# Assessing the Robustness of Climate Signals from the ECMWF Ocean Reanalysis System 4 (ORAS4)

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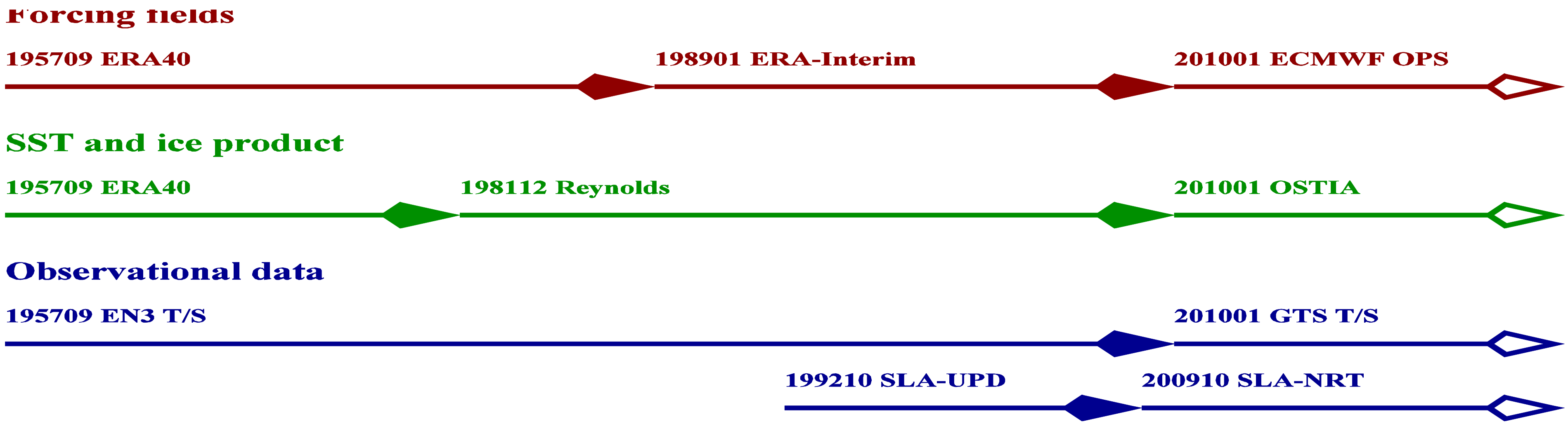
# OUTLINE

- When is a new ocean reanalysis produced?
  - Approx every 5 years
  - New observational quality controlled data sets, new atmospheric fluxes, improved methodology
  - Change of seasonal forecasting system
- At ECMWF the new reanalysis is ORA-S4 (Ocean Re-Analysis System 4)
  - Implemented operationally in 2011, providing initial conditions for Monthly and Seasonal.
  - It replaces the previous ORAS3 (vintage year 2006).
  - Value for climate: Ocean Re-analysis, initialization of decadal forecasts by EC-EARTH
- Brief Description of ORA-S4 components
- Validation of ORA-S4
  - Series of objective diagnostics and sensitivity experiments
- Assessing Robustness of some climate signals
  - Ocean heat content ( budget analysis)
  - Tropical thermocline
  - Attribution of sea level trends
- Dissemination of Results

# ORAS4: 5 ens members 195709 to present




## Main Ingredients (new in green)

**Ocean Model**: NEMO. Approx resolution 1x1 deg

**Data Assimilation:** NEMOVAR

**Data:** EN3-XBT corrected. Altimeter, SST as in figure

**Bias Correction:** estimated from Argo period

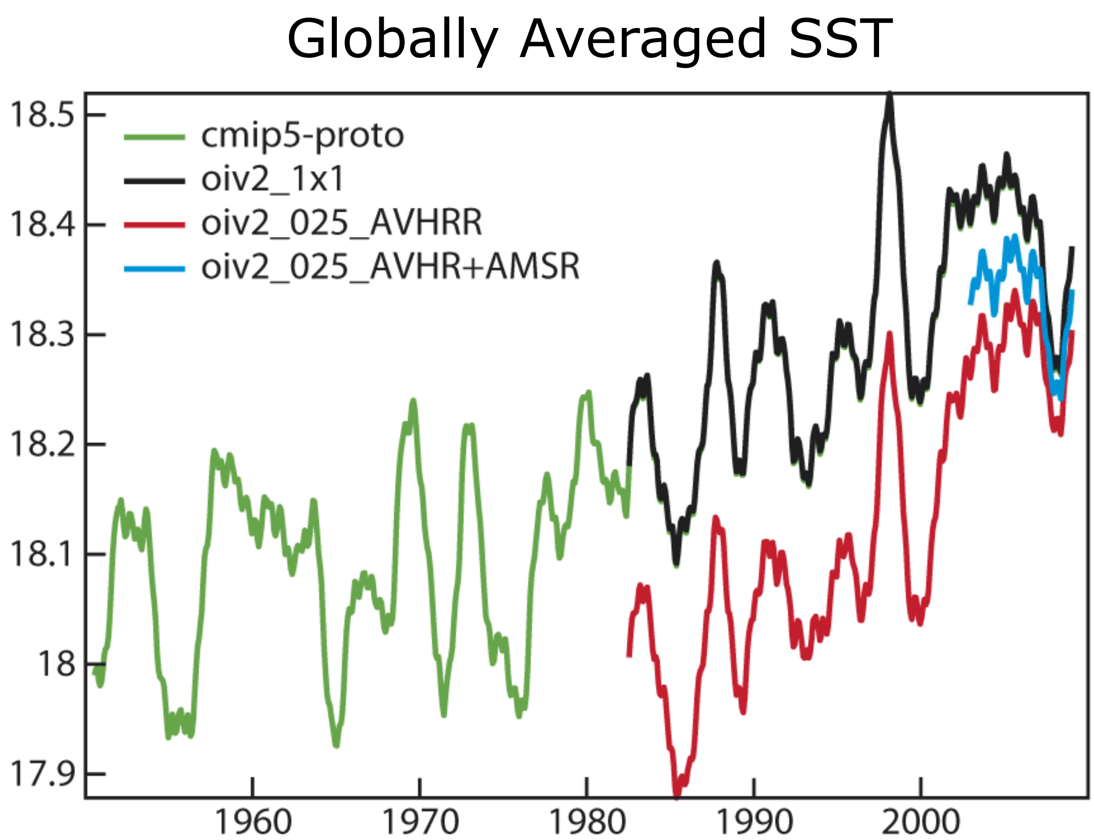
**Forcing:** ERA40/ERA-INTERIM/OPS

**Ensemble Generation:** wind perturbations, observation coverage, deep ocean

**Not changed even if new products were available**

- SST prior to 2010
- Mean Dynamic Topography
- Horizontal model resolution

# Which SST product to use?




We wanted to use the most up-to-date higher resolution SST reanalysis (back in 2010 this was OIv2_025_AVHRR)

OIV2_025_AVHRR: colder than other products in the global mean. Weaker interannual variability in tropics (not shown)

Differences decrease with time. Fit to insitu Temperature: bias cold in tropics, better in mid latitudes.

**DECISION: OIV2_1x1 until 2010 and OSTIA thereafter. There is sensitivity to the choice of SST (see later)**

# NEMOVAR

**Variational data assimilation system for the NEMO ocean model (follow up of OPAVAR)**

- Collaborative project with several institutions: CERFACS, MetOffice, INRIA, ECMWF
- Multiple loops. Adjoint and Tangent linear exist.

**NEMOVAR in ORAS4: Multivariate Incremental 3Dvar FGAT IAU**

Flow dependence background errors:

T error depends on vertical gradients

T/S relationship: linearized vertical profile displacement

Sea Level and density: vertical profile displacement taking into account stratification

Geostrophy

It assimilates T/S profiles and along track altimeter.

Automatic QC, thinning, supperobbing

See Mogensen et al 2012. ECMWF techmemo 668

http://www.ecmwf.int/publications/library/do/references/show?id=90389

**OUTSIDE NEMOVAR:**

SST is used to correct surface heat fluxes

Global Sea Level corrects the fresh water flux

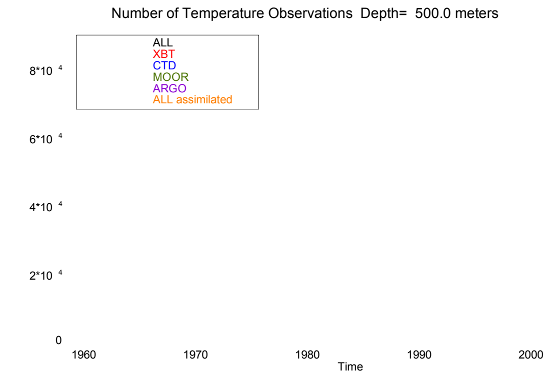
Bias Correction

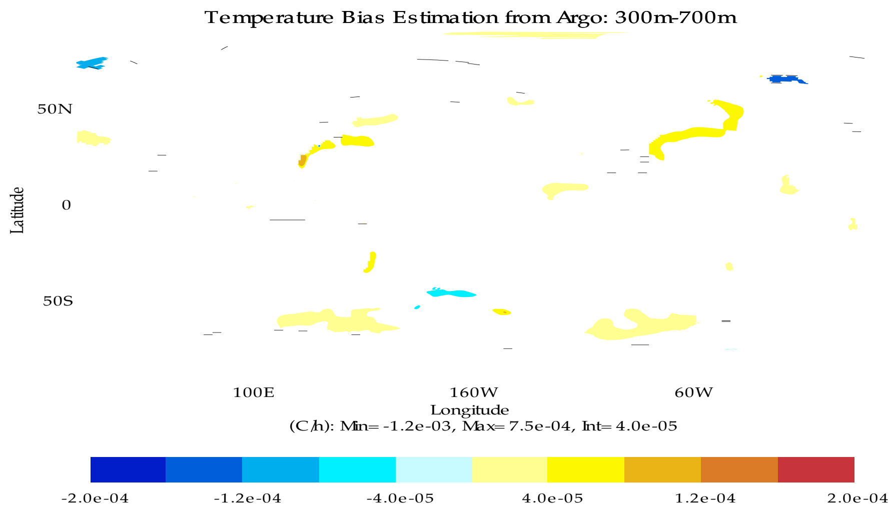
# Bias Correction Algorithm

$$\mathbf{b}^{f}{}_{k} = \bar{\mathbf{b}}_{k} + \mathbf{b}'^{f}_{k}$$

Seasonal term, estimated offline from Argo Period

Slow varying term, estimated online from assimilation increments $\mathbf{d}_k$




The offline bias correction is estimated from Argo period.

The correction is applied since 1957-00-01 to present.

It is a way of extrapolating Argo information into the past.

Bias online: Time evolution

$$\mathbf{b}'_{k} = \alpha \mathbf{b}'_{k-1} + \mathbf{A}(y)\beta \mathbf{d}_{k}$$

**Need to determine**:

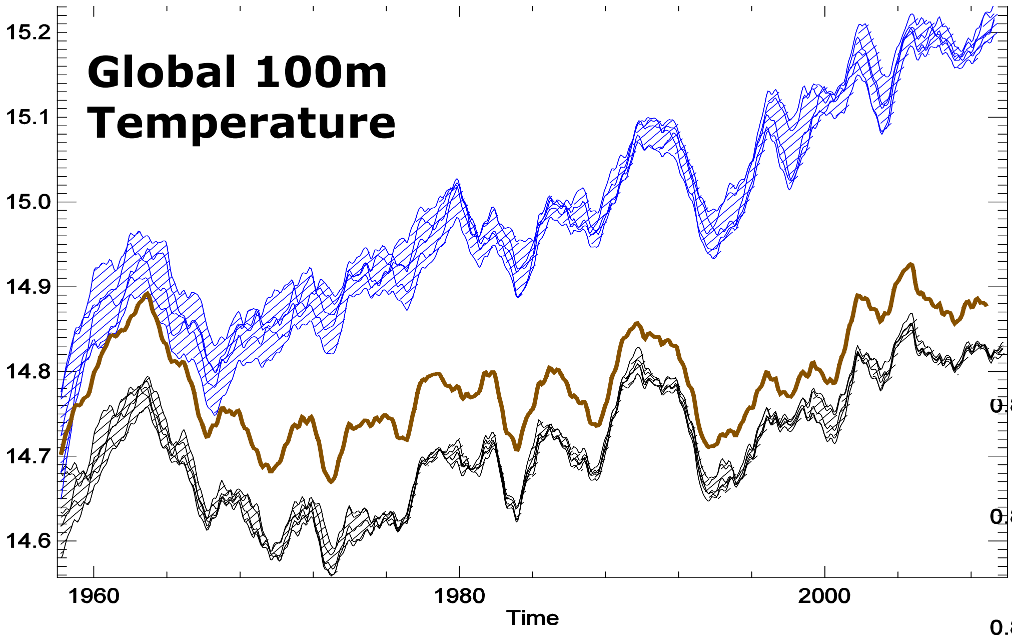
- Offline bias correction
- Time evolution of on-line bias: α (memory) and β (updating factor)
- **A(y)**: Partition of bias into T/S and pressure gradient.

  Function of latitude. At the equator the bias correction is mainly adiabatic (pressure gradient)

Refinement of Balmaseda et al 2007, Dee 2005, Bell et al 2002

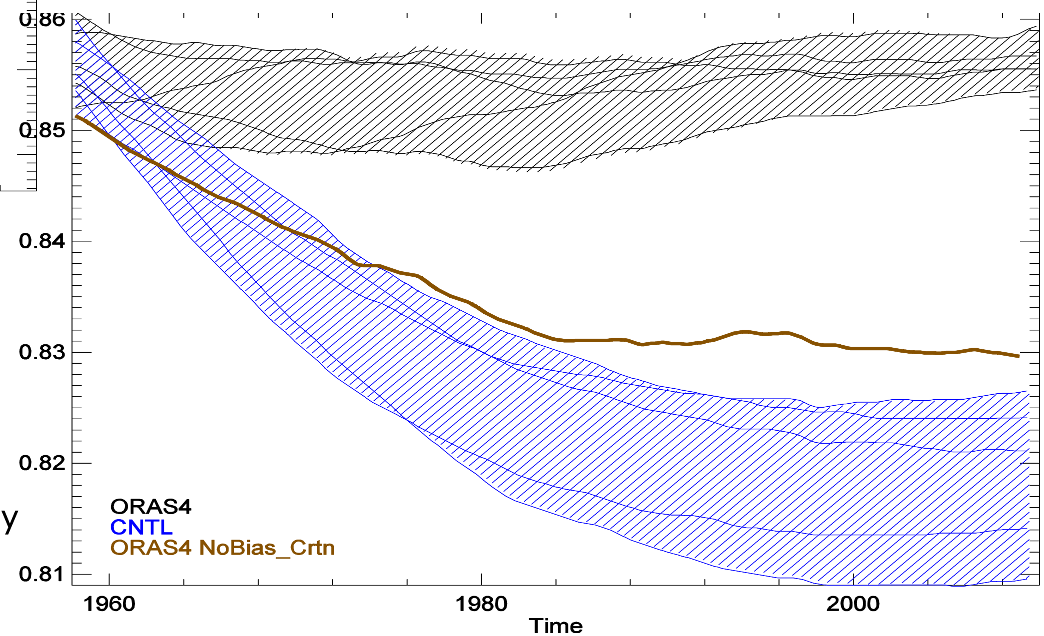
# Bias and ensemble generation

**CNTL**: Equivalent Model Simulation with SST/FW corrections. No NEMOVAR nor bias. 5 ens
**ORAS4: 5 ens.**
**ORAS4 no bias correction**




- Assimilation reduces ensemble spread respect CNTL
- In ORAS4 the spread decreases with time.
- The CNTL produces much stronger warming (model error).

**Temperature Below 3000m**




- The ensemble generates spread in the deep ocean
- ORAS4 has a stable deep ocean
- The CNTL model-only run drifts
- Without Bias correction, the deep ocean drifts substantially

# Assessment of ORAS4

- **Reference CNTL experiment:** Equivalent Model Simulation with SST/FW corrections. No NEMOVAR nor bias. 5 ens
- **Fit to assimilated data**
- **Comparison with independent data**

  ADCP Current meters from moorings. Sea Level Gauges.

  RAPID MOC. GRACE Bottom Pressure.
- **Comparison with other estimates**

  SL altimeter, OSCAR currents, Heat Content
- **Impact on Seasonal Forecasts**
- **Sensitivity Experiments and OSES**

# Fit to Observations (AN – OBS)

## Global: Temperature 100m

**RMSE** 1.5

1.0

0.5

**BIAS**

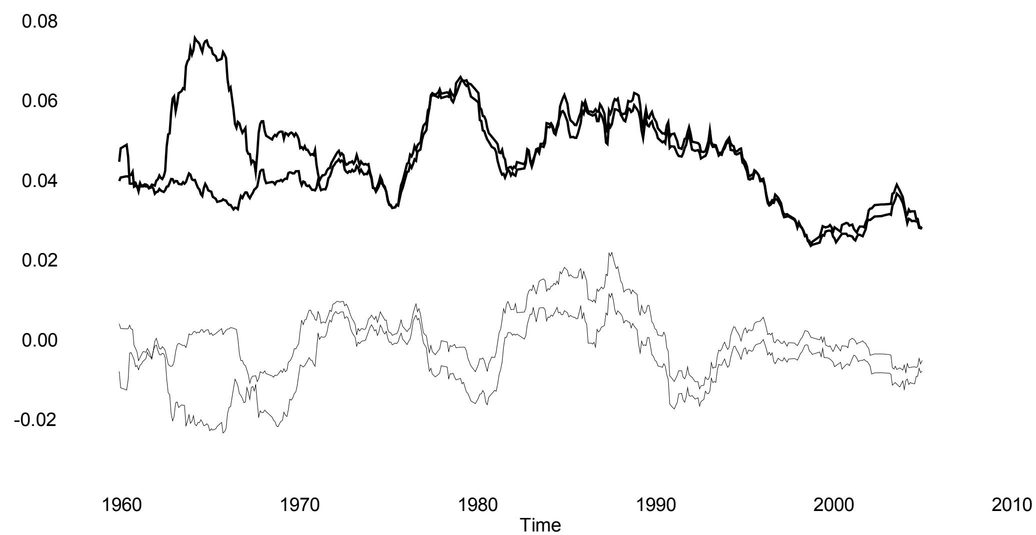
1960 1970 1980 1990 2000 2010
Time

**ORAS4** errors smaller than **CNTL**

Bias more stable in time.

This diagnostic is relevant for the evolution of ocean heat content

## Global: T below 3000m

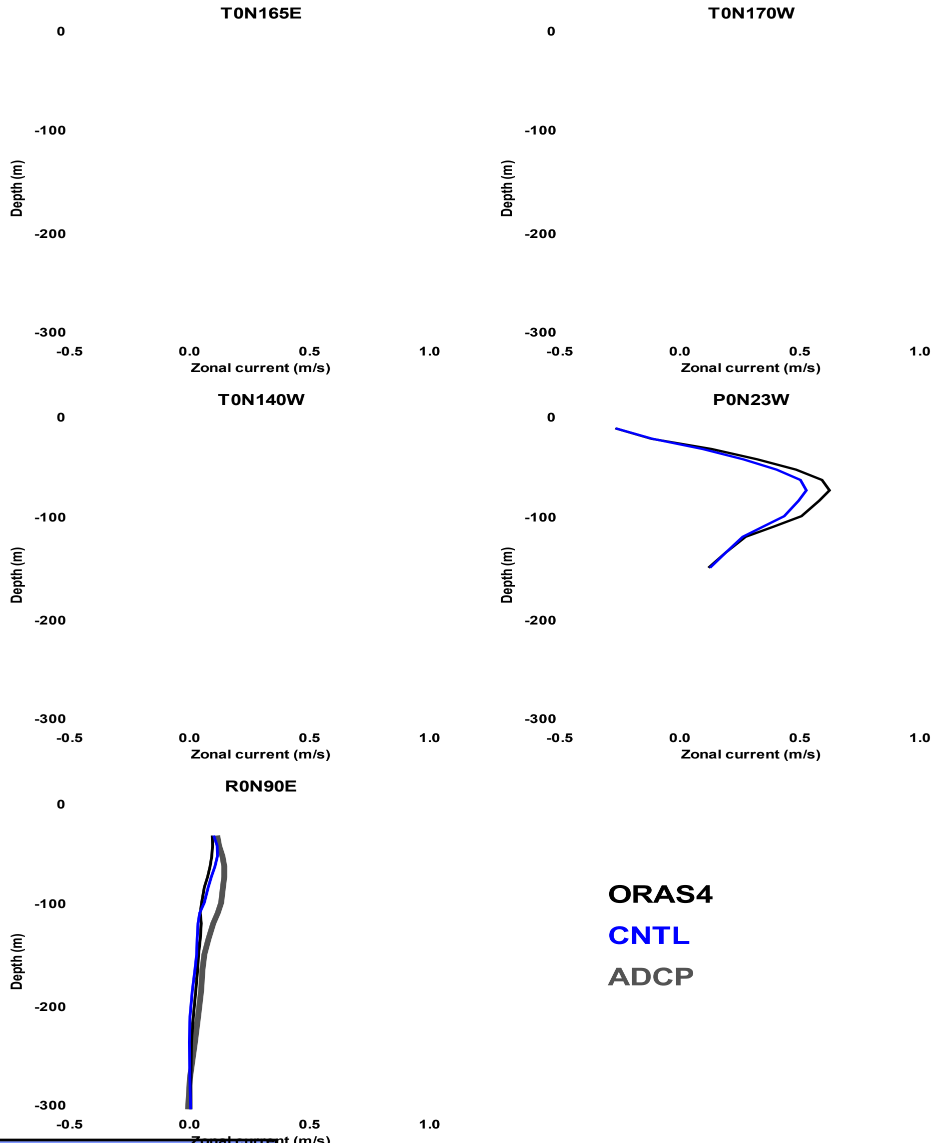



**ORAS4** **CNTL** **NoBias Correction**

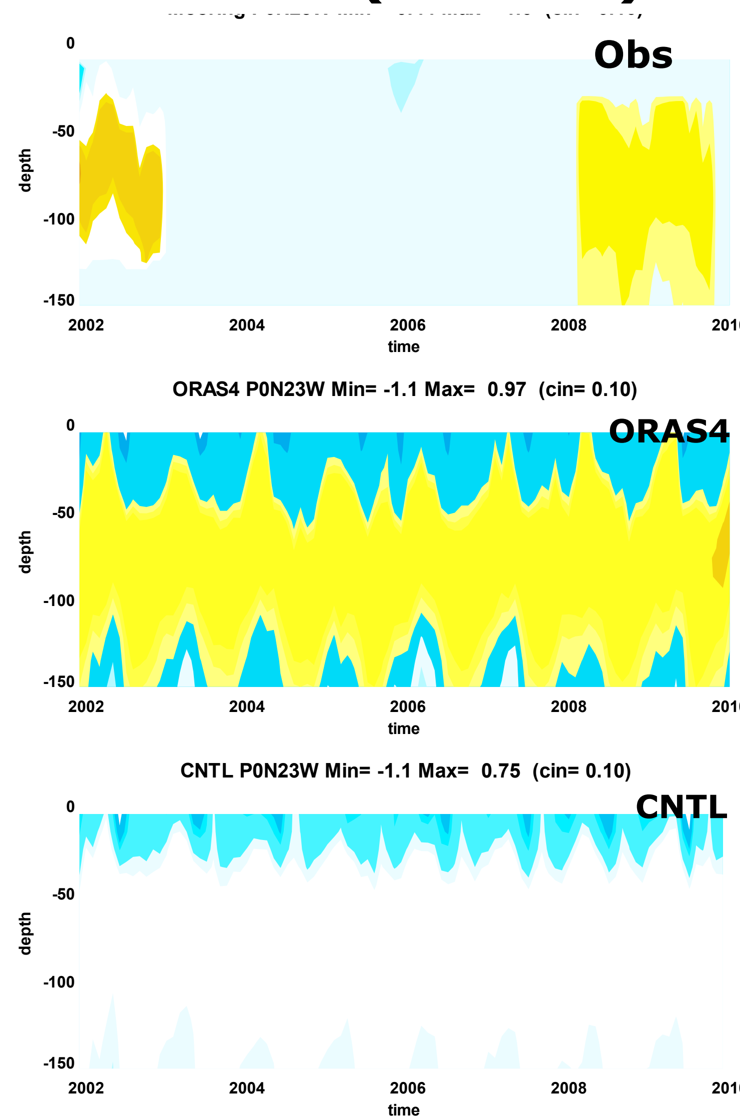
In the deep ocean the impact of bias correction is more noticeable

# Fit to ADCP Velocity Observations

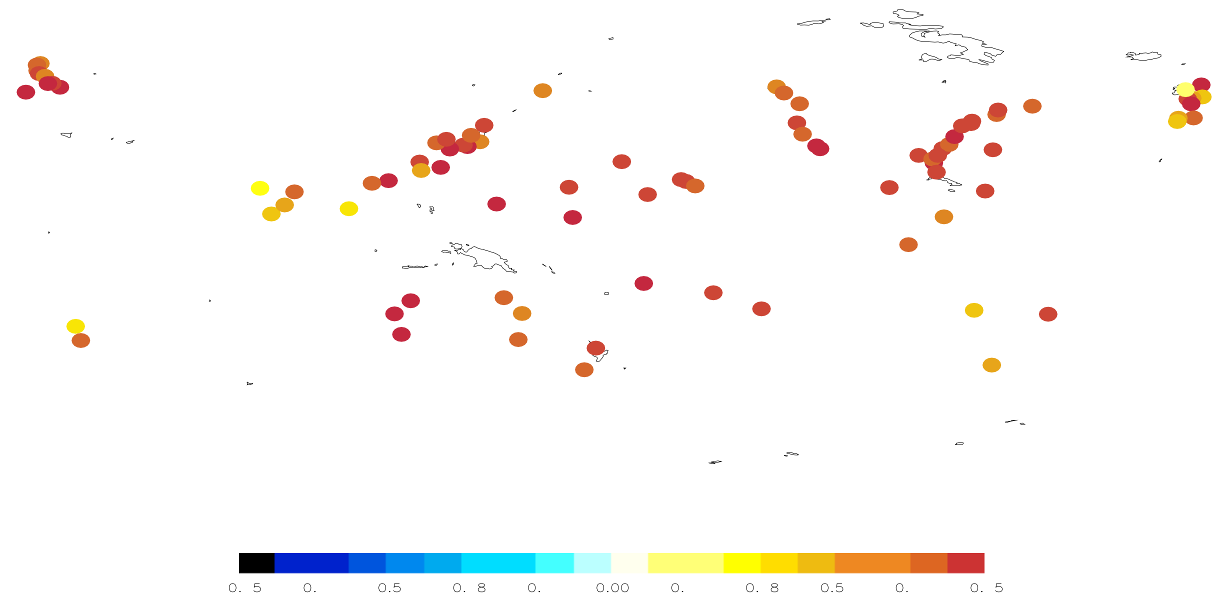
## TAO, PIRATA, RAMA



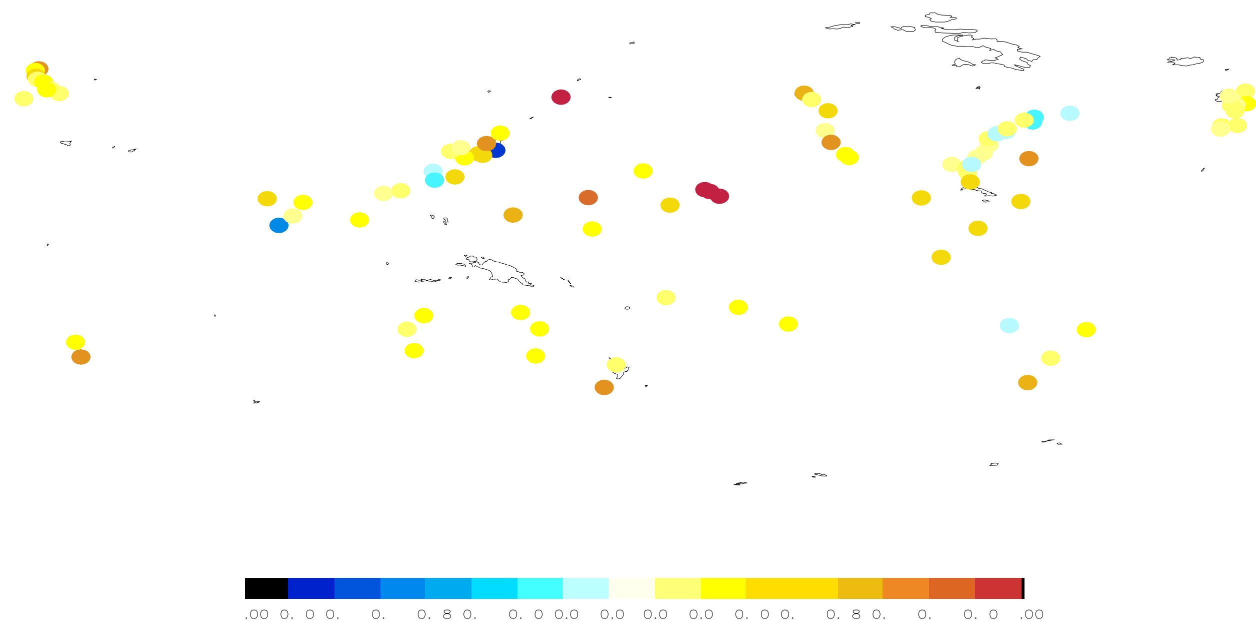

## PIRATA (Atlantic)



**ORAS4 (mean 0.72). 1960-2009**



**Correl ORAS4 – Correl CNTL**



# Time Correlation

## Sea Level from Tide Gauges.

## Independent data

**Overall improvement, problems at some locations**

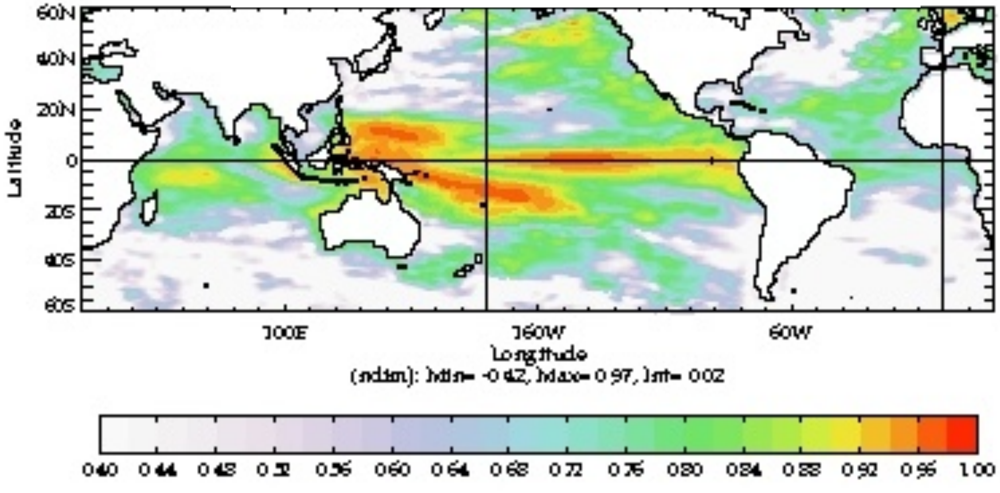
(usually in rich data areas, possibly related to the treatment of coastal observations)

Data courtesy of Anny Cazenave's group

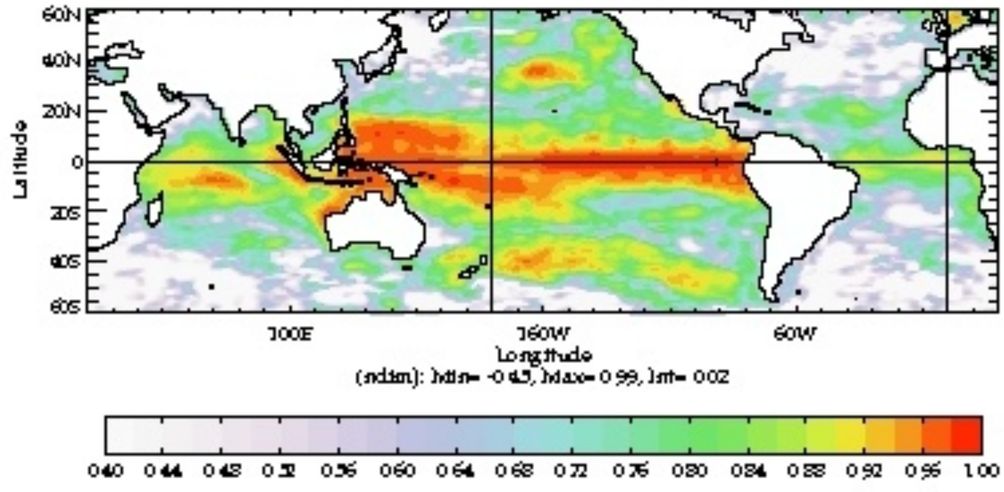
and US

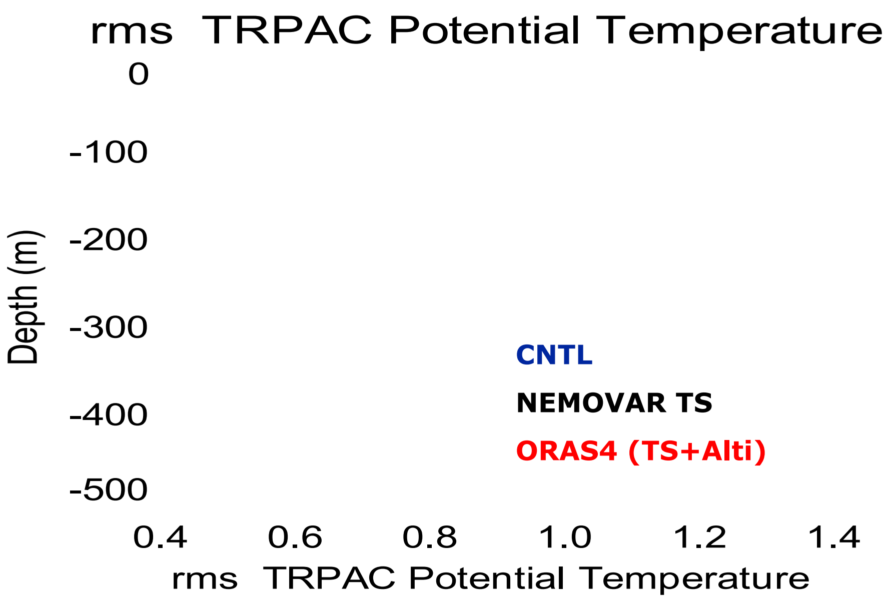
# Time correlation with altimeter SL product

## CNTL: NoObs

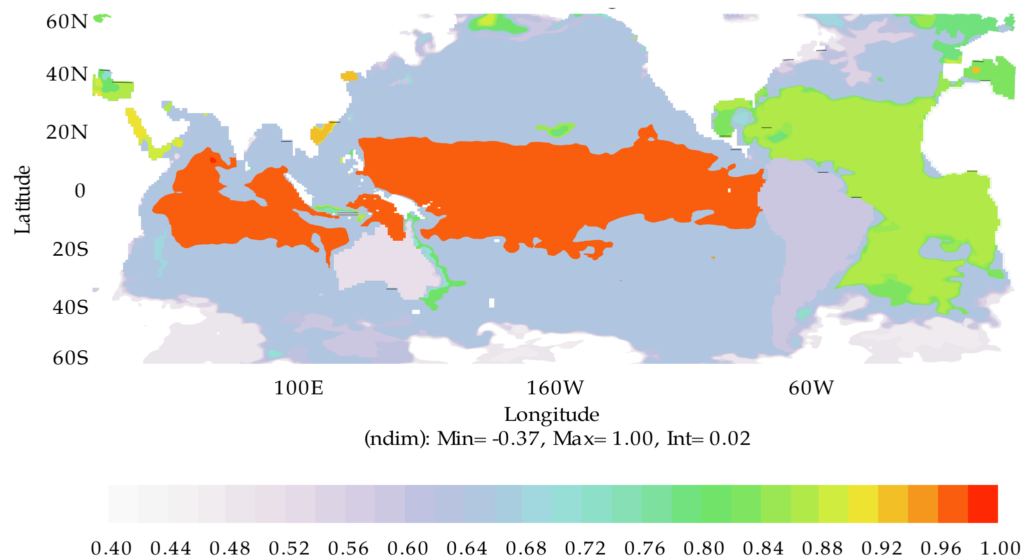



## NEMOVAR T+S



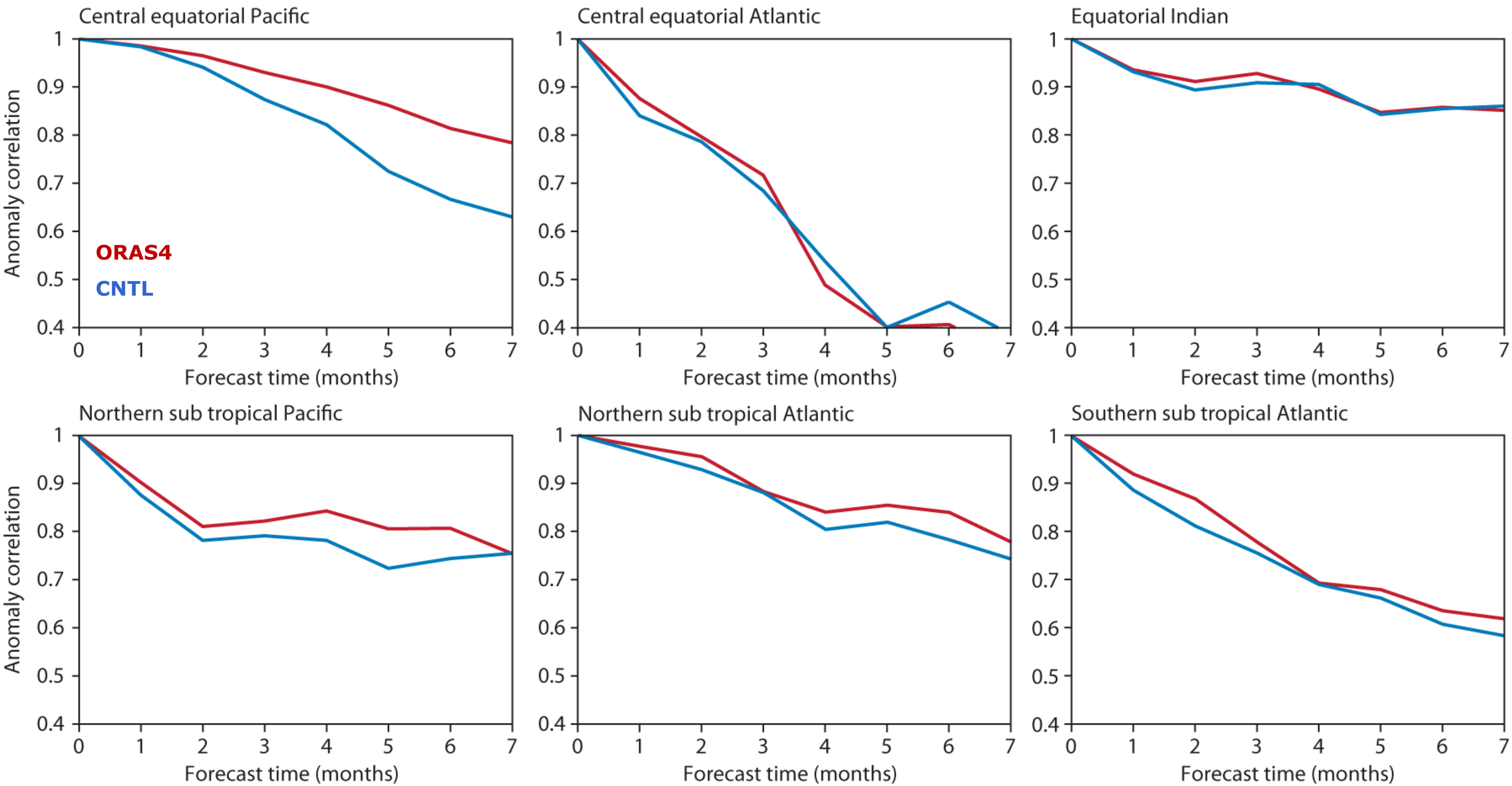




## ORAS4 T+S+Alti

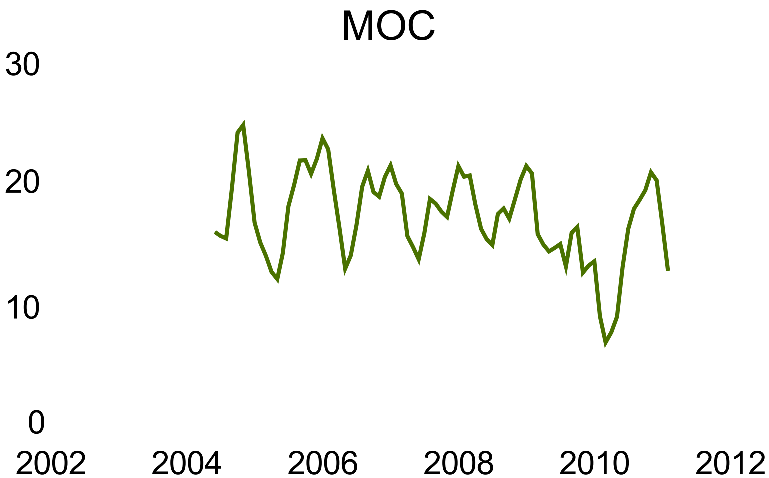


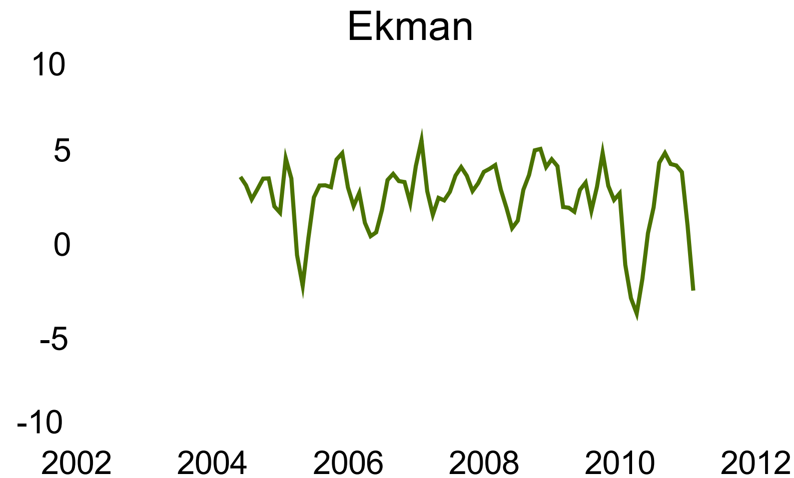
# Impact on Seasonal Forecast Skill

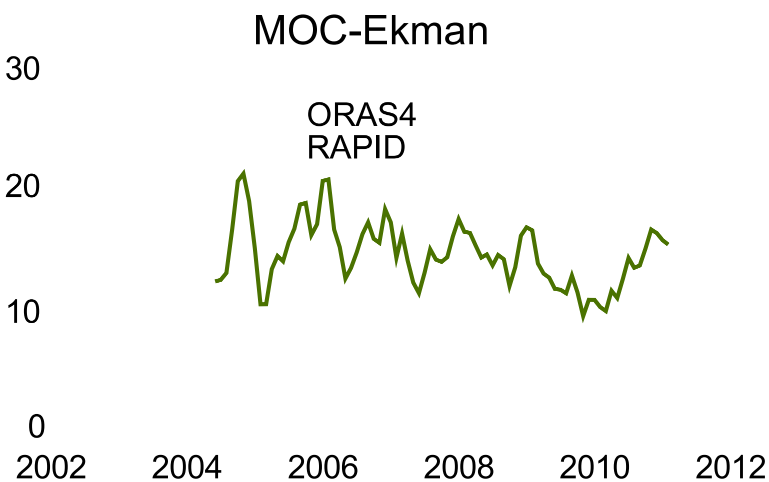
**Consistent Improvement everywhere. Even in the Atlantic, traditionally challenging are**



# Atlantic MOC at 26N.
# Comparison with RAPID data.



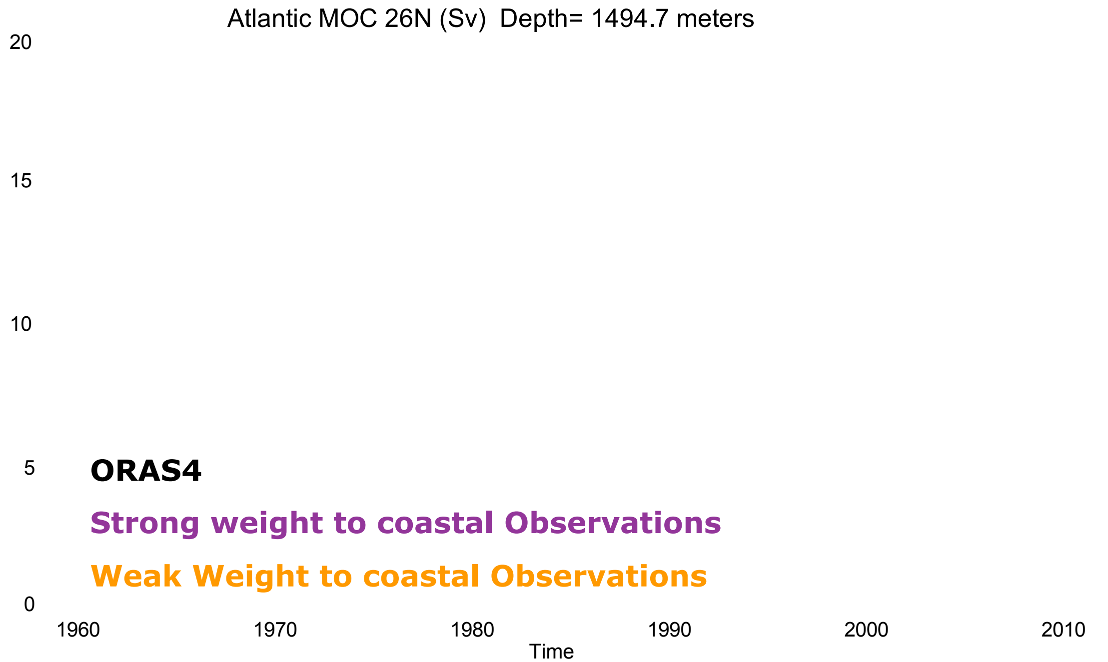

Weaker amplitude than RAPID (weaker Western Boundary current).

MOC is stronger at 40N (25Sv not shown)

Not bad variability, but record is too short. Note the minima in 2010 and 2011

# Sensitivity of Climate signals to aspects not covered by the ensemble generation

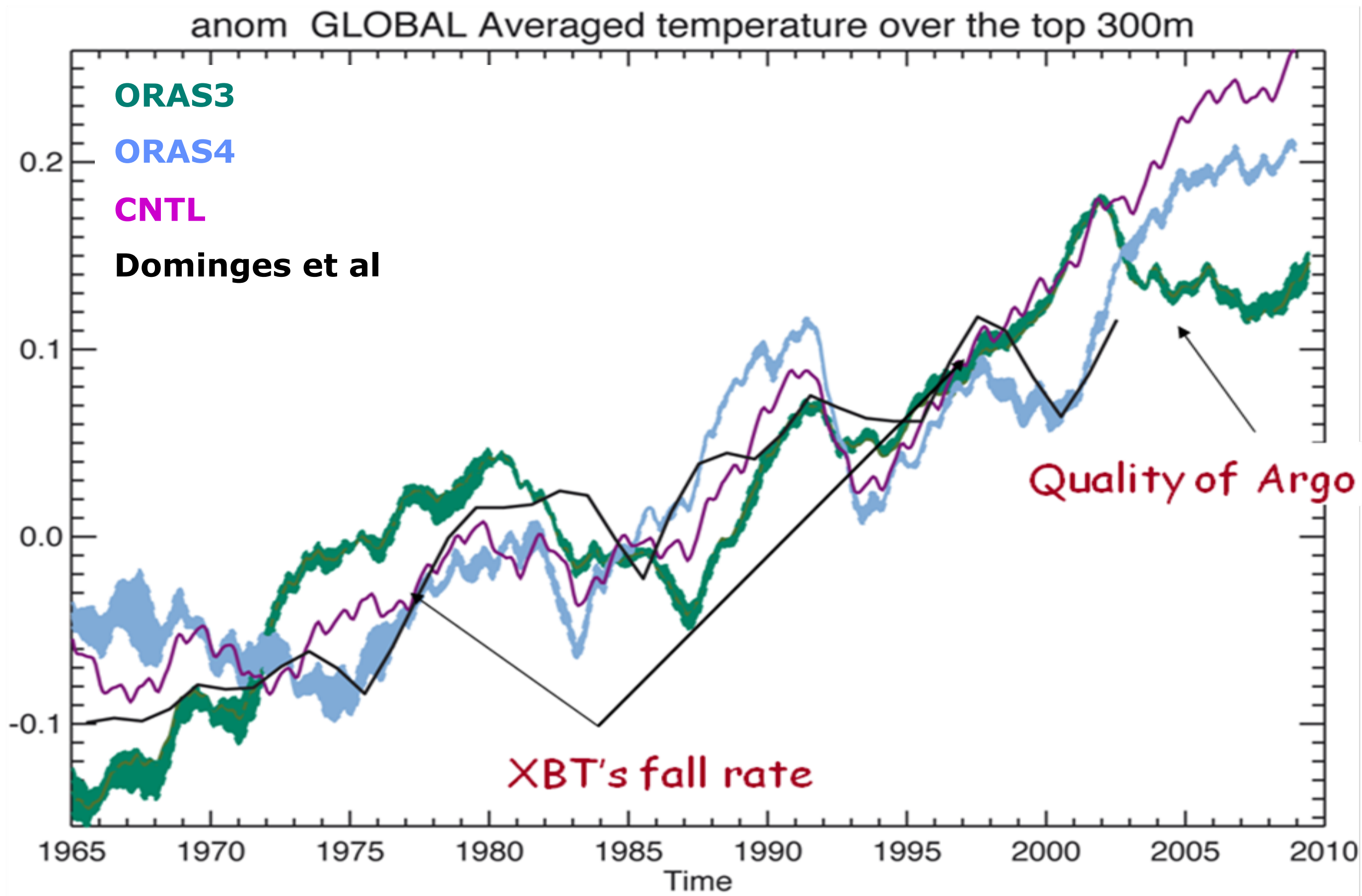
## Atlantic Meridional Overturning Circulation




Sensitivity to the treatment of Coastal Observations

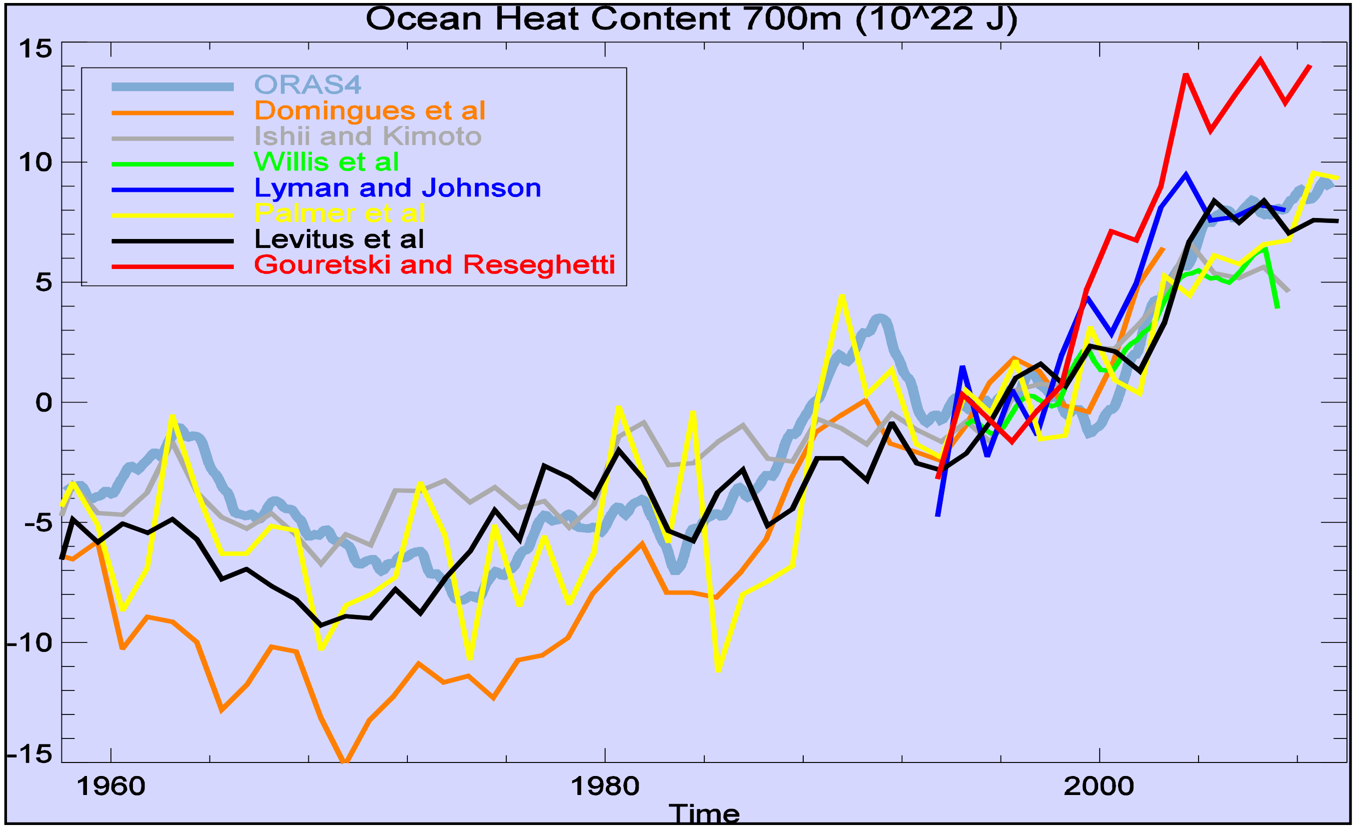
Interesting decadal variability

# Upper 300m Ocean Heat content



# Ocean Heat Content Upper 700m

## Comparison with observational estimates (State of the Climate)




**The ocean heat content in ORAS4 is consistent with observational estimates.**

**Difference with Yellow line is due to assim**

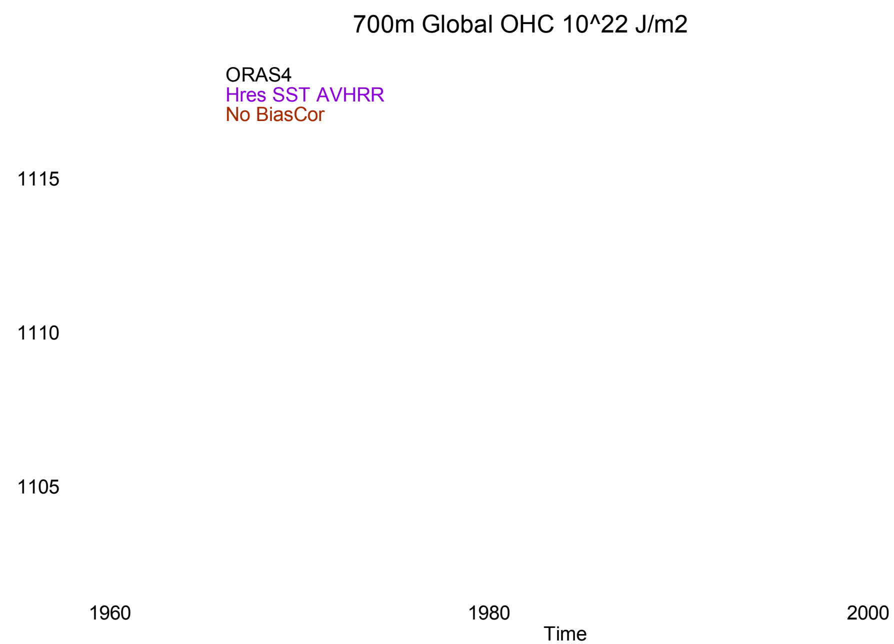
**CNTL, not shown, overestimates the ocean heat content**

# Sensitivity of Climate signals to aspects not covered by the ensemble generation

## Ocean Heat Content upper 700m

### Choice of SST

### Bias Correction

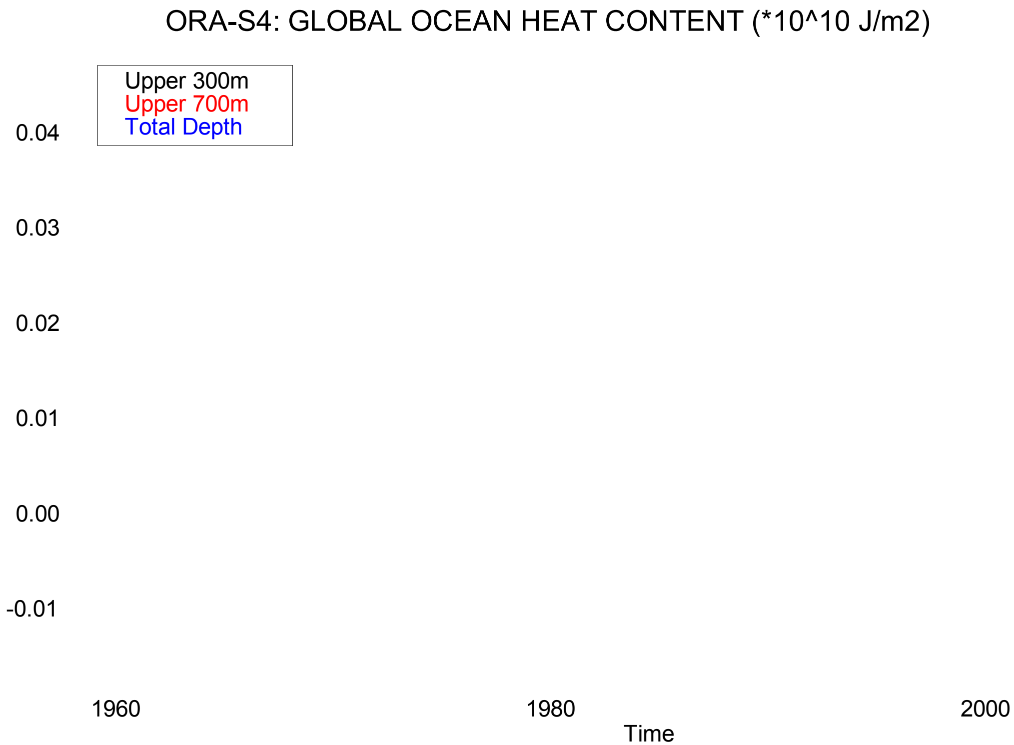



**ORAS4 (OIv2 1x1)**

**Hres SST AVHRR**

**ORAS4 No Bias Correction**

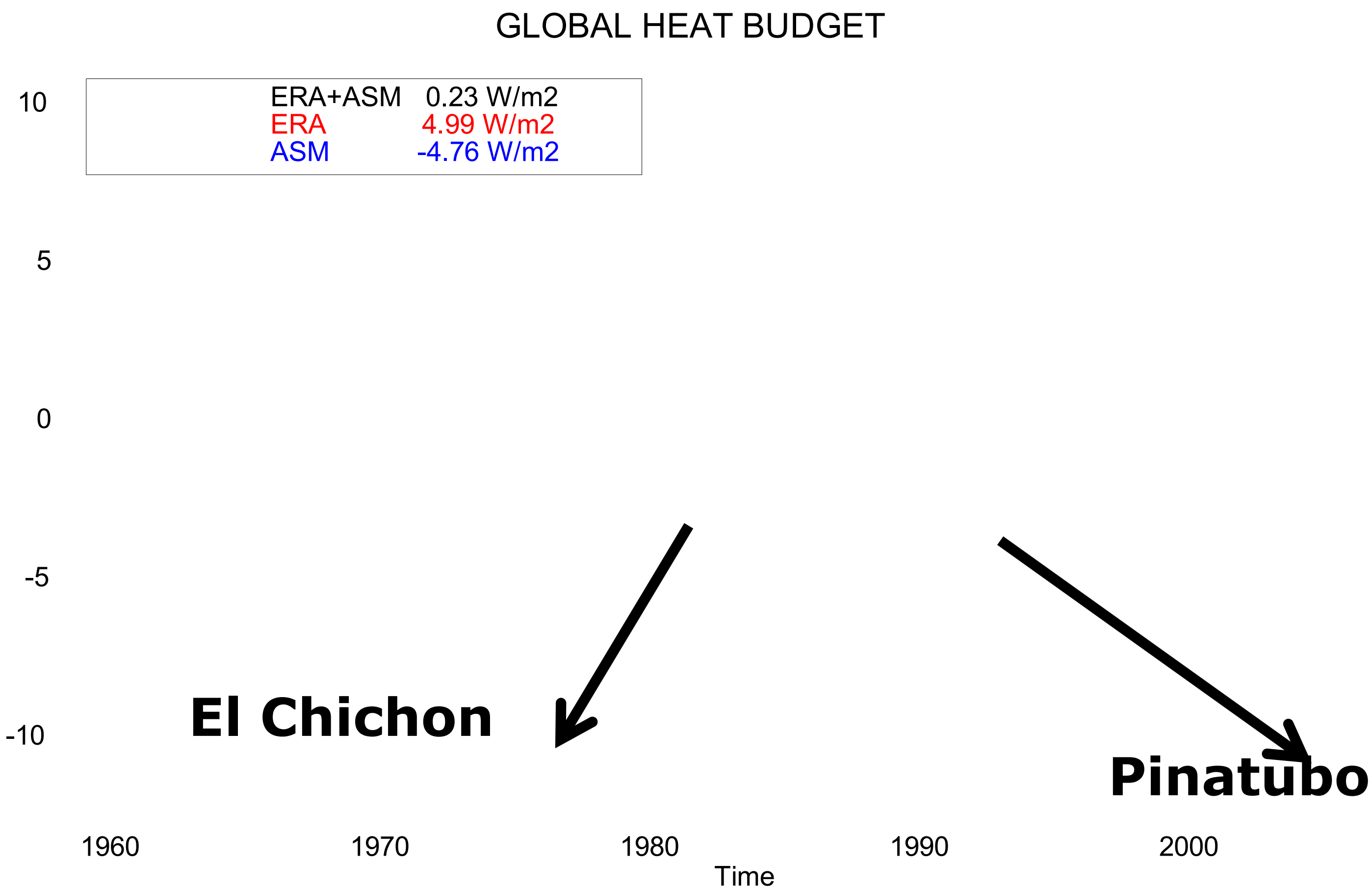
# Heat content Uptake by the Ocean

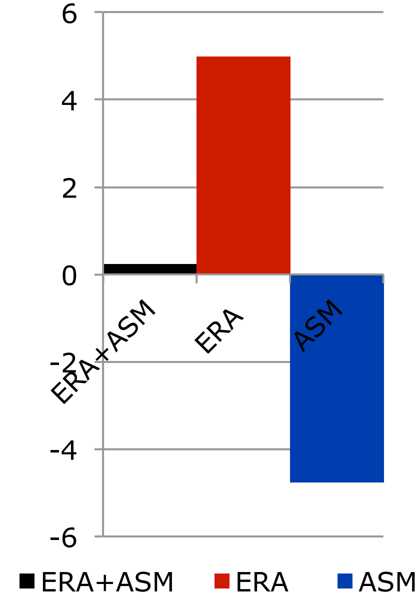



•Interesting vertical redistribution of the heat uptake How robust is it?

- Budget diagnostics
- Observing system experiments
- Any explanation?

# Sources  and sinks of heat




Large imbalance in the surface heat fluxes from Atmospheric re-analysis. Note jump in the transition to ERA-Interim, due to excessive solar radiation

Assimilation compensates for errors in the ERA heat flux, in both mean and variability

It can be shown that ASM contribution is largely from the bias correction

# Consistency Check

ORAS4 HEAT contributions (1.e22 J)

**Total Ocean Heat Content (from vertical T integral)**

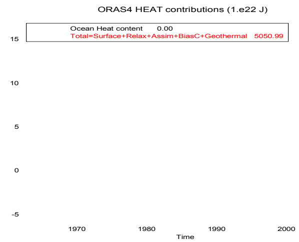
**Time Integral (ASSIM+ERA+geothermal)**

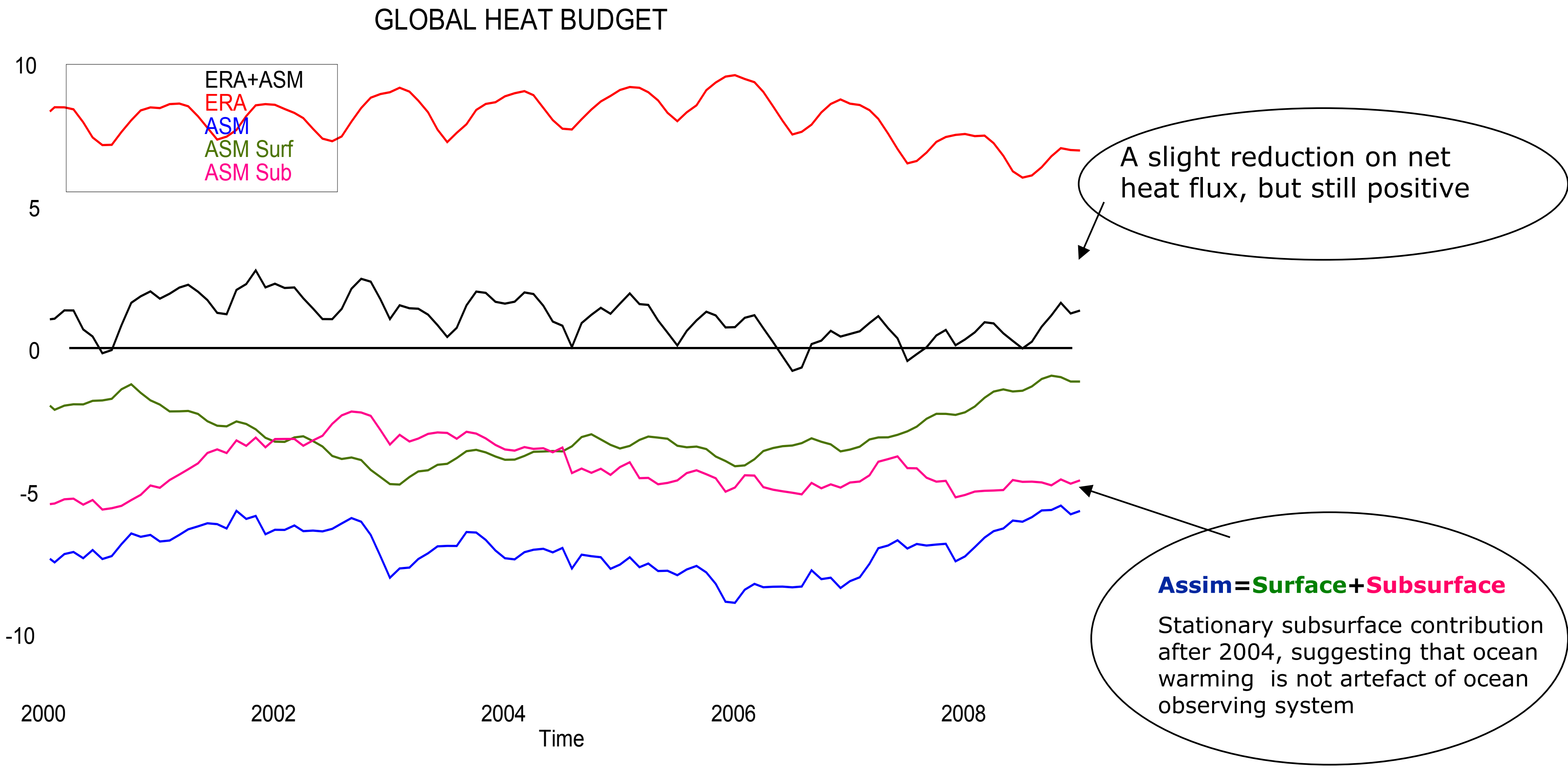
15
10
5
0
-5

1970 1980 1990 2000

Time

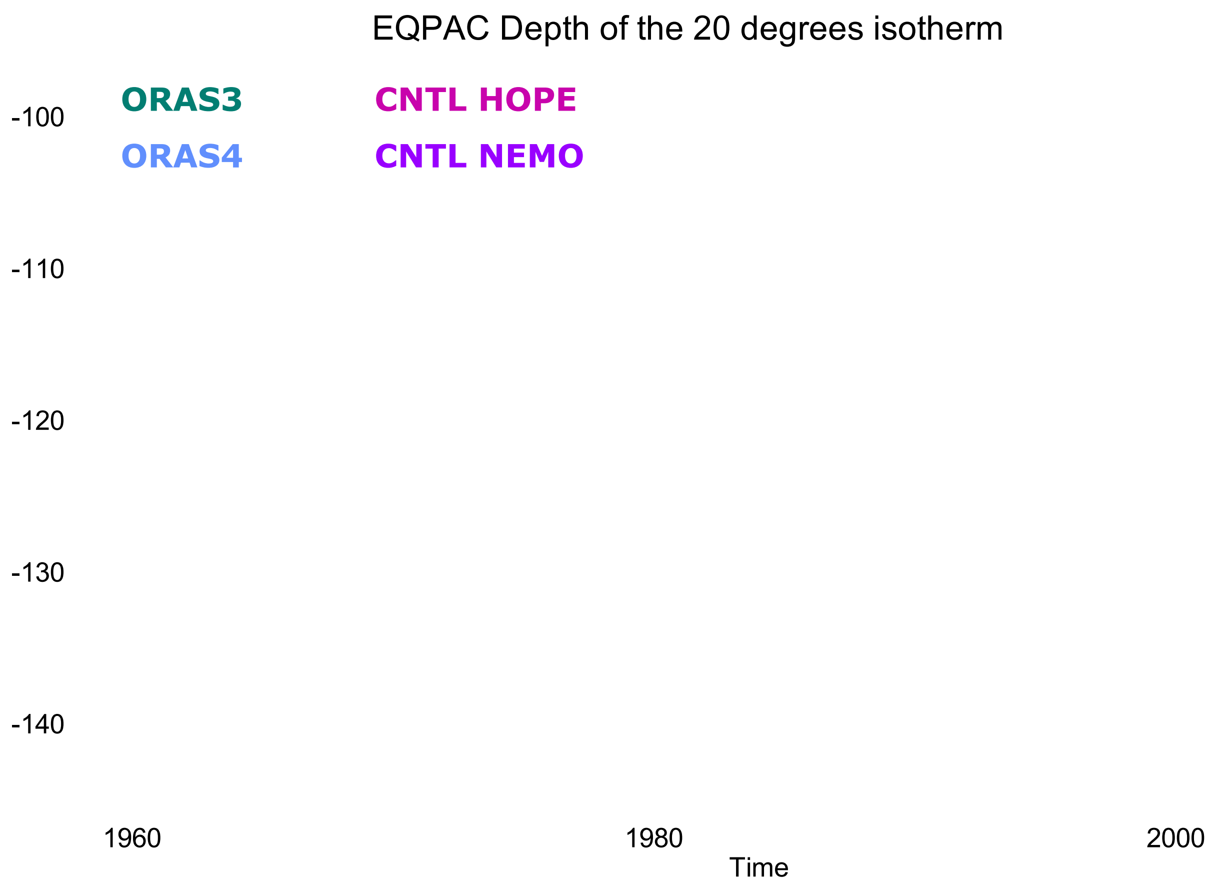
# Zoom on the last decade




Is it possible to close the earth heat budget by including the deep ocean?

# Trends in the Equatorial Pacific thermocline




Shallowing of the EQ Pac thermocline.

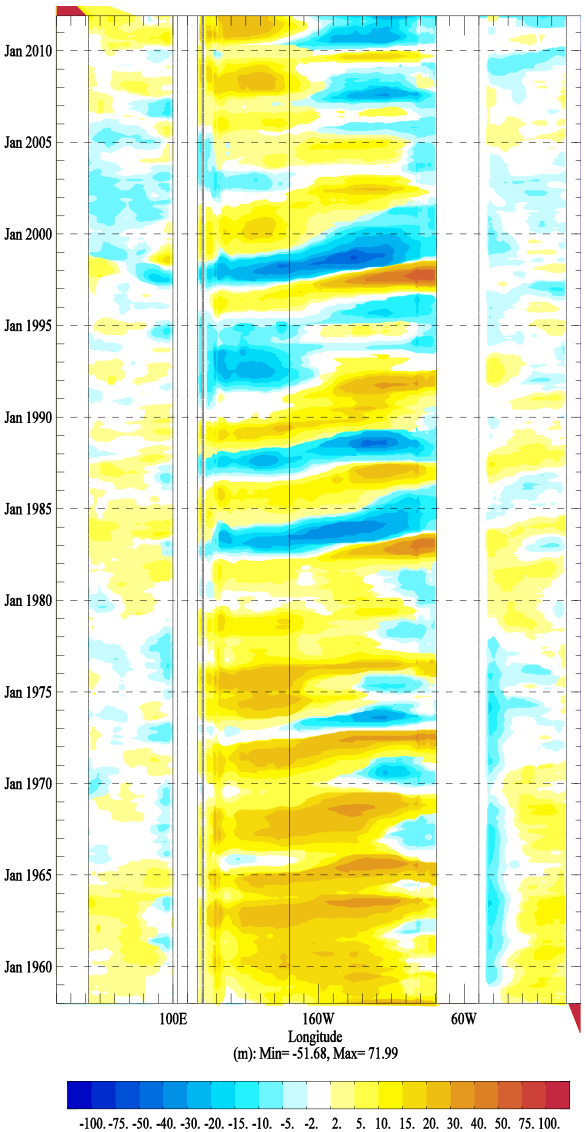
Robust: reproduced by different models, fluxes (ERA40/ERA Interim), and in assim

Decadal signal or global warming trend? Do climate models reproduce it in the XXC runs?

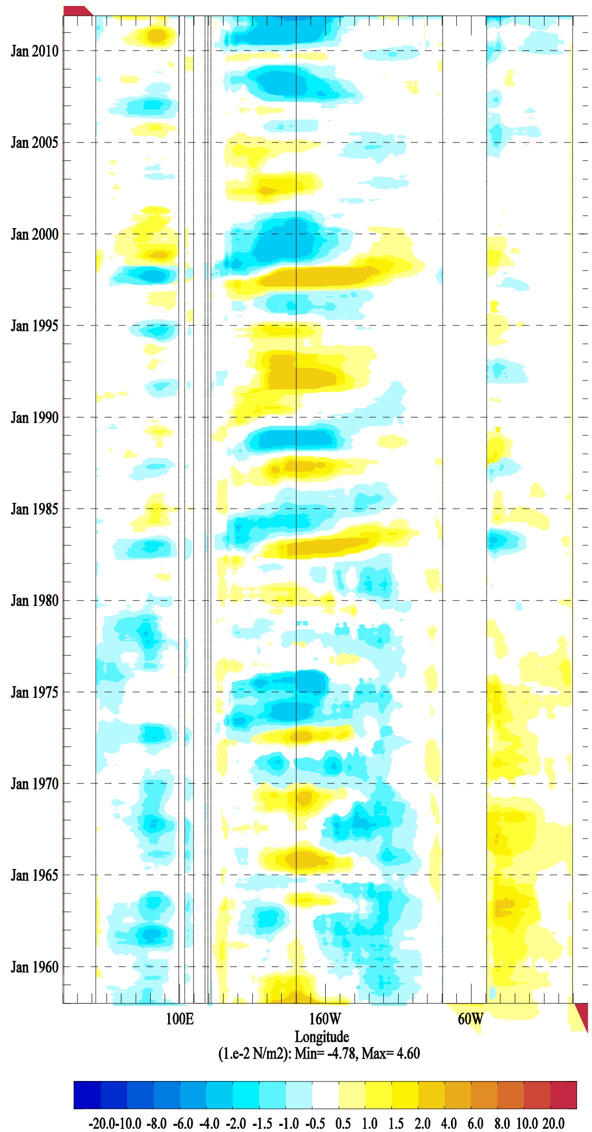
Related to changes in ENSO properties (Modoki ENSO)?

Equatorial anomalies (1981-2009 climate)

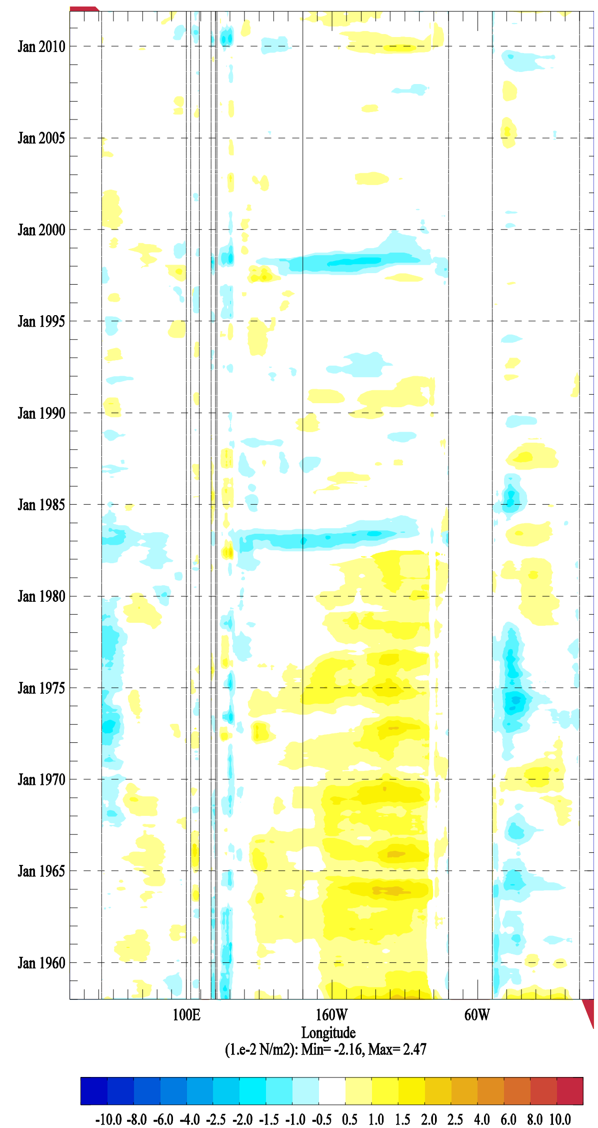
**D20C Isotherm**




**Zonal Wind Stress**




**Meridional Wind Stress**

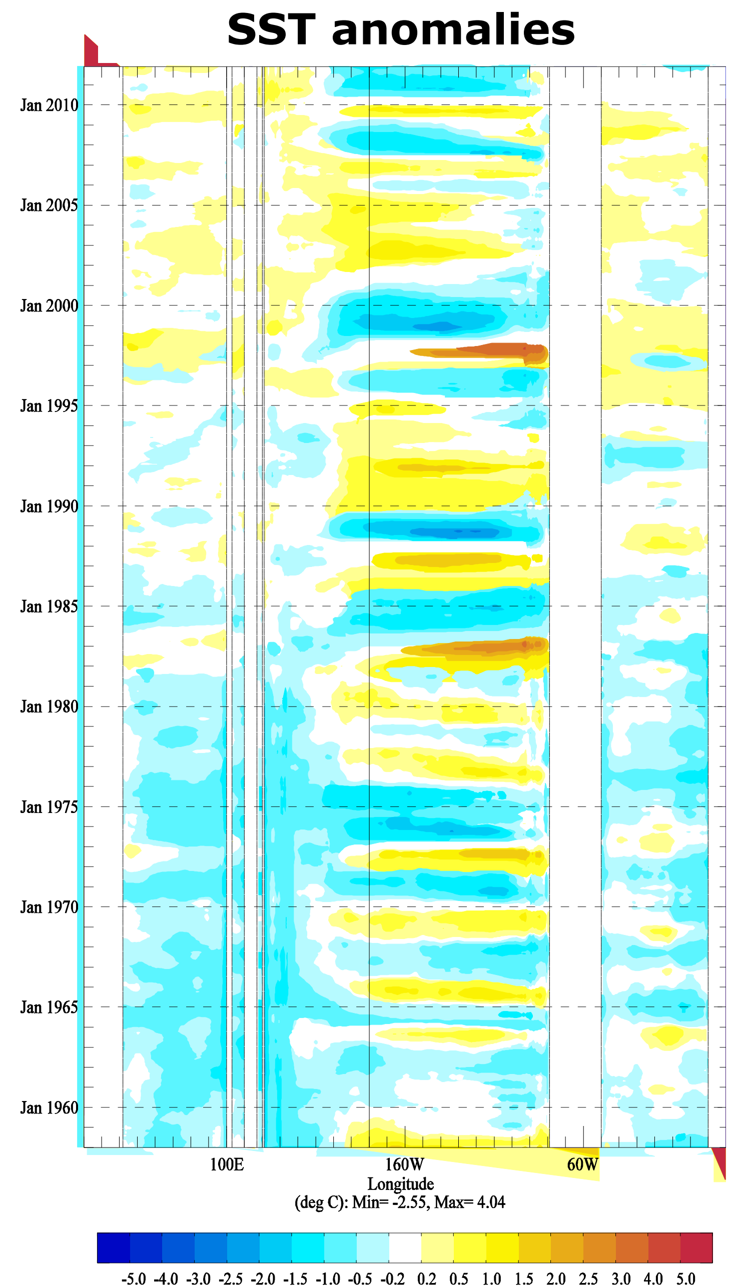


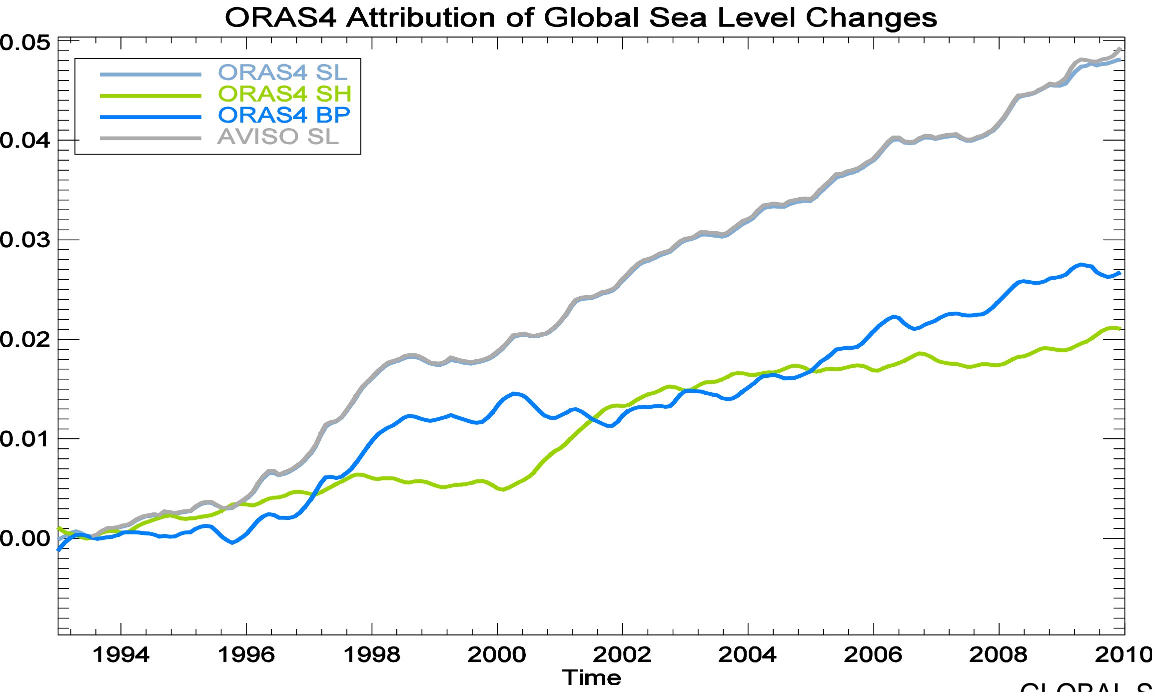

http://www.ecmwf.int/products/forecasts/d/charts/oras4/reanalysis/

# Wind signal likely caused by SST changes

Changes in Indian Ocean and Pacific Warm Pool SST, signature of global warming

Although changes seem robust and physically sound, we still should double check the impact of SST uncertainty in this signal.






# Sea Level Change

**Sea Level Change=**

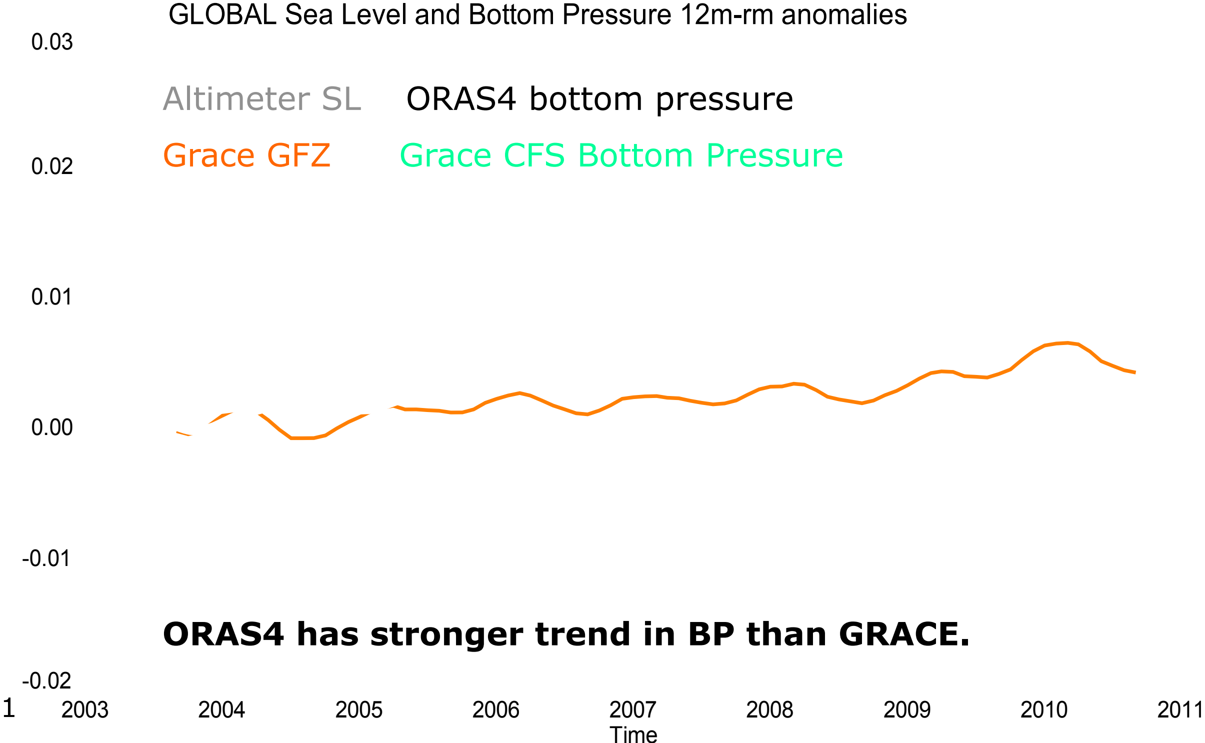
**thermal/saline expansion+ mass=**

**SH (steric)+ BP (bottom pressure)**

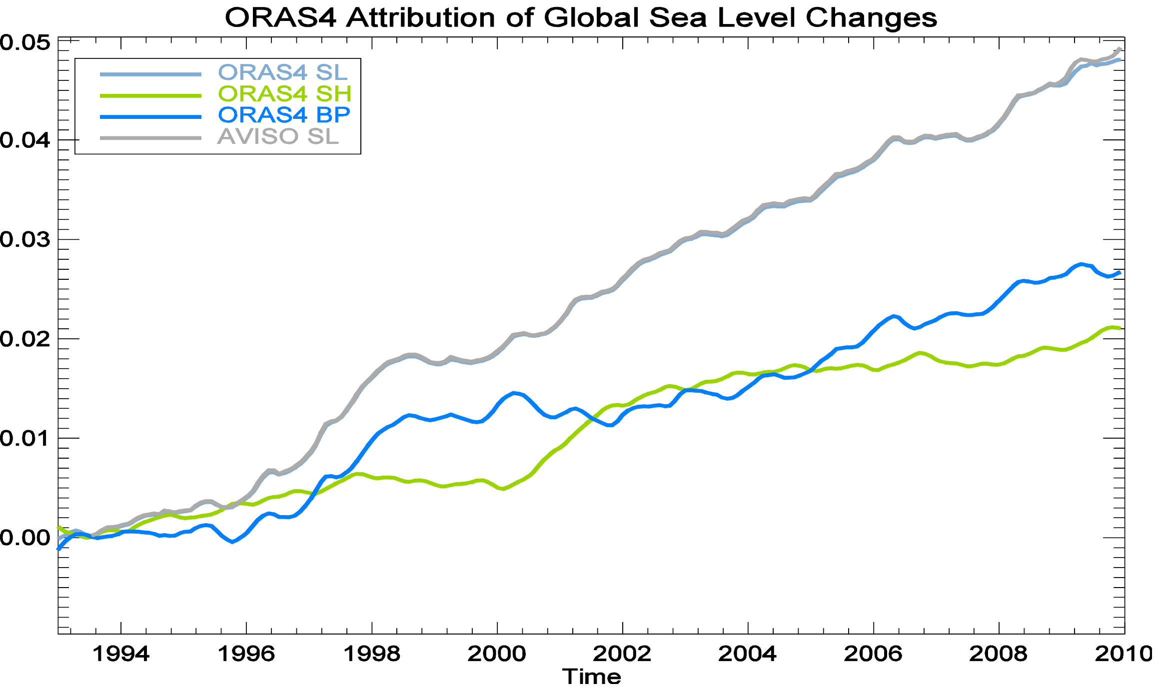
Global Sea Level is constrained by altimeter sea level

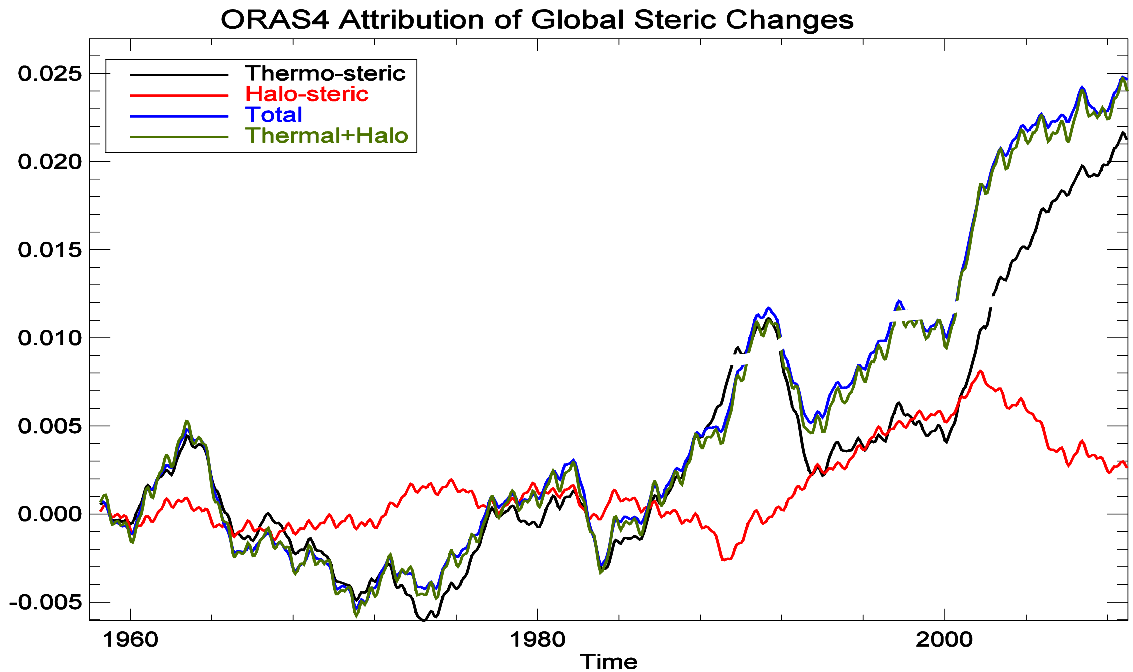
Steric is diagnosed from ocean subsurface (ocean observations)

Bottom pressure is the residual; can be compared with GRACE derived independent products



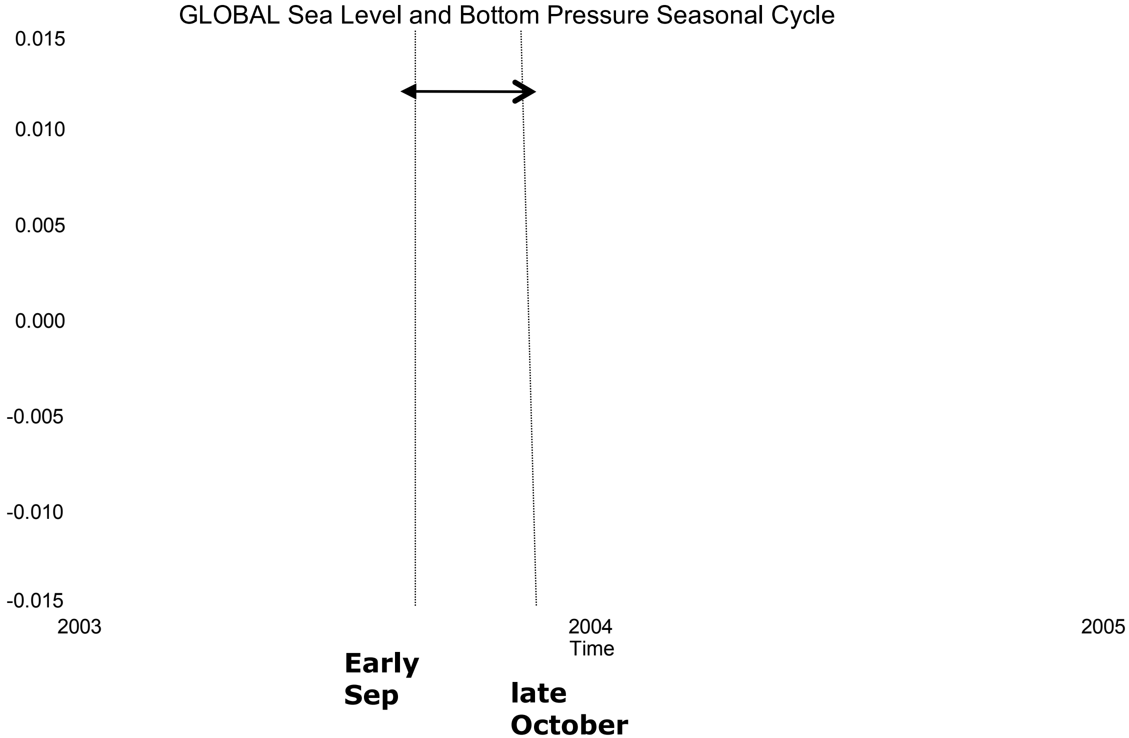

**ORAS4 has stronger trend in BP than GRACE.**


ORAS4 Attribution of Global Sea Level Changes
ORAS4 SL
ORAS4 SH
ORAS4 BP
AVISO SL
0.05
0.04
0.03
0.02
0.01
0.00
1994
1996
1998
2000
2002
2004
2006
2008
2010
Time


ORAS4 Attribution of Global Steric Changes
Thermo-steric
Halo-steric
Total
Thermal+Halo
0.025
0.020
0.015
0.010
0.005
0.000
-0.005
1960
1980
2000
Time

# Comparison with GRACE-derived bottom pressure

## Sea Level Change= Steric (thermal/saline expansion) + Mass (bottom pressure)




### SEASONAL CYCLE

Good agreement in amplitude

More than 1month phase difference

Both in CNTL and ORAS4

These are early results. Need to be understood. GRACE derived bottom pressure is an interesting product

# Summary

- ORA-S4 (Ocean Re-Analysis System 4) implemented operationally
  - Based on NEMO/NEMOVAR ORCA1 configuration. 1958 to present, 5 ensemble members
  - It provides initial conditions for EPS and Seasonal. Also used in initialization of CMIP5 decadal forecasts
- Validation of ORA-S4 (importance of time dimension)
  - Fit to the assimilated data. Comparison with independent data. Impact on forecast skill. Sensitivity exp.
  - Overall assessment: ORAS4 seems sound in the representation of tropical variability and heat content.
  - Uncertainty in Bottom Pressure variability. Weak Atlantic MOC at 26N, but stronger at 40N.
- Analysis of the Ocean Heat Content
  - Strong contribution of ocean observations (bias correction, assim increments, surface)
  - Interesting changes in the last decade affecting the vertical distribution of heat. Heat uptake by the ocean below 700m not negligible after 2000. Why only after 2000?
- Robust trends in the Equatorial Thermocline
  - Changes in the circulation, not only in the ocean heat content. Consistent with SST warming in Indian Ocean and Warm pool area. Physically sound, but still need to eliminate uncertainty on of SST.
- Attribution of Sea Level change: seasonal cycle and trend
  - Some disagreeement between ORAS4 and GRACE derived products. ]
- Web Pages for ORAS4. http://www.ecmwf.int/products/forecasts/d/charts/oras4/reanalysis/
  - Data in community servers (EasyInit, University of Hamburg). Shortly
  - Tech memo, papers (in preparation)

# Key Issues

- **Uncertainty in SST needs to be understood and represented.**
- **Importance of bias correction (for all reanalysis?) Still a bit adhoc.**
- **Importance of subsurface ocean observations in  the earth heat budget**
  - Why the deep ocean starts contributing only after 2000?
  - Continue revision and improvement of quality controlled observational data sets
- **Consistency (and uncertainty) between post-satellite and pre-satellite era:**
  - SST, Surface fluxes, Sea level
  - Other proxy data for validation
- **Continuous improvement in model and data assimilation**
  - High resolution ocean may have better MOC at 26N
  - Better treatment of background covariances may result in better WBC