Ocean Data Assimilation Requirements for Weather and Climate

The demand for multi-decadal ocean reanalyses is now larger than ever

- Monitoring of climate variability and change. Energy, water and carbon cycles. Sea Level Rise
- Initialization and calibration of forecasts from days to decades rely on ocean reanalyses

Requirements:

- **Temporal consistency and faithful representation of a wide range of time scales**:
  diurnal cycle-intraseasonal-seasonal-interannual-decadal variability –trends

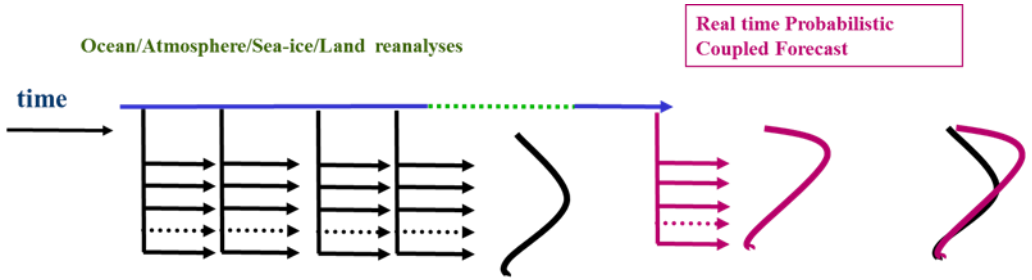
- **Physical thermo-dynamical balanced state estimatio**n:
  - so observational information can be propagated into the forecasts
  - so the energy water and carbon cycles associated with ocean transports can be reliably quantified

The requirements above are challenging in the presence of model error and an evolving but sparse ocean observing system

Ocean Data Assimilation Requirements for Weather and Climate

M.A. Balmaseda Beena Balan Sarojini, Michael Mayer, Steffen Tietsche, Retish Senan, Chistopher Roberts, Hao Zuo, Frederic Vitart, Tim Stockdale

Reliable Probabilistic Forecast rely on the quality of the ocean initial conditions from reanalyses



Well known challenge: Treatment of model error

- **Balance Equatorial Dynamics across time scales**
- **Need to extrapolate the observational information into the past**

New emerging challenges

- **Initialization of Mixed layer**
- **Initialization of the AMOC**
- **Initialization of Western Boundary Currents and Fronts**

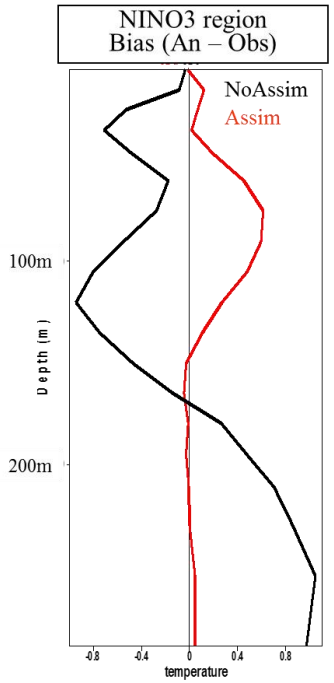
Traditional challenge 1: Dynamical Balance at the Equator

Assessment methods

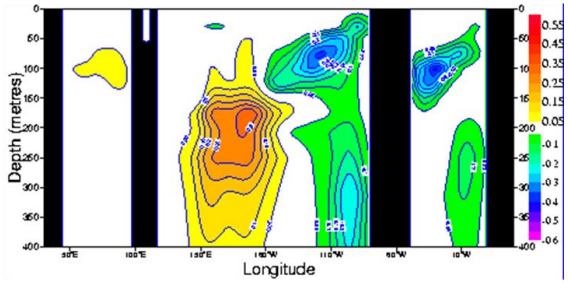
Comparison with Adcp current profiles

Statistics of assimilation error

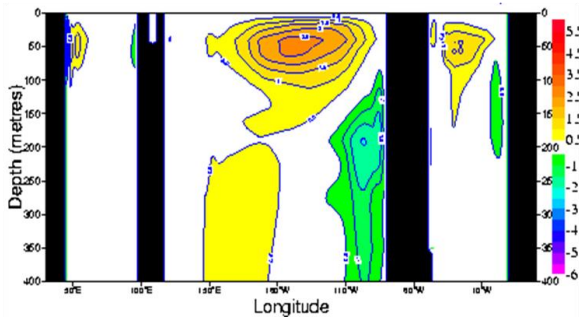
Comparison with a NoAsim run



T-Assim incr (C.I=0.05 C/10 days)



Vertical velocity (C.I=0.5m/day)



1) Model has systematic error: shallow and diffused thermocline

2) DA of Temperature corrects this error, but induces spurious vertical currents

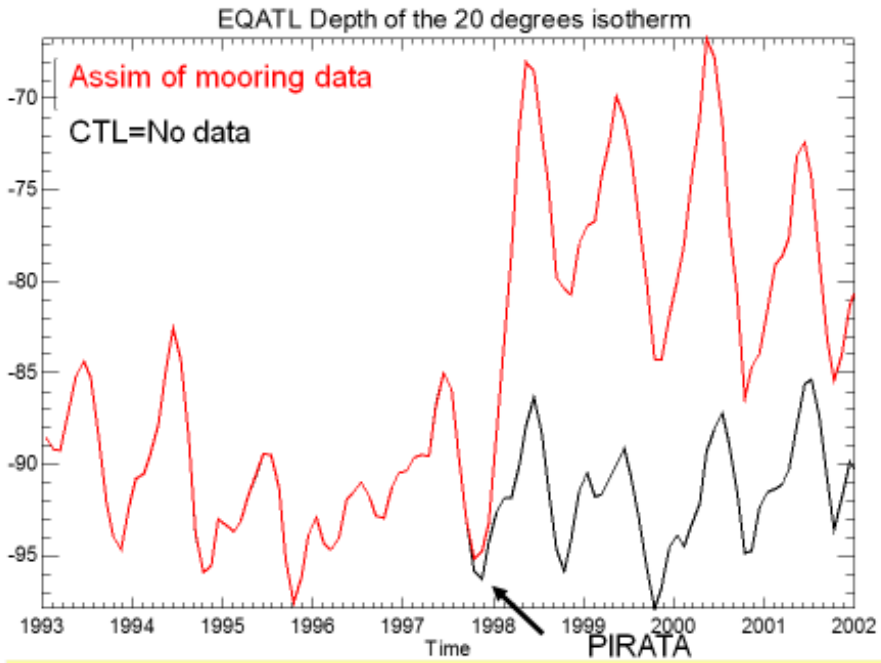
3) The spurious vertical currents create another systematic error

The data assimilation introduces systematic error in the analysis

Bell et al 2004 proposed a new dynamical balance at the equator for the long time scales
pressure gradients should balance the wind stress

Traditional challenge 2
Changes in observing system induce spurious variability in ocean reanalyses

The observing system will always be changing:
To achieve temporal reliable reanalyses it is important to extrapolate the observation information into the past.



Ocean had too deep thermocline. The assimilation of PIRATA observations corrects this error, but results on spurious variability in the time series

This can be done by including a bias correction term to the model tendencies

$$\mathbf{b}_c = \bar{\mathbf{b}} + \mathbf{b}'_c$$
$$\mathbf{b}'^{f}_{c} = \alpha \mathbf{b}'^{a}_{c-1} + \boldsymbol{\varepsilon}$$
$$\mathbf{b}'^{a}_{c} = \alpha \mathbf{b}'^{a}_{c-1} + \mathbf{A}\delta x_c$$

The bias correction has two terms

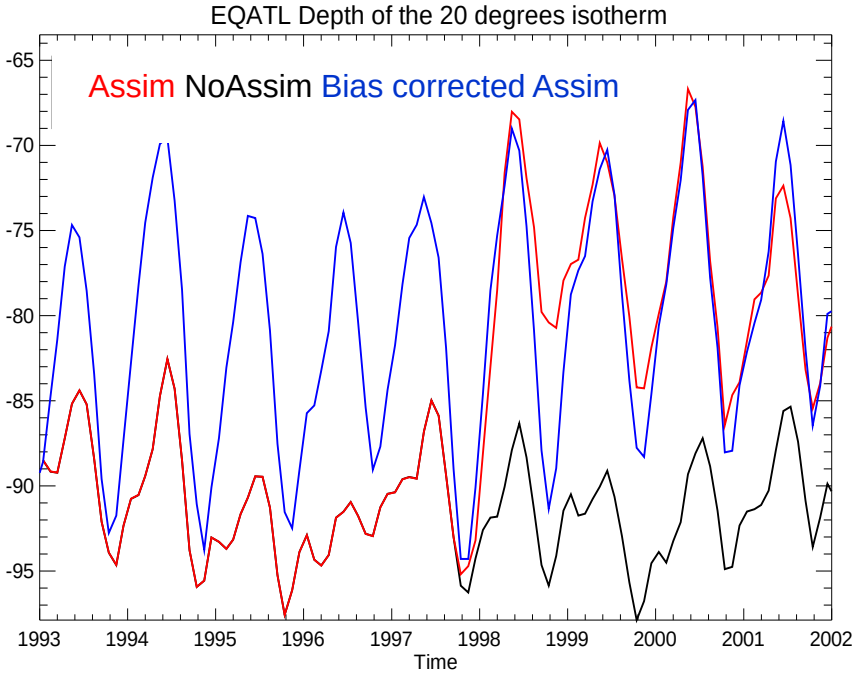
Б estimated offline from the well observed period
b' estimated online from assimilation increments

The explicit treatment of model bias in assimilation also allows imposing different dynamical balances for the increment and bias

$$\mathbf{x}^a = \mathbf{x}^f + \mathbf{b}^f + \mathbf{K}[\mathbf{y} - \mathbf{H}(\mathbf{x}^f + \mathbf{b}^f)]$$
$$\mathbf{b}^a = \mathbf{b}^f + \mathbf{L}[\mathbf{y} - \mathbf{H}(\mathbf{x}^f + \mathbf{b}^f)]$$

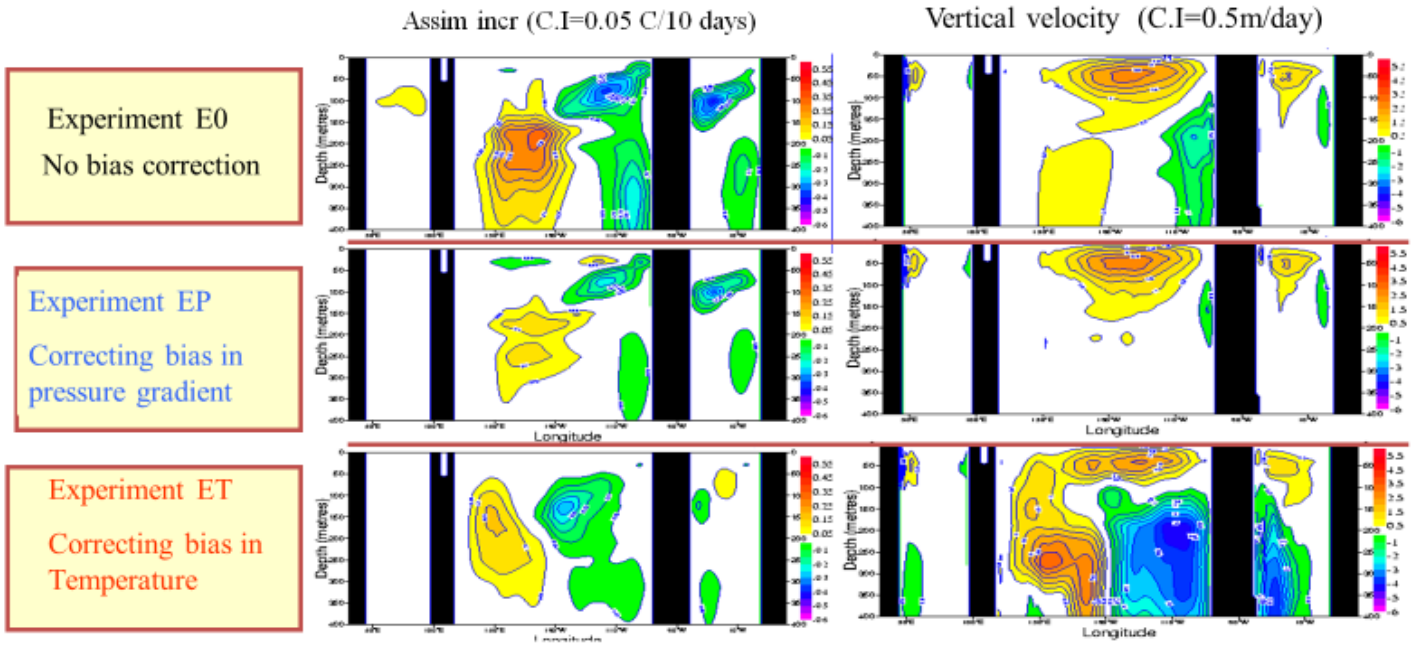
Balmaseda et al 2007

Importance of treatment of model error in ocean data assimilation



1) The extrapolation to the past of the PIRATA information alleviates the problem of spurious temporal variability

2) Sensitivity to dynamical balances in bias



2) Correction of model error requires the correct dynamical balance for long time scales.

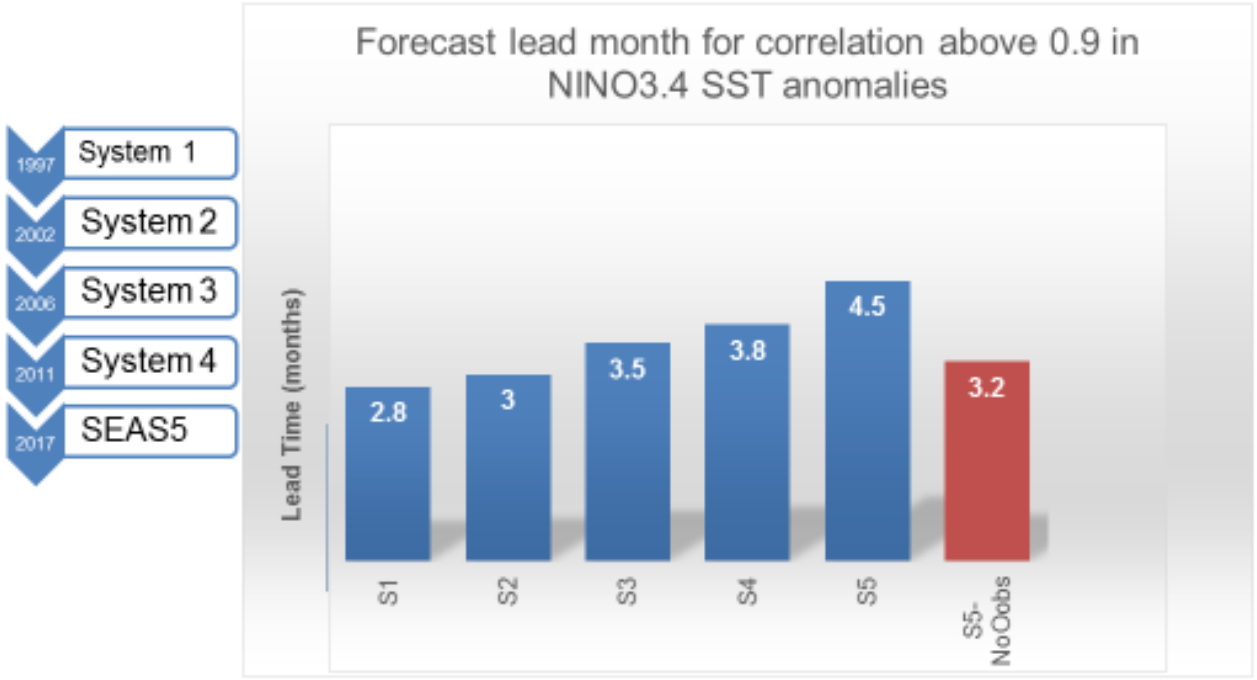
Only by applying the adequate dynamical the problem with spurious dynamical currents is alleviated

Time to make further progress in this direction?

Balmaseda et al 2007

Part II: Emerging challenges

Contribution of Ocean Data Assimilation to 20 years of Progress on ENSO prediction at ECMWF

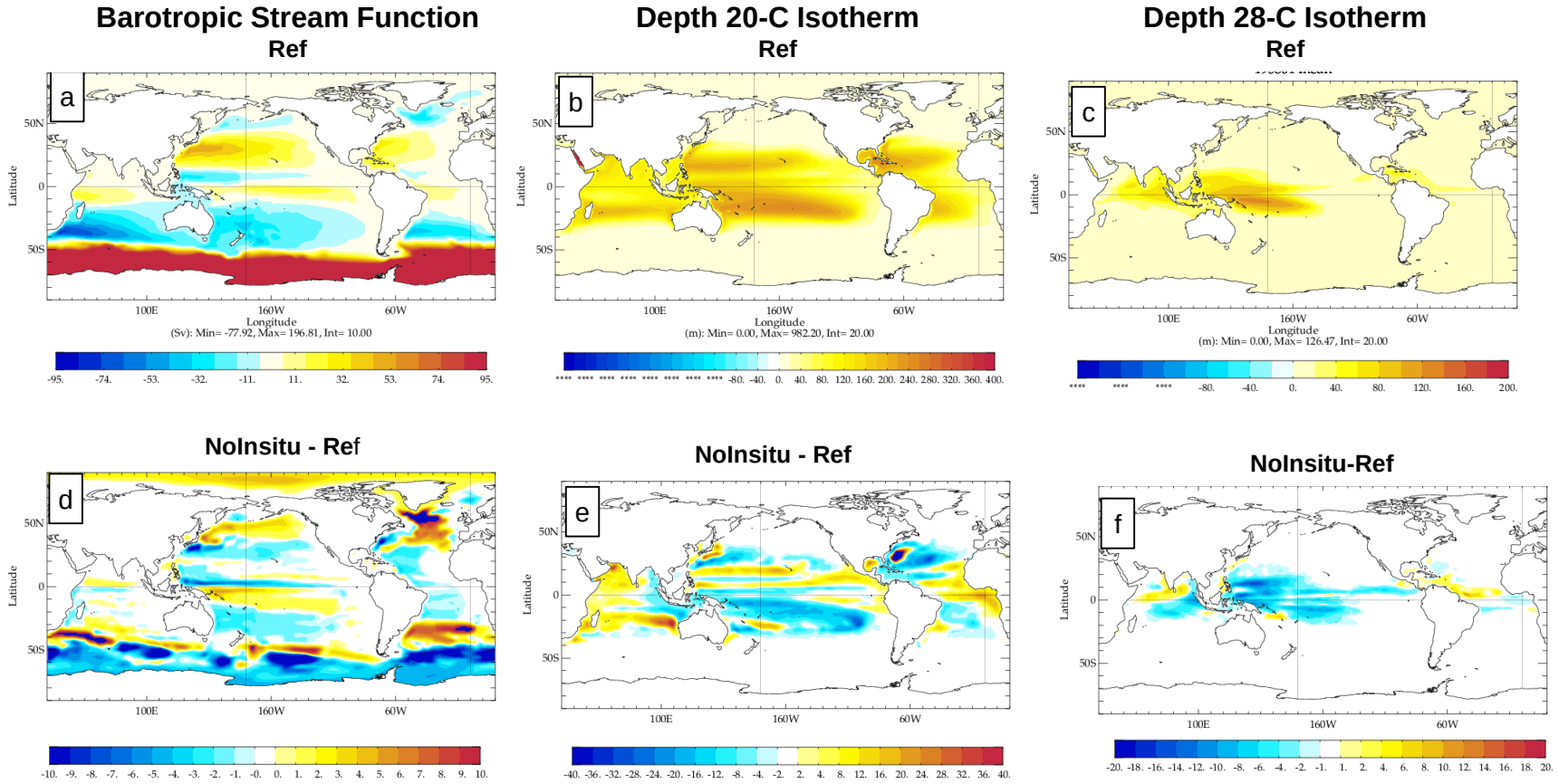


Substantial progress over the years on ENSO

Seamless predictions bring new challenges for ocean data assimilation methodology

- Initialization of ocean mixed layer and MJO
- Representation of decadal variations and trends
- Initialization of WBC and SST fronts

Impact of Ocean Assimilation on mean state of ocean initial conditions



In-situ observations have an impact on:

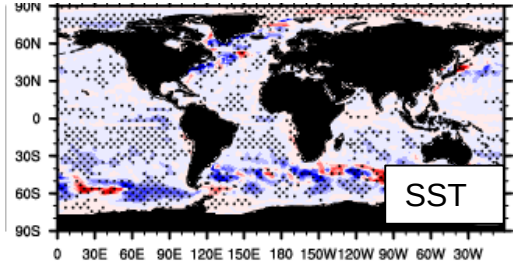
- The global circulation (BSF) –large memory-potential to impact multiyear forecasts
- Thermocline depth (D20)- potential to impact seasonal forecasts (several months adjustment time)
- Warm pool (D28) and mixed layer (not shown)- potential to impact monthly forecasts

From Initial condition differences to Seasonal Forecast differences: Sea Surface Temperature

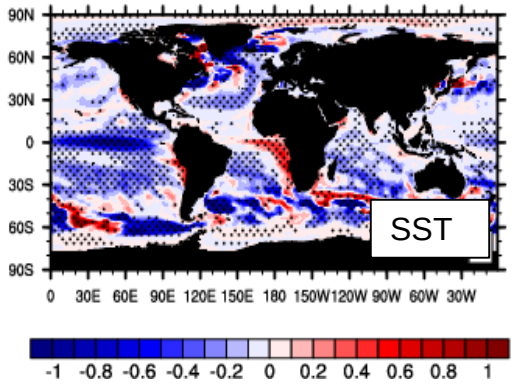
May starts 2005-2015 JJA verification

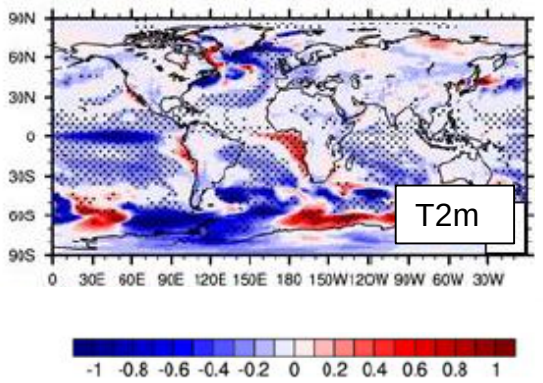
NoInsitu -Assim

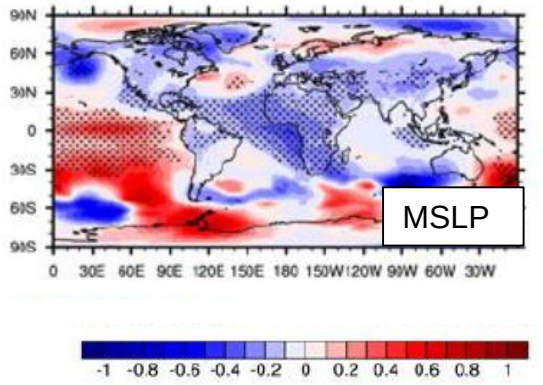
Mean difference on Ocean Initial Condition



Mean difference on seasonal forecasts

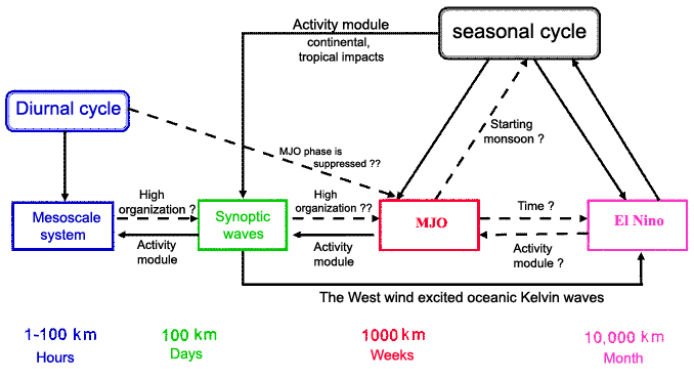






- Impact of observations visible in SST initial condition. Impact small but significant.
- **Fast**: Removing observations induces overall cooling in forecasts (likely Mixed layer processes. Different sign of impact between SST and OHC in Indian Ocean (not shown))
- **Medium** : Strong dynamical cooling (warming) in Pacific(Atlantic) cold tongue by removing observations.
- **Slow:** In Extratropics and gyres, impact on SST Forecast resembles the impact on OHC initial conditions (not shown)

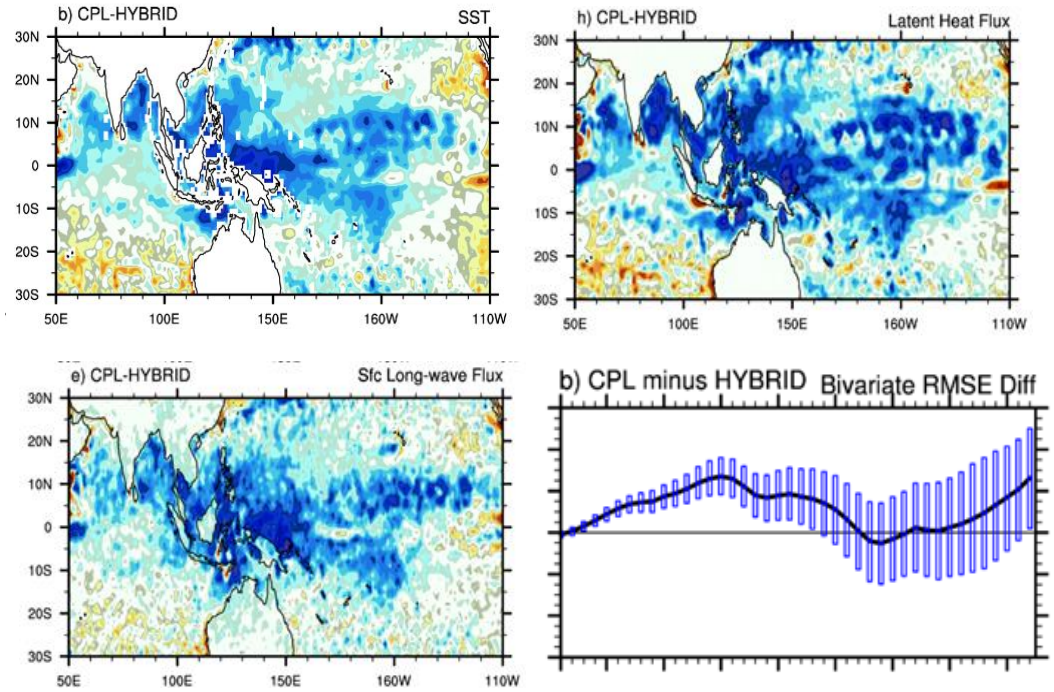
New Challenge 1: Initialization of the Ocean and Atmosphere boundary Layers



Knowledge, understanding, modelling and assimilation of O-A boundary layer processes is essential, especially over warm pool regions.

Warm Pools are brewing pots for climate, enabling interactions among multiple variables, temporal and spatial scales

Impact of Coupled DA on MJO prediction mediated by the ocean mixed layer



CPL: coupled DA ocean and atmosphere initial conditions (CERA-SAT)

HYBRID: atmosphere from Coupled DA, ocean from uncoupled reanalyses (ORAS5)

Ocean DA matters for the MJO prediction

Yao et al 2020 submitted to MWR

Initialization of O-A Boundary layer is an important knowledge gap

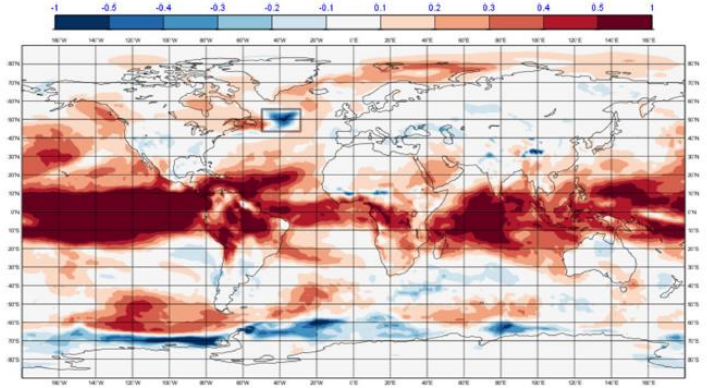
Current data assimilation systems are not designed to represent A-O boundary layers. This problem should better treated in a coupled DA framework.

Assimilation of ocean variables has **a visible but uncontrolled impact** of Ocean Boundary Layer over warm pool, which immediately affects the atmospheric forecasts.

A major challenge for progress with coupled data assimilation is the knowledge of primary balances constraining the boundary layer, needed to model error covariances.

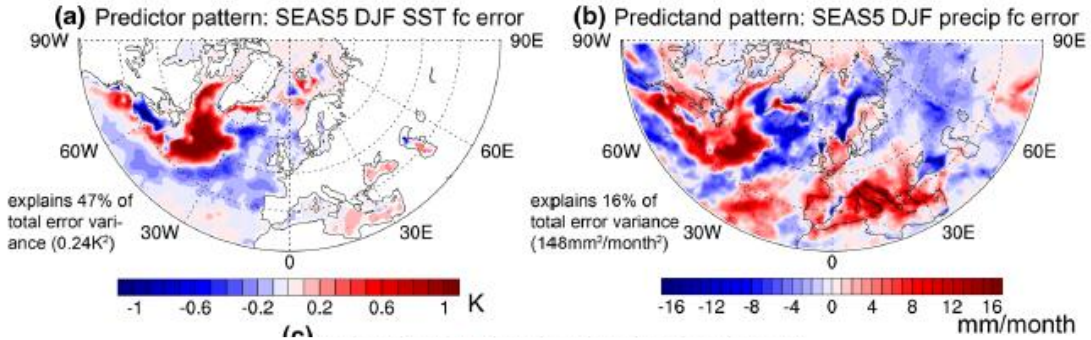
New Challenge 2: Representing decadal variability and trends. Example: AMOC

Skill of ECMWF Seasonal Forecasting System SEAS5
CRPSS DJF T2m from Nov.



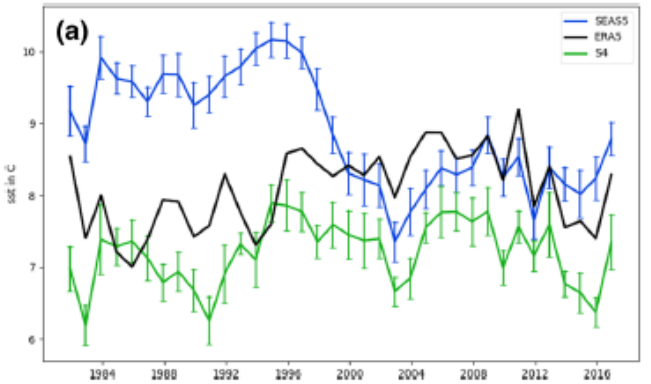
SEAS5 skill showed a skill “hole” over NA Subpolar Gyre
Not visible when using low resolution ocean

This error in SST explains ~17% of precipitation error in NA

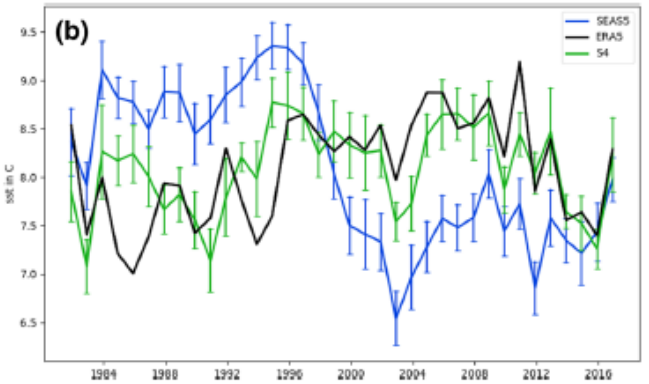


The degradation is related with non stationary errors FC, due to spurious decadal variability in ORAS5, which make SEAS5 forecasts difficult to calibrate

SST in NEGB region



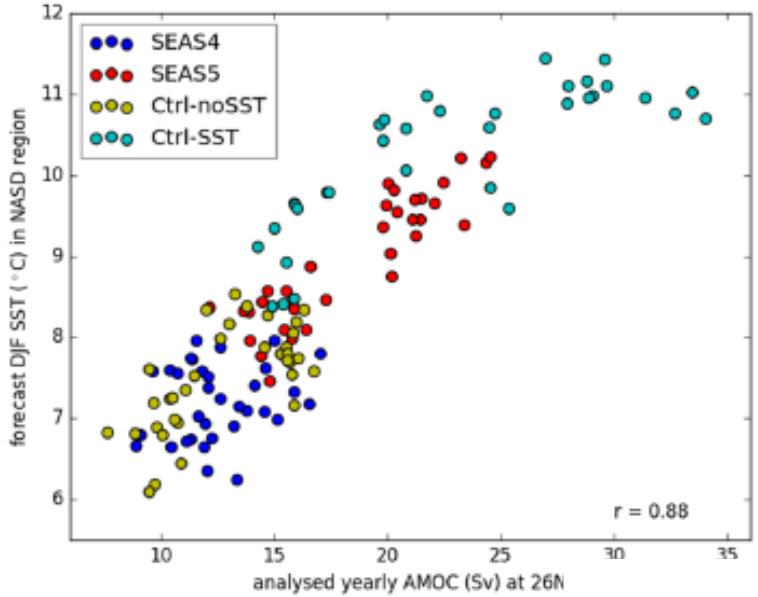
SST anomalies in NEGB region



From Tietsche et al 2020

The SST variations in Subpolar Gyre strongly influenced by AMOC on initial conditions

SST SF versus AMOC in ocean initial conditions



We conduct experiments without data assimilation

- Ctrl-SST: as ORAS5 but SST is only constrain
- Ctrl-noSST: forced simulation no SST constrain

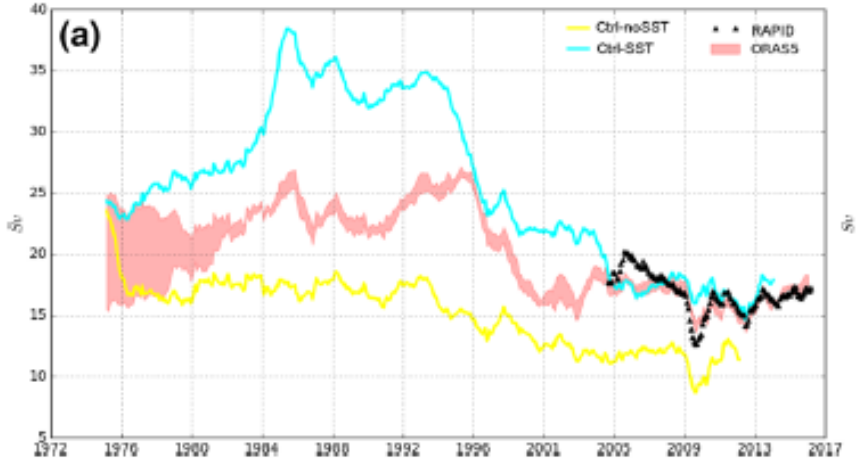
In Ctrl-SST, the AMOC spurious decadal variability is even larger than in ORAS5.

Removing the SST constrain (Ctrl-NoSST) produces weaker AMOC and no variability.

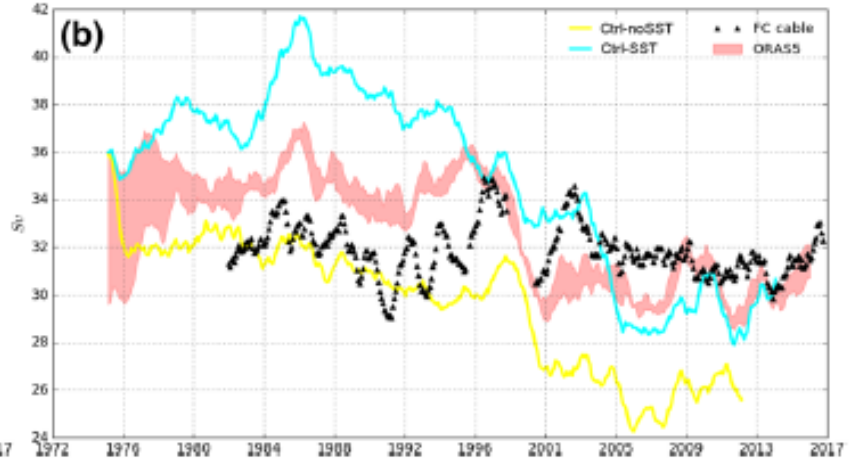
Further diagnostics indicate that the strong SST relaxation impacts the deep convection and AMOC variability.

From Tietsche et al 2020

AMOC



Florida St. transport

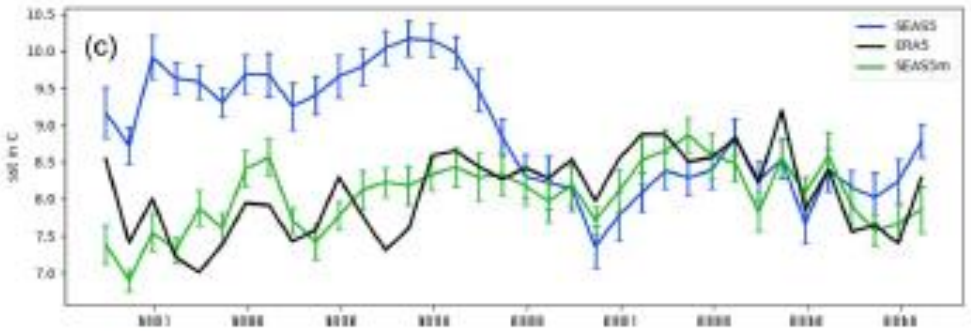


Impact of SST relaxation

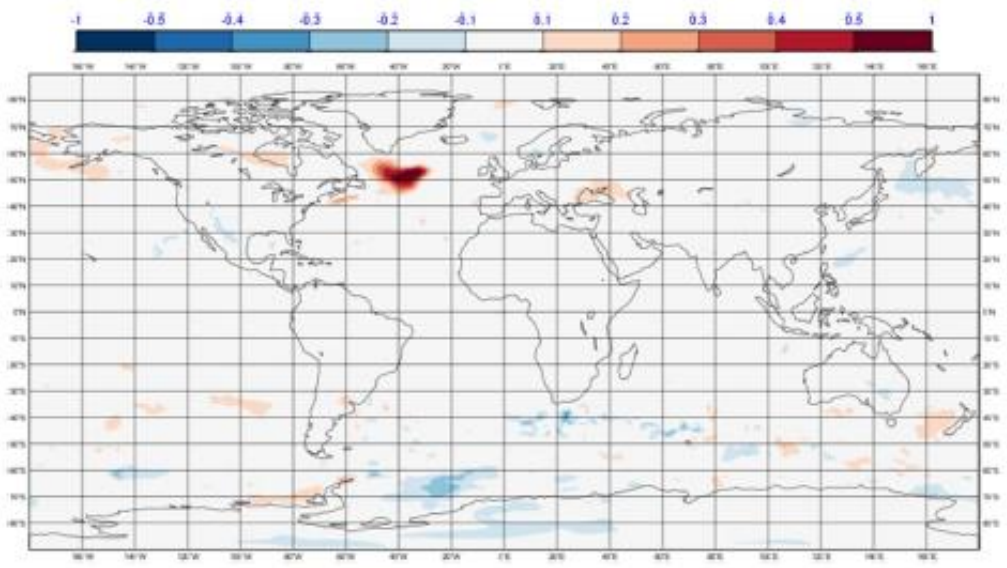
We conduct an experiment with reduced SST relaxation ORAS5m/Seas5m

In Seas5m, the seasonal FC of SST no longer have spurious decadal variability, and are possible to calibrate

There is no-longer “skill hole” in the NA

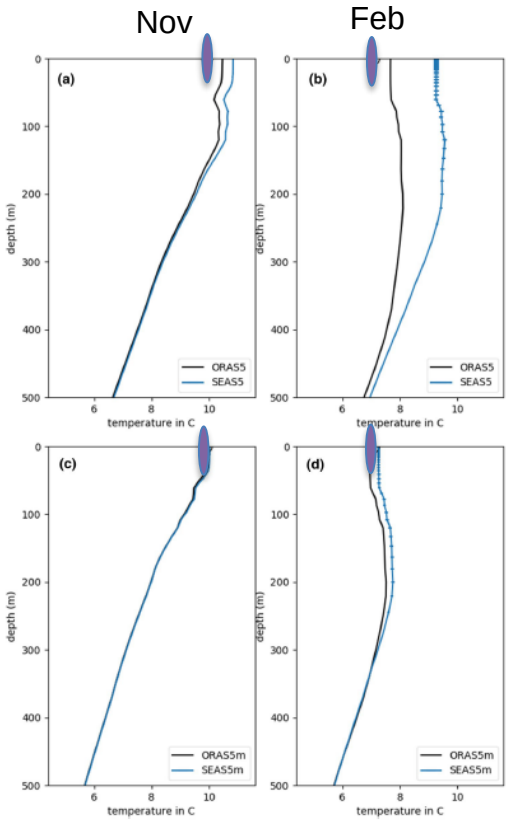


CRPSS SEAS5m-SEAS5



Reducing the SST relaxation in this region produces better analyses and seasonal forecasts

T profiles in NEGB



ORAS5
SEAS5

ORAS5m
SEAS5m

ERA5

New Challenge 3: Initializing Western Boundary Currents and SST fronts

Background:

- The role of WBC on climate is well established
- Over past few years, the role of air-sea interaction over WBC and SST fronts has gained increasing attention (e.g Minobe 2008)
- There is evidence that WBC influence weather and extended range forecasts. Example: partial coupling approach at ECMWF NWP.
- The representation and initialization of WBC is a major challenge for coupled DA.

Questions arising:

- Which ocean resolution is needed?
- How to balance resolution with ensembles?
- Can we initialize the WBC in low resolution models?
- How to design multi-scale DA methods?

Artificially correcting Gulf Stream SST errors improves extended range forecasts over Europe

From Roberts, Vitart, Balmaseda 2020, GRL

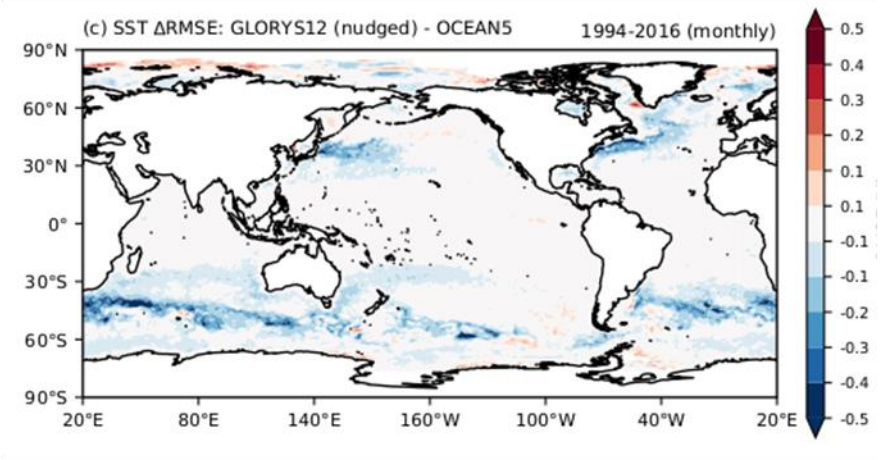
Can we initialize a low-resolution ocean model from a high-res ocean reanalyses?

Extended range coupled forecasts use ORCA025. initialized by ORAS5.
ORAS5 has large errors in WBC
Experiment: Initialize the ORCA025 with GLORYS12

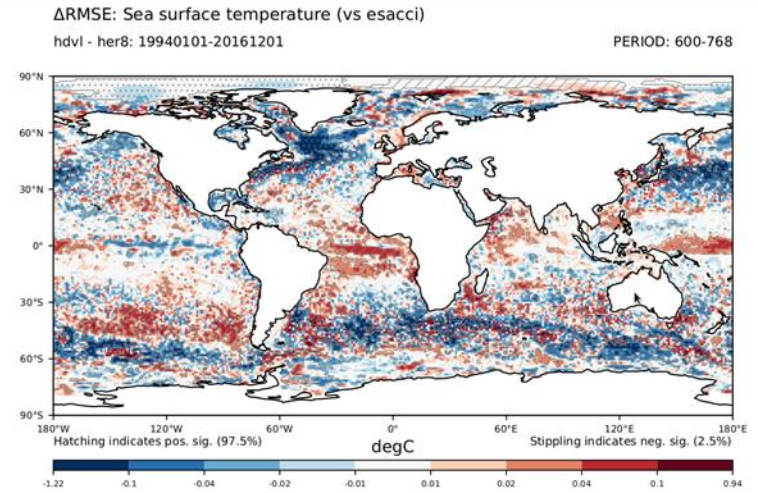
Questions:
- Does the method constrain the initial conditions? **Yes**
- For how long is the initial conditions information retained?
- Does it have any impact on the forecasts of atmospheric variables?

The impact of better Gulf Stream ocean initial conditions is visible at week 4.

Initial conditions



FC Week 4

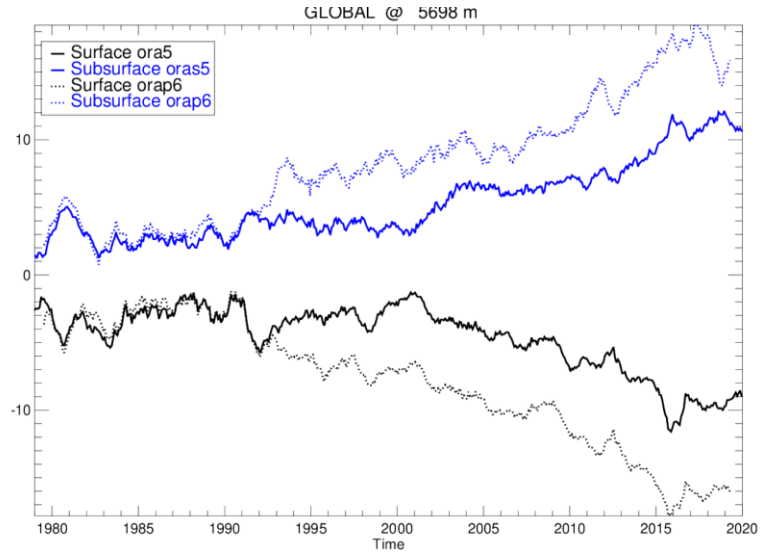


Work in progress.

Courtesy of Chris Roberts

Energy Budget diagnostics in ocean reanalyses

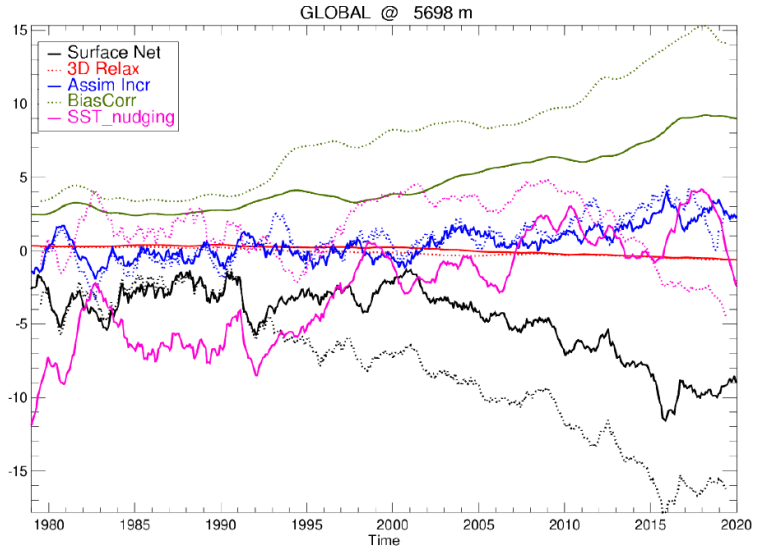
Inventory of terms grouped in surface and subsurface



Subsurface=Assm Incr + BiasC+ 3D Rex
Surface Net = Surf Fluxes +SST nudging

Solid: ORAS5 Dashed=ORAP6

Inventory of terms contributing to OHC variations



The contribution of ocean observations is of the opposite sign as that from surface net heat flux**.** Not optimal.

- In ORAS5, these terms diverge with time after 2000 (advent of Argo?)
- In ORAP6, the divergence is noticeable with the assimilation of altimeter

The –ve trend in surface heat flux is unrealistic in a warming climate

Most likely cause is the inconsistent exchange of fluxes in uncoupled model**.**

Possible Implication: high resolution ocean reanalyses should be done in coupled mode.

The main balance is **between bias correction (BC)** and **net surface flux**

Assimilation increment mostly unbiased (e.g. BC works) , but +ve values after 2010

SST relaxation is **no**t responsible for the negative trend in surface net flux. So the spurious –ve values and trends may be related with using bulk formulation in uncoupled mode.

The stronger divergence in ORAP6 possibly related to better representation of WBC and SST fronts.

Summary and Recommendations (wish list)

- Temporal consistency and physical balance across time scales is a prime requirement for ODA methods for reanalyses and initialization of seamless forecasts
  - This requires proper treatment of model systematic error: temporal extrapolation and balances
- **Evaluation methods for temporal and physical consistency are required, beyond fit to observations in short assimilation windows**
  - Temporal statistics for sufficiently long periods (**including temporal correlation and trends**)). But these are costly, since require long reanalyses.
  - Comparison with independent data are very valuable (currents from moorings, RAPID and Florida Current transports) Opportunity with TPOS?
  - Important to have as benchmark a NoAssim run. OSES are also good evaluation methodology
  - **Extended and Seasonal forecasts** can detect ocean assimilation quality. Arguably expensive
  - Efficient evaluation metrics for DA across time scales are needed and should be sought (Statistics of error growth, cheaper emulators?)
  - **Physical consistency arguments** extremely important when observations are lacking (e.g. energy budget diagnostics)
- New challenges for ODA emerging from the experience of seamless forecasting
  - Initialization of ocean mixed layer has a visible impact in forecasts at early lead times. Probably best tackled within the Coupled-DA framework.
  - Assimilation of SST (e.g. vertical propagation of surface information) is needed. This will have implications on mixed-layer initialization, deep convection, ocean circulation, and heat uptake.
  - Affordable solutions for correctly initializing the WBC should be explored for ensemble forecasting