Impact of Ocean Observations on the ECMWF Ocean DA System and Medium-range Weather Forecasts

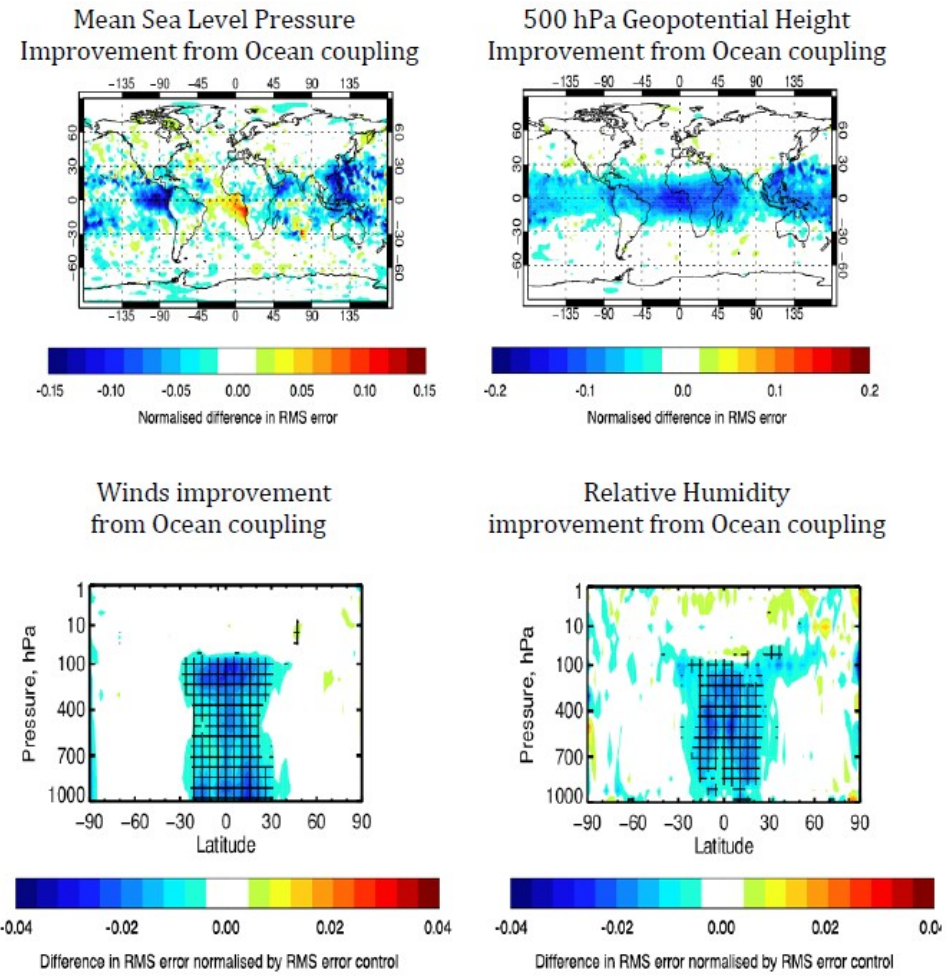
Hao Zuo, Kristian Mogensen, Eric de Boisseson, Sarah Keeley

European Centre for Medium-Range Weather Forecasts

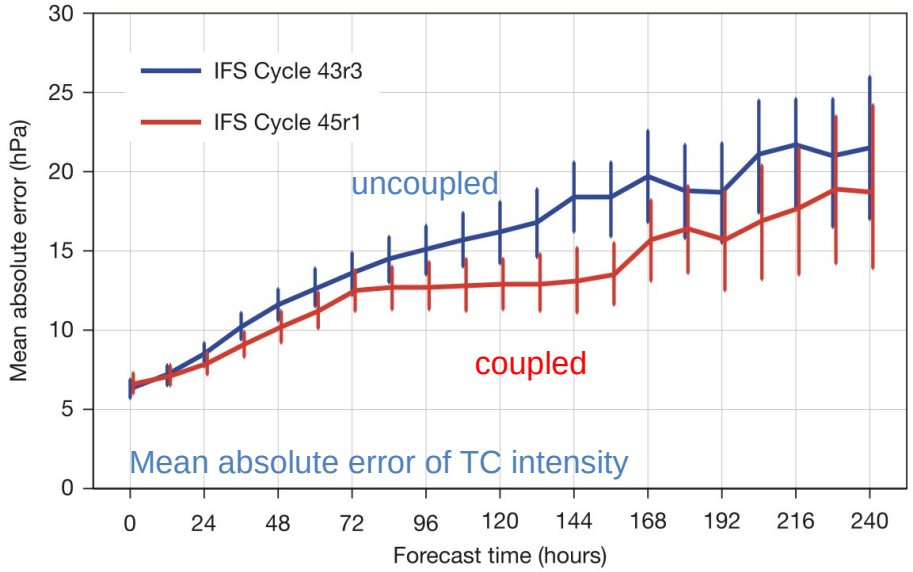
Hao.Zuo@ecmwf.int

OceanPredict CP-TT/DA-TT workshop
October 26-30, 2026, ECMWF, UK

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).

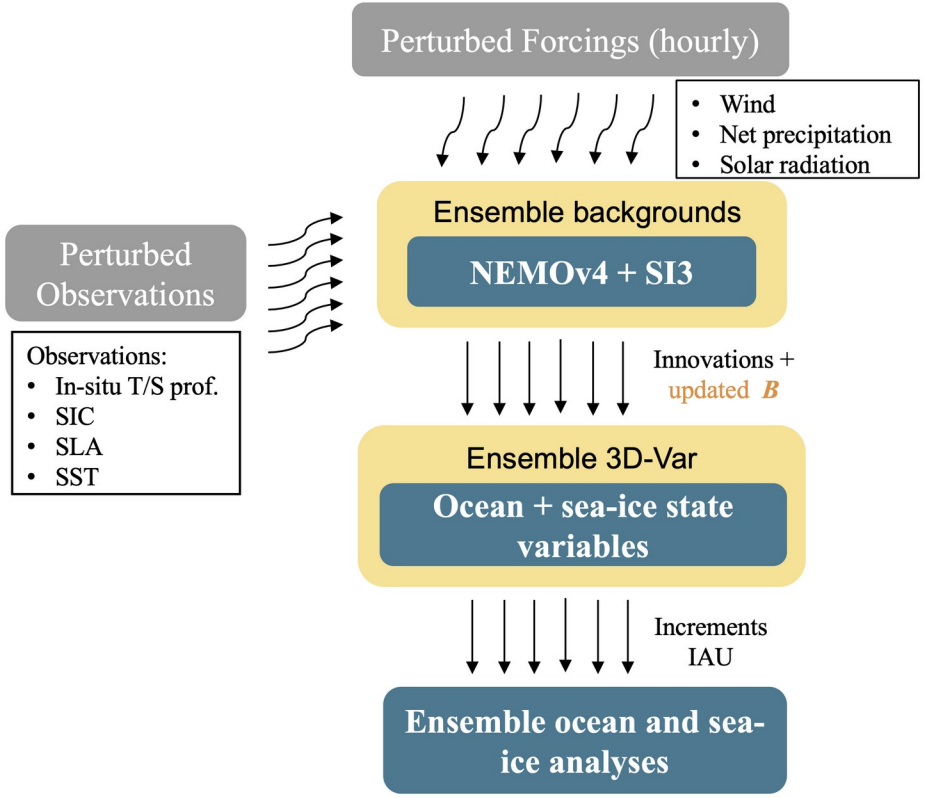


ECMWF ocean (and sea-ice) reanalyses



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		

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

Other updates

- *Updates on Ensemble generation*
- *Updates on Bias Correction scheme*
- *Assimilation of L3 OSI-SAF SIC with SI3*
- *Updates on SSH DA with new MDT approach and refined balance relationship*
- *New method on FWB/GMSL constrains*
- *Update observations datasets*

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*)

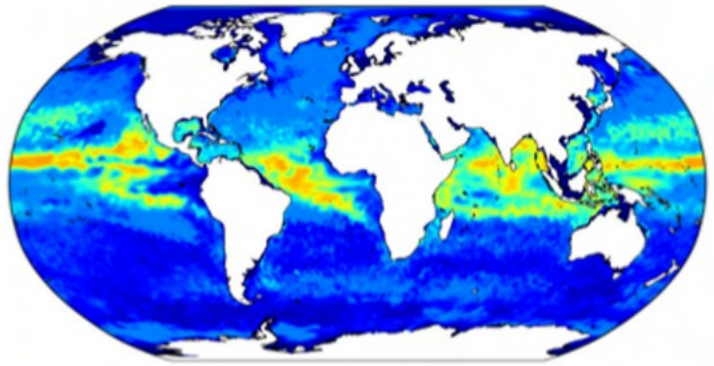
$$B_h = K_b D_h^{1/2} C_h D_h^{1/2} K_b^T$$

is the hybrid covariance matrix; is the correlation matrix (using hybrid diffusion operator); is a block-diagonal matrix of variances (using hybrid std dev).

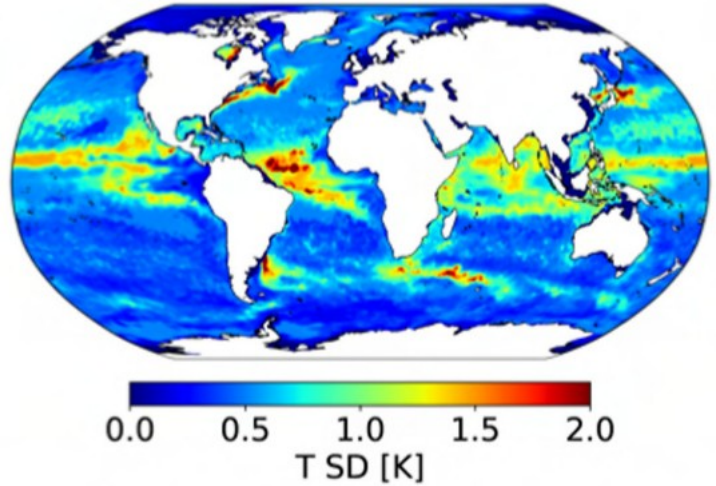
Hybrid background-error standard-deviation formulation

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

Parameterized



Hybrid



(Chrust et al., 2024, QJRMS)

ECMWF OCEAN & SEA-ICE REANALYSIS

ORAS6 REANALYSIS

A new ocean foundation for forecasts and climate

6TH GENERATION

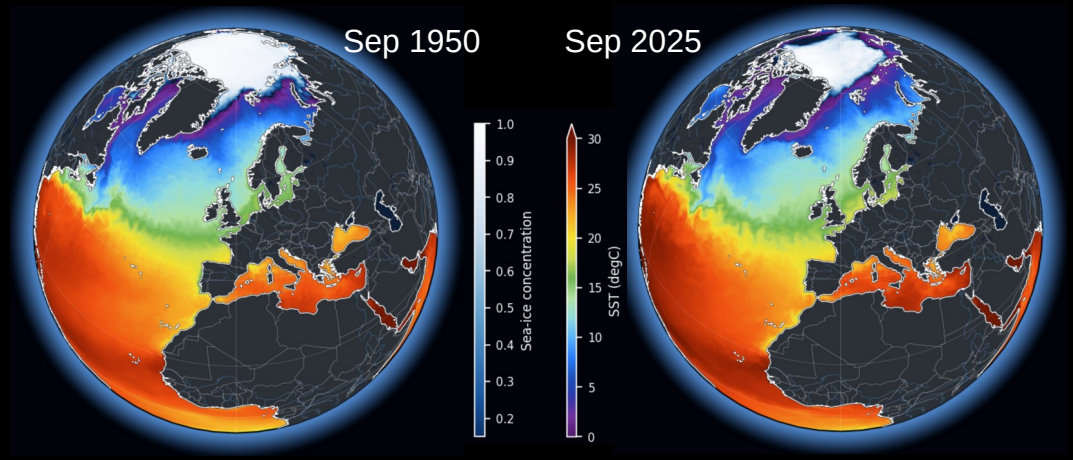
1950–PRESENT
continuous global record

11 MEMBERS
ensemble reanalysis

¼° × 75 levels
global ocean grid

Hourly 2D
Daily 3D
83 variables

SST and sea-ice concentration



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

~30%
lower SST RMS error

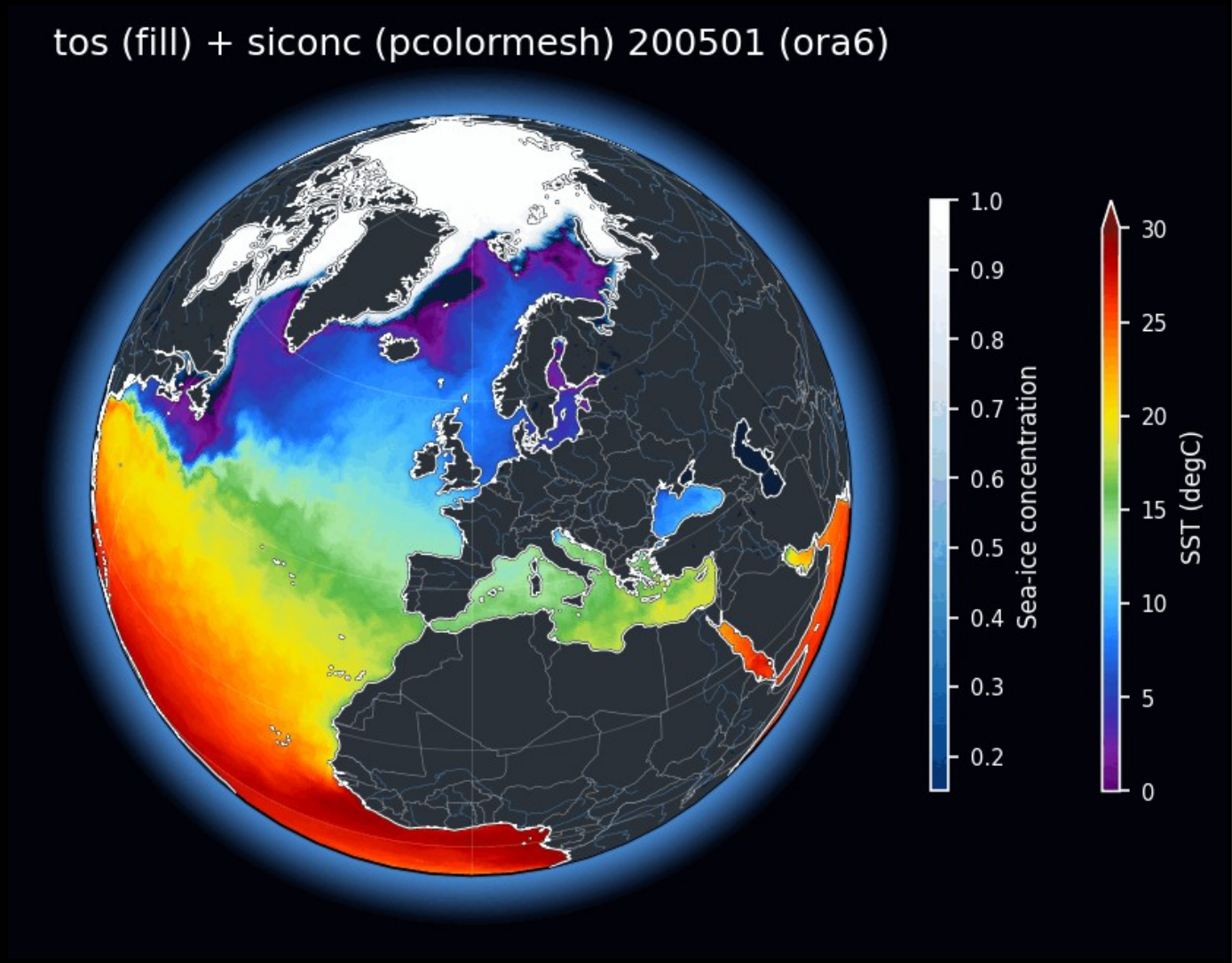
~15%
lower temperature fit error

3–4 DAYS
SST forecast skill gain

POWERS FORECASTS • SUPPORTS ERA6 • CLIMATE MONITORING • TRAINS AIFS

Production complete · archive consolidation underway

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

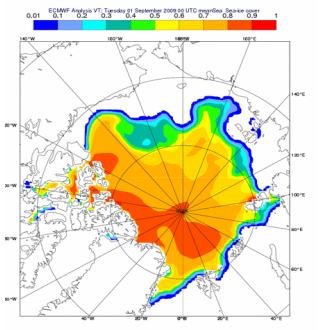


ECMWF

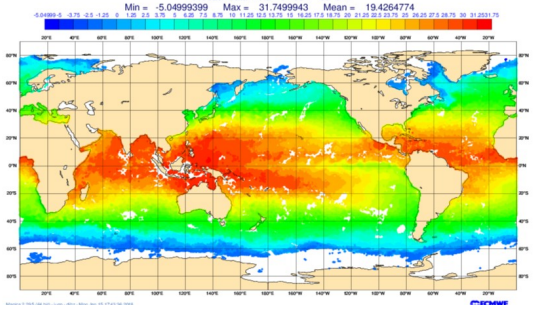
What observations are used by ORAS6 ?

Satellite data

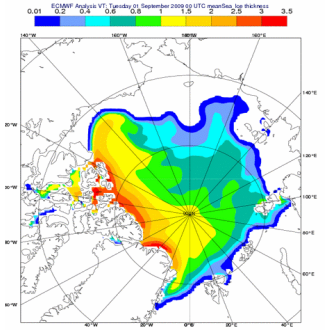
Sea-ice concentration



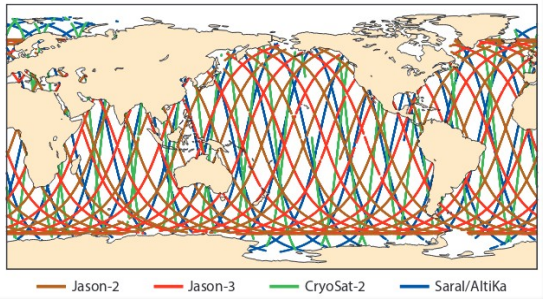
SST (IR, PMW)



Sea-ice thickness - FB (under-development)



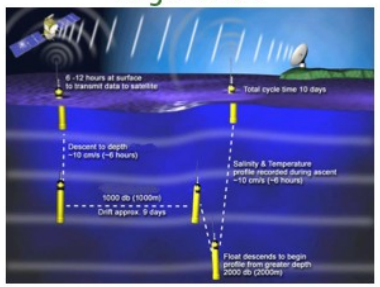
Sea-Level Anomaly (Altimeter)



ORAS6

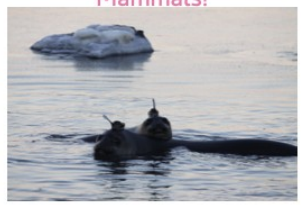
Ocean in situ data

Argo floats



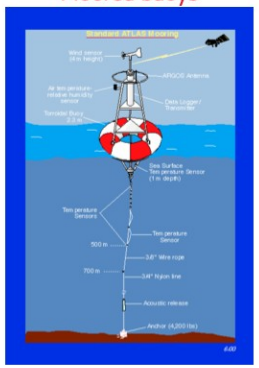
Argo operational cycle.
[Argo 2018]

Mammals!



[MEOP et al. 2015]

Moored buoys



[PMEL 2018]

Ship based observations





[CSIRO 2001]

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

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).

ECMWF

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

Extra OSEs

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

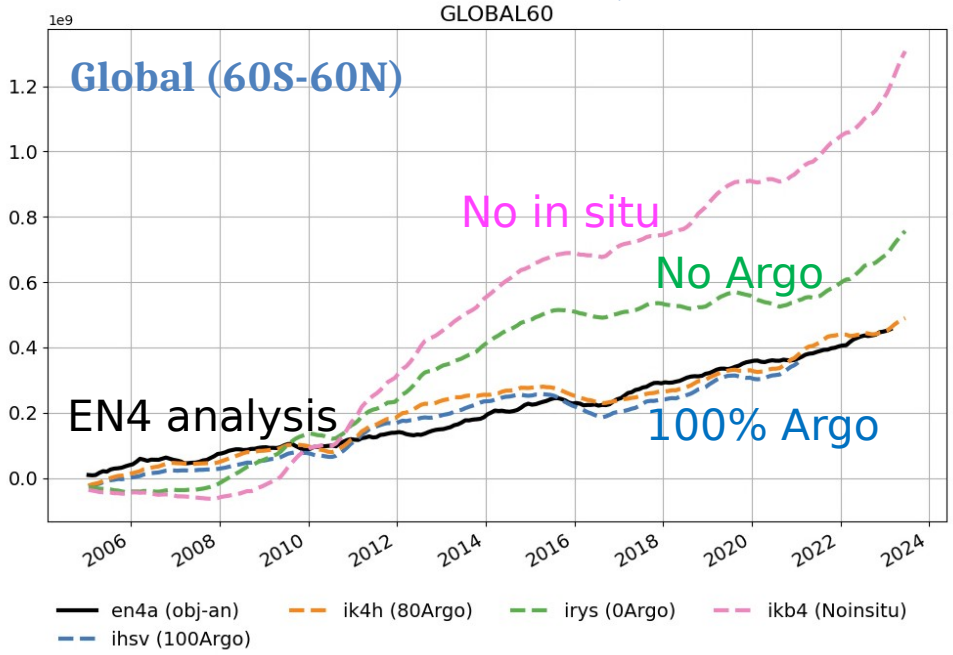
ECMWF

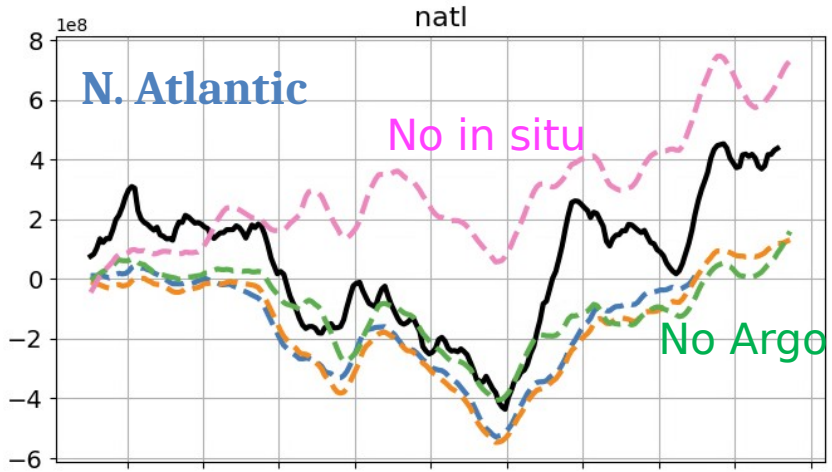
Impact on climate monitoring – ocean heat content

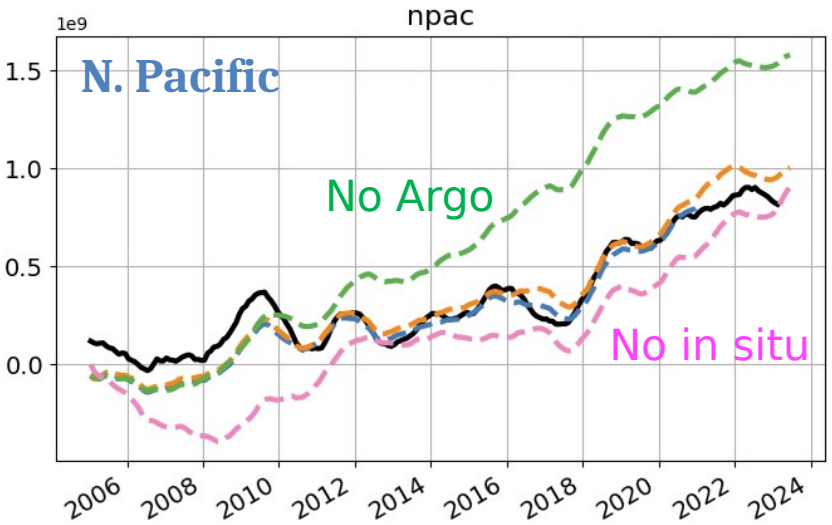
Argo observations play a critical role in monitoring ocean heat content changes, but **their impact varies considerably by region**.

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

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







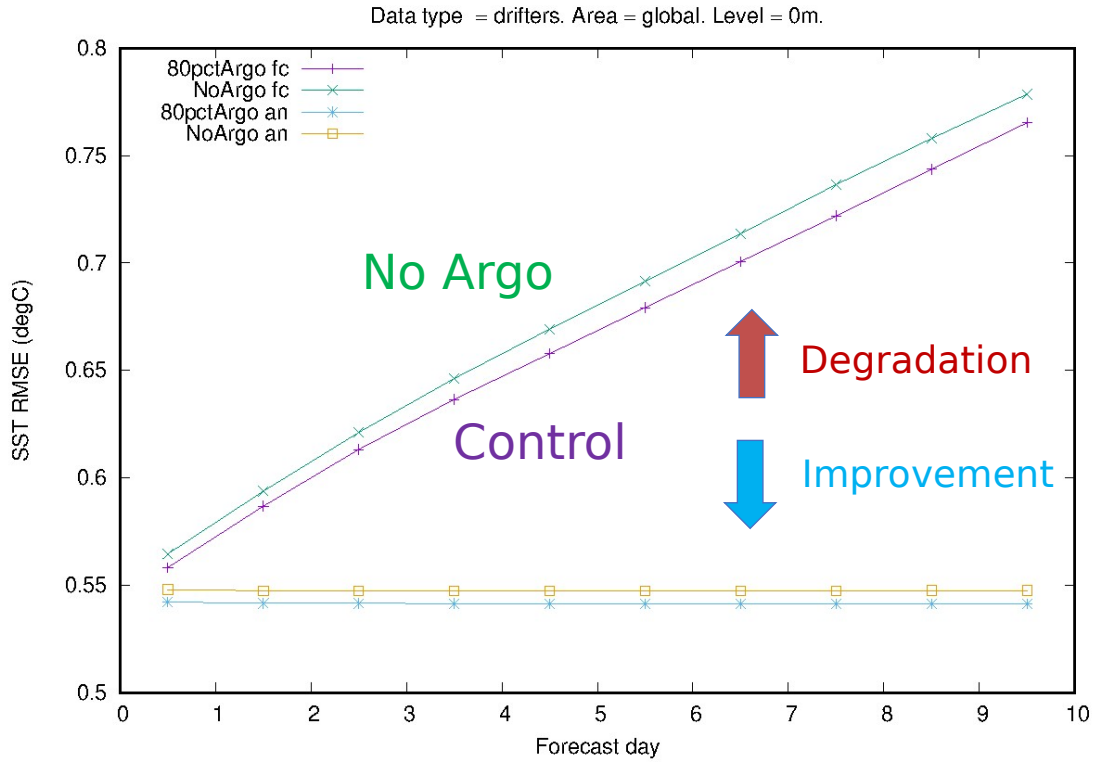
Impact on medium-range forecasts – Argo

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

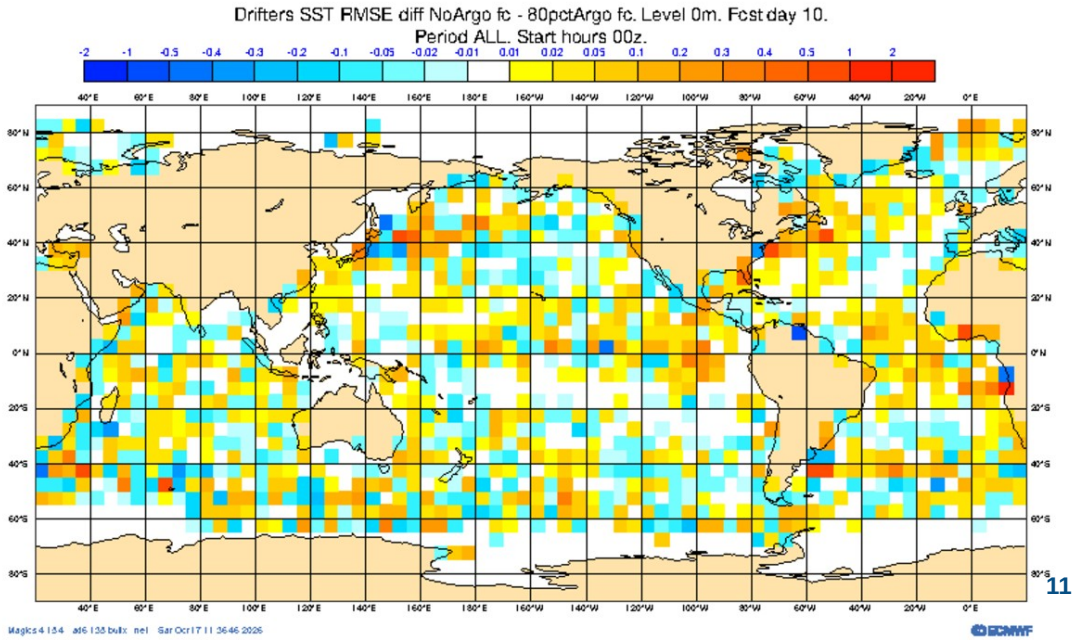
- Removing Argo data degrades **SST forecasts** (by ~1-day) at day 10**.**

SST forecast errors



Verification against drift SST (passive)

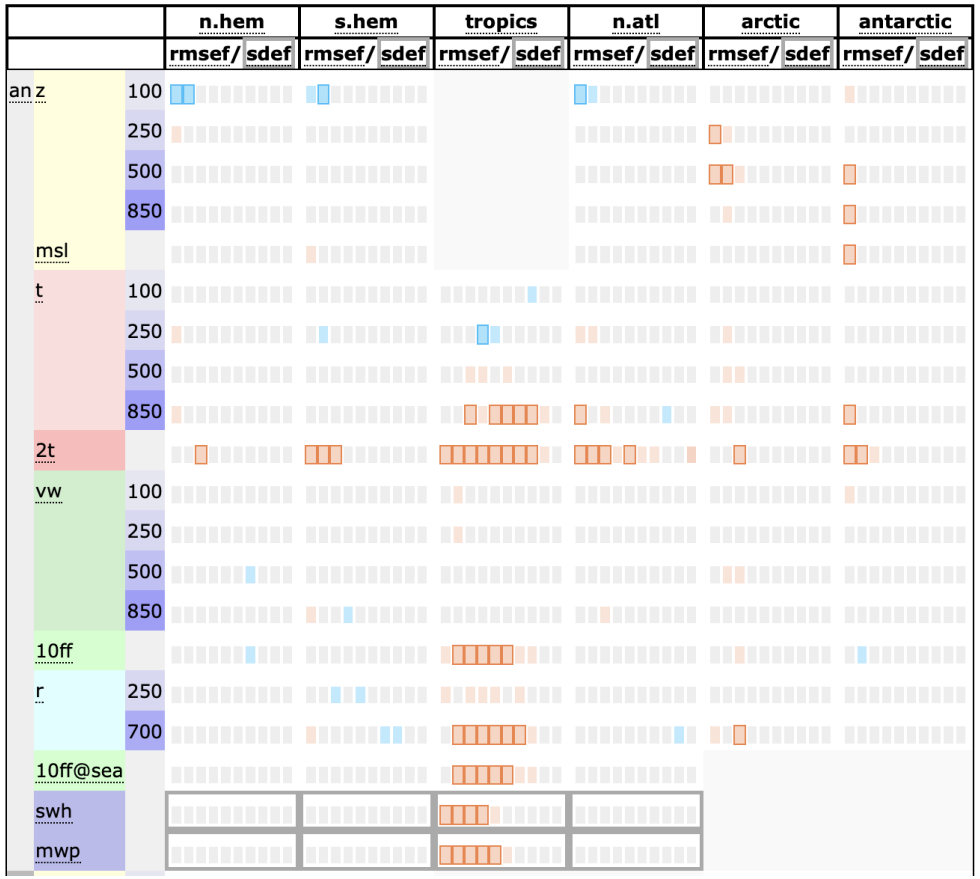
RMSE of SST FC at day-10: NoArgo - Control



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)*

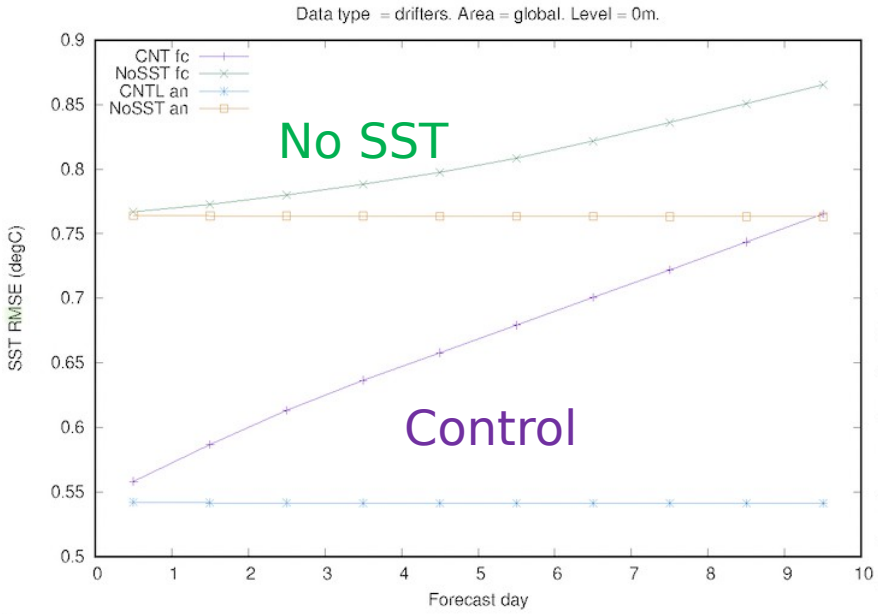
Degradation

Improvement

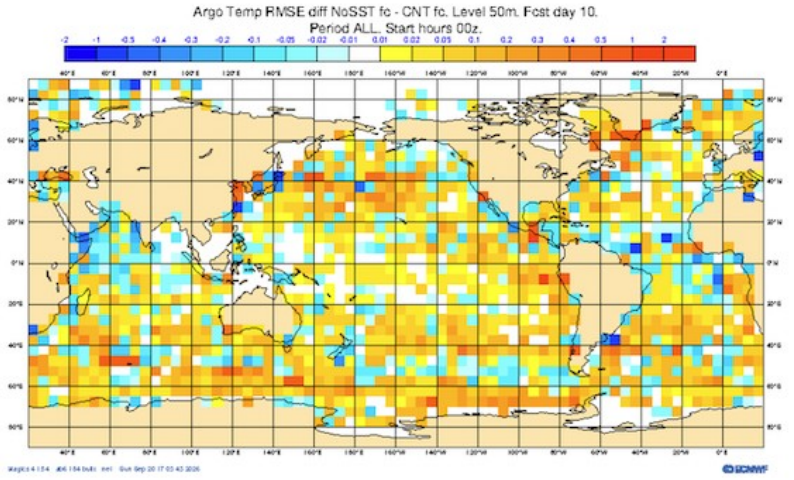
Impact on medium-range forecasts – SST data

- **Withholding SST observations** strongly degrades SST forecast accuracy (by ~10-days).
- 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



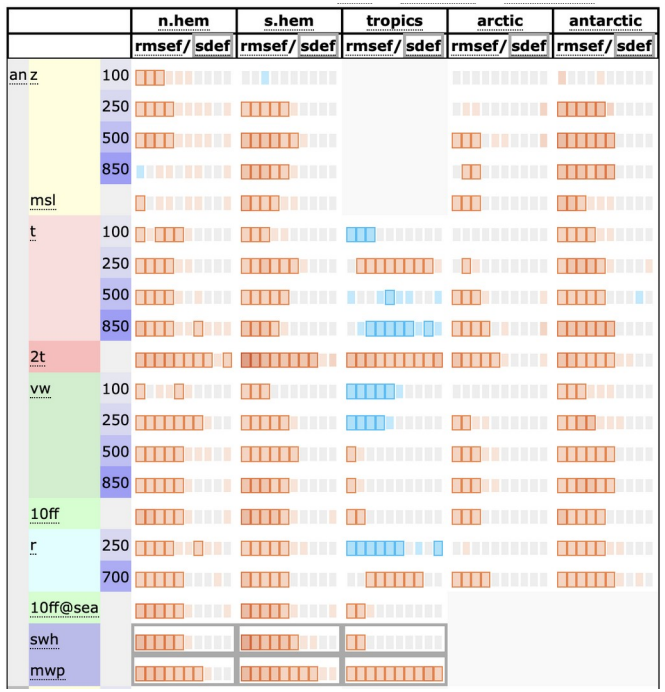
RMSE of 50m T FC at day-10
NoSST - Control



KEY TAKEAWAY

Largest impact among the OSEs performed

Atmospheric forecast errors
NoSST – Control

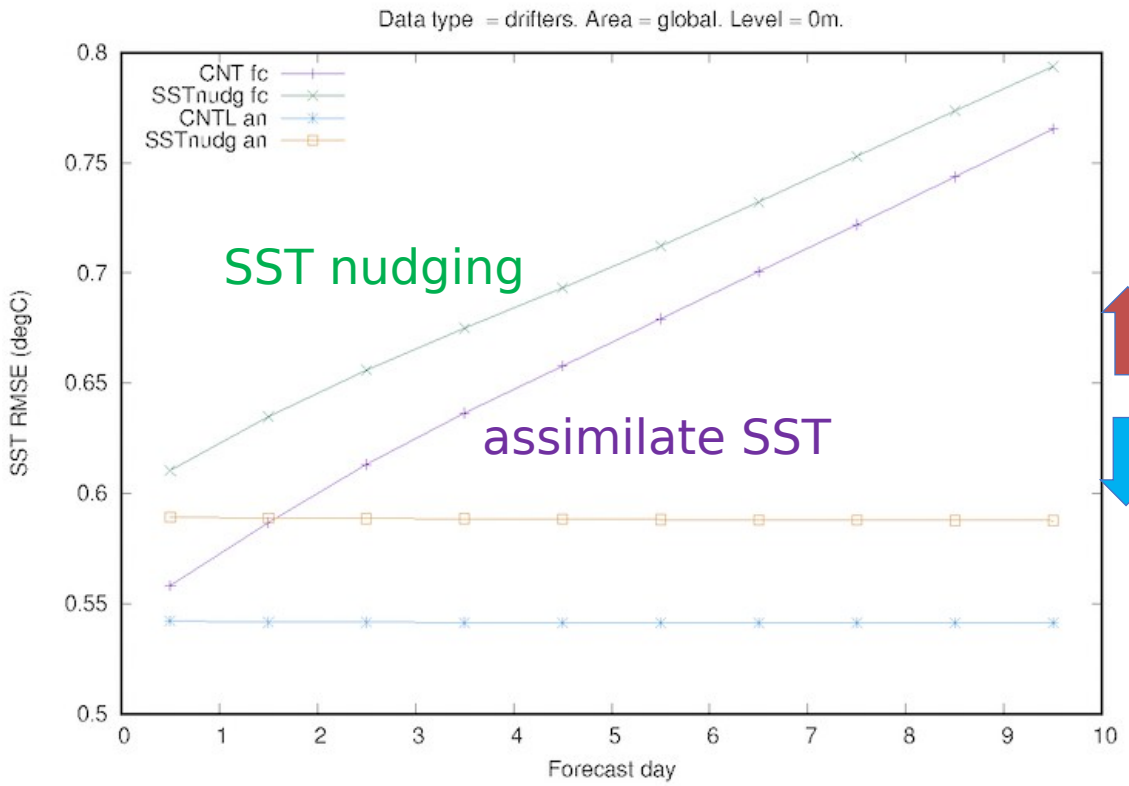


Impact on medium-range forecasts – SST data

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

KEY TAKEAWAY

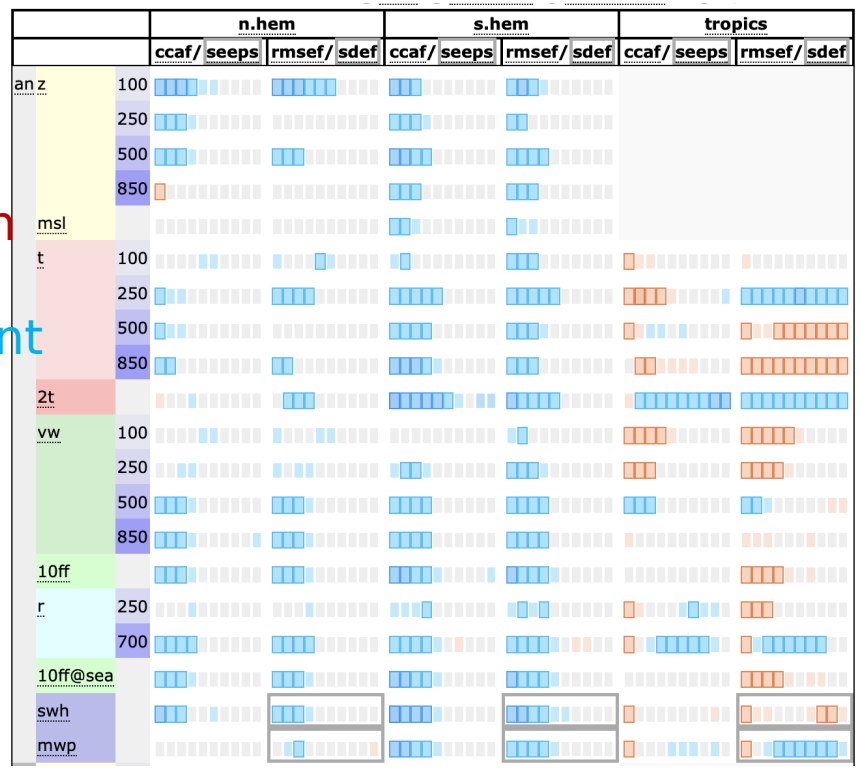
How to ingest SST observations is the key



Degradation

Improvement

Atmospheric forecast errors: SST DA – SST nudging



ECMWF

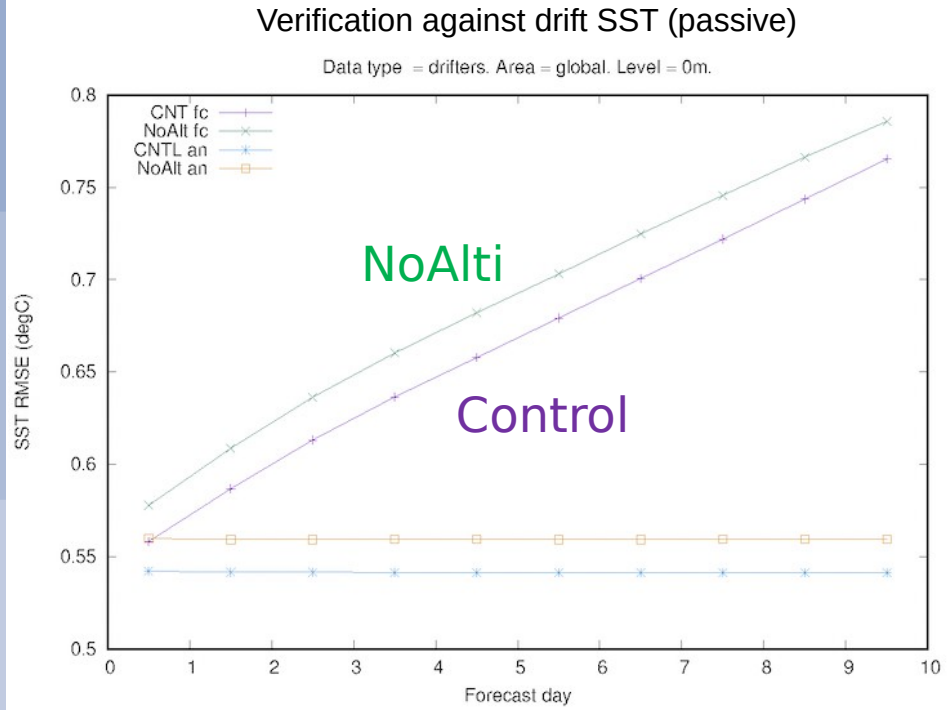
Impact on medium-range forecasts – Altimeter data

- **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.

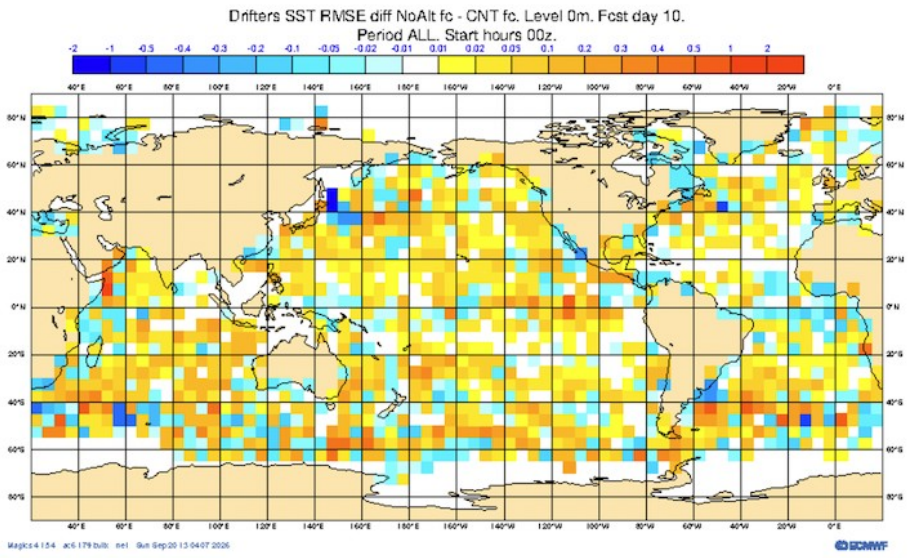
ATMOSPHERIC SIGNAL

Altimeter data show significant cycle-scale impact

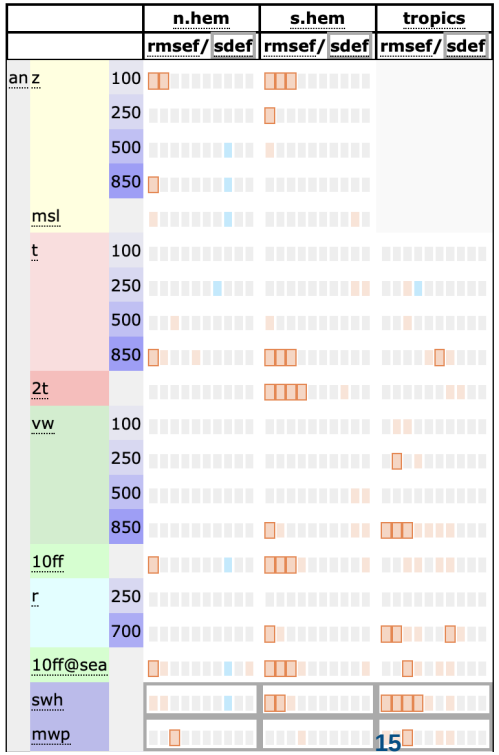
SST forecast error through day 10



RMSE of SST FC at day-10: NoAlti - Control



Atmospheric forecast errors NoAlti – Control



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

ADD OBSERVATIONS

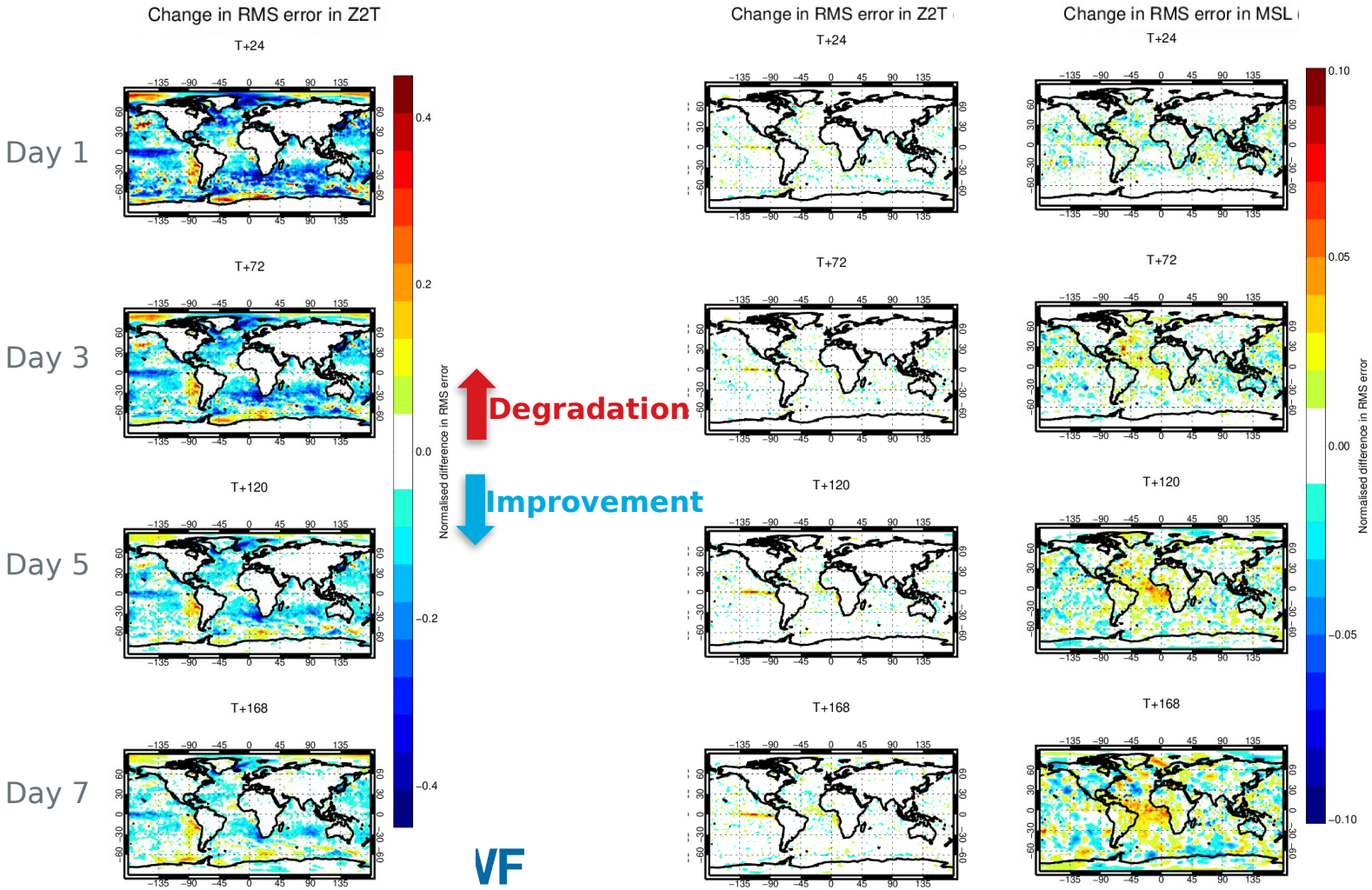
In-situ + altimeter

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

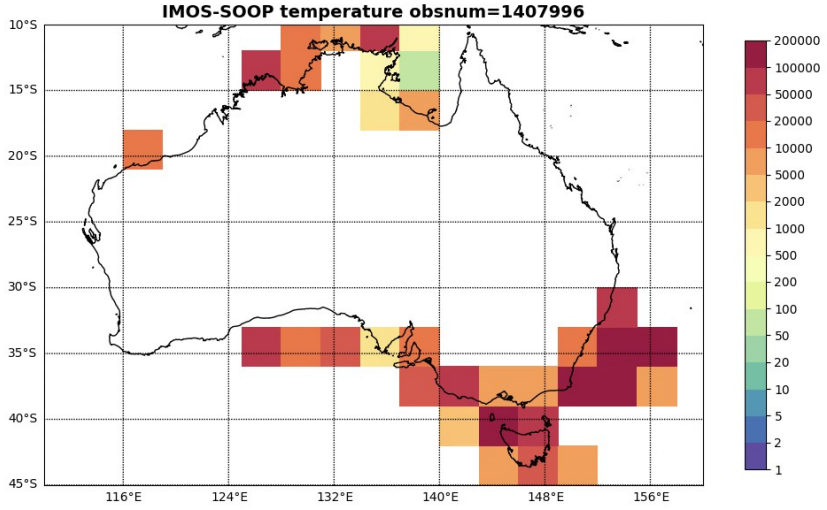
- Temperature sensors attached to fishing gear
- Around the Australian coast, part of the FVON network
- Available from 2022 onward, including NRT data
- Additional FVON data (e.g. Atlantic ARC) is being processed

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

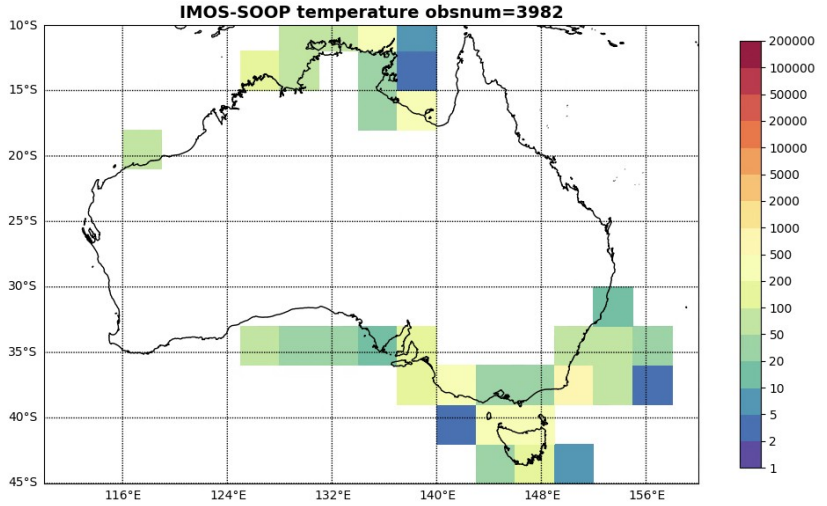
Raw data



QC + SPATIAL / TEMPORAL THINNING

→

After thinning



ECMWF

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

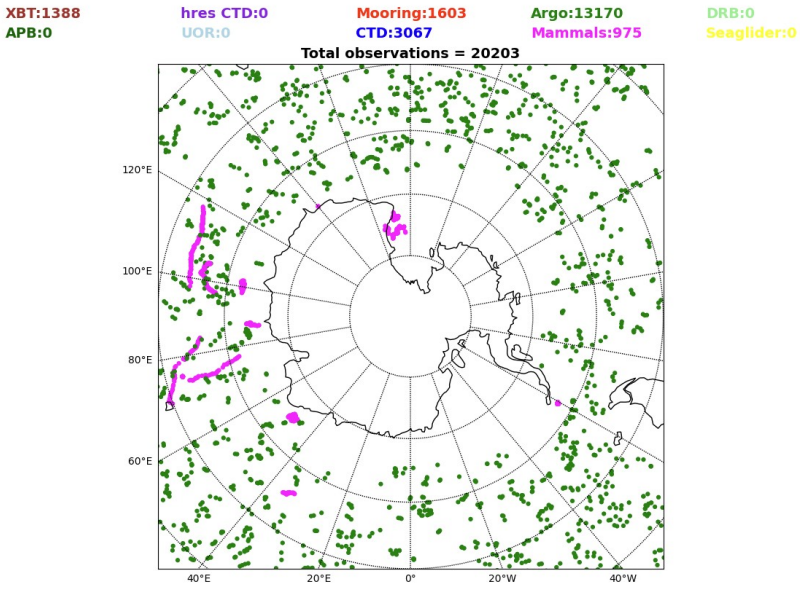


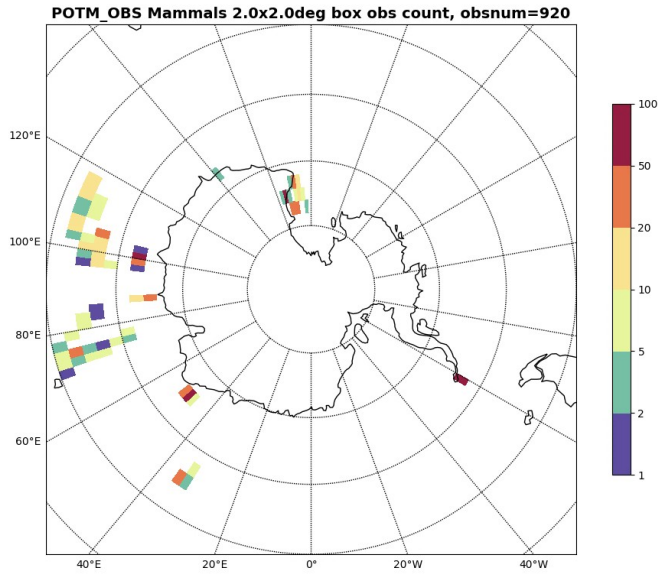
Images from anibos.com



Images from anibos.com

Animal-borne data in June 2023





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.

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.

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

Thank you!

Hao Zuo

ECMWF

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www.ecmwf.int

Extra slides