Impact of satellite ocean-surface observations with ocean data assimilation

NWP SAF Workshop on Satellite Observations of the Earth System Interfaces

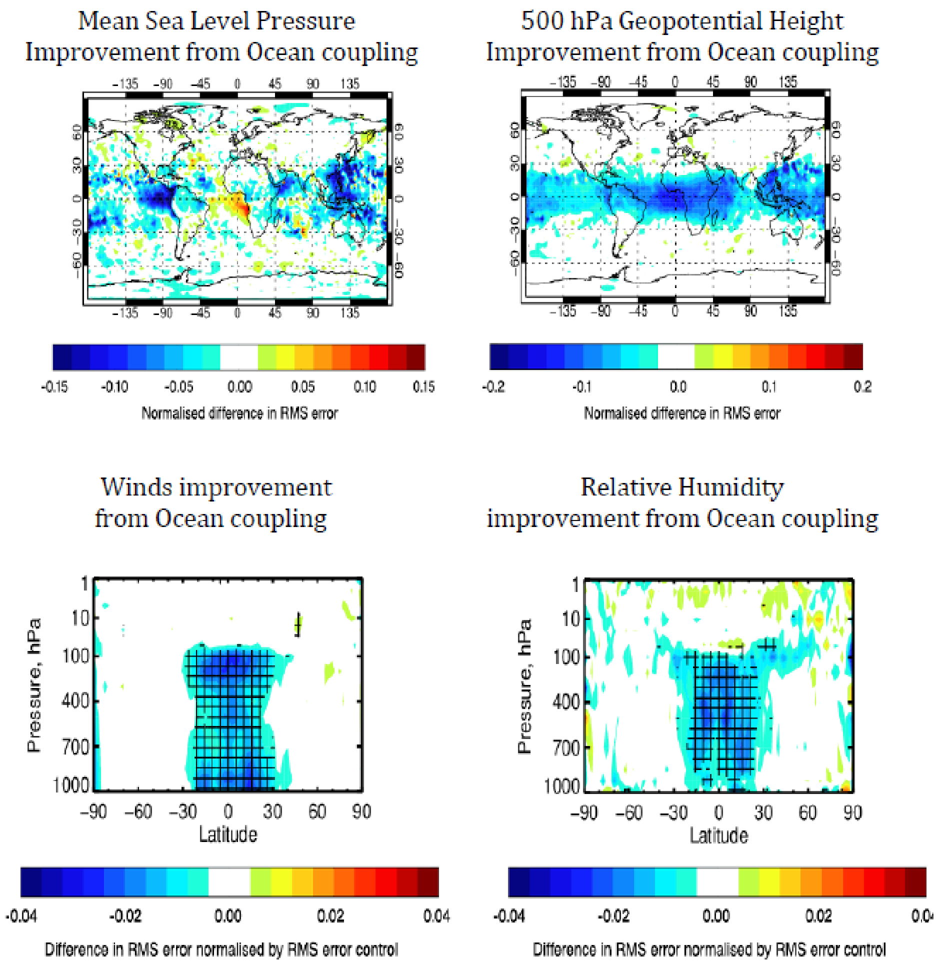
Hao Zuo, Kristian Mogensen, Eric de Boisseson, Sarah Keeley, Philip Browne, Magdalena Alonso Balmaseda, Marcin Chrust, Patricia de Rosnay, Toshinari Takakura

ECMWF

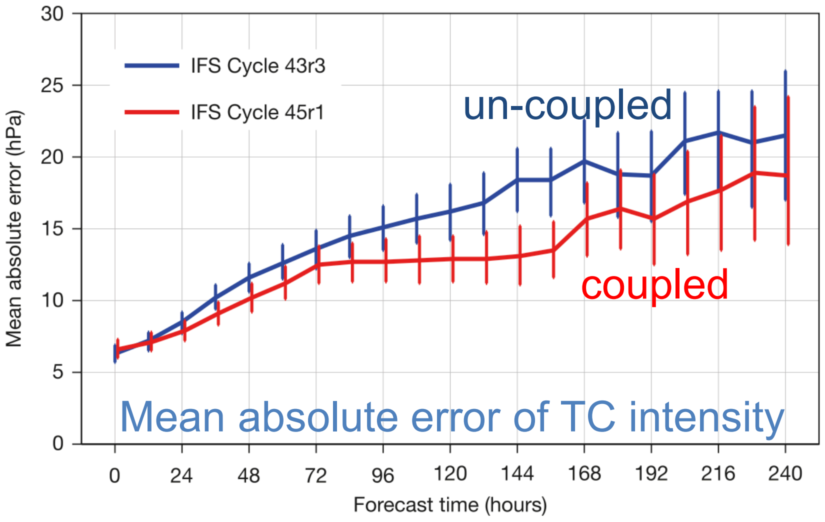
Outline

- Ocean and sea-ice DA at ECMWF
- Impact of satellite ocean surface observations with ODA

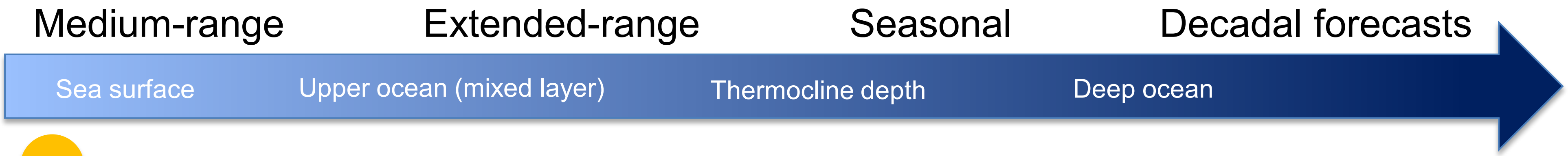
Why Ocean DA?

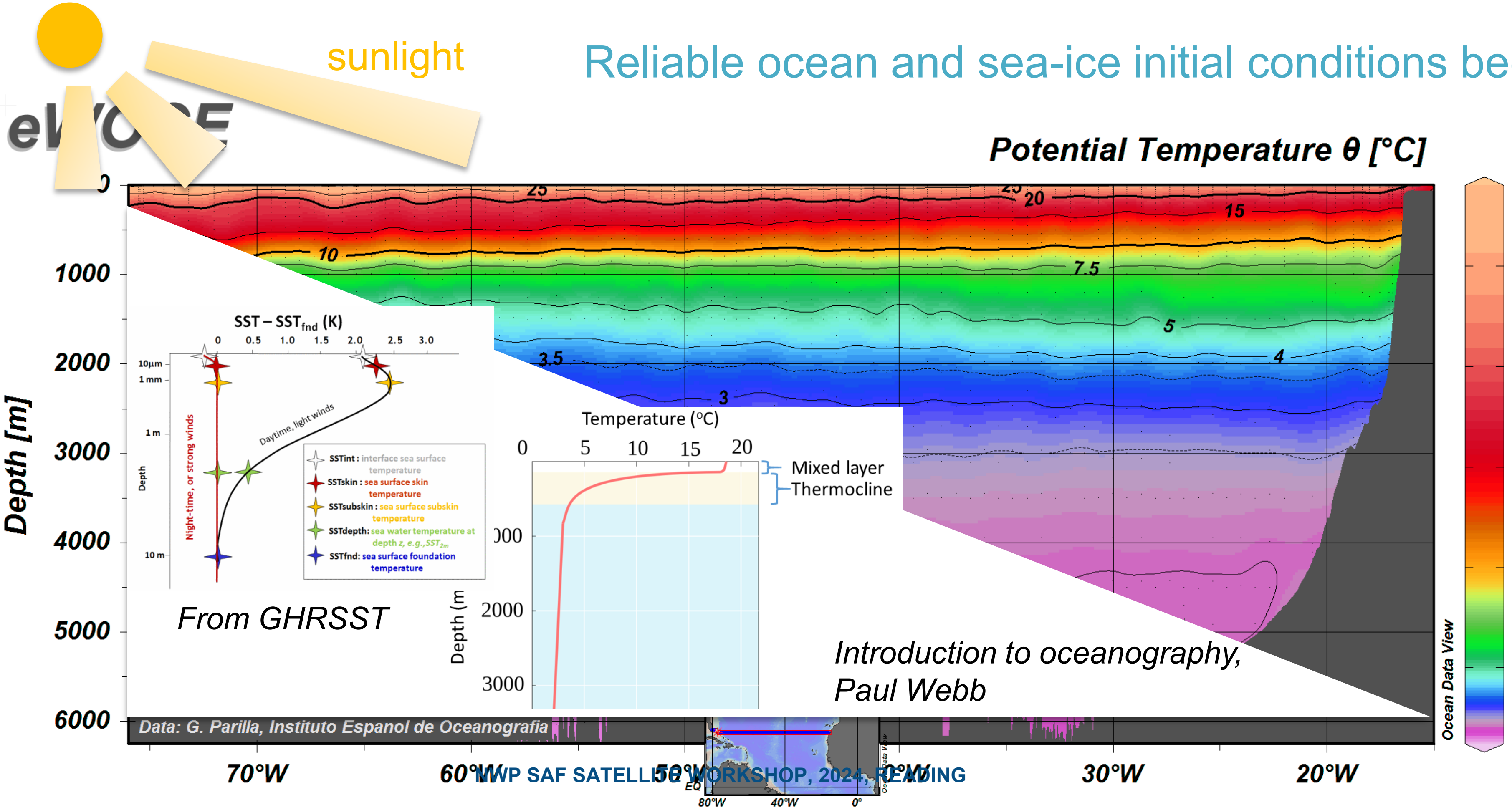


- ECMWF forecasts became coupled for all timescales since 2018 (CY45R1) - include dynamical ocean and sea-ice components (*Mogensen et al., 2018, Buizza et al., 2018*).
- Coupling (**partial**) with the ocean improves the weather forecast scores, with reduced RMSE (blue) in Day+5.
- Coupling with ocean reduces intensity error in HRES forecasts of tropical cyclone (TC).



Why Ocean DA: from medium-range to decadal forecasts





Reliable ocean and sea-ice initial conditions become critical !

Mogensen et al., 2017: "… the upper ocean stratification is the key in determining the strength of the coupled feedback (of tropical cyclone forecasts)."

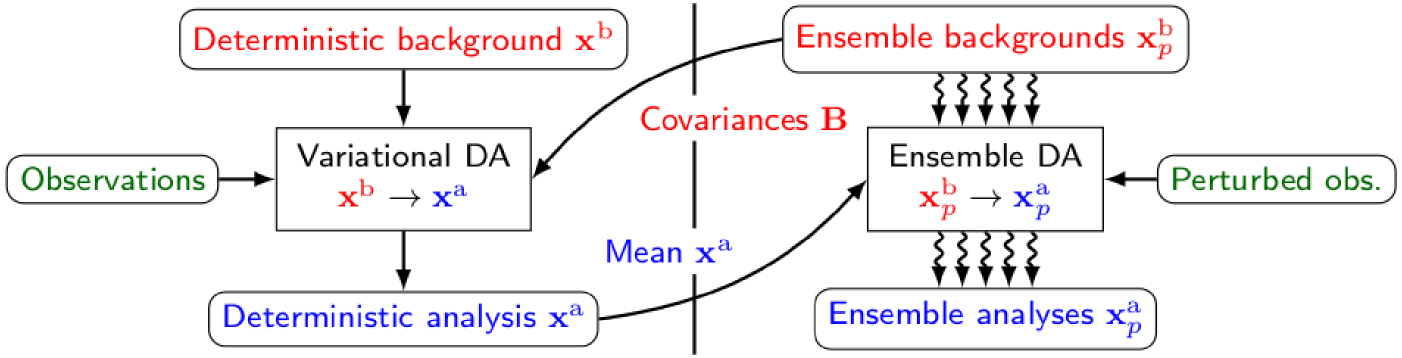
How to do Ocean DA at ECMWF

NEMOVAR (CERFACS/ECMWF/INRIA/Met Office)

En Variational DA system for **NEMO** ocean model

- Solves a linearized version of the full non-linear cost function.
- Incremental **3D-Var FGAT** running operational
- Background correlation model based **diffusion operators**
- Background errors are correlated between different variables through **balance operator**

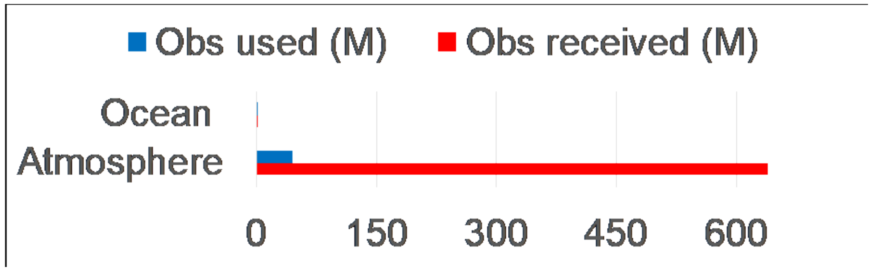
Generate an ensemble of analyses from an ensemble of background states and perturbed observations



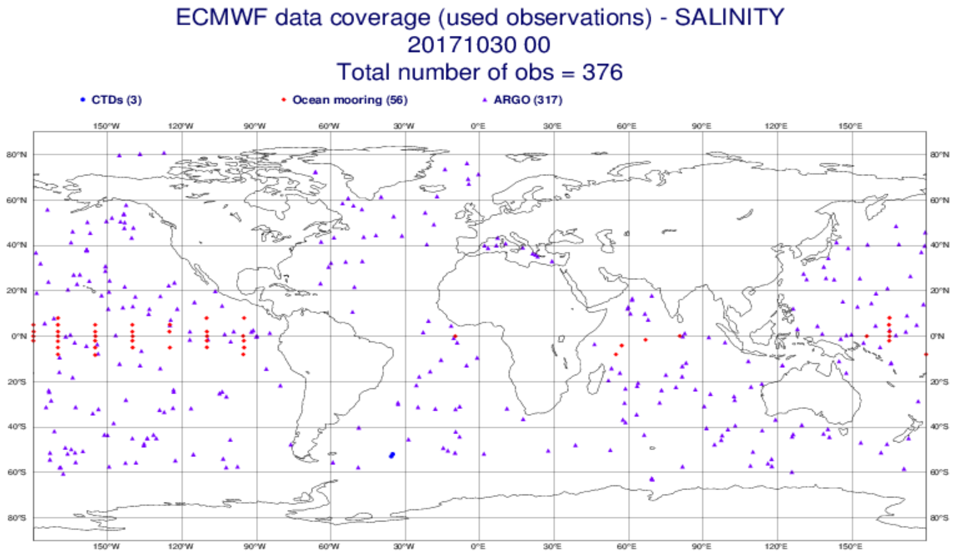
Weaver et al 2003,2005;
Daget et al 2009;
Mogensen et al 2012;
Balmaseda et al 2013;
Zuo et al., 2017;
Chrust et al., 2021

Ocean in-situ observations

- Ocean in-situ observing network is **very sparse** compared to atmospheric observations.
- Very **uneven distribution** of observations: Southern ocean was poorly observed until ARGO period. Deep ocean still under sampled (Deep Argo).
- **Temporal discontinuity** is normal: lack of funding; expensive and difficult to maintain; relies on local contributions.



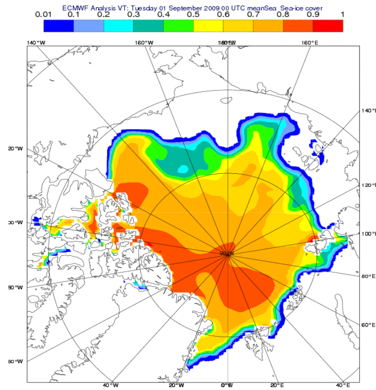
Ocean in-situ observation is about 1/1000 to 1/10000 smaller than Atmospheric observation



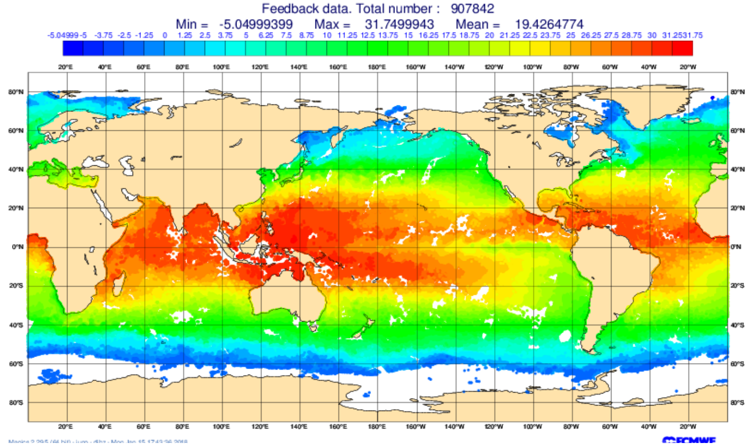
Satellite sea surface observations

- Satellites provide important observations on monitoring sea surface states (*SST, SSS, sea-ice states, sea surface height, surface currents, ocean color*).
- These sea surface observations are **complemental** data sources to the ocean **in-situ** observing networks.
- Main Challenge: **balance contributions** from in-situ and satellite observations.

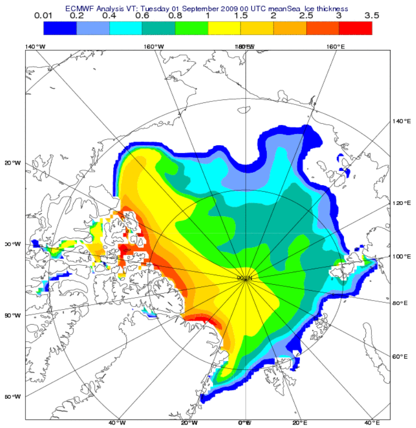
Sea-ice concentration



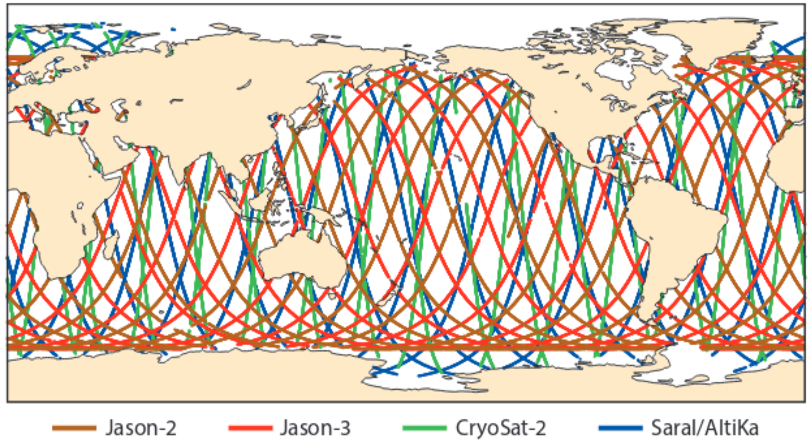
SST (IR, PMW)



Sea-ice thickness



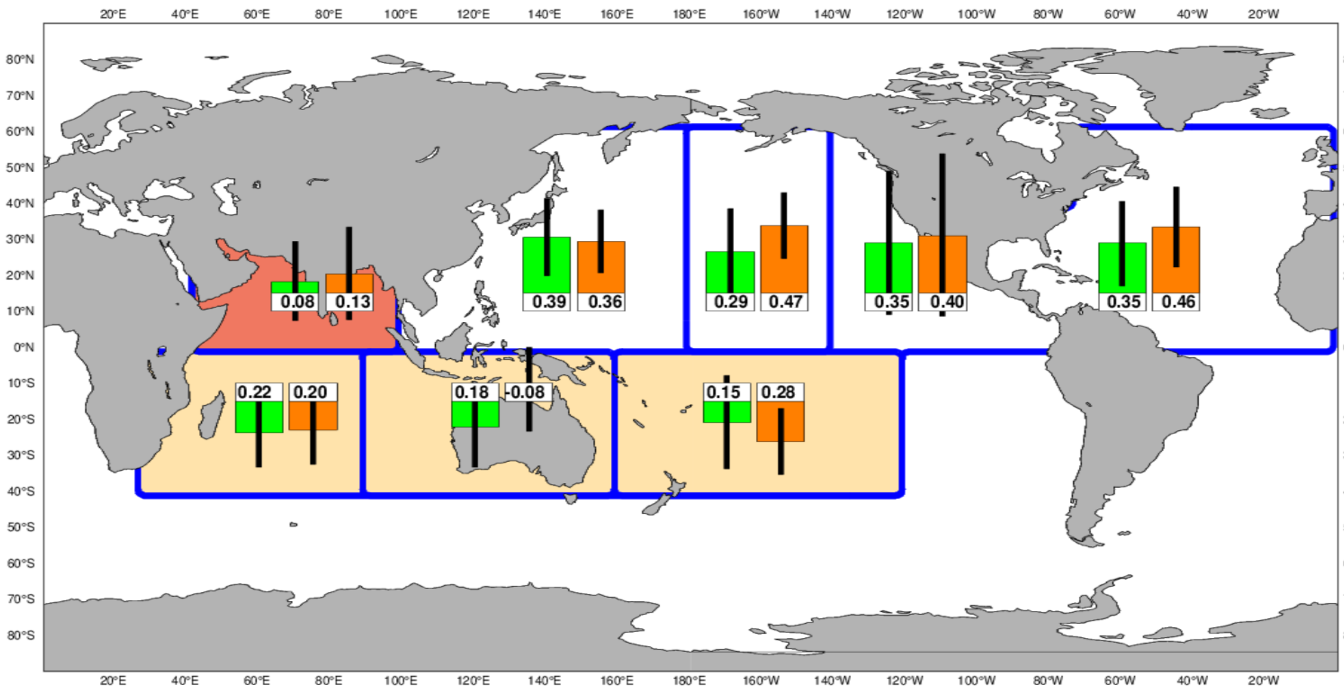
Sea-Level Anomaly (Altimeter)



Impact on TC forecasts

- Most positive impact of **altimeter SLA** assimilation on Tropical Cyclone Forecasts (extended-range).
- The assimilation of SLA from altimeter in the ocean needs the essential support of the subsurface observations of T and S, at risk of serious degradation.

No SLA **CTRL** *(Correlation with observed TC energy)*



Aug/Sep **May/Nov** **Feb**

Extended range (day16-45, re-performed 1994 to 2016)

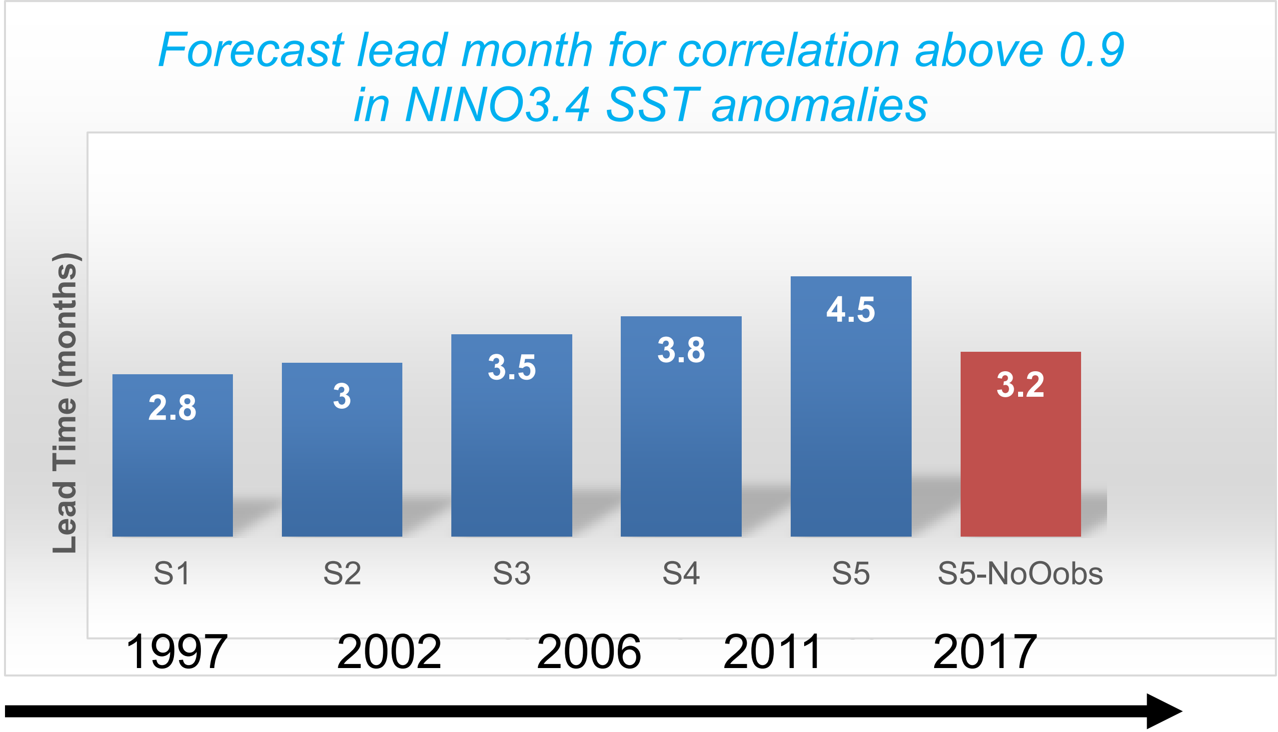
Courtesy *of Frederic Vitard ECMWF*

Impact on seasonal forecasts – SEAS5

OCEAN5 provides ocean and sea-ice initial conditions for all ECMWF coupled forecasting systems since 2018, including ENS, HRES and SEAS5.

Adding Ocean DA leads to

- Gain about 2 months in ENSO prediction skill
- Without ocean observations and DA, we would lose about 15 years of progress (from S1 to S5).



Upcoming updates on ECMWF Ocean DA – ORAS6

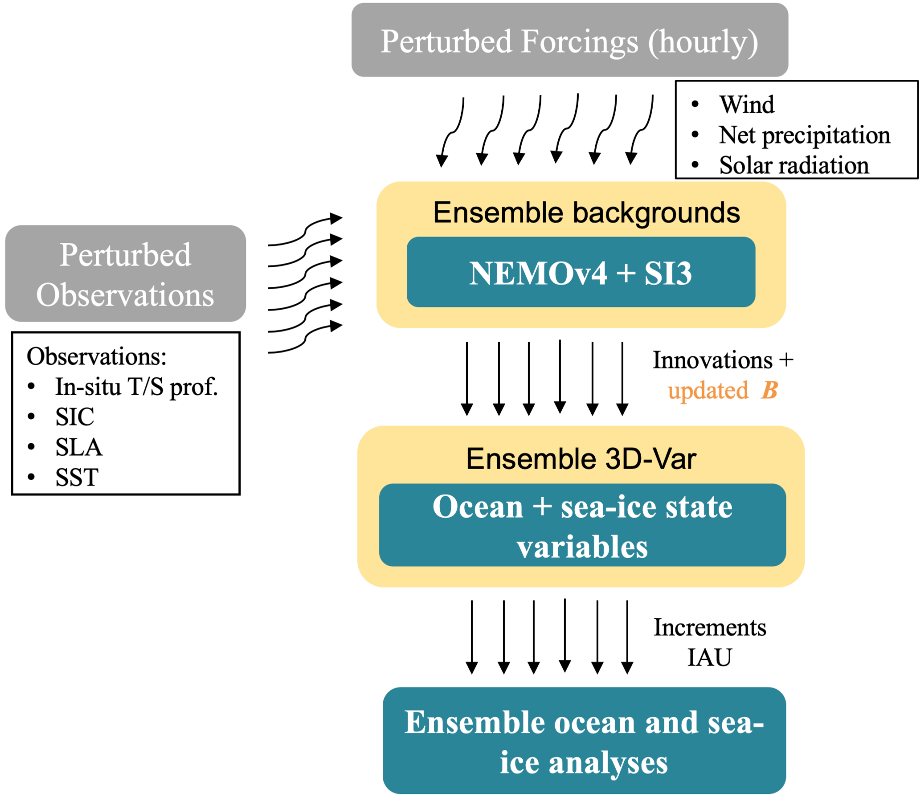
Development of ORAS6 has been partially supported by EU-funded projects: C3S-ERGO, CMEMS-GLORAN and their follow-ups.

Climate Change Service

climate.copernicus.eu

COPERNICUS MARINE SERVICE GLOBAL OCEAN MFC

Entrusted Entity by EU Mercator Ocean International



Zuo et al., NL180, 2024

	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

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

Outline

- Ocean and sea-ice DA at ECMWF
- Impact of satellite ocean surface observations with ODA

Impact of assimilation of SST data

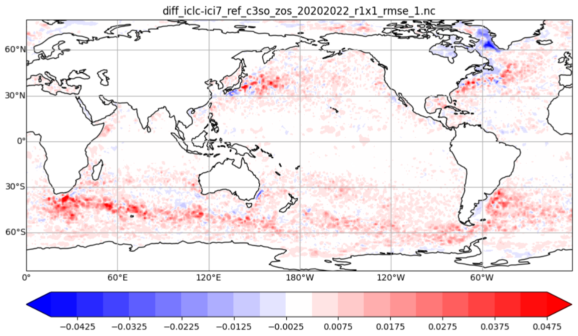
Assimilation of L4 SST with En3DVar

- 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. local solar time).

Changes in fit-to-obs RMS errors - removal of SST DA

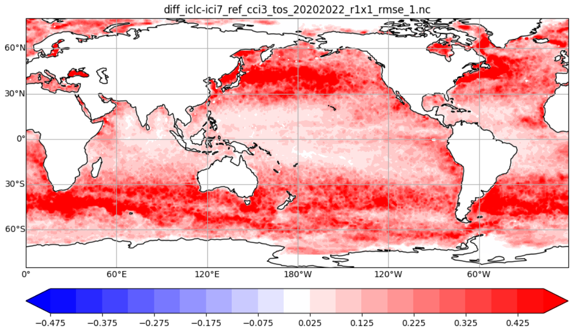
Results from OSEs between 2020-2022

SSH



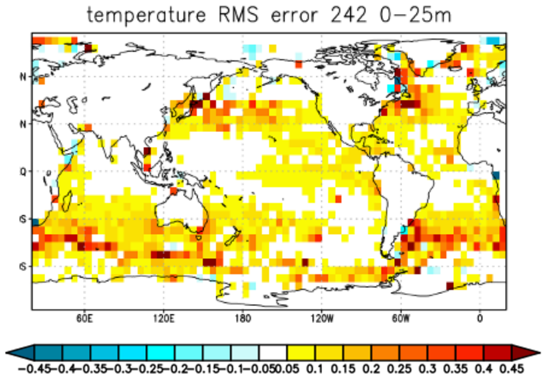
against AVISO/CMEMS

SST

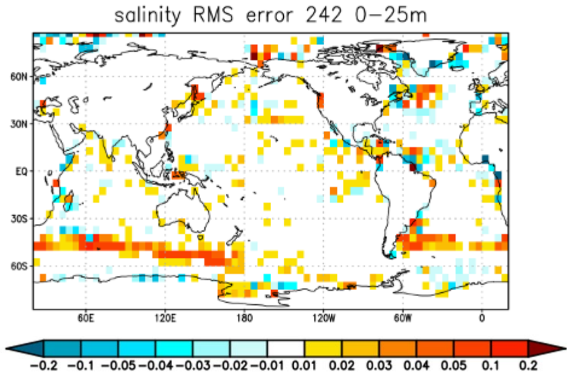


against ESA CCIv3

Upper ocean T



Upper ocean S



against all in-situ

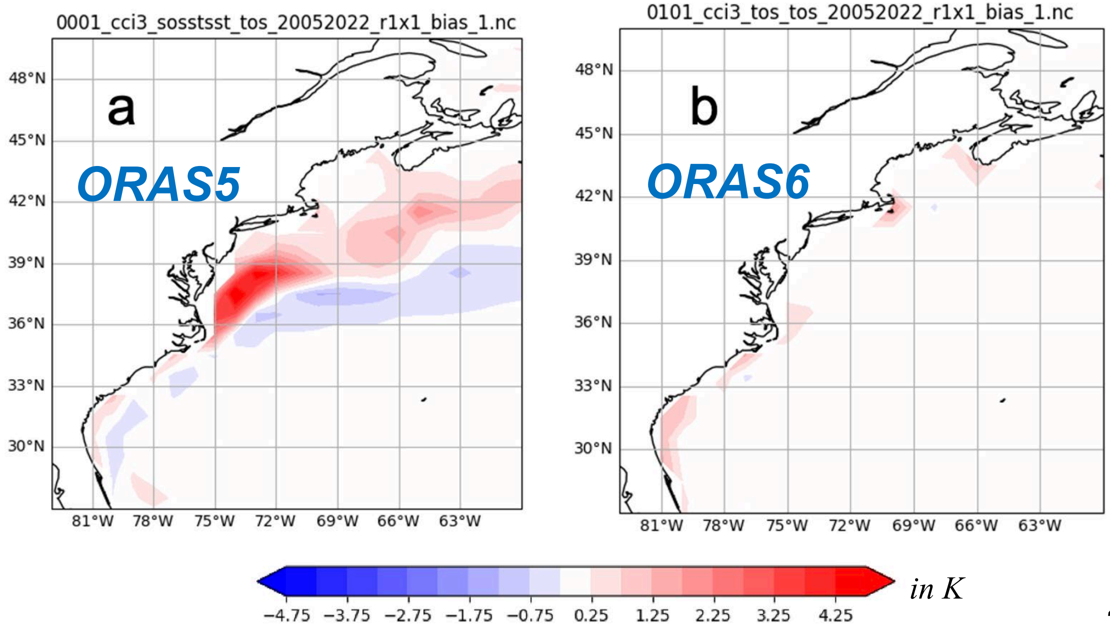
Impact of assimilation of SST data

L4 gridded SST product (ESA-CCIv3) is directly assimilated in the ORAS6 system

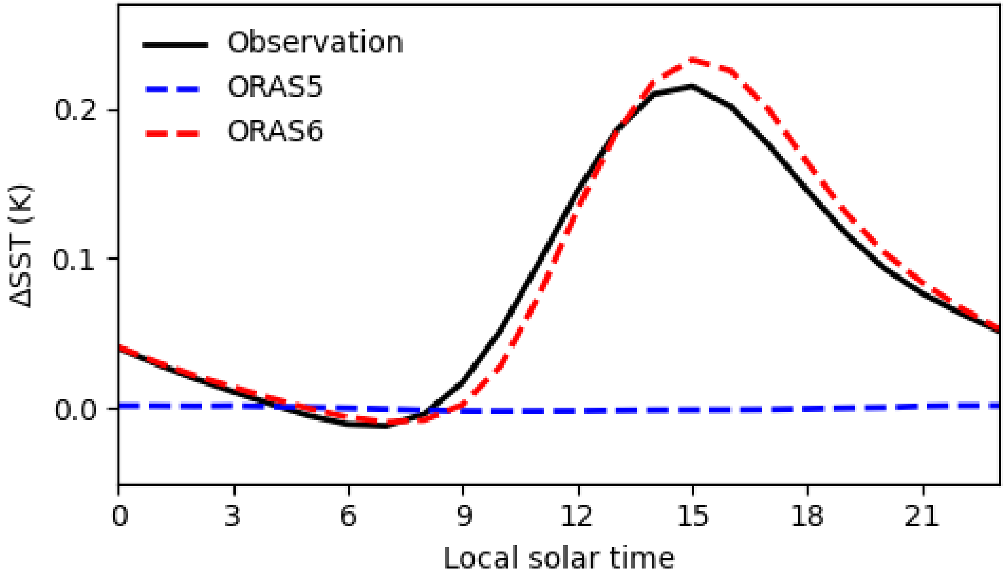
- Greatly reduced **SST biases** in the GS region – partial coupling no longer needed !
- Good representation of **SST diurnal cycle** – possible for hourly coupling

Improvement also attributes to hourly ERA5 forcing and improved physical models

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



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



Zuo et al., NL180

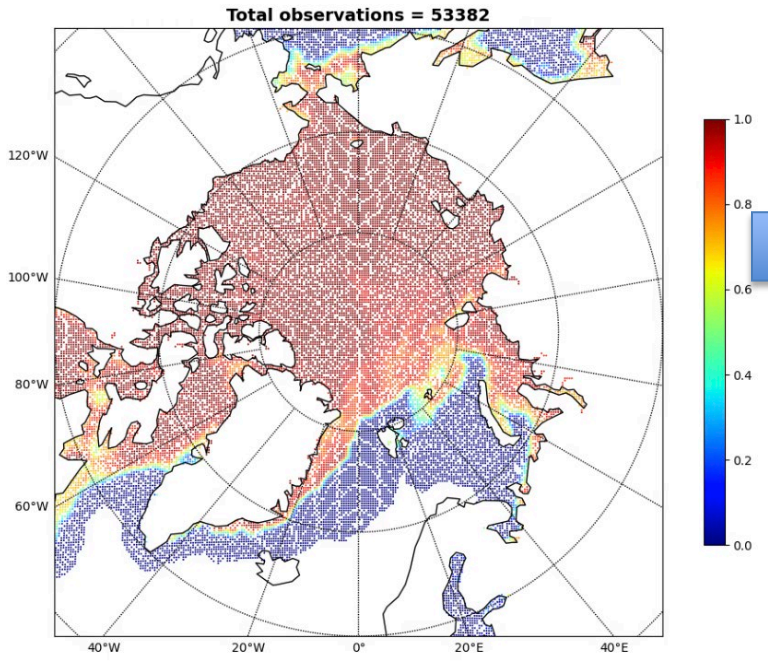
Impact of assimilating Sea-Ice Concentration data

L3 Sea-Ice Concentration (SIC) data from OSI SAF (CDR/ICDR) is assimilated in the ORAS6 system

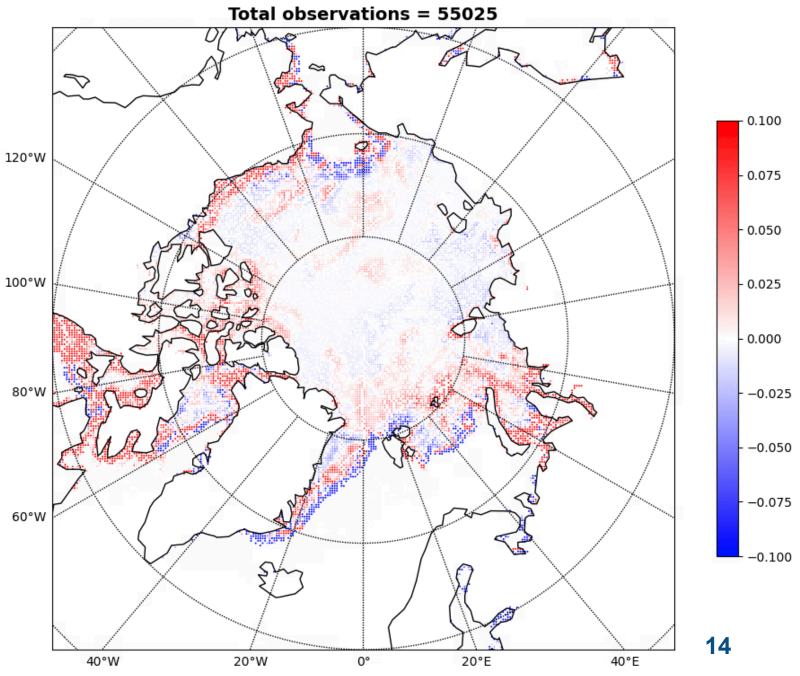
- Treated as **univariate** but within single minimization together with ocean state variables
- **Pre-thinned** with stratified random sampling method
- Uncertainties in sea-ice data are accounted for by perturbing SIC values with **analysis** and **structure errors** (Zuo et al., 2017)

with 10km resolution there is ~1 milion obs per day from L3 OSI-SAF, pre-thinned with 0.25 deg box

Daily SIC from OSI-SAF 450a (20151231)



Model background - obs

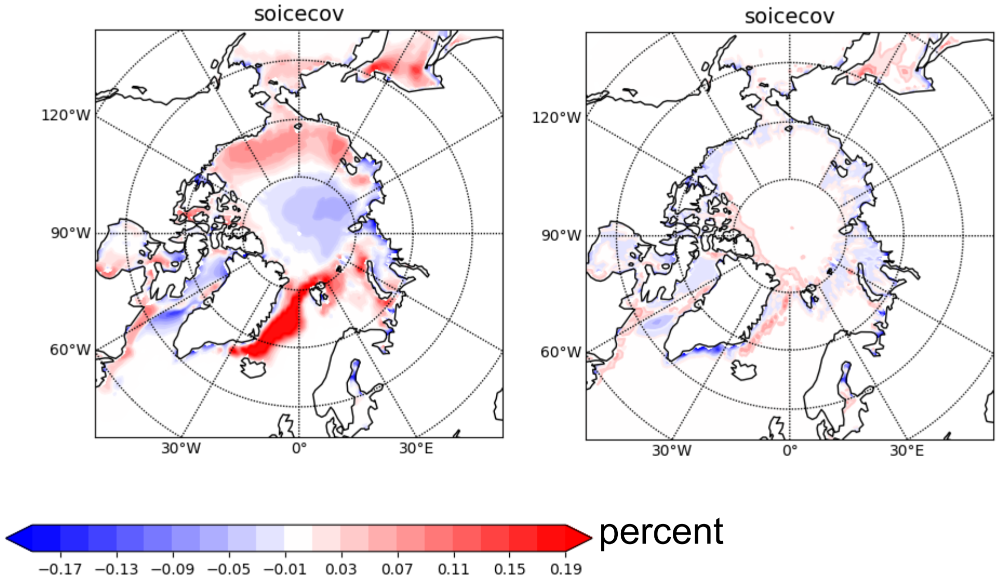


Impact of assimilating Sea-Ice Concentration data

Assimilation of SIC data leads to improved sea-ice state performance in both **sea-ice concentration** and **sea-ice thickness**.

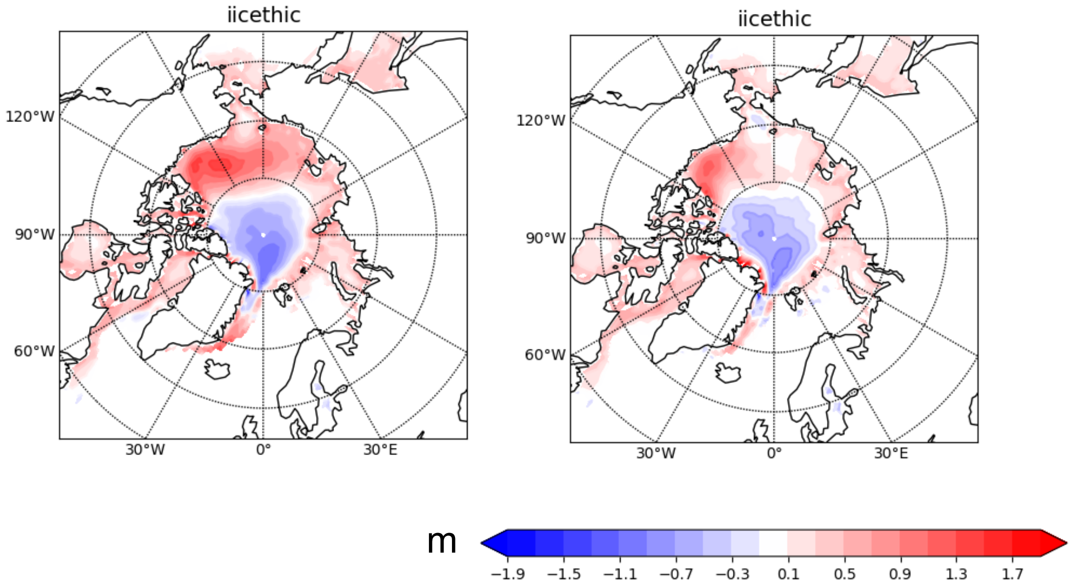
SIC mean biases (1980-2016)
against OSI-SAF 430 data

No SIC | + SIC DA



SIT mean biases (2011-2016)
against CS2SMOS data

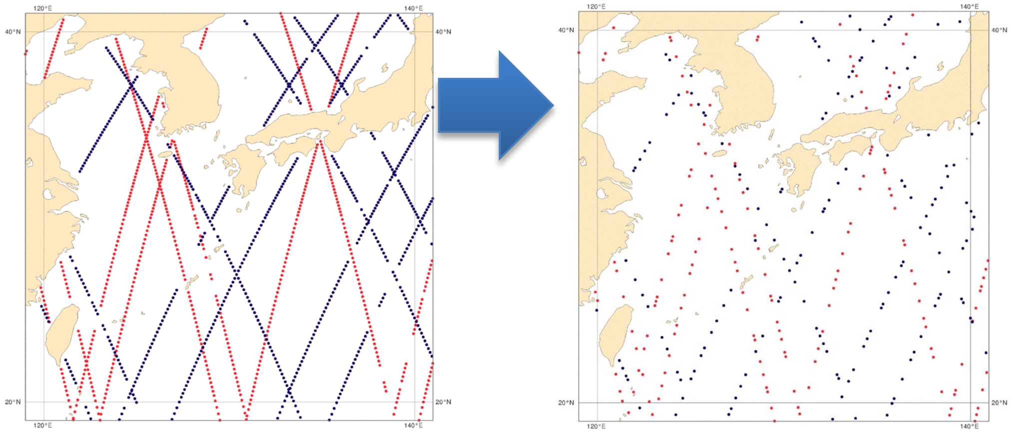
No SIC | + SIC DA



Impact of assimilation of satellite altimeter data

- Assimilate L3 along-track SLA data to constrain **regional sea-level changes**
- Assimilate L4 gridded MSLA data to constrain **global mean sea-level changes**
- Assimilate SLA with an updated **MDT** approach (by accounting for regional SL trend errors)

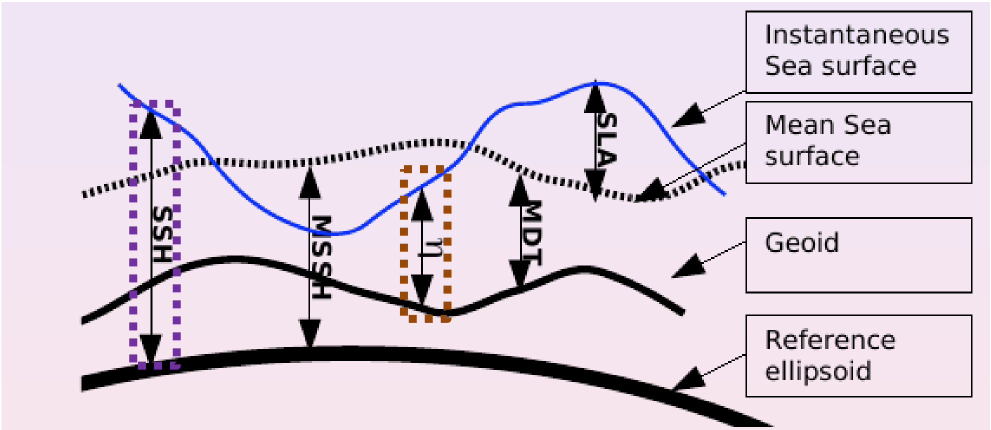
Superobbing/Thinning of SLA obs



ERS-2: 13005 Envisat: 0 Envisat N: 0

Jason-1 N: 0 Jason-2: 0 T/P: 13219

MDT approach



Altimeter measures SSH (respect reference ellipsoide)

Model represents η (ssh referred to the Geoid)

SSH-Geoid= η

Impact of assimilation of satellite altimeter data

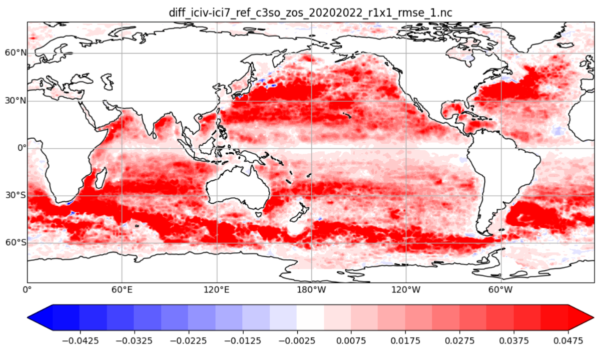
Assimilation of altimeter SLA data improves ocean states in

- regional sea-level changes
- mean SST
- sub-surface temperature and salinity
- large-scale ocean circulations

Changes in fit-to-obs RMS errors - removal of SLA obs

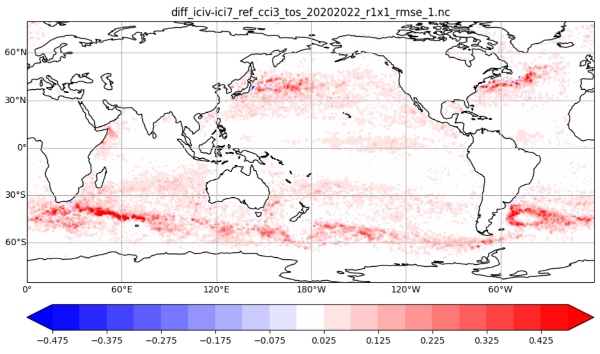
Results from OSEs between 2020-2022

SSH



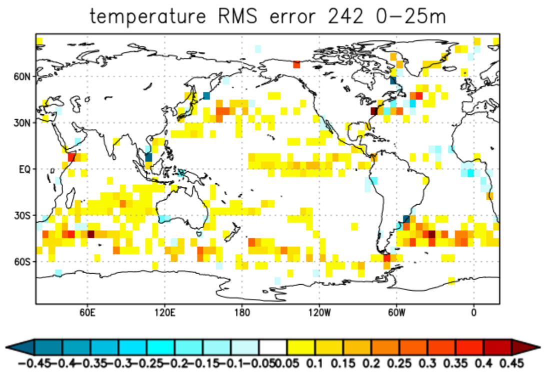
against AVISO/CMEMS

SST

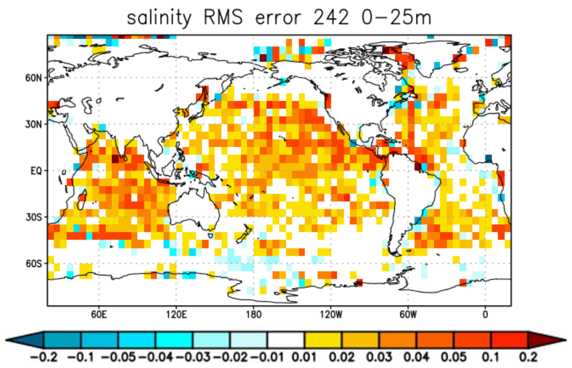


against ESA CCIv3

Upper ocean T



Upper ocean S



against all in-situ

Impact studies with OSEs and coupled forecasts

Assessments of ocean observation impacts with a prototype of the new ECMWF coupled forecasting system

- ➢ single deterministic coupled forecasts
- ➢ **fully coupled** between atmospheric and ocean/sea-ice
  - 9 km atmosphere
  - 25 km ocean
  - 20210601 to 20220601 with one 10 day forecast per day starting at 00z
- ➢ Initialized from various ocean and sea-ice initial conditions (OSEs), in collaboration with the **SynObs** project.

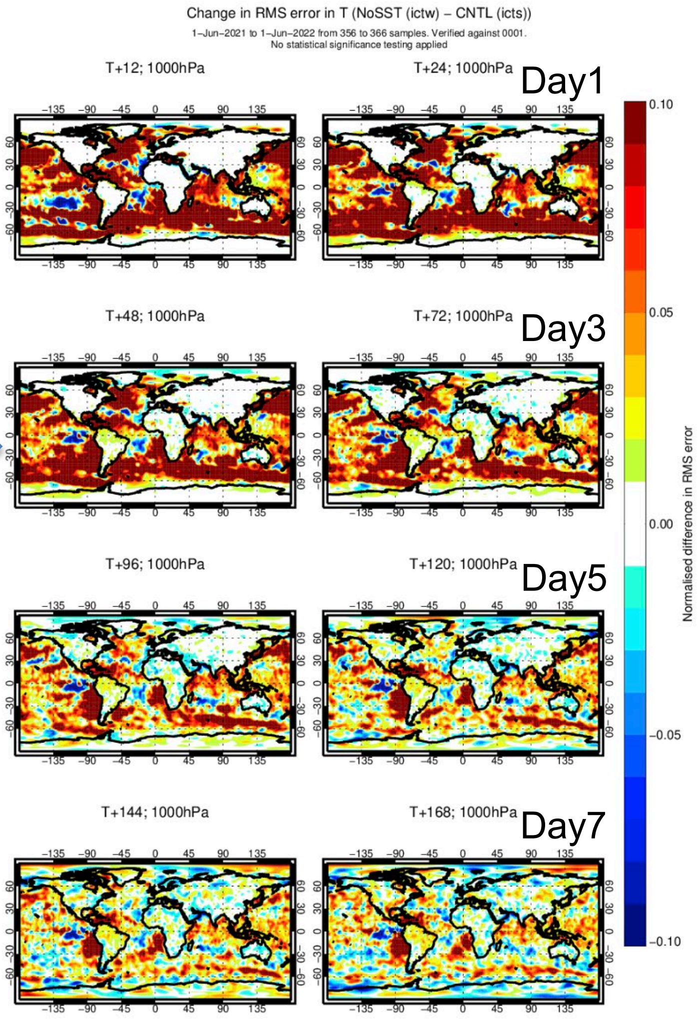
Configuration of OSEs									S2S Priority
1	CNTL		SST	Argo 80%	Mooring	Other TS	Alt. (optional)	Required
2	NoAlt		SST	Argo 80%	Mooring	Other TS		Optional
3	NoArgo		SST		Mooring	Other TS	Alt. (optional)	Recommended
4	NoMoor		SST	Argo 80%		Other TS	Alt. (optional)	Recommended
5	NoSST			Argo 80%	Mooring	Other TS	Alt. (optional)	Recommended
6	NoInsitu		SST				Alt. (optional)	Required
7	SSTonly		SST					Required
8	Free							Optional
9	HalfArgo		SST	Argo 40%	Mooring	Other TS	Alt. (optional)	Optional
10	Oper	Oper. Setting	SST	Argo 100%	Mooring	Other TS	Nadir Altimeter	Optional

Impact studies with OSEs and coupled forecasts

Changes in surface temperature forecast errors (normalized)

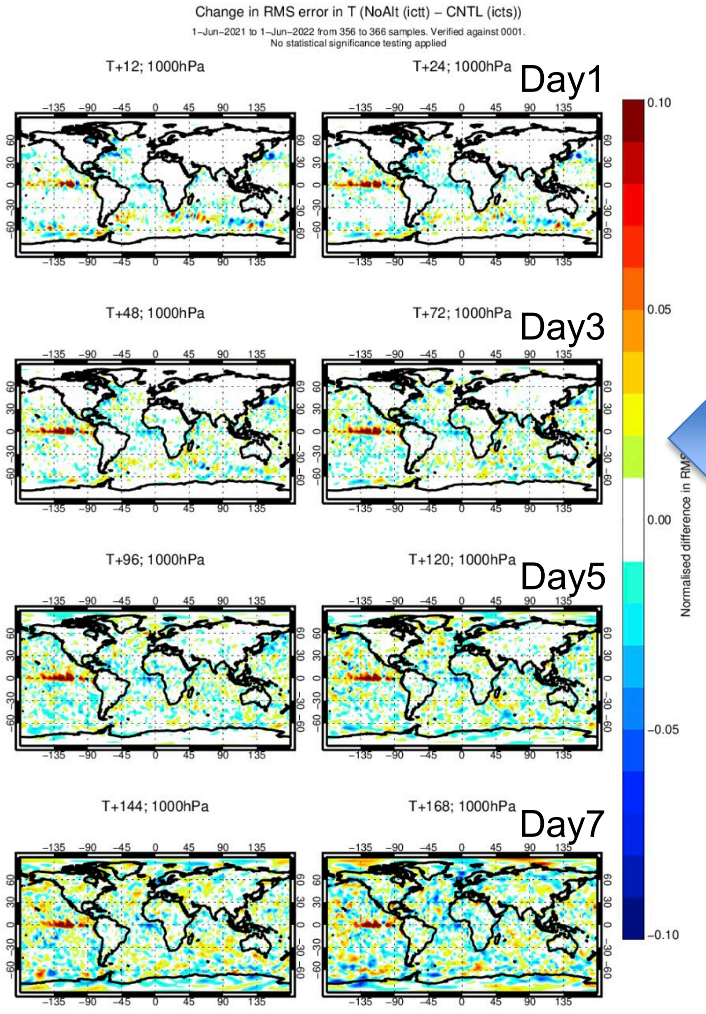
(Reference is CNTL run with all observations)

Removal of SST data



Degradation

Improvement



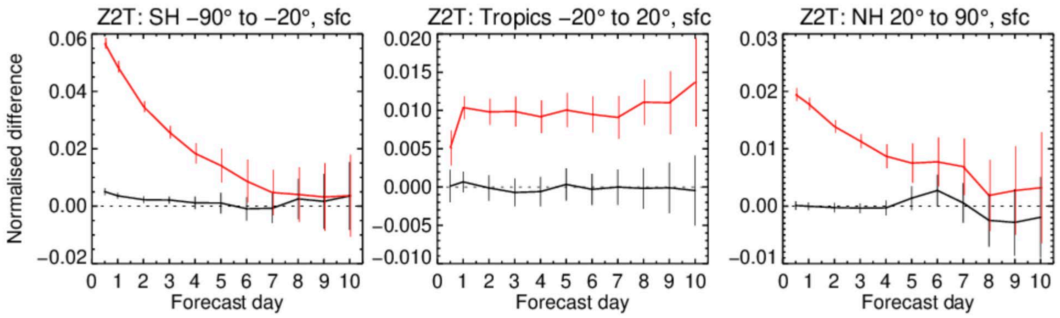
Removal of Altimeter data

Impact studies with OSEs and coupled forecasts

- Positive impact from SST observation lasts longer **in the tropics**.
- Assimilation of altimeter observations has **sizable positive impact** on forecasting atmospheric variables.

Changes in forecast errors – atmospheric variables

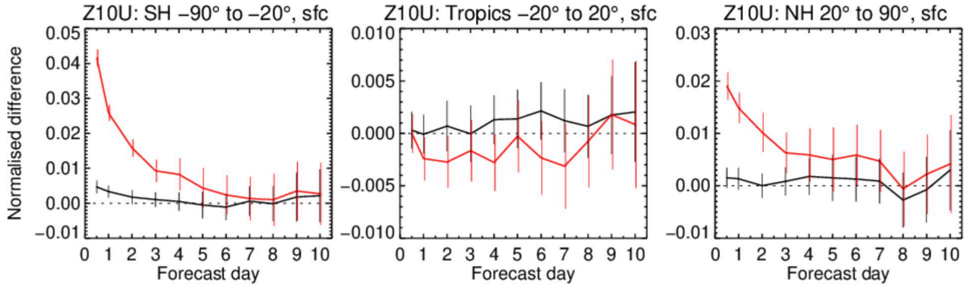
Z2T



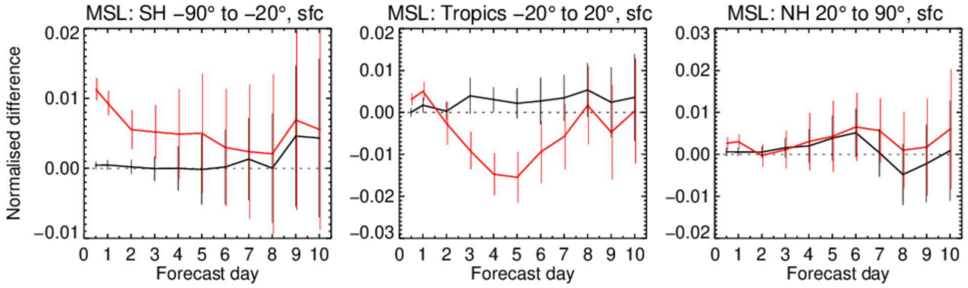
Reference is CNTL run
with all observations

Removal of Alti
Removal of SST

Zonal wind at 10m



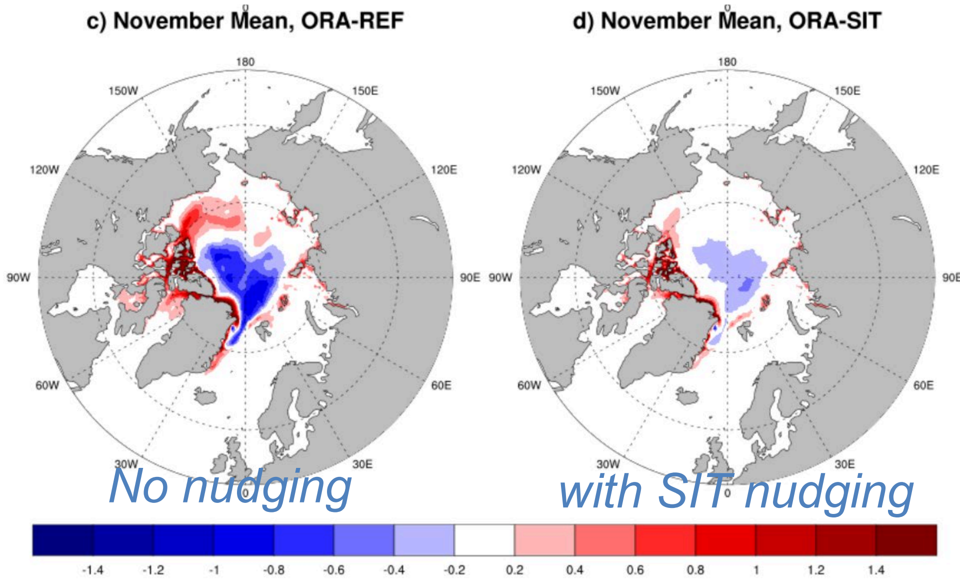
MSL



Sea-ice thickness DA and impact on seasonal forecasts

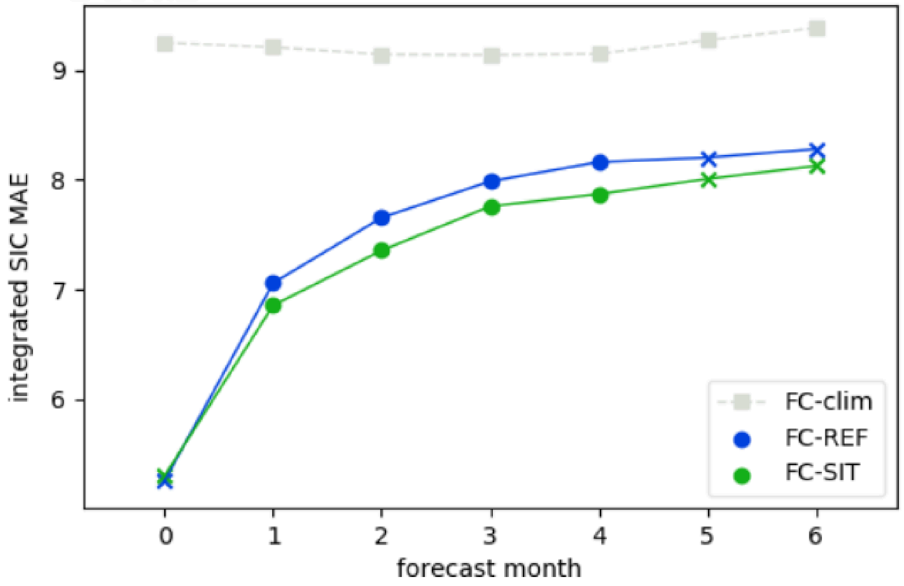
- Introducing nudging towards sea-ice thickness data (CS2SMOS) in OCEAN5 leads to improved sea-ice forecasts in SEAS5, especially for forecasts started in spring season.

Bias in sea-ice thickness



Mean absolute error in SIC forecasts

(2011-2016, verified against OSI-401-b)



Balan Sarojini, et al. 2021

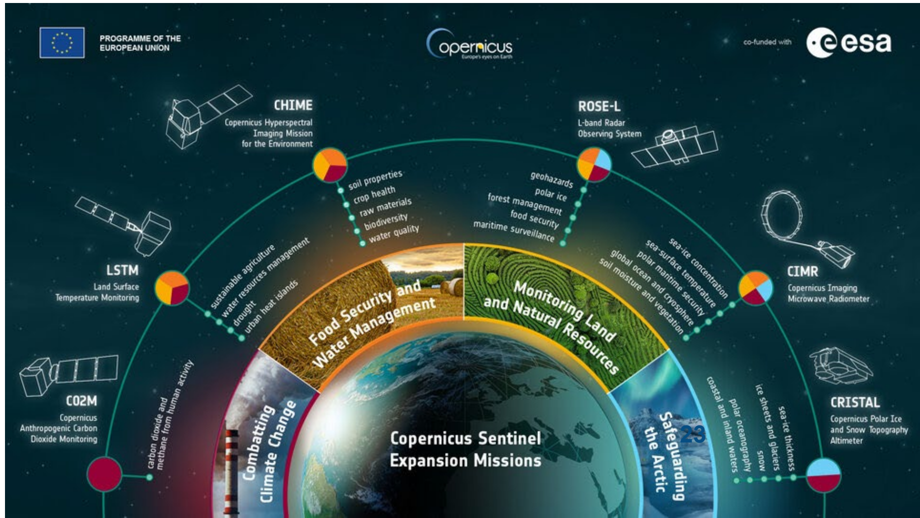
5% reduction of errors between lead months 2-5

Summary

- Satellite ocean-surface observations are **essential** input for ocean and sea-ice analysis and are **complementary** to the ocean in-situ observing networks.
- Assimilation of ocean-surface observations (SST/SIC/SLA) with the ECMWF En3DVar system leads to **improved ocean and sea-ice initial states** (*SST at WBCs, diurnal cycle, upper ocean temperature and salinity, regional/global sea-level changes, sea-ice conditions*).
- **Removing SST** data from the Ocean DA system has **the largest negative impact** on coupled forecasts performance (medium-range), degrades both ocean and atmospheric variables.
- **Removing altimeter SLA** data also degrades SST forecasts (in the tropics) and leads to small but significant degradation in forecasted atmospheric variables (Z2T, Z10U, MSL). Impact is comparable to other atmospheric model changes in **a typical ECMWF IFS Cycle upgrade**.
- ECMWF will exploit new satellite ocean-surface observations, such as upcoming Copernicus Expansion Missions (**CRISTAL/CIMR**), with a coupled assimilation approach.

DANTEX - Data Assimilation and Numerical Testing for Copernicus Expansion Missions

- A 3-year initiative funded by ESA, targeting DA and NWP testing of the upcoming Copernicus Expansion Missions (CIMR, CRISTAL and LSTM) and existing Sentinel-1 mission.
- Develop novel ways to exploit **interfaces observations** from satellite (e.g. sea-ice thickness and snow depth, land temperature) by targeting **cryosphere, land and ocean waves**.
- Exploit **raw observations** (level 1 data) via new methods on **forward models**, including machine learning approach.
- ECMWF-ESA kick-off meeting on **18 November**.



Extra slides

Global Ocean ReAnalyses at ECMWF

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

2000 | 2010 | 2020

1997 ORAS1 | 2001 ORAS2 | 2007 ORAS3 | 2012 ORAS4 | 2018 ORAS5 | 2024 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		

ODA 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).

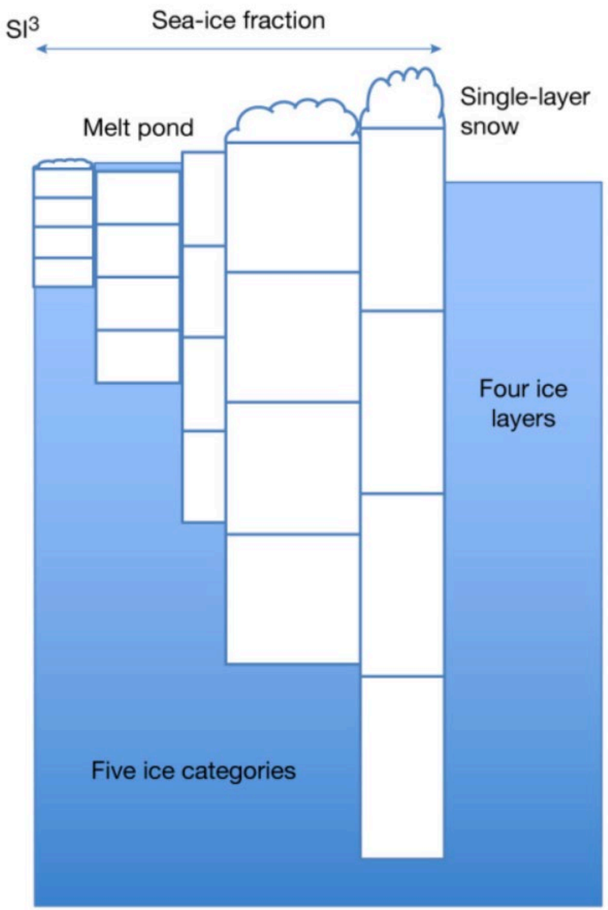
Hybrid background error std formulation

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

Chrust et al., submitted to QJRMS

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

Sea-ice DA with Multi-category SI3 model



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

(Keeley et al., NL180)

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

- Distribute of total increment among different thickness categories using model **background thickness profile** (-7% fit-to-obs errors)
- Introduce **thermodynamic balance** between sea-ice and ocean state variables (another -7% reduction of errors)

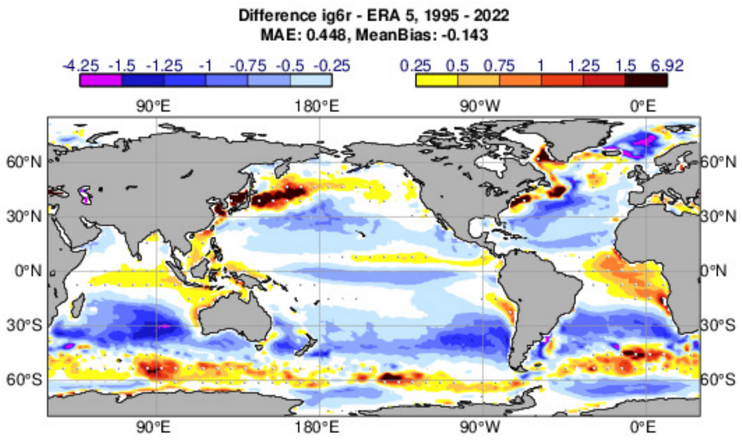
Browne et al., in preparation

Impact on seasonal forecasts – all ocean observations

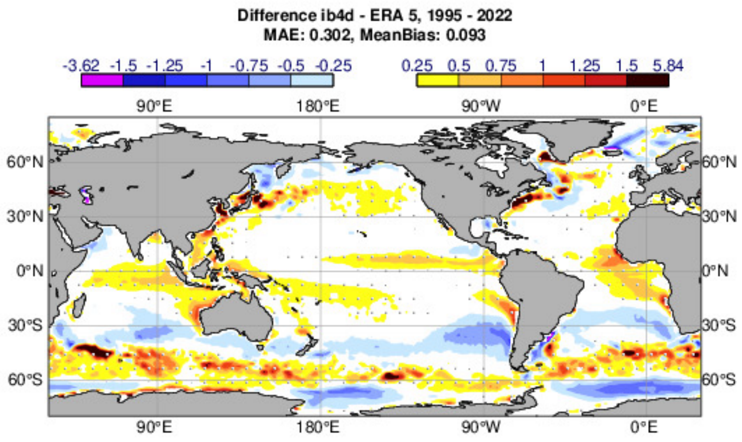
- Data assimilation reduces the overall cold SST bias and reduces the warm bias in South Tropical Atlantic
- The existing warm biases remain (slightly enhanced in some regions but notably reduced in South Tropical Atlantic)

Mean SST forecasts errors in DJF (Nov starts)

None-ERA5



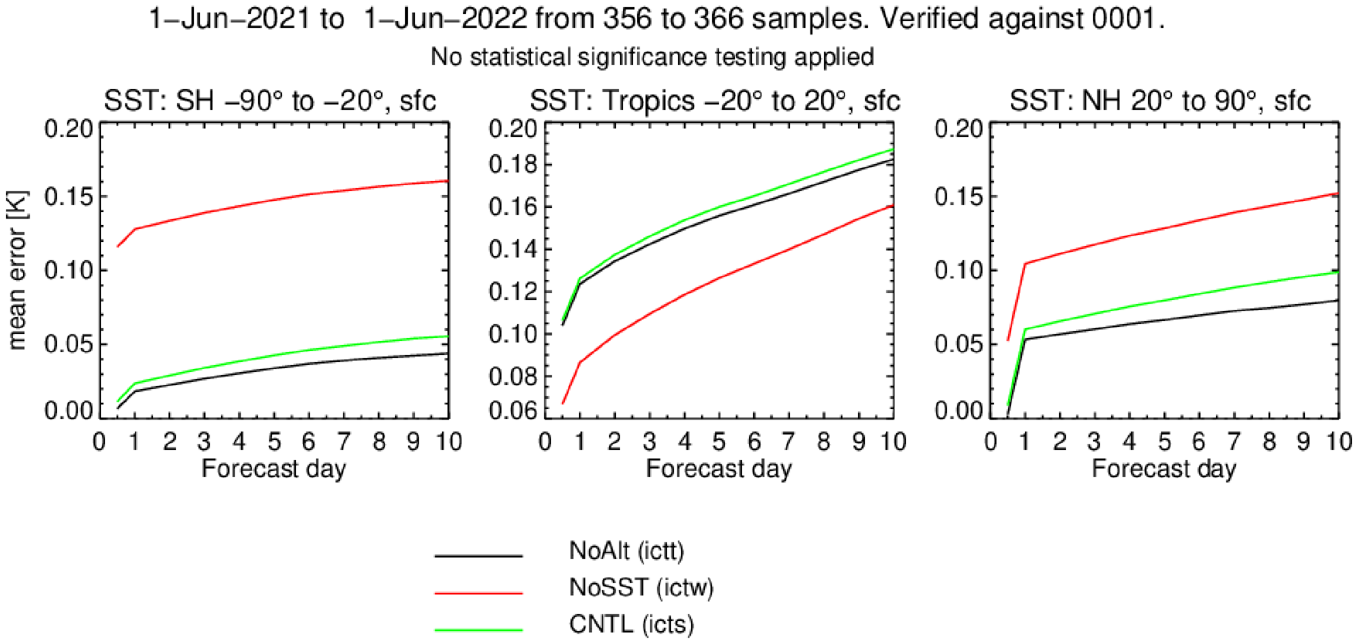
REF-ERA5



Impact of satellite obs on medium-range forecasts

- Assimilation of altimeter observations leads to slightly cooler SST (positive impact)
- Assimilation of SST significantly reduces warm biases in the extra-tropics, but not in the tropics.

Mean errors in SST forecasts



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Challenges in ORAS6 development

- How to deal with a **changing observing system** and **sparse data** in the pre-Argo/pre-Sat periods.
  - balancing satellite/surface observations and in-situ observations
  - Adaptive DA (e.g. EDA) for the changing observing network
  - Bias correction

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.