Ocean and Sea-Ice ReAnalysis

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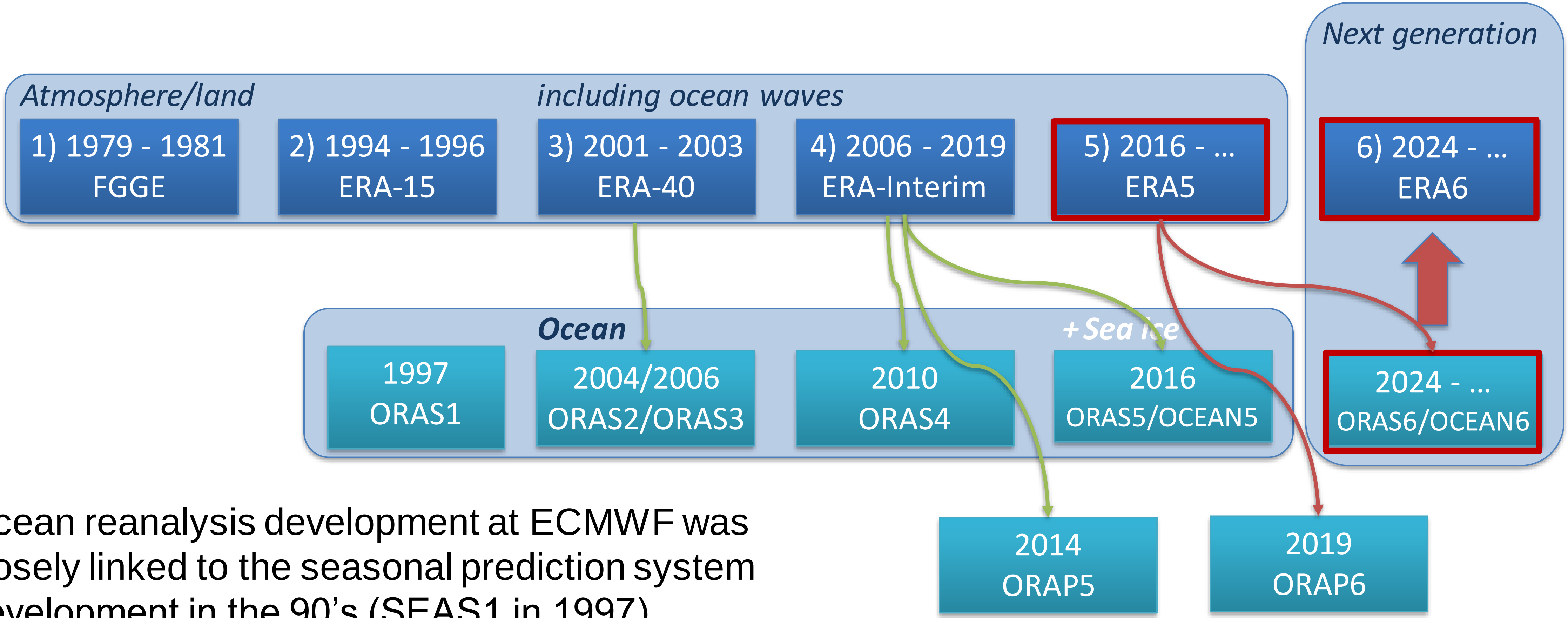
European Centre for Medium-Range Weather Forecasts

Outline

- **Ocean and sea-ice reanalysis (ORAs) at ECMWF**
- Applications of ORAs
- ORAs system components
  - Numerical model Observations Data assimilation method
  - Boundary conditions
- ORAS6 system
- Strengths, Weaknesses and Challenges

Ocean and sea-ice reanalysis at ECMWF

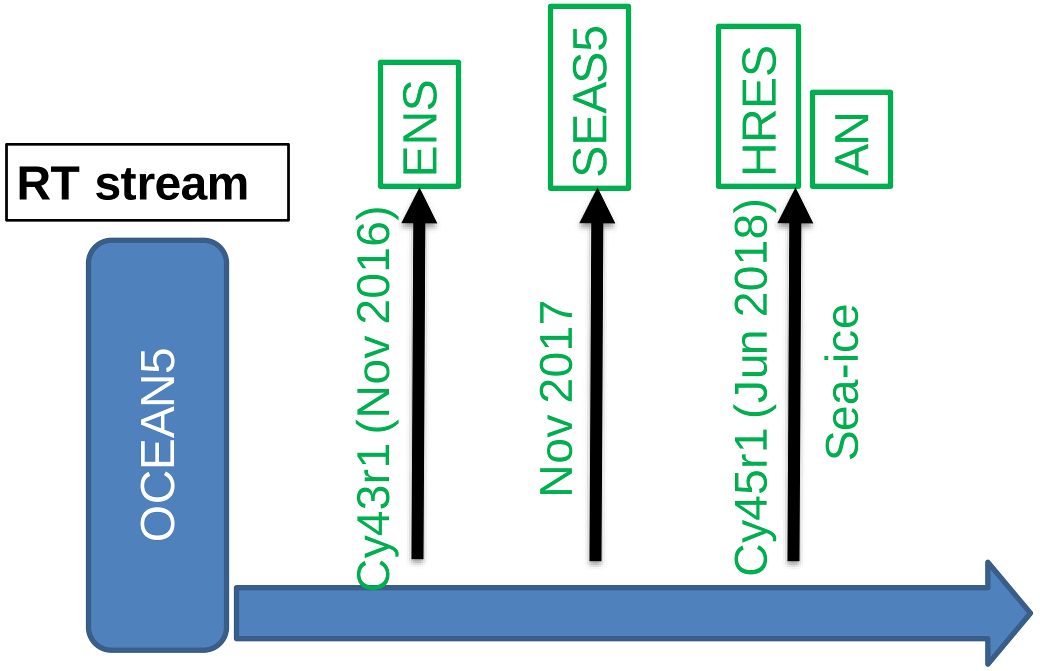


Ocean reanalysis development at ECMWF was closely linked to the seasonal prediction system development in the 90’s (SEAS1 in 1997)
→ Need for an ocean model and assimilation and ocean reanalysis

Ocean and sea-ice reanalysis at ECMWF

ORAS5/OCEAN5 provides ocean and sea-ice initial conditions for all ECMWF coupled forecasting system (Zuo et al., 2018). OCEAN5 also provides SST and SIC conditions for the ECMWF atmospheric analysis system (Browne et al., 2018)

- ORAS3: HOPE, OI
- ORAS4: NEMOv3 1-deg; 3DVar-FGAT; +SLA DA
- ORAS5: NEMOv3 ¼-deg + LIM2, +Sea-Ice DA
- ORAS6: NEMOv4 + SI3, En3DVar, +SST DA



Zuo et al., 2018, TM 823

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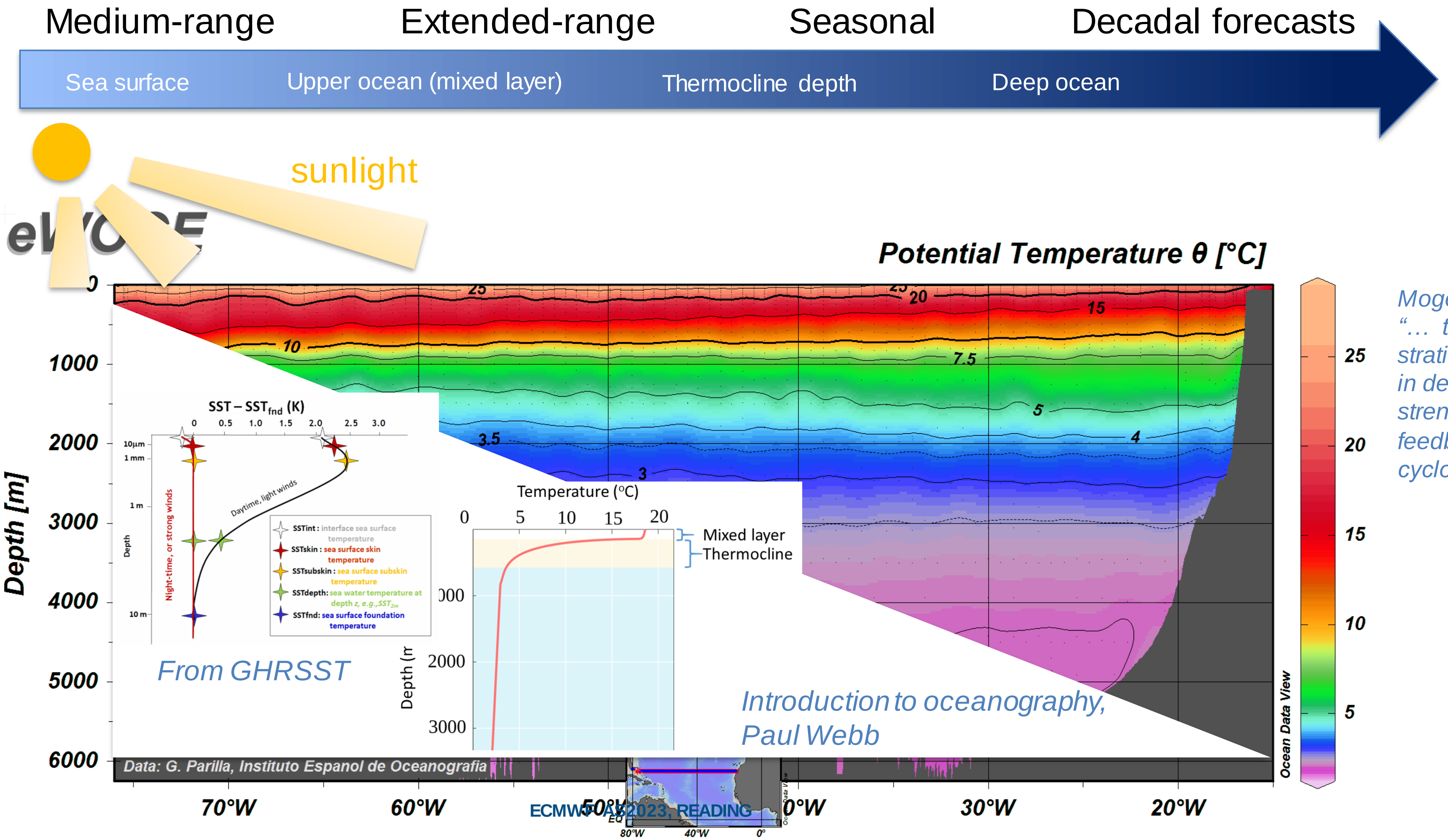
Applications of ORAs

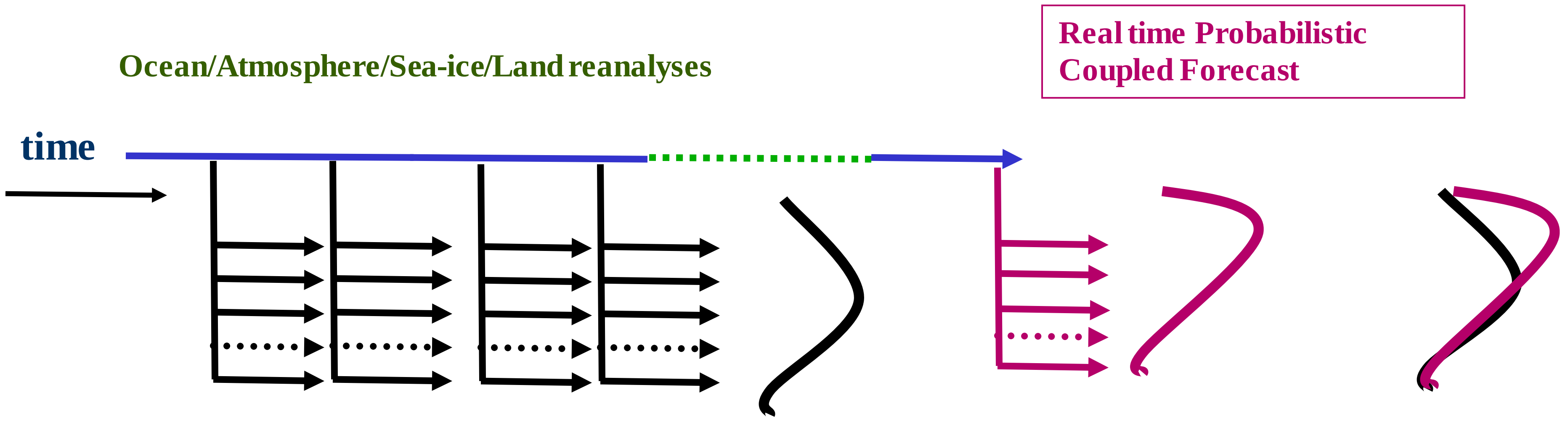
- Forecasting: initialization of coupled forecasts
  - NWP, monthly, seasonal, decadal
  - Calibration and reforecasts
- Verification/evaluation/co-design of Global Ocean observing network (OSE/OSSE)
- Climate applications
  - reconstruct & monitor the ocean (ECV/EOV);
  - study EEI and energy/water cycle;
- Towards coupled DA system (weakly -> quasi-strong -> strong …)
- Other Commercial applications (oil rigs, ship route …), safety and rescue, environmental (algii blooms, spills)

Applications: sub-seasonal to decadal forecasts



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

Applications: calibration and reforecasts



Reforecasts require historical reanalyses for initialization, consistent with real-time initial conditions

Reforecasts are needed for

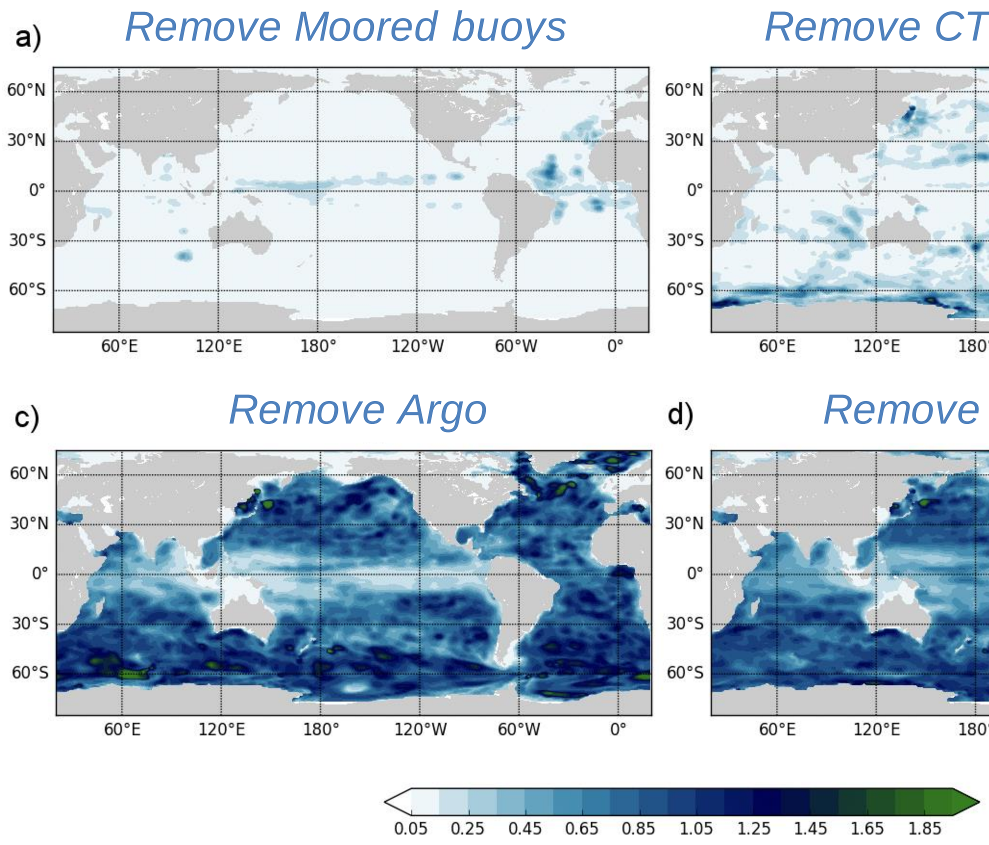
Calibration: dealing with model error

Detection of Extreme Events

Skill estimation

Applications: observing system co-design and impact studies

Maps of normalized RMSD of Temperature (upper 700m) in OSEs

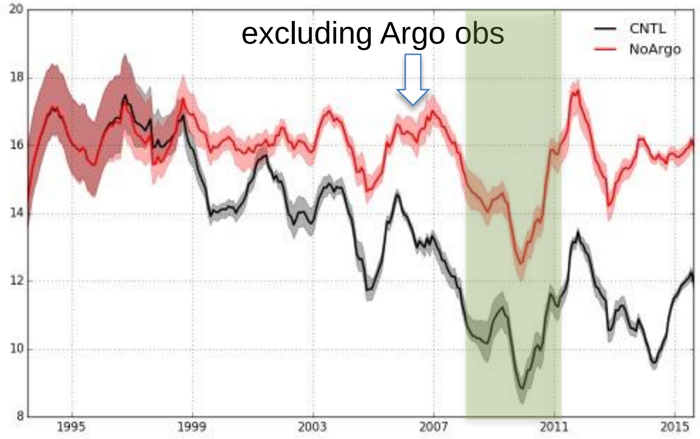


RMSD w.r.t a reference reanalysis, in which all in-situ data are assimilated.

Zuo et al., 2019, Ocean Science

During 2009/2010, there was a transient 30% weakening of the AMOC driven by anomalies in geostrophic and Ekman transports (*Roberts et al,. 2023*)

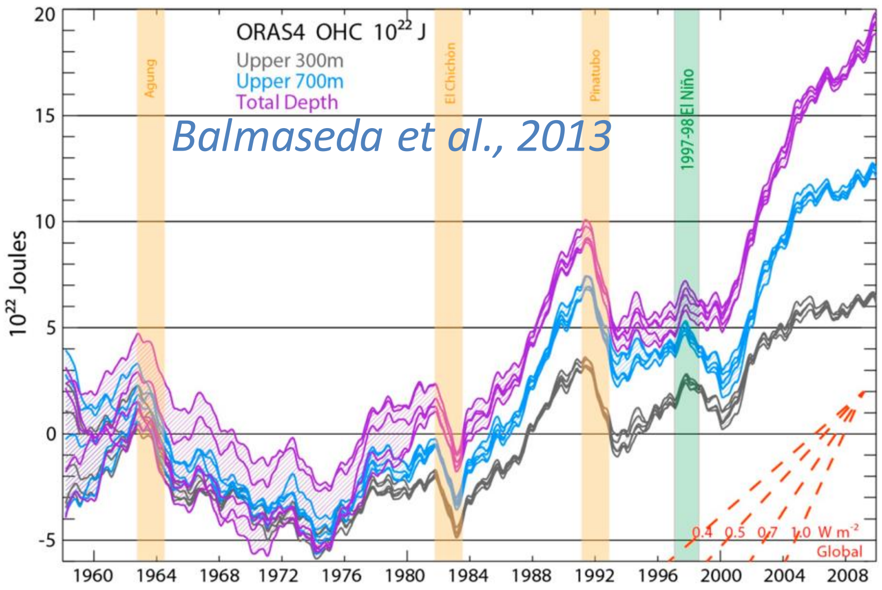
Maximum AMOC fluxes (in Sv) at 26.5 N



Applications: monitoring climate signals

ORAs provides continuous coverage of the global oceans constrained by law of physics and observations input, and therefore can resolve higher frequency variability in ocean than methods that rely primarily on in situ data.

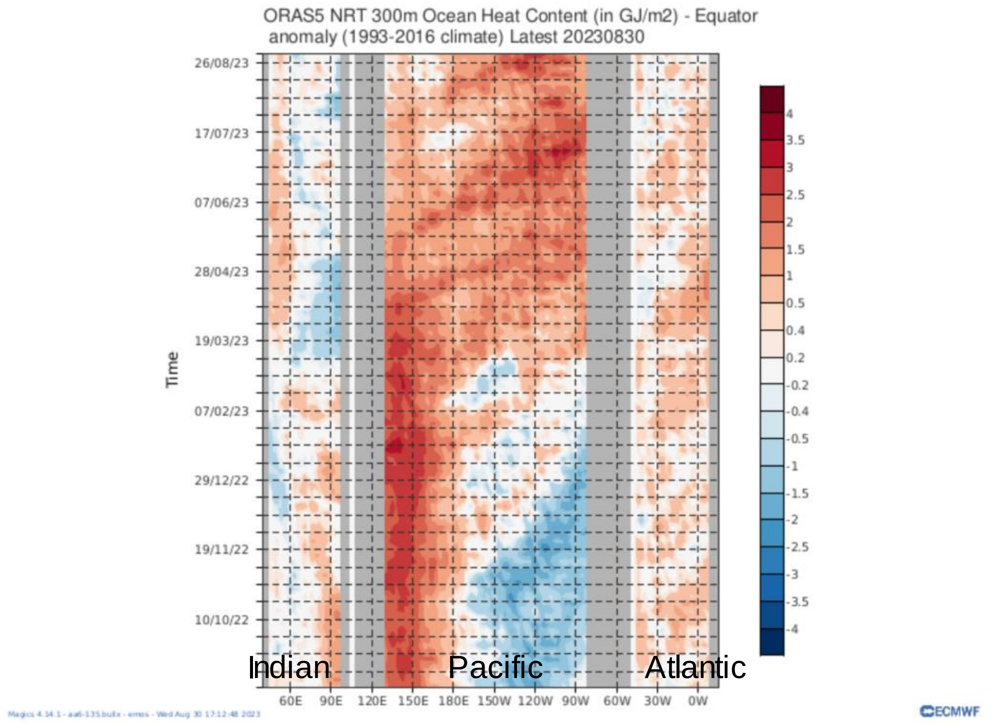
Ocean heat content changes



ORAS4 suggests that there is more heat absorbed by the deeper ocean after 2004.

ORAS5 NRT monitoring of OHC300

Longitude-time, 1-yr daily record



https://charts.ecmwf.int/catalogue/packages/oras5_nrt/

ECMWF

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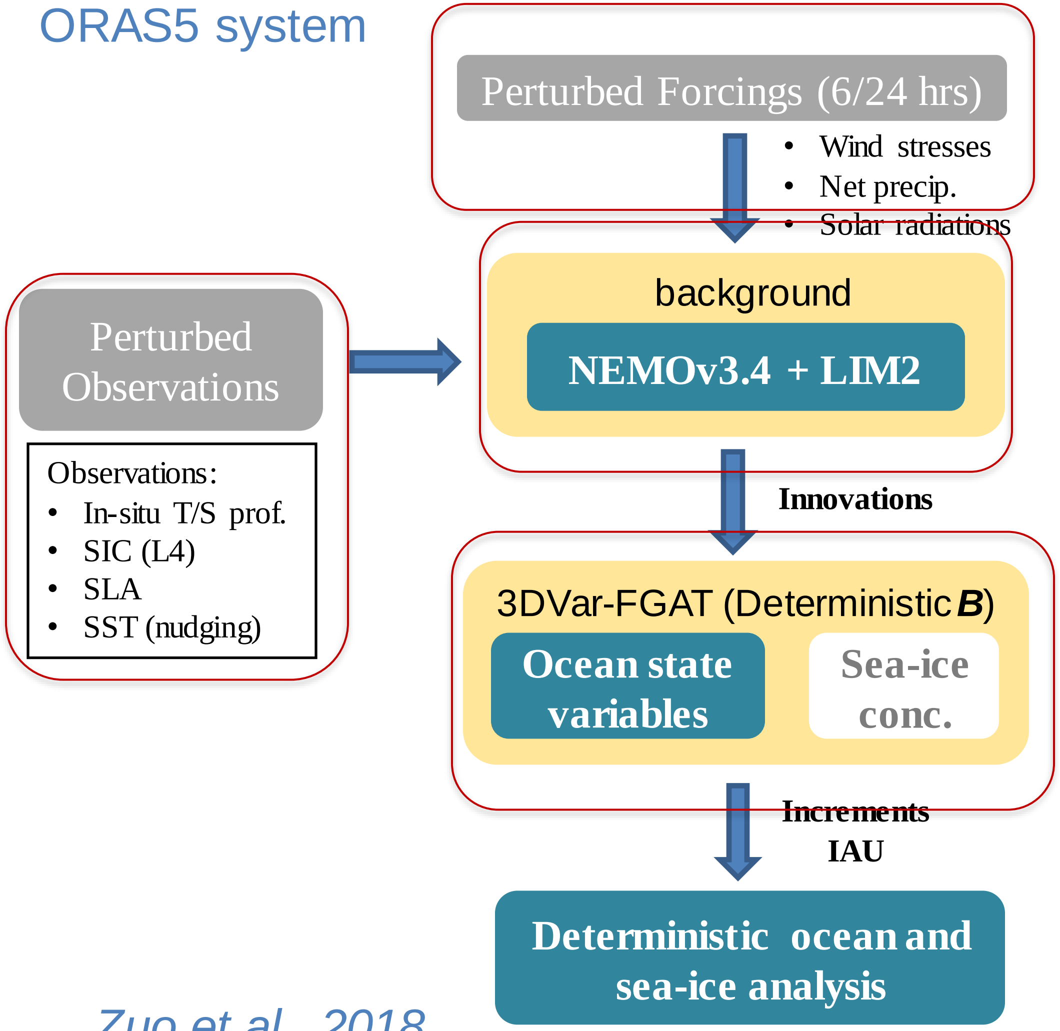
ECMWF ORAs systems

ORAS5 system



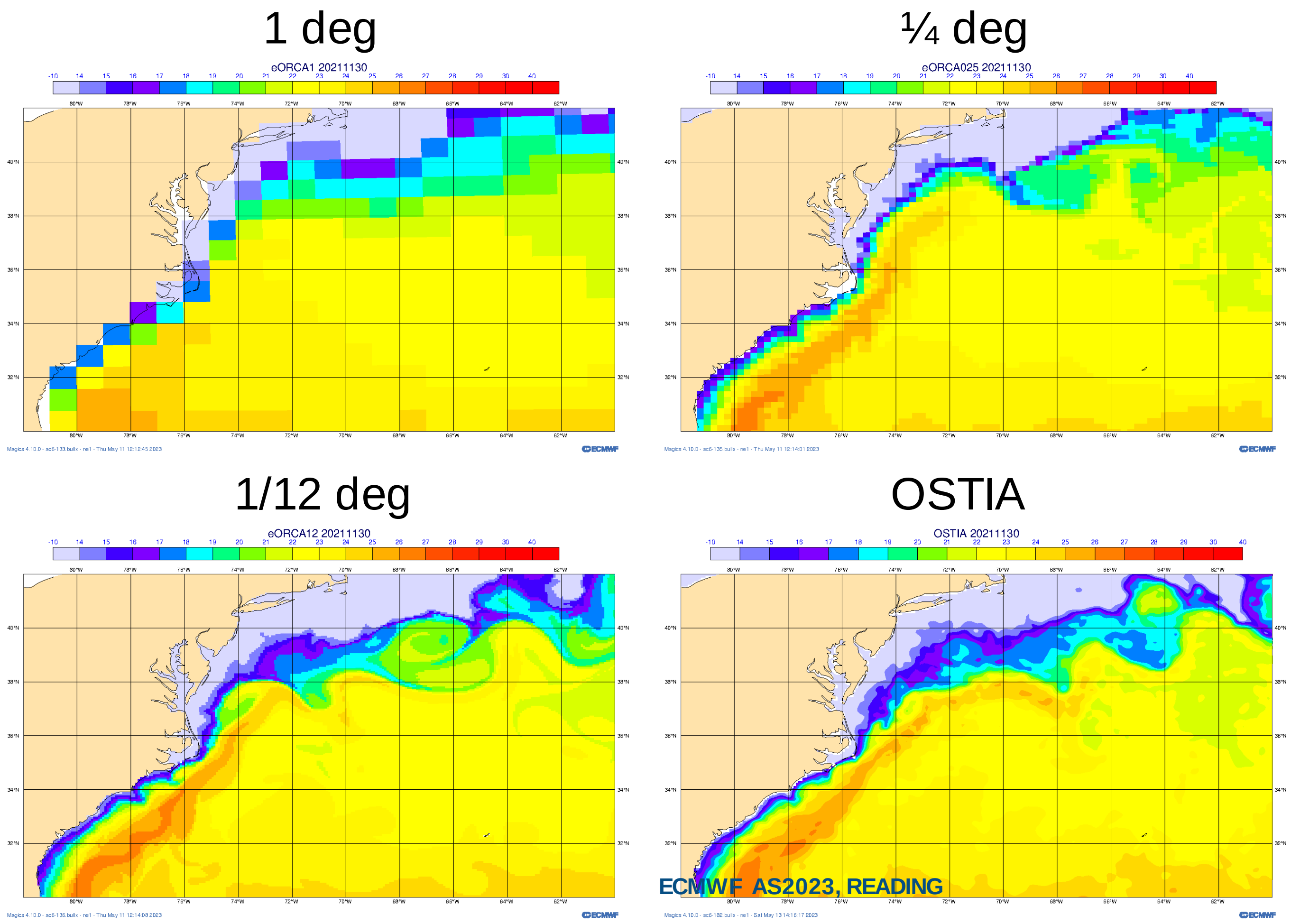
Zuo et al., 2018

ORAS5 is deterministic ocean and sea-ice reanalysis

- *5 member generated with perturbed forcing and observation inputs.*
- *Each member is a deterministic analysis produced with 3DVar-FGAT approach.*
- *No feedback between ensemble backgrounds and Covariance* ***B***

Numerical model in ORAs: ocean model

Numerical model will always be prone to biases, due to unsolved and poorly represented processes (model resolution, parameterisations, boundary conditions …).



Snapshot of the Gulf Stream from different NEMO V4 configurations (top left 1°, top right 0.25°, bottom left 1/12°) compared to the OSTIA observation SST production (bottom right).

ECMWF AWS2023

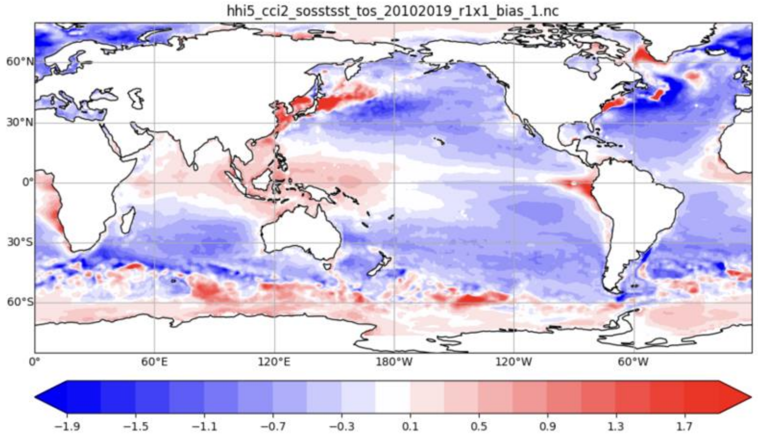
Numerical model in ORAs: ocean model

Different numerical models (ocean and sea-ice), and the same model but in different configurations, can have very different characteristics and biases patterns. To “correct” them will impose different constrains on DA method and/or observation input.

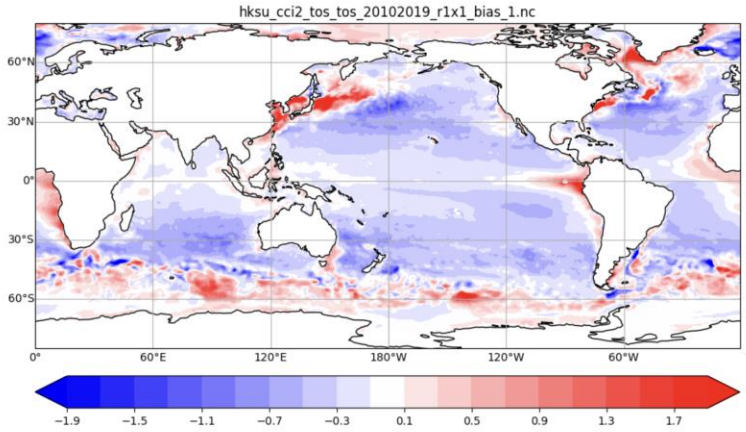
Mean SST biases

Same model resolution and forcings; without data assimilation
Verified against ESA CCI2 SST

NEMOv3.4



NEMOv4



- NEMOv3.4 used CORE bulk formula
- NEMOv4 used IFS bulk formula
- Differences in mixing due to parameterisations in the TKE scheme

Numerical model in ORAs: sea-ice model

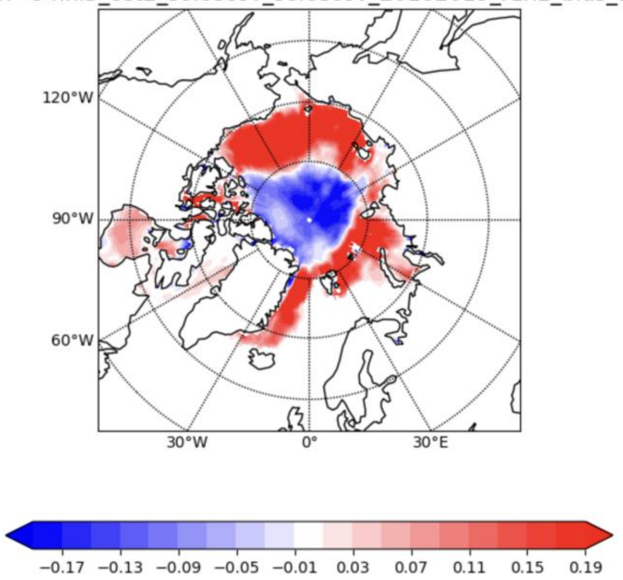
- The sea ice state is important for setting the flux exchange between the polar oceans and the overlying atmosphere.
- More complex models (like SI3) may help better capture the evolution of the ice but may also be more challenging to constrain with our assimilation systems.

Mean SIC biases (Sep)

Same model resolution and forcings; without data assimilation
Verified against OSTIAv2 SIC

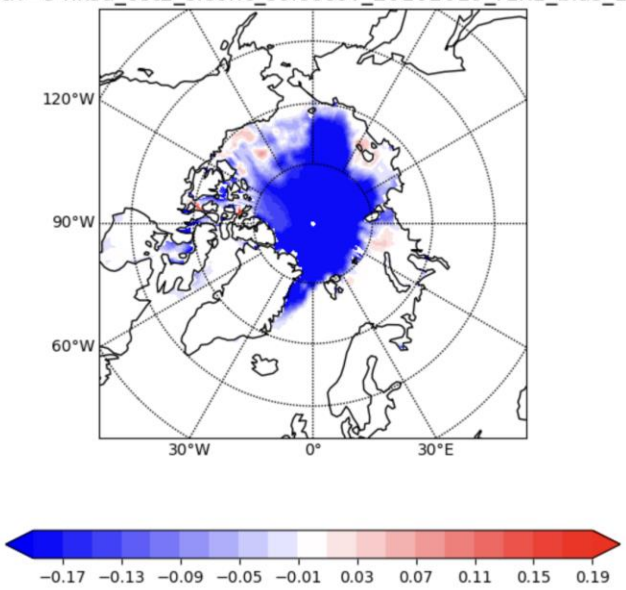
LIM2

month=8 hhi5_ost2_soicecov_soicecov_20102019_r1x1_bias_12.nc

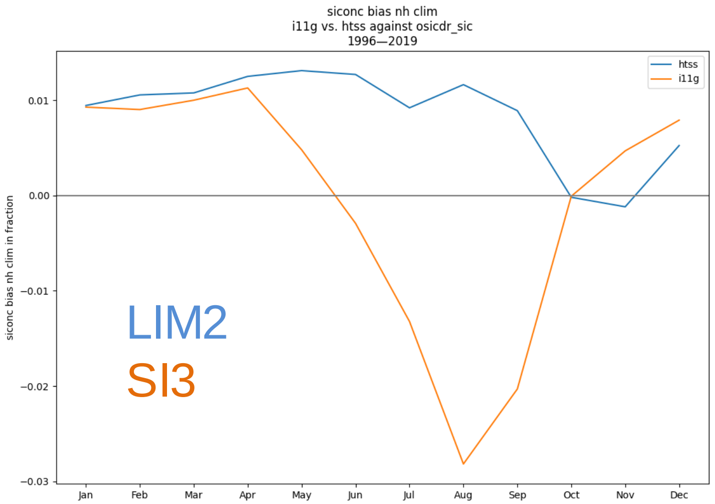


SI3 (multi-cat.)

month=8 hksu_ost2_siconc_soicecov_20102019_r1x1_bias_12.nc



NH ice conc bias (1996-2019)



Numerical model in ORAs: sea-ice model

Considerations with SIC DA in SI3 (multi-category sea-ice model with melt ponds)

- How to distribute increments among different thickness categories
- Where to apply sea-ice increments in the ice time-stepping scheme
- Introduce thermodynamic balance between sea-ice and ocean state variables
- Grow sea-ice from open water with DA increment
- Interaction between sea-ice increment and ice advection

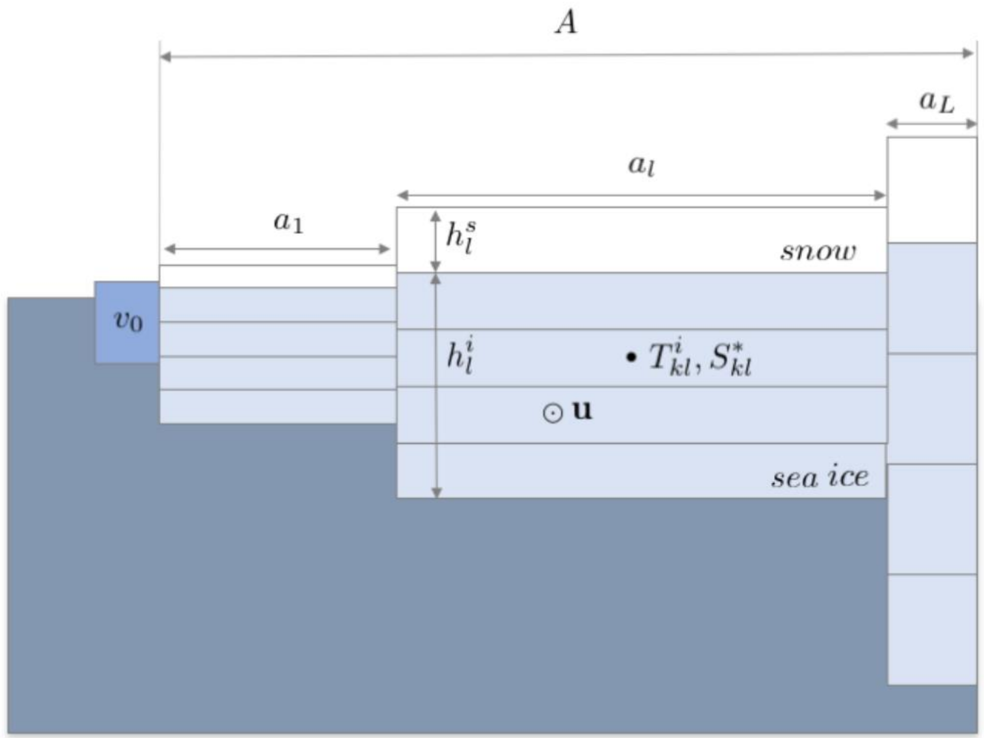


Figure 1.1.: Representation of the ice pack, using multiple categories with specific ice concentration ($a_l, l = 1, 2, ..., L$), thickness (h_l^i), snow depth (h_l^s), vertical temperature and salinity profiles (T_{kl}^i, S_{kl}^*) and a single ice velocity vector (u).

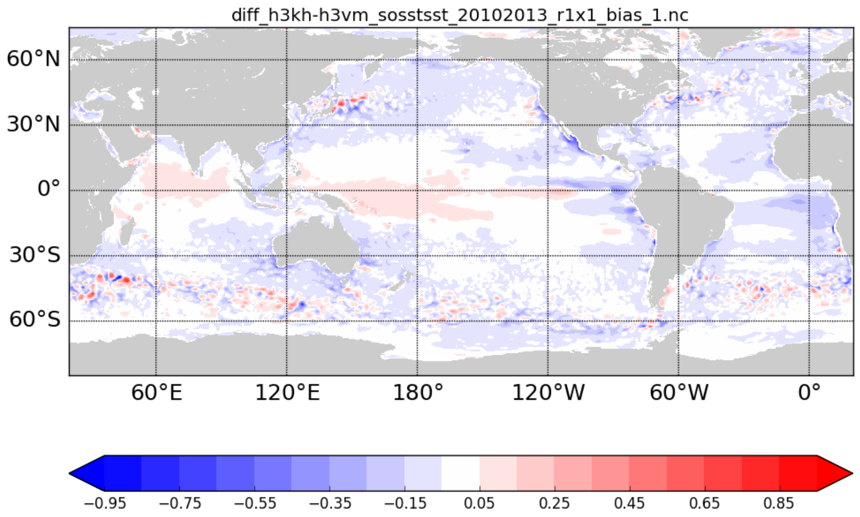
Atmospheric boundary conditions

- Earth sub-system reanalysis requires some boundary conditions (ocean/sea-ice/land/wave/atmosphere).
- ORAs is driven by atmospheric forcings (wind stresses, net precipitations, solar radiations) as well as land freshwater input.

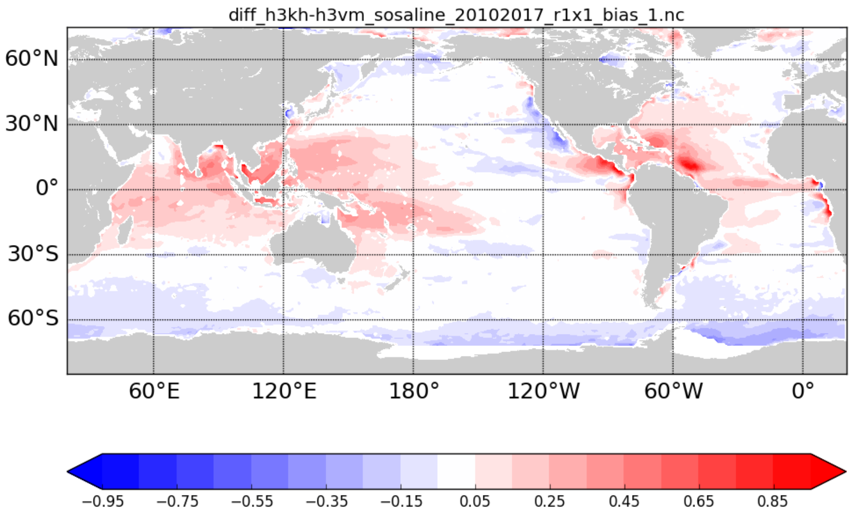
ERA5 vs ERAint

Same model version, no data assimilation

Mean SST difference



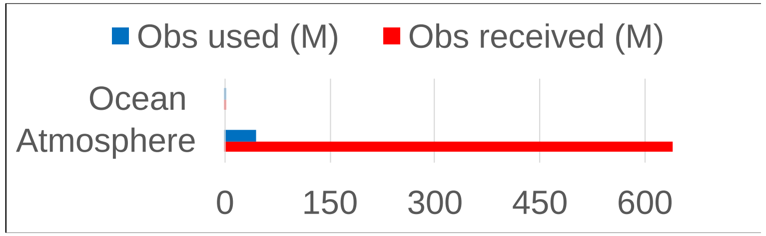
Mean SSS difference



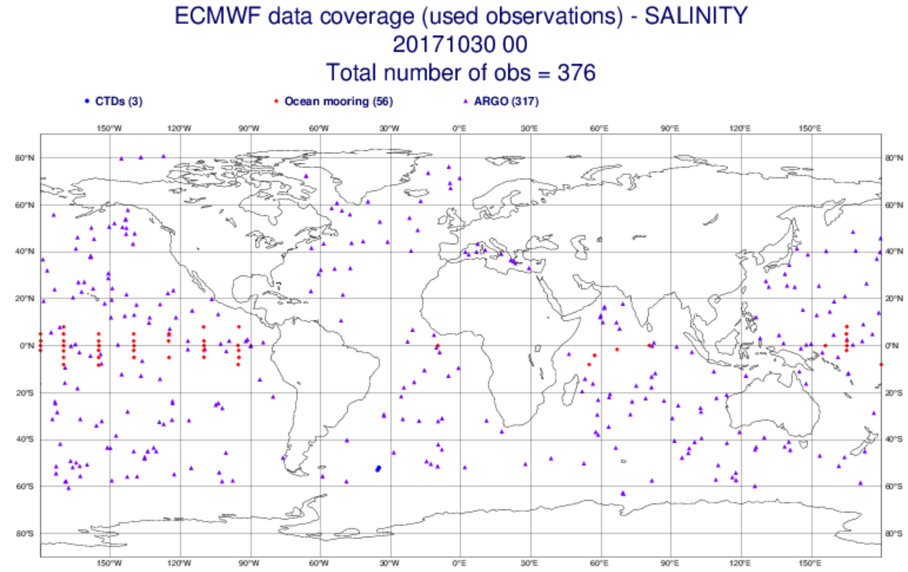
SST difference is mostly due to changes in ERA5 shortwave/longwave radiations.
SSS difference is directly related with precipitation changes in ERA5

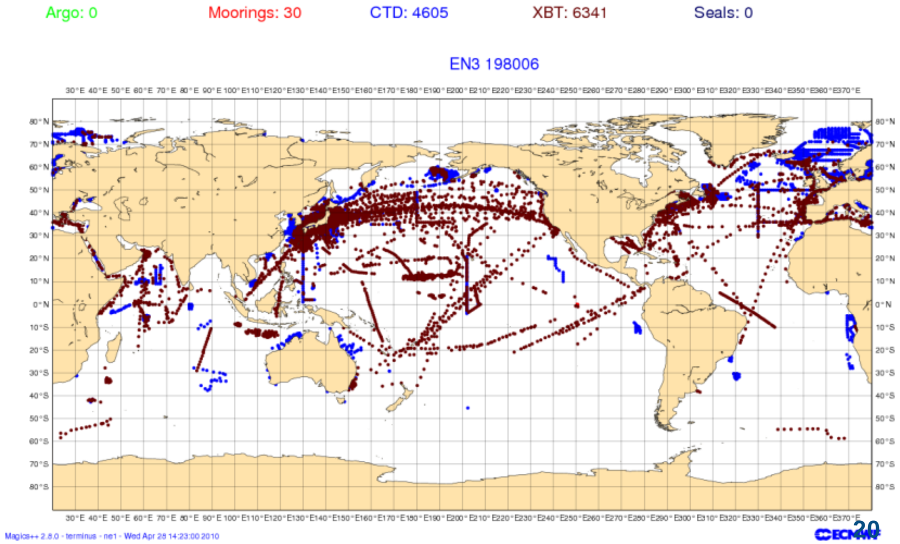
Ocean in-situ observations

- 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).
- Discontinuity is normal: Lack of funding; expensive and difficulty to maintain; relies on local contributions



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

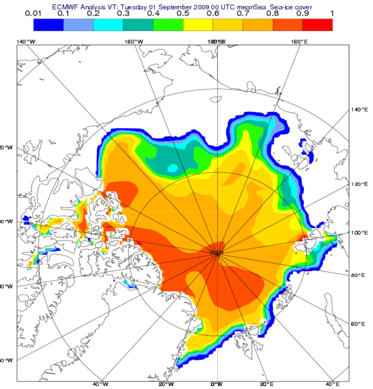




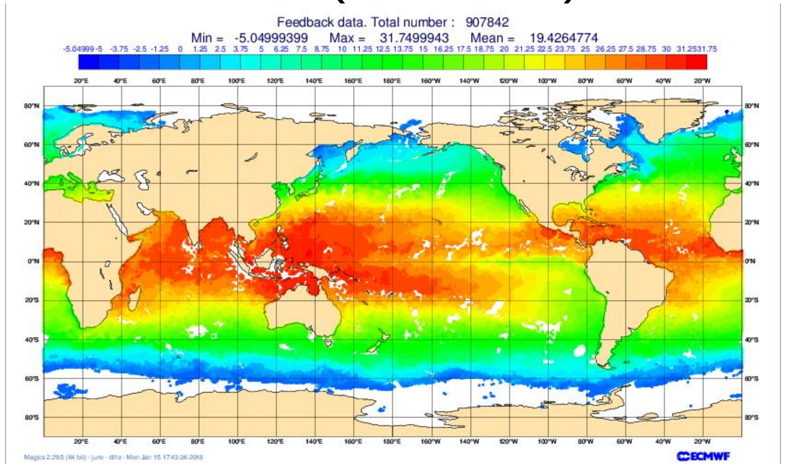
Satellite sea surface observations

- Satellite provide important observations on monitoring sea surface states (SST, SSS, sea-ice states, sea surface height, surface currents, ocean color, etc).
- These sea surface observations are essential input for ocean and sea-ice reanalysis system and works as complemental data sources to the ocean in-situ observing networks.
- Challenge to deal with various data densities among different in-situ types, and between in-situ and satellite observations.

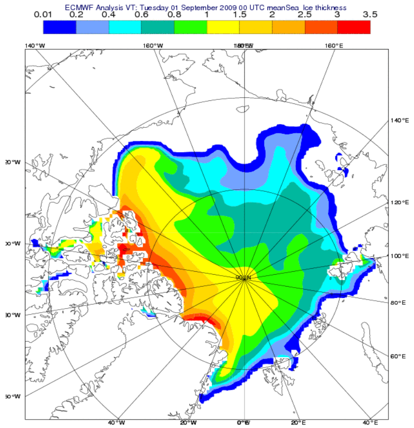
Sea-ice concentration



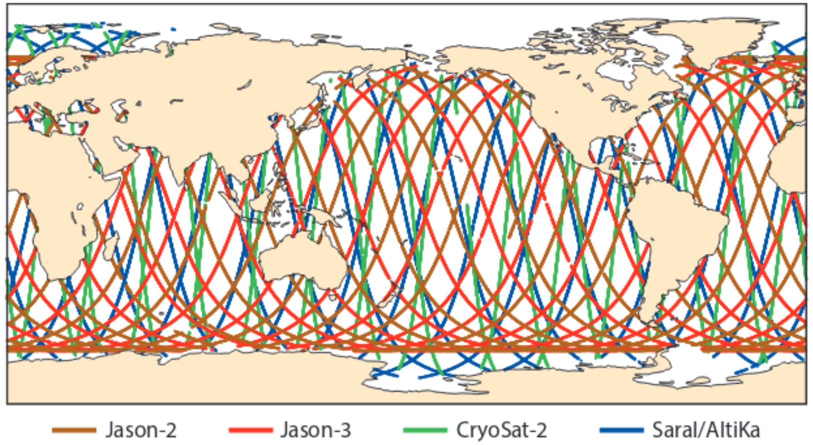
SST (IR, PMW)



Sea-ice thickness



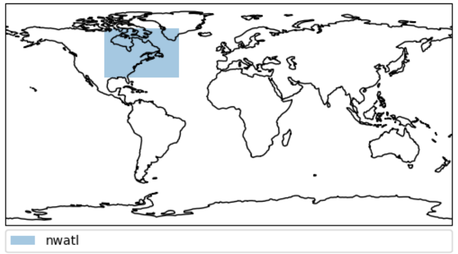
Sea-Level Anomaly (Altimeter)



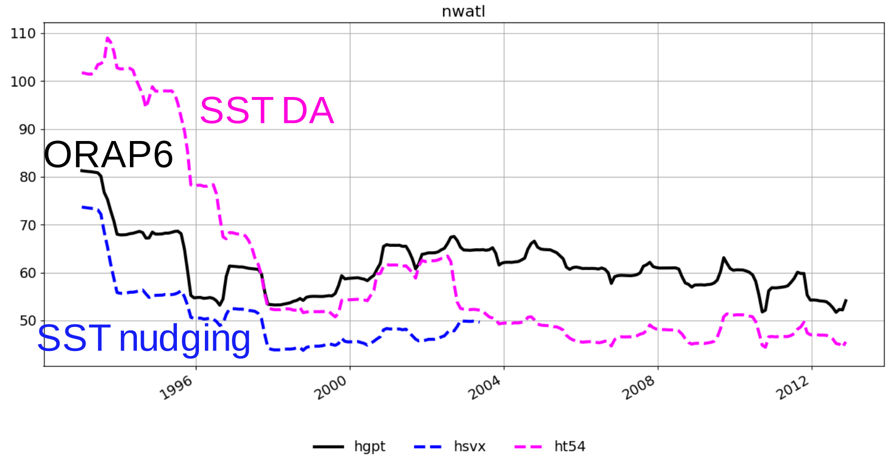
Imbalance between satellite and in-situ observations

Deal with imbalance between number of satellite surface observations and in-situ profiles is a challenge for ocean DA system.

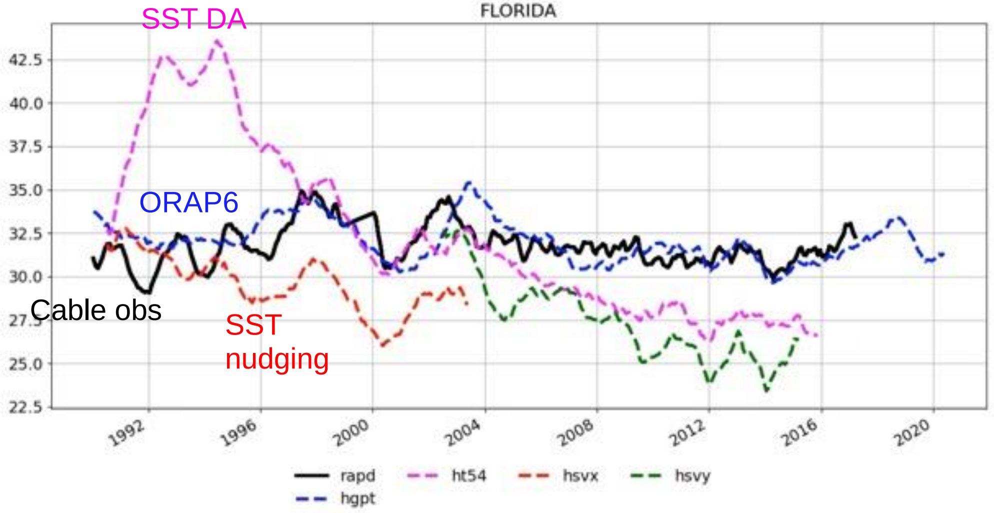
- Without Argo data to anchor the subsurface ocean state, assimilation of SST data introduce strong cooling in the Labrador Sea, which then leads to excessive deep water formation that feed into over-estimation of the AMOC in 1990s.
- To tackle this: obs pre-processing; EDA vertical diffusion tensor; model bias correction



MLD depth (m) at NW Atlantic Ocean



Florida strait transports (Sv)



Ocean DA at ECMWF: 3DVar-FGAT

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, 4D-Var in research model
- Background correlation model based **diffusion operators**
- Background errors are correlated between different variables through **balance operator**

3DVar-FGAT as in Daget et al 2009

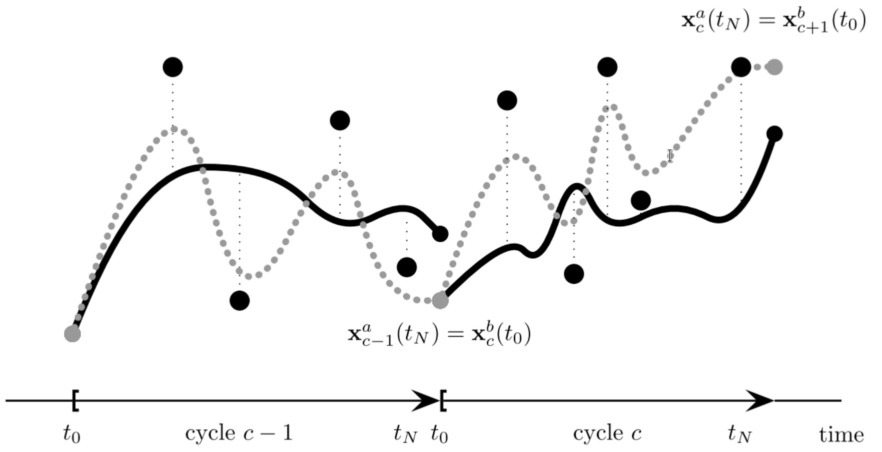
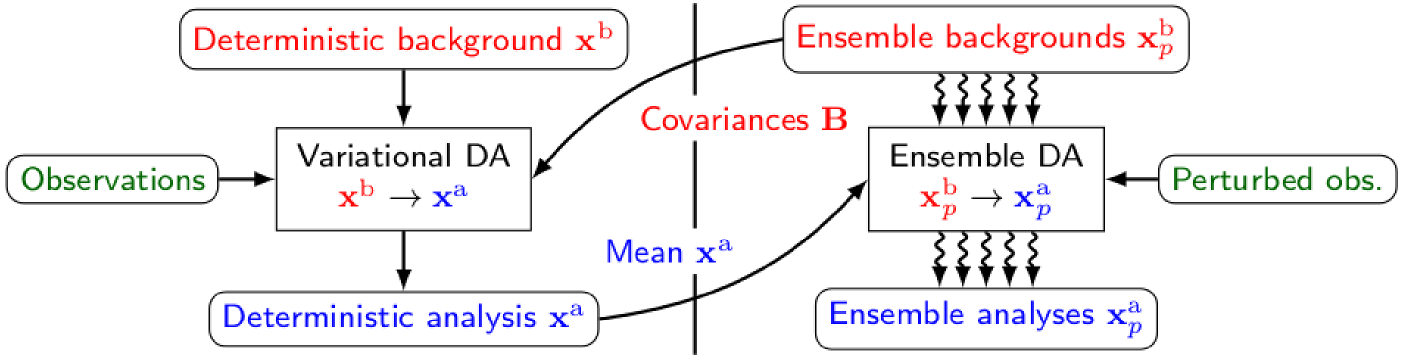


Figure 1: Schematic illustration of the procedure used to cycle 3D-Var. On each cycle c, the model is integrated from t_0 to t_N starting from a background initial condition $\mathbf{x}_c^b(t_0)$ (grey dots) to produce the background trajectory $\mathbf{x}_c^b(t_i)$ (black solid curve). The difference between the observations $\mathbf{y}_{c,i}^o$ (black dots) and their background counterpart $(\mathbf{H}_{c,i}\mathbf{x}_c^b(t_i))$ is computed (represented by the vertical thin dotted lines) for use in the 3D-Var FGAT minimization. After minimization, the model integration is repeated from the same initial condition $(\mathbf{x}_c^b(t_0))$ but with the analysis increment applied using IAU. This produces the analysis trajectory $\mathbf{x}_c^a(t_i)$ (grey dashed curve). The updated model state $\mathbf{x}_c^a(t_N)$ at the end of cycle c is then used as the background initial condition for the next cycle $c+1$ (grey dots).

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

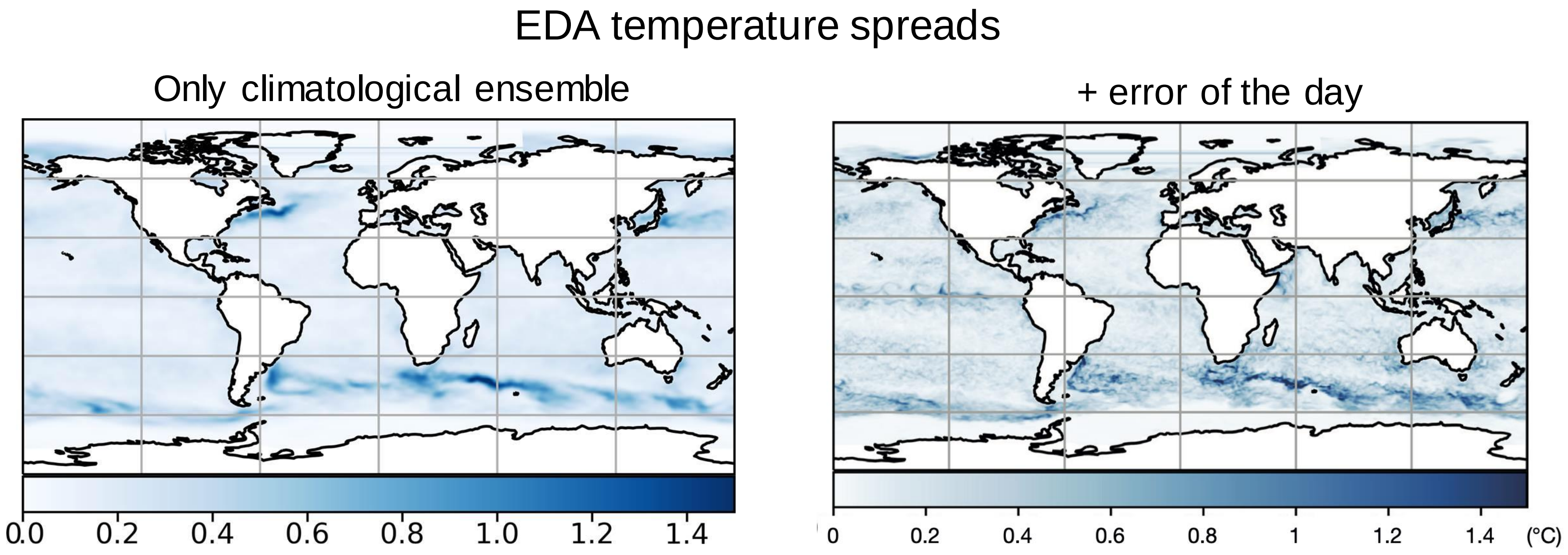
Ocean DA at ECMWF: En3DVar

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



- Ensemble DA perturbations simulate errors for the deterministic system;
- 3D-Var analysis for both deterministic and ensemble system;
- Observation and surface forcing perturbations as in ORAS5 (Zuo et al. 2017);
- Implementation of stochastic physics in NEMO (A. Storto, CMRE).

Ocean DA at ECMWF: En3DVar with Hybrid-B



Chrust et al., 2021

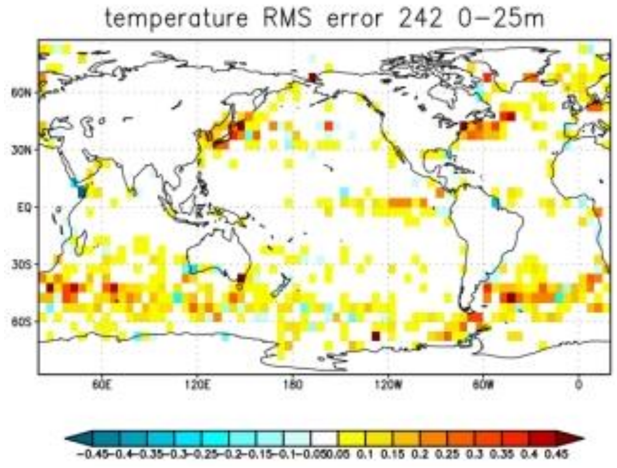
Ocean temperature spread at the surface from an Ensemble of Ocean Data Assimilations. The highest background errors are in western boundary current and Antarctic Circumpolar Current regions. This shows more details than without errors of the day, including a more detailed structure of sub-mesoscale eddies with much sharper fronts, and a hint of tropical instability waves in the tropical Pacific Ocean

Ocean DA at ECMWF: En3DVar with Hybrid-B

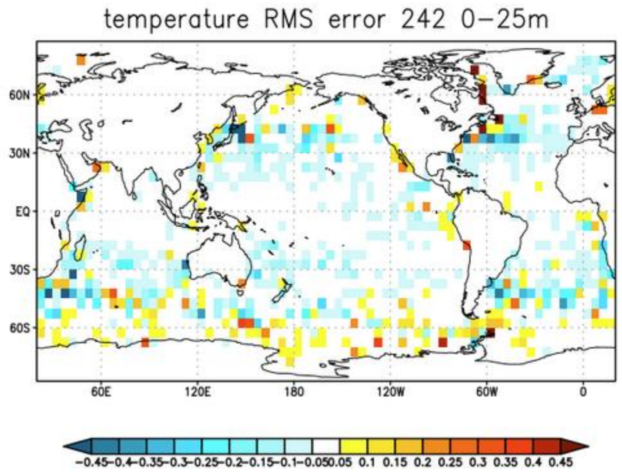
- Assimilation of SST with *parameterized* vertical correlation tensor increased SST biases
- Flow dependent vertical correlation scales (EDA) is essential, thanks to the factorized formulation of normalization factors;

Changes in fit-to-obs RMSE: SST DA – SST nudging
(verified against all in-situ obs: Argo/XBT/CTD/moored/animal/etc)

- SST DA performance is much worser than SST nudging with parameterized diffusion tensor (as in OCEAN5)



- Switching to hybrid tensor with ensemble vertical tensor improve WBCs and ACC



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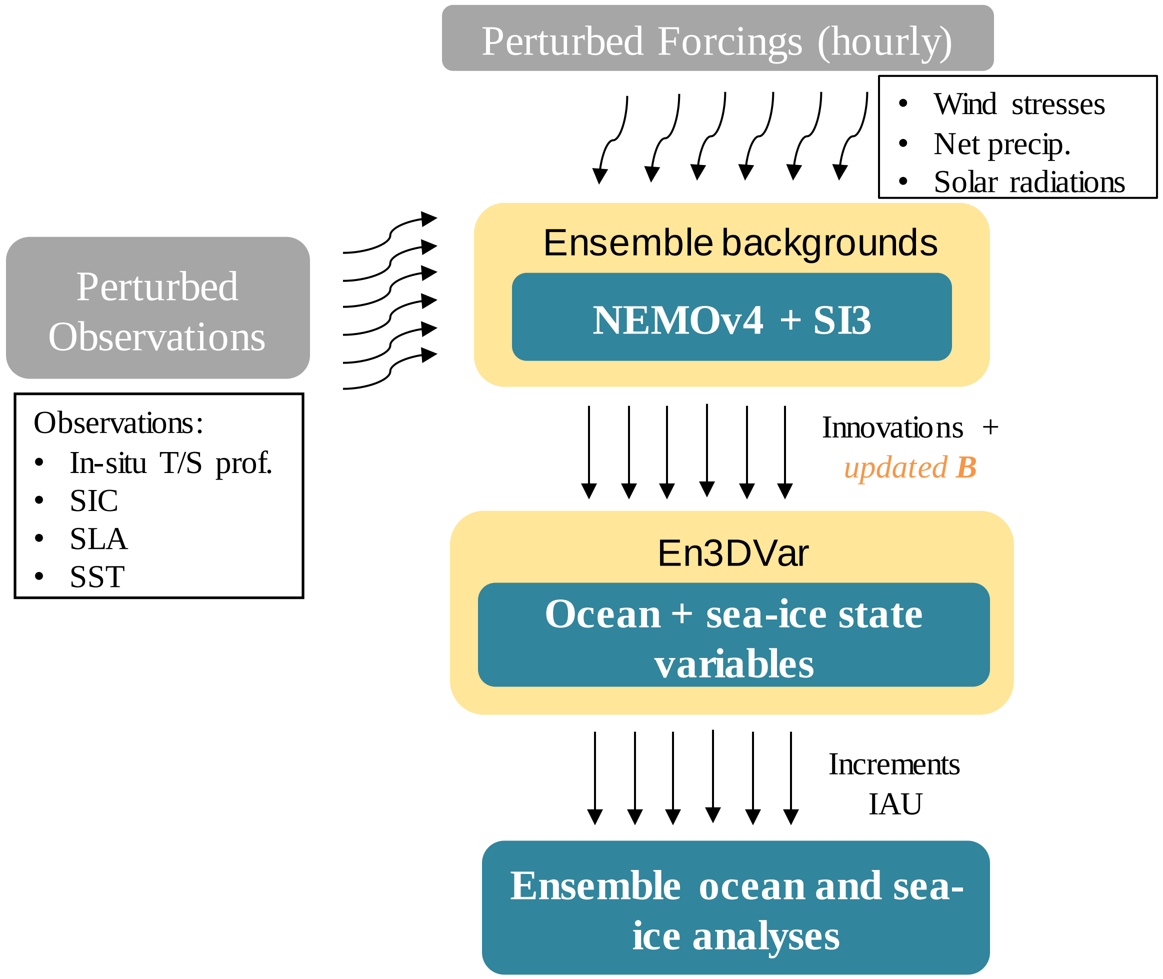
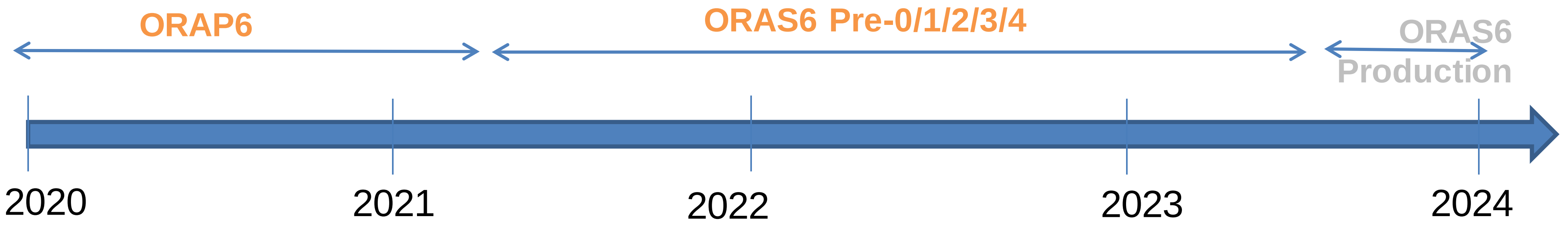


Overview of the ECMWF ORAS6 system

ORAS6 is the new ECMWF ensemble ocean and sea-ice reanalyses. ORAS6 will replace ORAS5 to provide ocean and sea-ice initial conditions for all ECMWF coupled forecasts in 2024 (including ERA6).

- *NEMOv4 + SI3 (¼ deg +75 level)*
- *Assimilates ocean in-situ and surface observations*
- *Use En3DVar FGAT scheme, 11 members*
- *Covariance **B** is updated every cycle with ensemble backgrounds, generated by perturbed forcings and observations*

ORAS6: Timeline



	Forcing		Model		Data Assimilation				Ens. Gen.		Observations			
	Atmos.	FWB	Ocean	Sea-ice	B cov.	Bias Corr.	SST	Sea-ice	Ens num	Pert.	SL	Insitu	SIC	SST
ORAS5/ OCEAN5	ERA40/ERA-int (6/24hr)	GRACE+ MSLA	NEMOv3.4 ¼ deg., 75 levels	LIM2 (single-cat)	3DVar FGAT	a-prior + online	Nudging	Weekly-coupled	5	V3: Obs + forcing	DT2018	EN3	OSTIA L4	HadISST2+OSTIA L4
ORAS6	ERA5 hourly	New FWB distr.	NEMO4 ¼ deg., 75 levels	SI3 (multi-cat.)	En3DVar + Hybrid-B	2-step offline + online	En3DVar	Single minimization	11	V4: Obs + forcing	DT2021	EN422	OSI-SAF L3 (v3)	OSTIAv2 L4

Evaluation of ORAS6: sub-surface states

- ORAS6 uses EDA with hybrid-B formulation, which is essential for SST DA.
- Among all tested hybrid-B configurations, using hybrid horizontal diffusion tensor (*parameterized tensor in tropics + climatological tensor in extra-tropics*) together with an *ensemble-based vertical diffusion tensor* that updates every cycle has the best performance

Temperature fit-to-obs RMSE changes w.r.t ORAS5

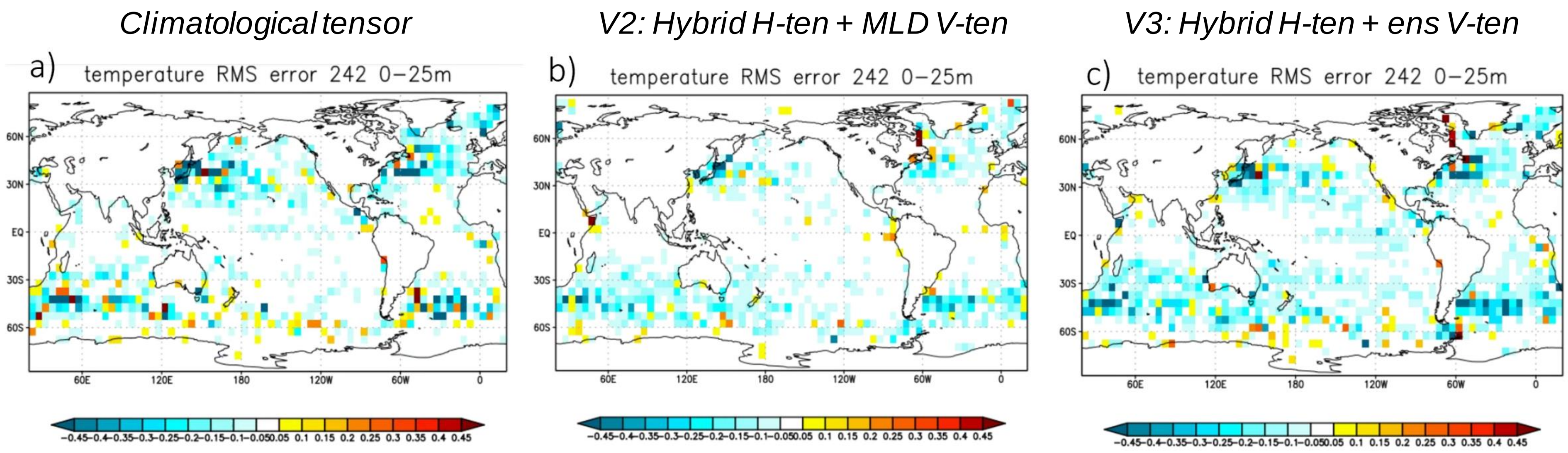


Figure xx Changes in temperature RMS errors (in K) in different hybrid-**B** configurations w.r.t to OCEAN5-like parameterized **B**: a) with full climatological diffusion tensors; b) with hybrid horizontal tensor (tropics-parameterized + extra tropics-climatological) + mixed layer depth based vertical tensor; c) retuned hybrid horizontal tensor (reduced length-scale at tropics) + EDA based vertical tensor. Temperature RMS errors are computed over 2020 and from sea surface to 25 m depth. Blue colours indicate hybrid-**B** configurations are closer to observations than parameterized **B.**

Evaluation of ORAS6: SST

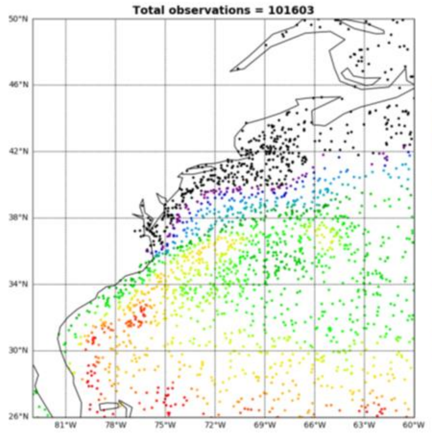
OSTIAv2 SST data is directly assimilated in the ORAS6 system

- This has greatly reduced SST biases in the GS region but only if *ensemble based vertical diffusion tensor* is used.
- Improvement also attributed to ERA5 forcing and improved upper ocean mixing in the physical model.

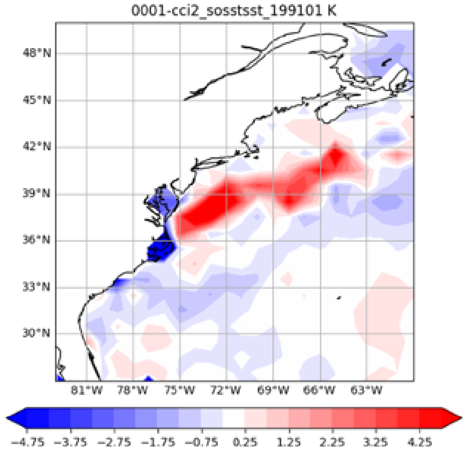
SST biases in the Gulf Stream regions (Jan 1991)

ORAS6 (SST DA)

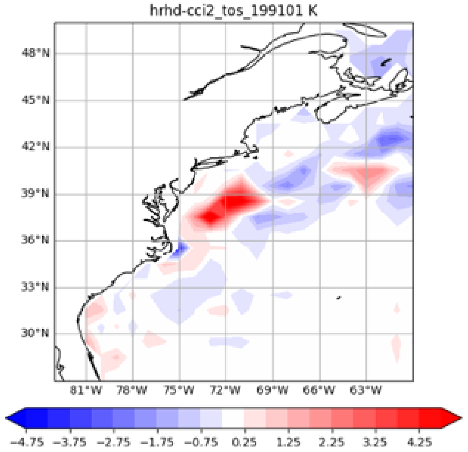
OSTIA SST



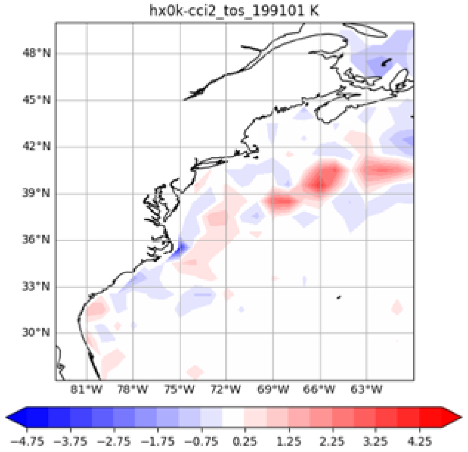
ORAS5 (SST nudging)



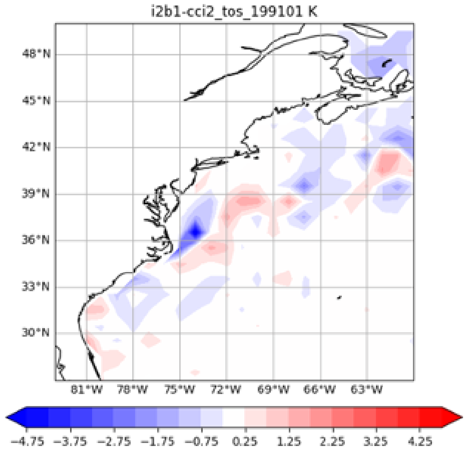
Prep-1



Prep-2



Prep-3.5

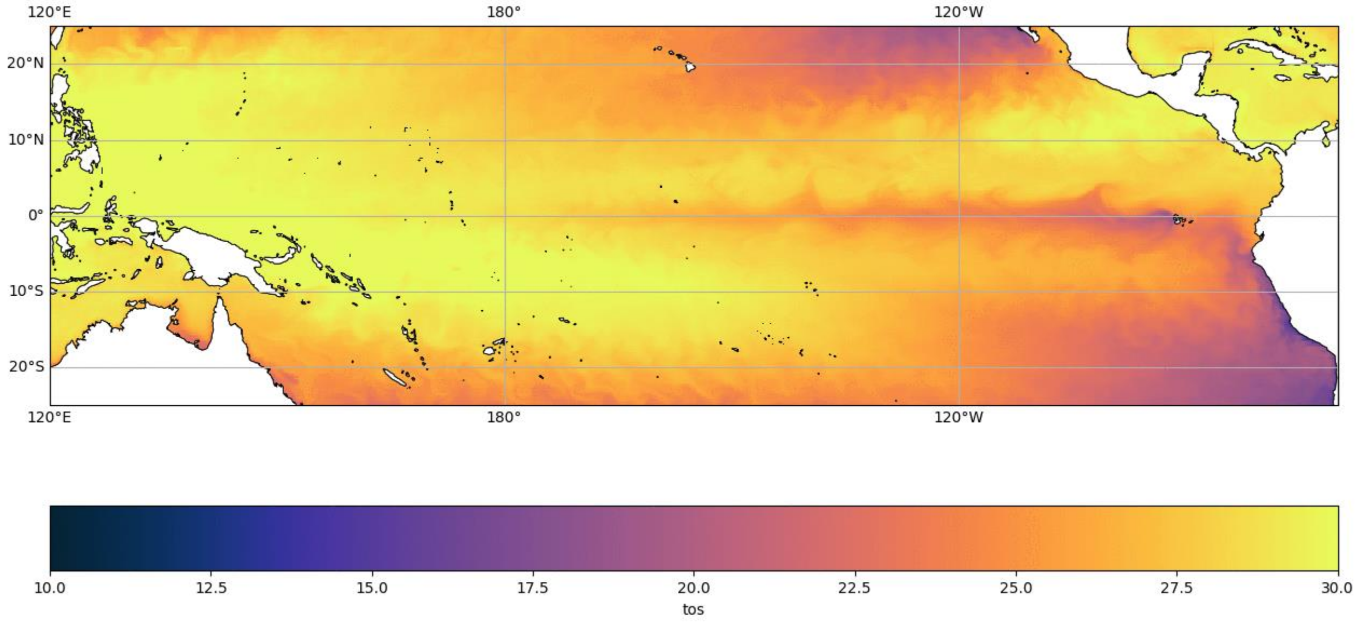


AWS2023, ECMWF

Evaluation of ORAS6: diurnal cycle

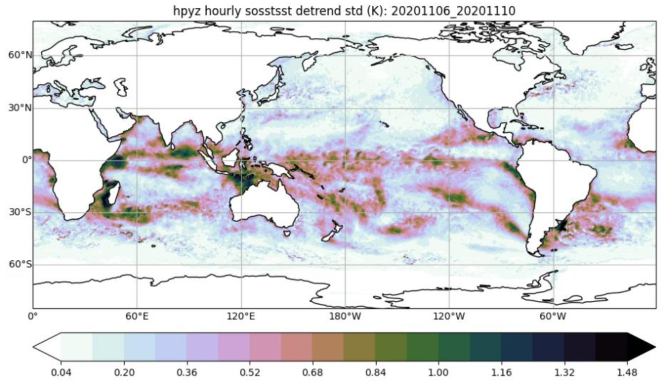
- Compared to SST nudging, direct assimilation of SST with En3DVar *improves the diurnal cycle (by ~15%)* in the ORAS6 SST analysis
- Realistic TIW representation in the ORAS6 prototype with hourly ERA5 forcing and assimilation of SST data

Daily SST in ORAS6 prototype

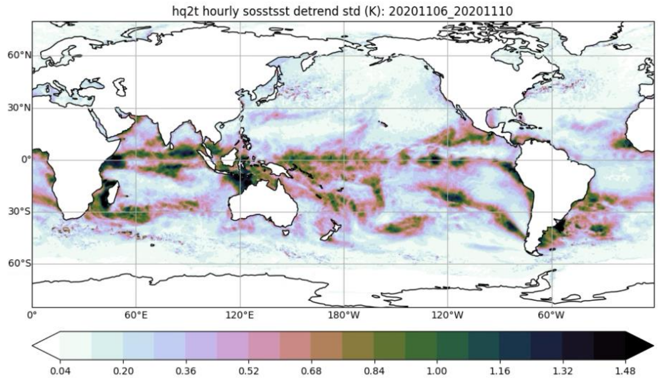


SST diurnal range (in K, 5-day mean)

SST nudging



SST DA



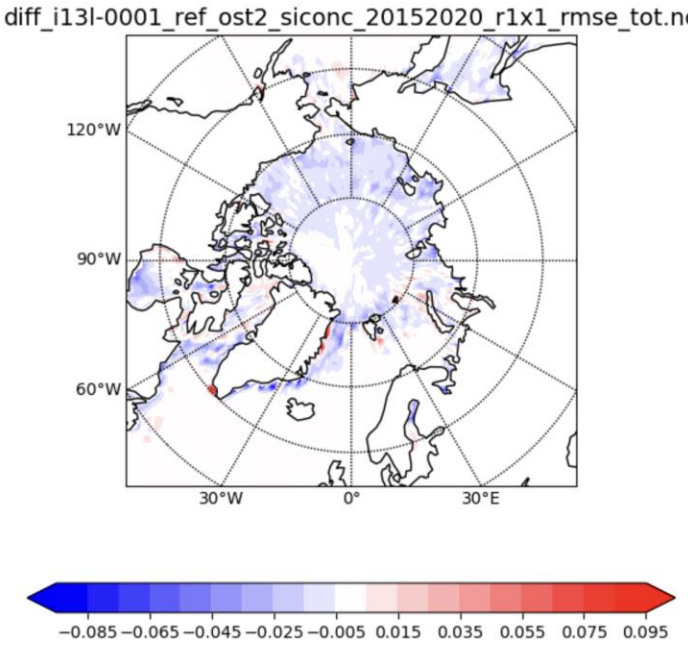
Evaluation of ORAS6: sea-ice

Sea-Ice Concentration data from OSI SAF L3 (CDR/ICDR) is assimilated through En3DVar scheme in the ORAS6 system

- Treated as univariate but with single minimization
- Uncertainties in SIC obs is accounted by perturbing SIC values with AE and SE (*Zuo et al., 2017*)

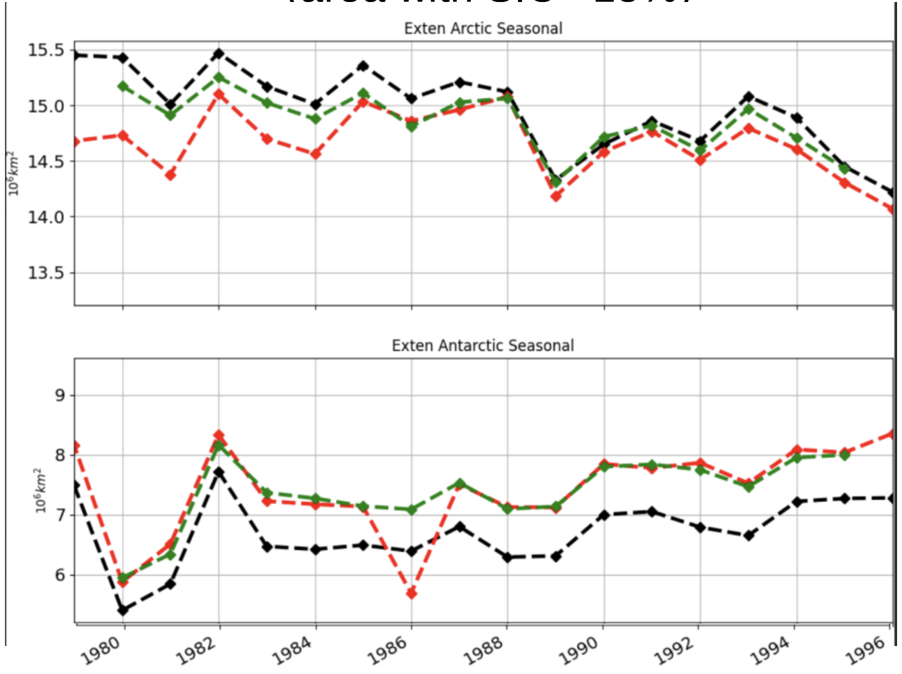
SIC RMSE: ORAS6 – ORAS5

(2015-2020, against OSTIA2)



April sea-ice extend

(area with SIC >15%)



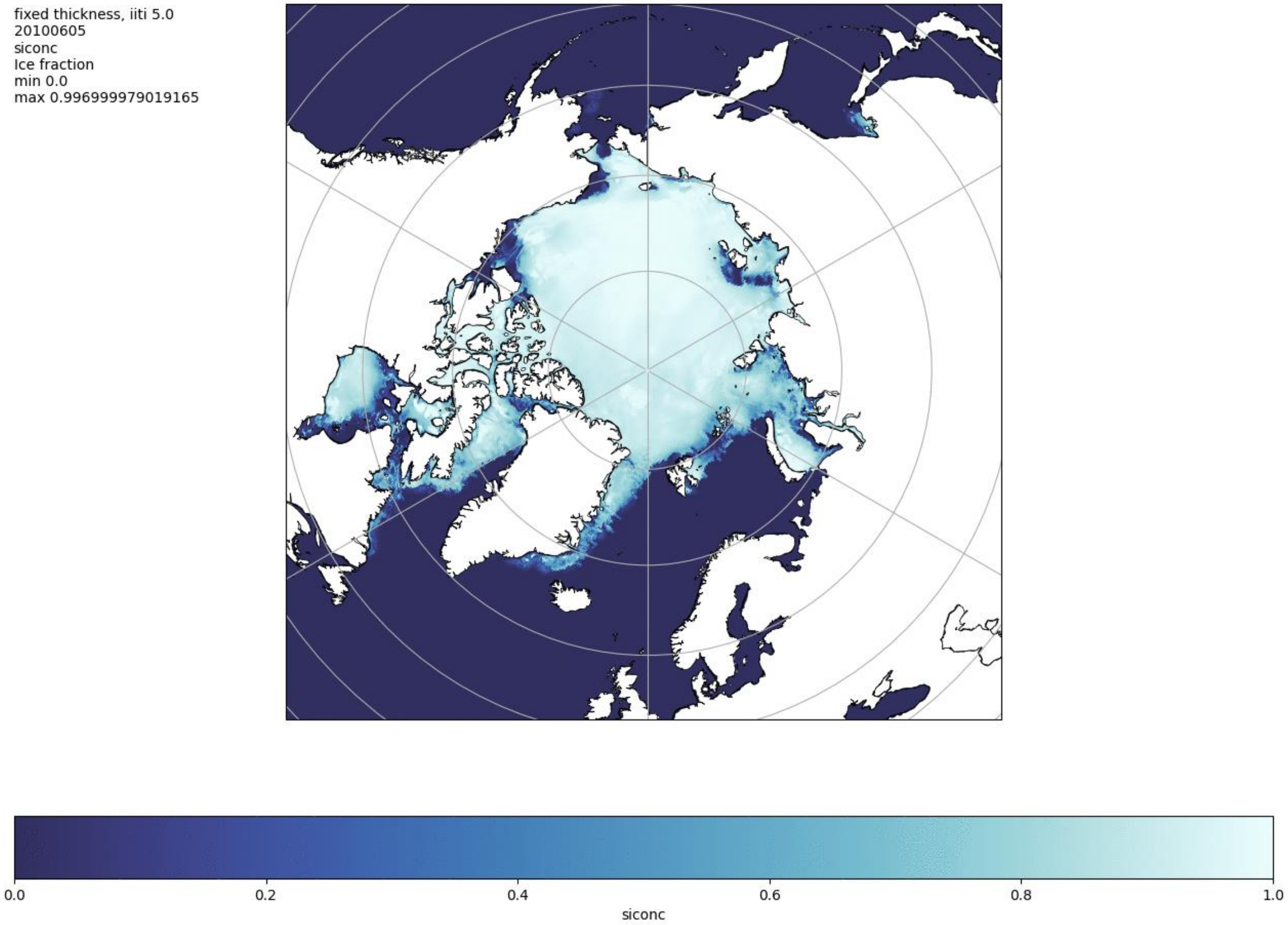
- The Arctic sea-ice extend (SIE) in ORAS6 is better consistent with NSIDC records
- No more spurious Antarctic SIE extreme event in 1986 in ORAS6

Evaluation of ORAS6: sea-ice

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

- ORAS6 will provide daily sea-ice reanalysis (sea-ice concentration and thickness, snow depth, sea-ice drift …) that covers 1955-NRT

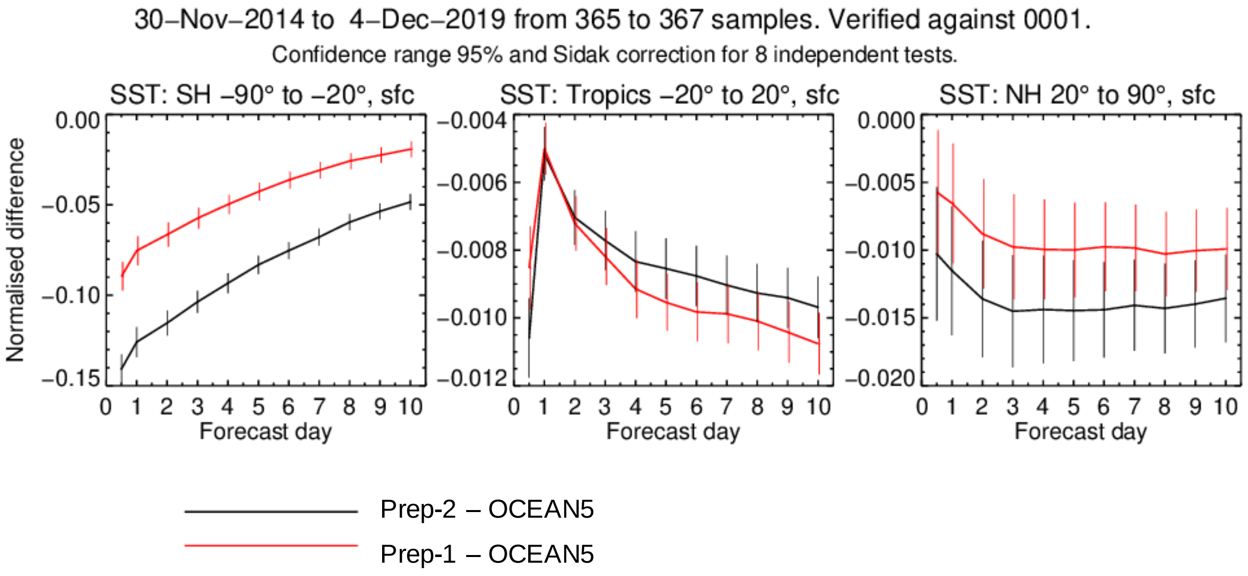
Daily sea-ice concentration from ORAS6 prototype



Evaluation of ORAS6: impact on NWP

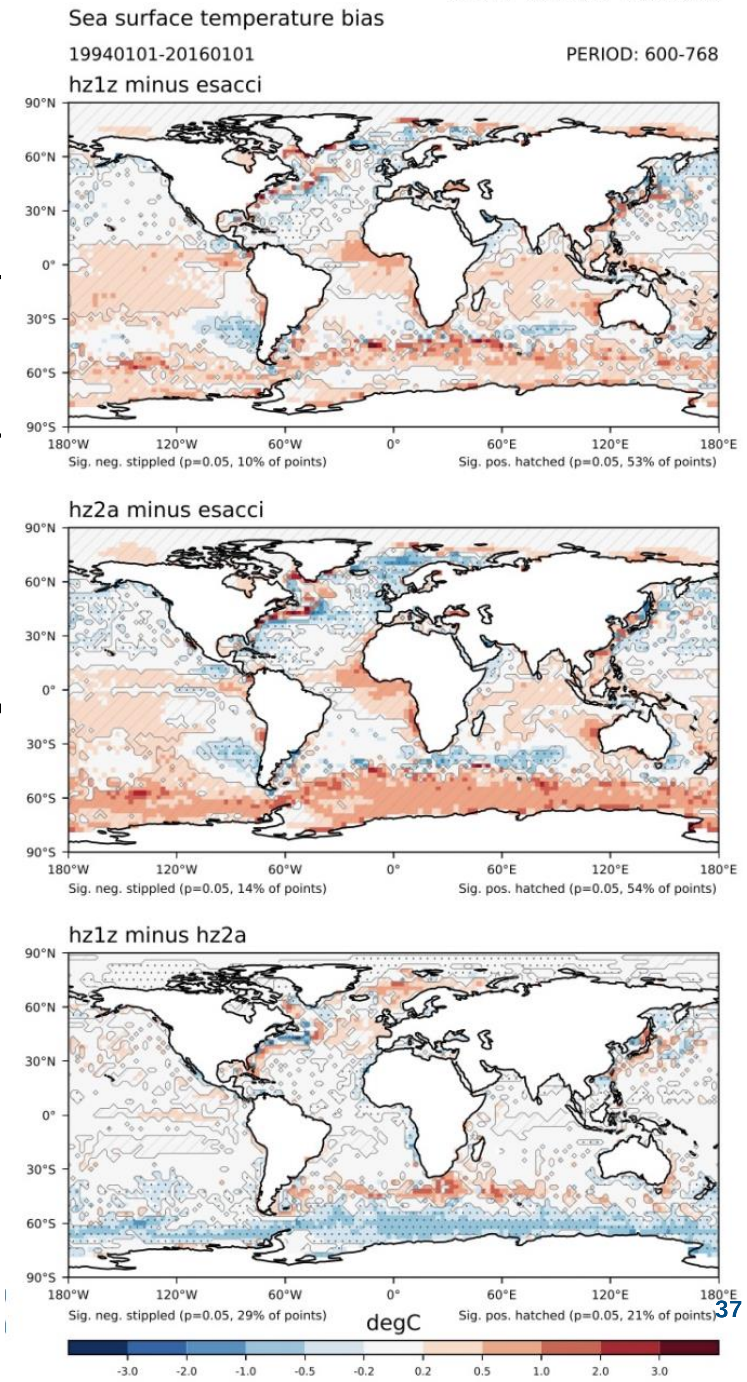
Positive impacts are visible when initializing ocean and sea-ice components of our coupled forecasting system from ORAS6 prototype with SST DA

Medium-range forecasts



Extended-range forecasts (week 4)

Jan start dates



ORAS6 prototype

ORAS5

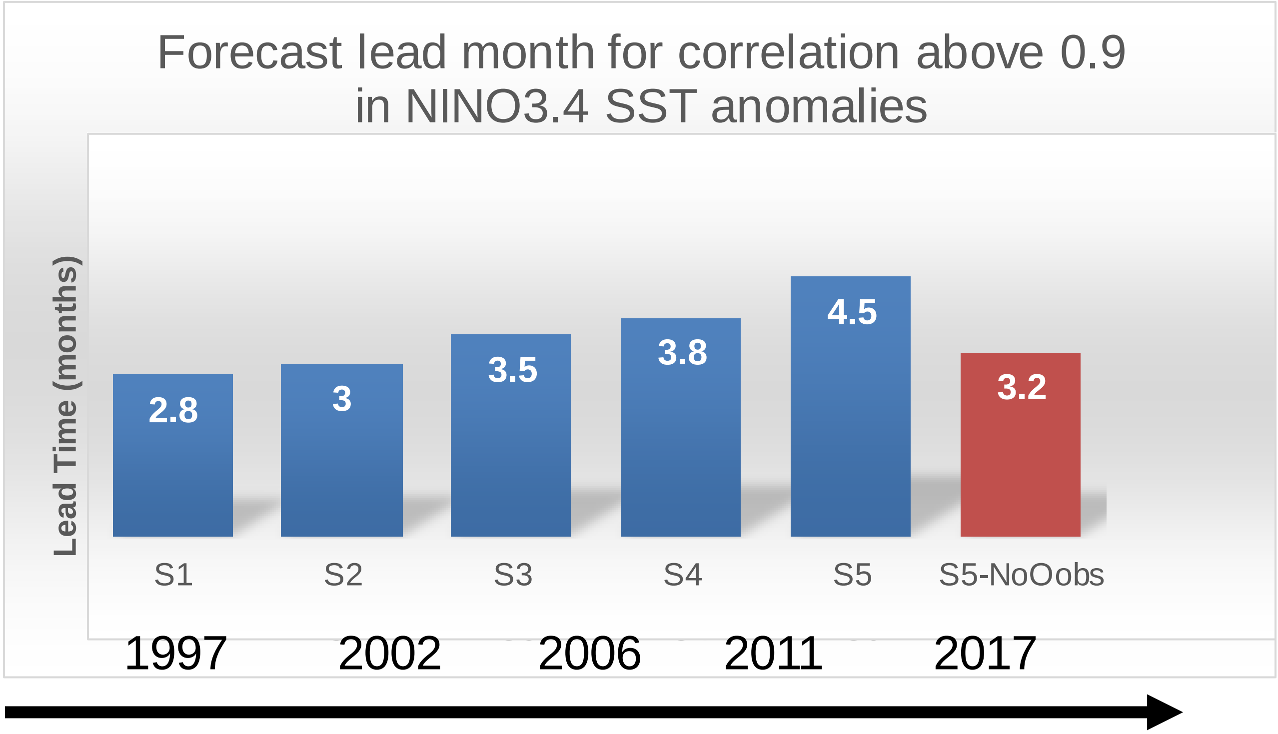
difference

Outline

- Ocean and sea-ice reanalysis (ORAs) at ECMWF
- Applications of ORAs
- ORAs system components
  - Numerical model Observations Data assimilation method
  - Boundary conditions
- ORAS6 system
- **Strengths, Weaknesses and Challenges**

ORAs in coupled forecasts

ORAS5/OCEAN5 provides ocean and sea-ice initial conditions for all ECMWF coupled forecasting system: (ENS, HRES, Seasonal). OCEAN5 also provides SST and SIC conditions for the ECMWF atmospheric analysis system (Browne et al., 2018)



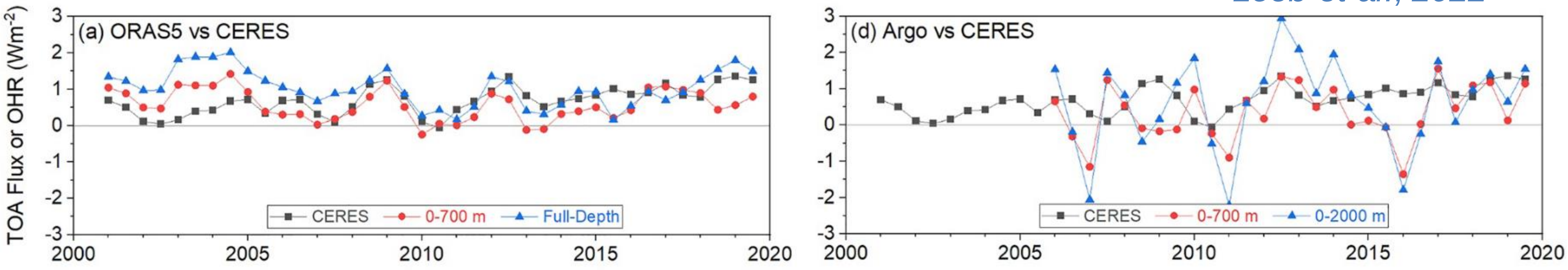
- Gain about 2 months in ENSO prediction
- Without Ocean observation and DA, we would lose about 15 years of progress.

ORAs in Climate monitoring

- Compared to objective analysis product, ORAs use numerical models to provide physically consistent background states for ingesting observations.
- ORAs provide continuous coverage of the global oceans and therefore can resolve higher frequency variability in ocean than methods that rely primarily on in situ data.
- ORAs benefit from continuous improvements in earth system model, thanks to increased model resolution and better representation of physical processes.

Ocean energy changes: ORAS5 vs Argo

Loeb et al., 2022



Recent ORAs are reliable data sources in study of ocean contributions in EEI (Mayer et al., 2021, 2022, Loeb et al., 2022).

Challenges in ORAs to support different applications

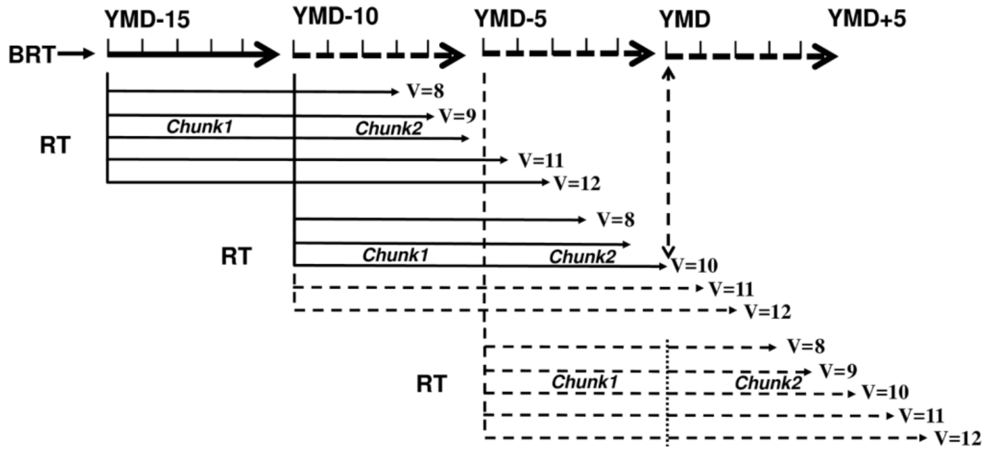
Ocean ORAs and Real-time analysis

- One system approach (Ocean Reanalysis + analysis) to initializing all coupled forecasts (from short-range to seasonal forecasts) is very challenging.
- Ocean data assimilation system that is optimized based on the latest NWP configuration and recent global ocean observing system, may not be sound for climate reanalysis purpose. "A central goal of climate data assimilation is to … optimizing the use and interpretation of limited climate observations", from WCRP Climate workshop 2023.

How do we go forward?

- Flow-dependent background correlation model (EDA)
- Use staged but linked streams: Delay/anchor streams with "frozen" system to ensure consistency and calibration of hindcasts/extended-range forecasts; NRT stream to allow system updates on model, data assimilation and new emerging observations.

OCEAN5 BRT and RT components



Zuo et al., 2019

Challenges in ORAs for Climate monitoring

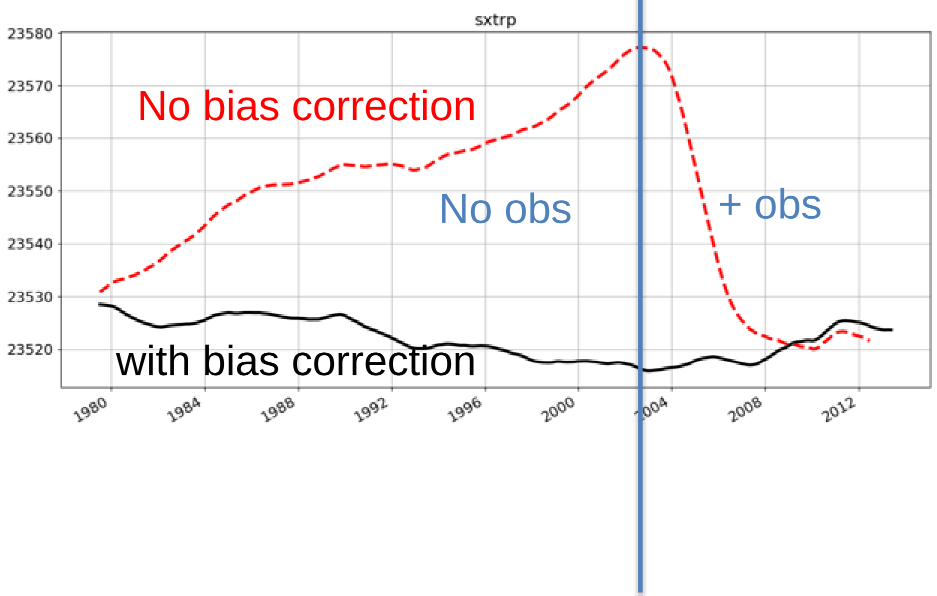
Constrain ocean with sparse observing network

- High uncertainties in re-construction of historical ocean events (heat content, transports) with various ORA products, especially when considering the deeper ocean below 1000m (Lee et al., 2010; Palmer et al., 2017, Storto et al., 2020).
- How to deal with changing observing system is one of the main challenge in ORAs.

How do we go forward?

- Use recent observation information retrospectively ?
  - Smoothing
  - nudging
- Bias correction

Salt content (0-700m) in the Southern Ocean



Summary

- ECMWF has a long history in developing ocean (and sea-ice) reanalysis product, initially to support seasonal forecasting system. ORAs is now used to provide initial conditions for all ECMWF coupled forecasting system and plays an important role in C3S climate monitoring service.
- Quality of an ocean reanalysis mostly depends on: i) quality of the numerical model; ii) efficiency and effectiveness of the data assimilation method; iii) availability and quality of observations; and iv) boundary conditions.
- ECMWF is developing the 6th generation of ocean and sea-ice ensemble reanalysis-analysis system – ORAS6. Major system updates include a new Ensemble based variational DA system with a hybrid-B approach; new NEMOv4 + SI3 model; ERA5 hourly forcing; direct assimilation of SST; among others.
- ORAS6 development is in its final consolidation phase. ORAS6/OCEAN6 will provide initial conditions for future ECMWF coupled forecasts (including ERA6) with a cycle update scheduled in 2024.
- This is very challenging to meet different requirements from various ORAs applications (subseasonal-to-decadal prediction, climate monitoring).