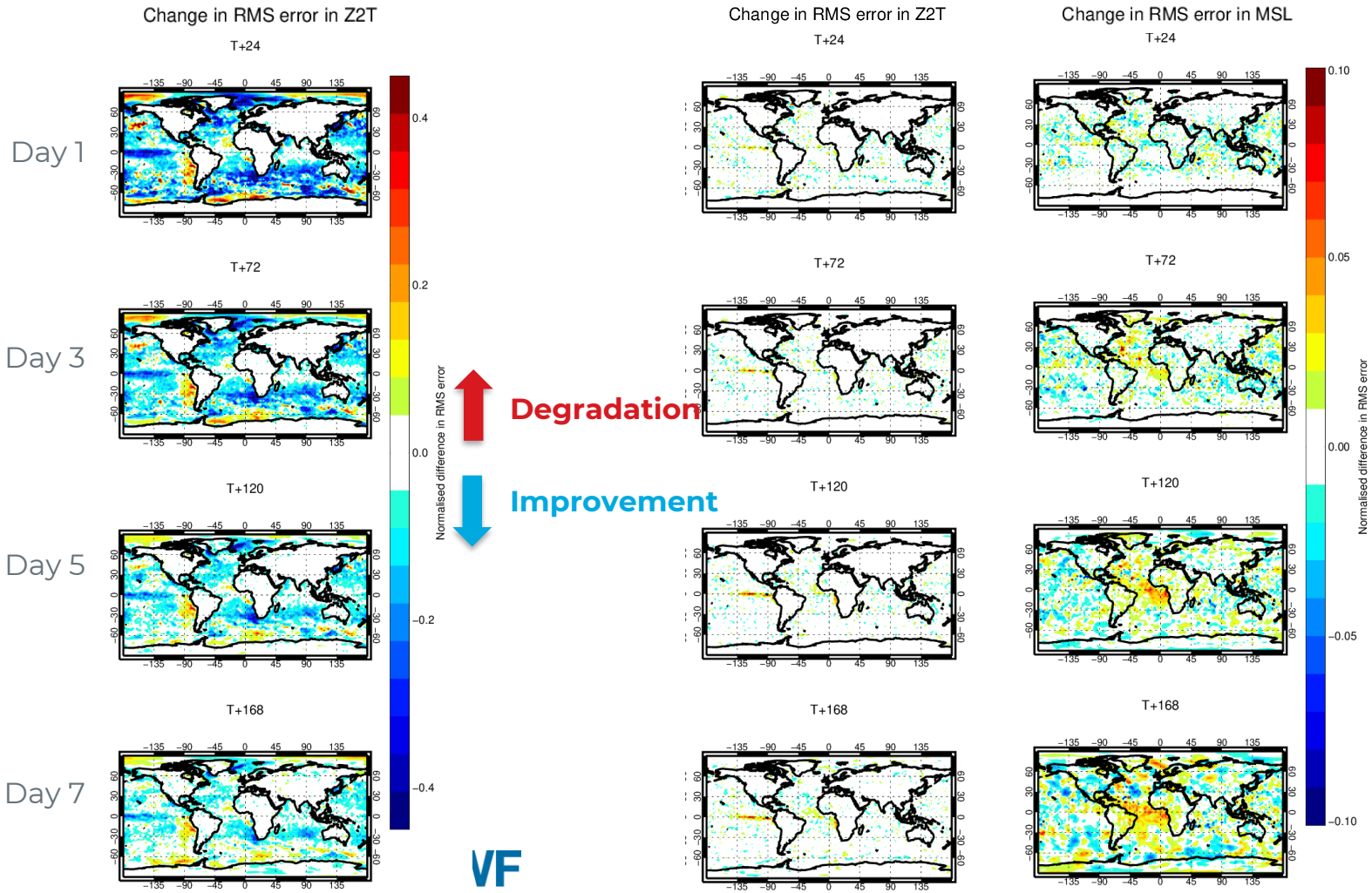
In-situ + altimeter

Reference is a free run without data assimilation

WITHHOLD OBSERVATIONS

Remove all in-situ

Reference is the CNTL including all data



KEY TAKEAWAY

In-situ data have a greater impact when SST observations are absent

- **Adding in situ and altimeter data** substantially improves 2 m temperature forecasts.
- **Withholding in situ observations** degrades 2 m temperature forecasts near the equator and mean sea-level pressure forecasts over the Atlantic Ocean.

Additional OSE – IMOS-SOOP data (FVON)

OBSERVATION COVERAGE

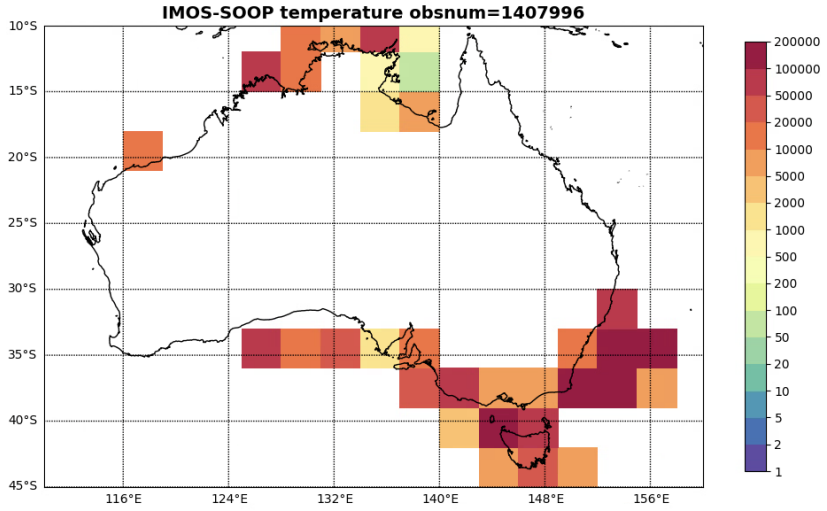
- Temperature sensors attached to fishing gear
- Around the Australian coast, part of the FVON network
- Available from 2022 onward, including NRT data
- Additional FVON data (e.g. Atlantic ARC) is being processed

ASSIMILATION REQUIREMENTS

- **Revised QC settings are required** (e.g. blocklist checks for water depth and distance to coast), as nearly all IMOS-SOOP data are in coastal or shallow-water regions.
- **Spatial and temporal thinning is required** because fishing vessels collect high-frequency samples (every few minutes).

IMOS-SOOP data in 2023

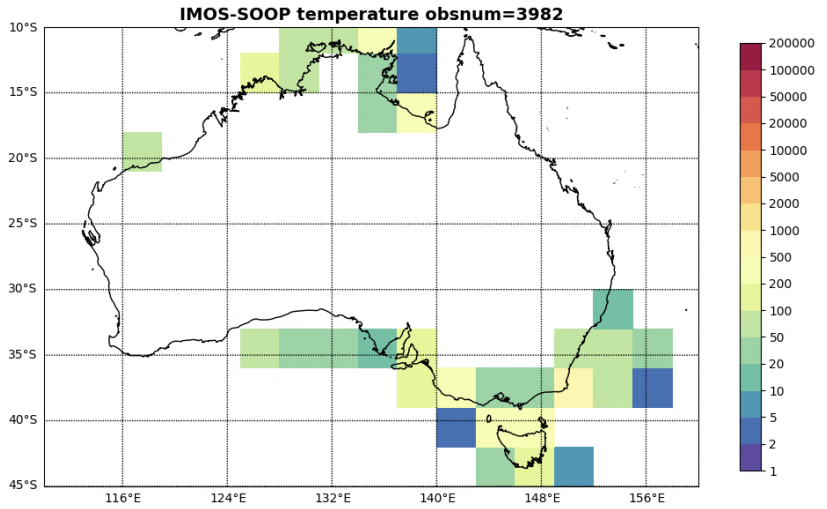
Raw data



QC + SPATIAL / TEMPORAL THINNING

→

After thinning



ECMWF

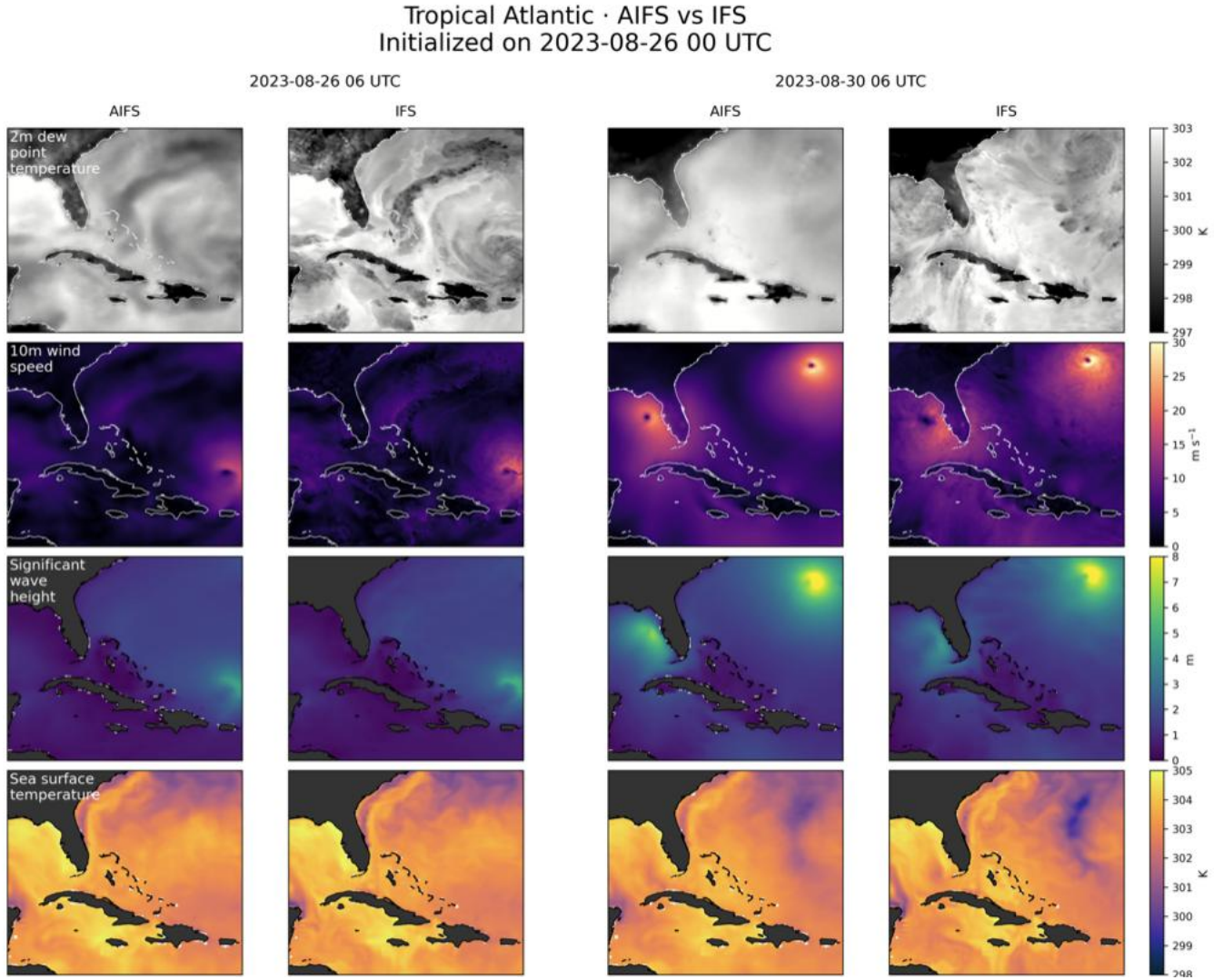
OSEs with the AIFS Marine ML model

Representing the surface ocean in **ECMWF's data-driven forecasting system, AIFS** – https://arxiv.org/pdf/2604.25559

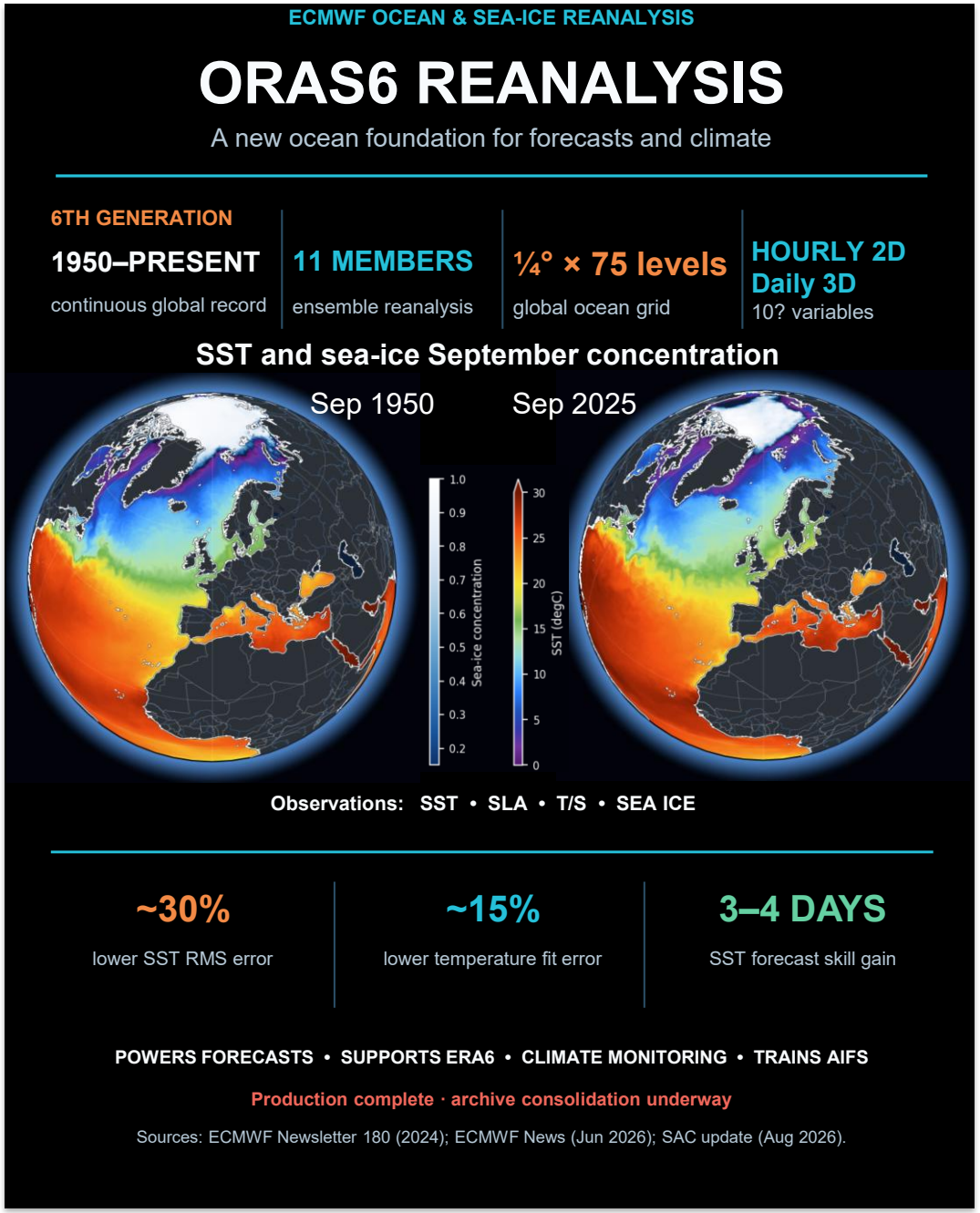
- Use a single ORAS6 member as the training data set (1993–2023)
- Representing the surface ocean in AIFS affects medium-range weather forecasts

Ongoing work on AIFS Marine OSEs

- **Retrain AIFS marine** with different OSE reanalyses
- Use OSEs as different initial conditions



Hahner et al., 2026



Summary

- **ORAS6 provides a modern OSE foundation.** Upgraded ocean–sea-ice models, hourly ERA5 forcing and ensemble-based variational assimilation support a consistent 1950–present record.
- **Observation impacts are clear.** Argo is critical for upper-ocean monitoring and forecasts; withholding SST causes the largest medium-range degradation, while altimetry and other in situ data also produce significant signals.
- **Impact depends on context.** OSEs reveal strong regional and cross-system dependencies – for example, in situ observations become more influential when SST is absent.
- **New networks need tailored assimilation.** FVON and animal-borne observations extend sampling, but require adapted quality control and spatial–temporal thinning.
- **Data are ready to use.** SynObs distributes ORAS6 Pilot OSE outputs for multi-system studies.

Thank you!

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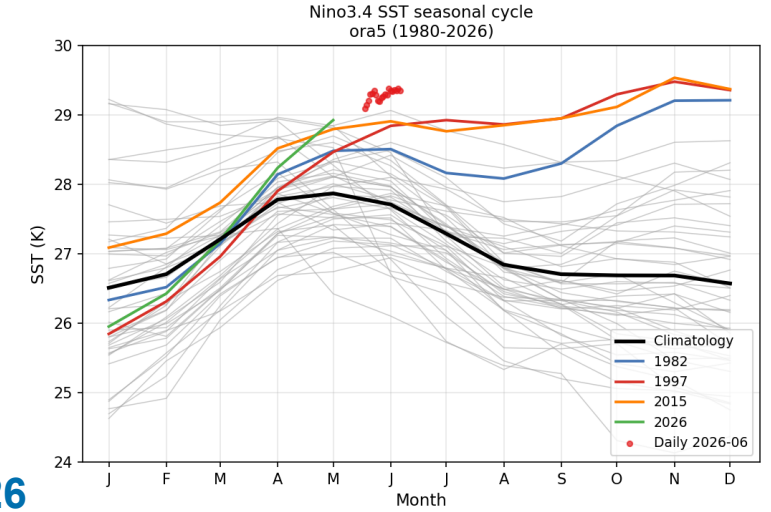
www.ecmwf.int

Extra slides

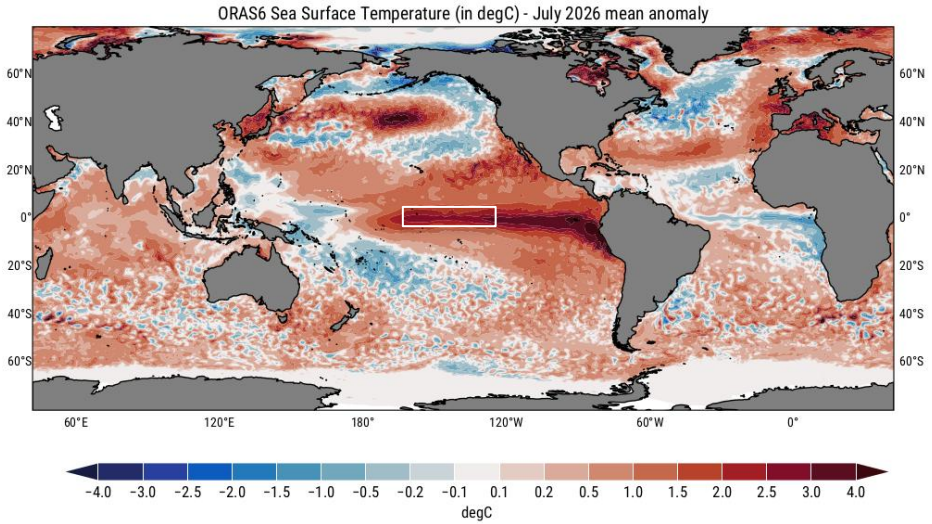
Ocean Real-time Monitoring – the 2026 El Niño

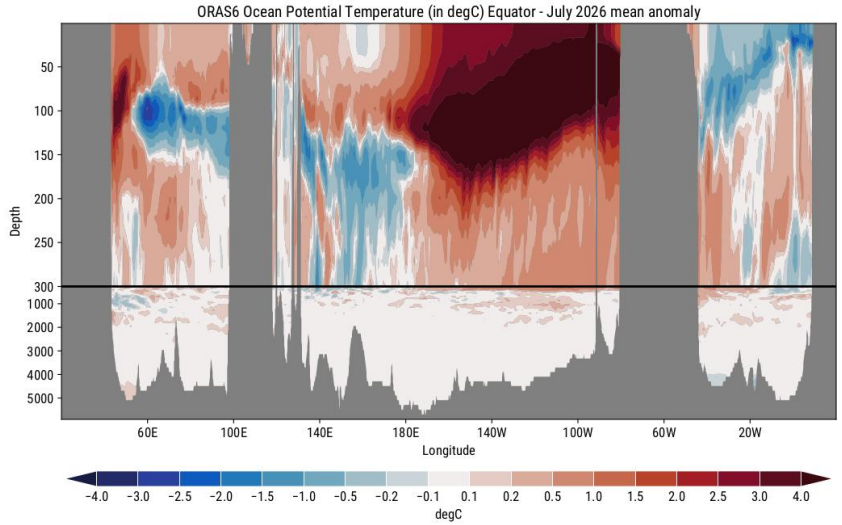
- **ORAS6** enables real-time monitoring of ocean conditions using **67 two-dimensional** and **16 three-dimensional variables.**
- **The 2026 El Niño event** provides an example, with **extreme sea-surface warming** in the central and eastern equatorial Pacific and a **major eastward shift** of the western Pacific warm pool.
- **Could this event still be represented and monitored if some observing networks were unavailable?**

Niño 3.4: 5N-5S, 170W-120W



Ocean temperature anomaly in July 2026





ECMWF

Additional OSE – animal-borne data

OBSERVATION CONTEXT

- Animal-borne ocean-sensor data (AniBOS/IMOS) form an emerging GOOS network.
- Temperature and salinity data are collected from marine mammals, such as seals and turtles.
- Data are identified by a common WMO station ID (Q990-----).
- **The block-out experiment is ongoing.**

ANIMAL-BORNE SENSORS



Images from anibos.com



Images from anibos.com

Animal-borne data in June 2023

