Data assimilation in the ocean

Magdalena A. Balmaseda

Outline of lecture

- Applications of ocean data assimilation
- Ocean DA versus Atmosphere DA
- The ocean observing system
- An example of Ocean DA: NEMOVAR
  - Background co-variances
  - Balance relationships: temperature, salinity, sea level and velocity
  - Altimeter assimilation
  - Bias correction
  - Ocean reanalysis
- Evaluation Metrics
- Strengths and weakness
- Future directions
  - Coupled data assimilation.

OCEAN DA: components

1. **The *blue* ocean**: ocean dynamics.
   - Primary variables: potential temperature (T), salinity (S) current (U,V) and sea surface height (SSH).
   - Density is a function of T and S though the equation of state.

2. **The *white* ocean**: sea-ice. Not covered here
   - Sea ice concentration and thickness. Very few thickness obs
   - Non gaussian errors. Unknown balance relationships

1. **The *green* ocean**: biogeochemistry. Not covered

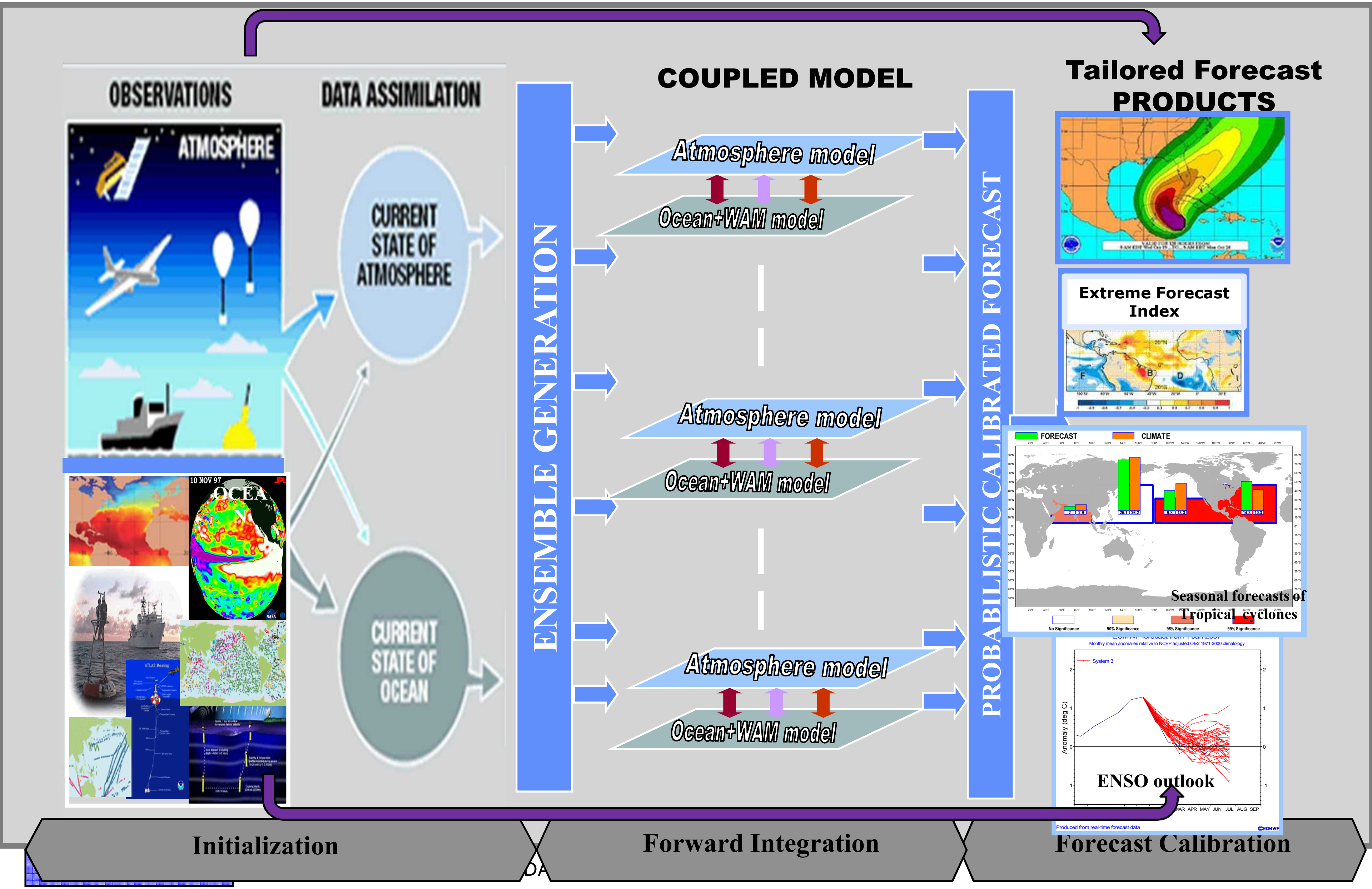
Why do we do ocean DA?

- **Initialization of coupled models**
    - NWP, monthly, seasonal, decadal.
    - Different depths of the ocean are involved at different time scales
    - Climate resolution (global ~1x1 to 1/4x1/4 degrees)

- **To reconstruct and monitor the history of the ocean** (re-analysis)

- **To detect and forecast the ocean mesoscale**
    - High resolution ocean analysis (regional, ~1/3-1/9-1/12 degrees)
    - Defence, commercial applications (oil rigs …), safety and rescue, environmental (algii blooms, spills)

End-To-End Coupled Forecasting System

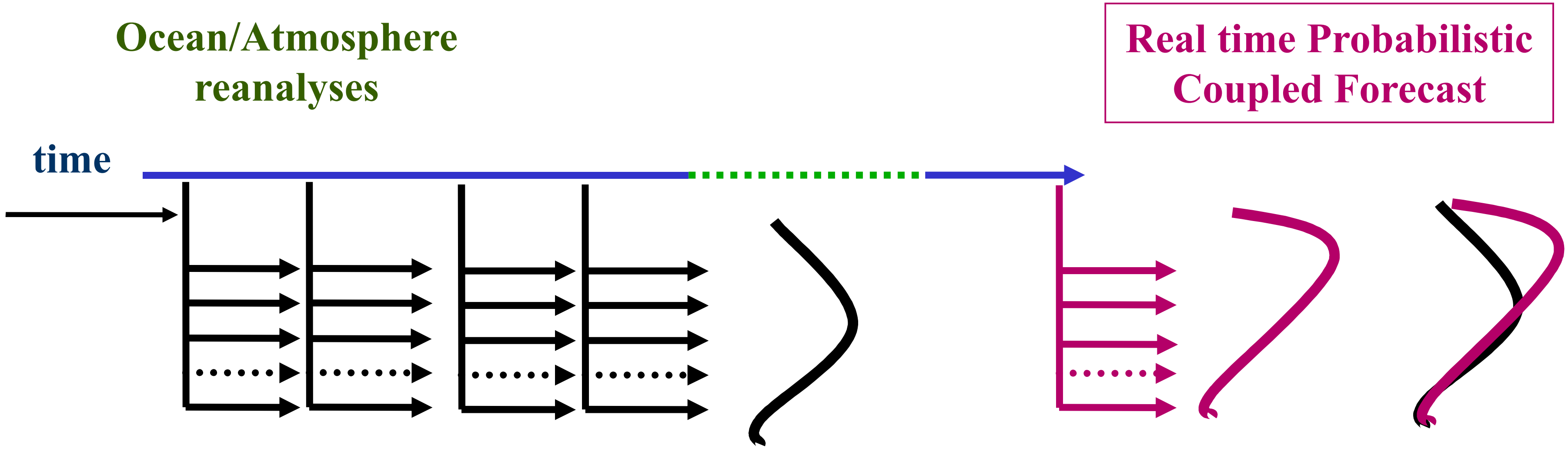


Calibration and Reforecasts:

-Correcting model error

-Extreme Events

-Tailored products **(health, energy, agriculture)**



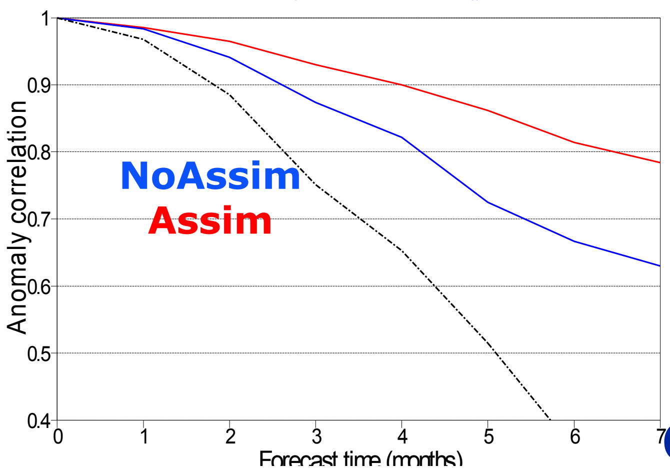
Hindcasts, needed to estimate climatological PDF, require a historical ocean and atmospheric reanalyses

Consistency between historical and real-time initial conditions is required.

Ocean Reanalysis for

Seasonal

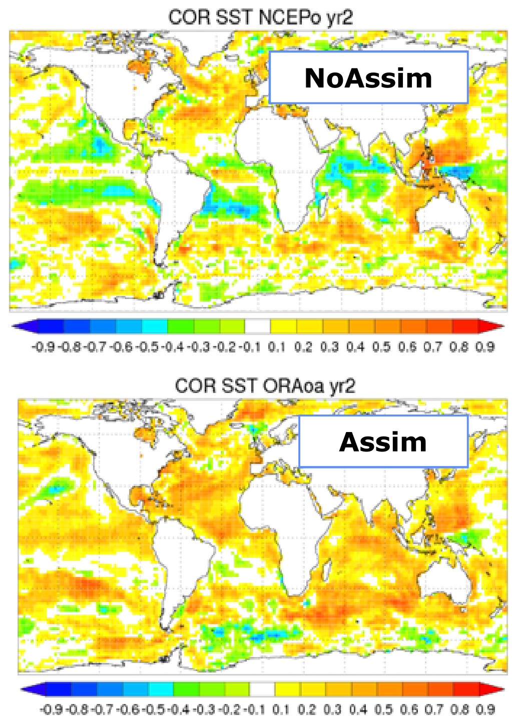
Forecasts of SST Central Pacific Anomaly Correlation



NoAssim is Ocean model simulation with SST constrain

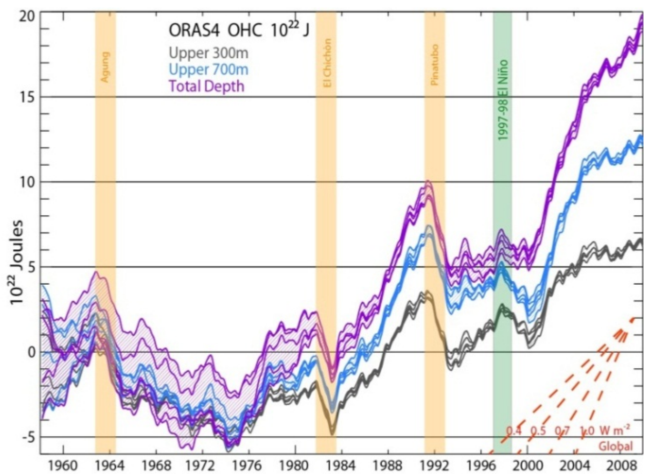
Decadal Forecasts

SST Correlation (MPI)



From Polhmann et al

Climate Studies



Ocean Heat Content from ORAS4

ECWMF ORAS4: Ocean Reanalysis System 4
Balmaseda et al, 2013, QJ
Balmaseda, Trenberth and Kallen, GRL 2013

Ocean versus Atmosphere: some facts

- **Spatial/time scales** The radius of deformation in the ocean is small (~30km) compared to the atmosphere (~3000km).

  Radius of deformation =c/f where c= speed of gravity waves. In the ocean c~<3m/s for baroclinic processes.

  Smaller spatial scales and Longer time scales

- **The ocean is strongly stratified in the vertical,** although deep convection also occurs

  Density is determined by Temperature and Salinity

- **The ocean is forced at the surface** by the wind/waves, by heating/cooling, and by fresh-water fluxes.

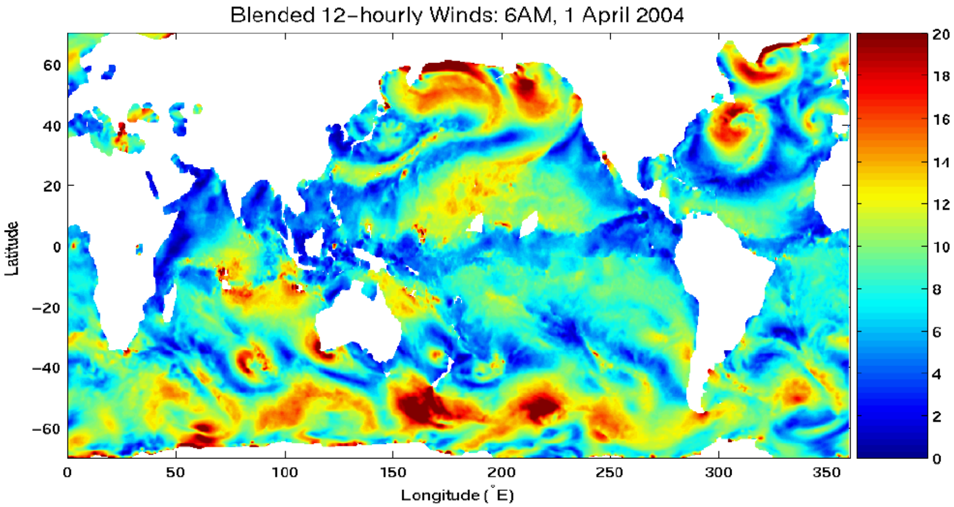
  For modelling this means that uncertainty in forcing fluxes contributes to uncertainty in model results.

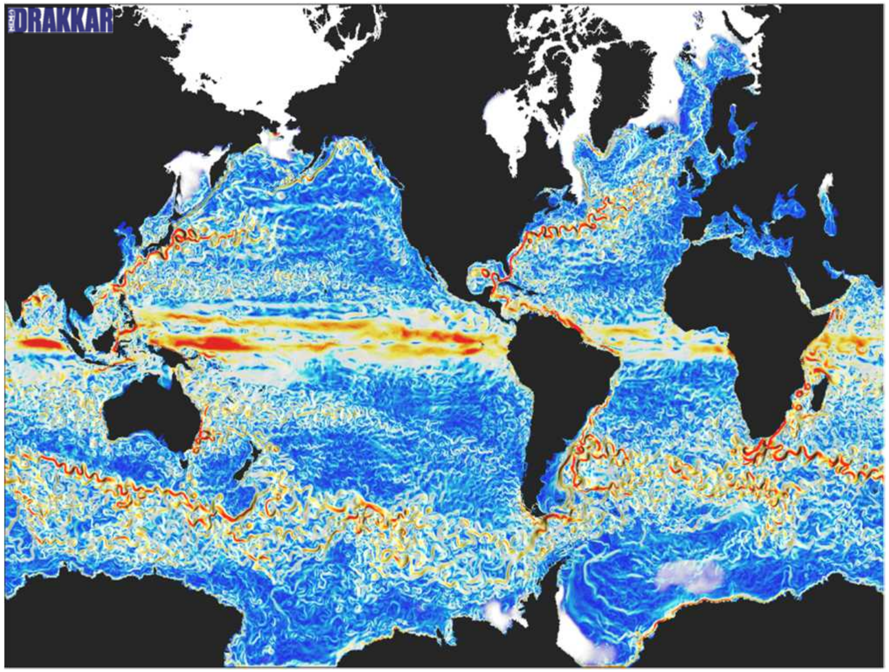
- **The electromagnetic radiation does not penetrate into the ocean**, which makes the deep ocean difficult to observe from satellites.

  The surface of the ocean can however be observed from space

- **The ocean has continental boundaries;** dealing with them is not trivial in data assimilation

(Zhang et al.,)





Atmospheric wind speed (12h)

Ocean current speed **(model simulation, 5 day mean)**

Basis for extended range forecasts: monthly, seasonal, decadal

- The forecast horizon for weather forecasting is a few days. Sometimes it is longer e.g. in blocking situations 5-10 days.

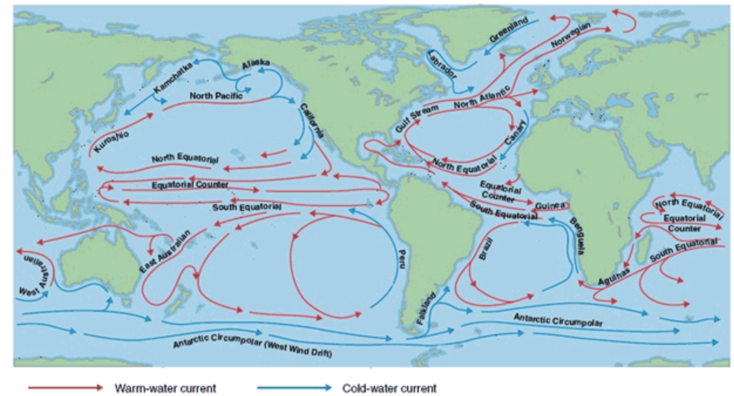
- Sometimes there might be predictability even longer as in the intra-seasonal oscillation or Madden Julian Oscillation.

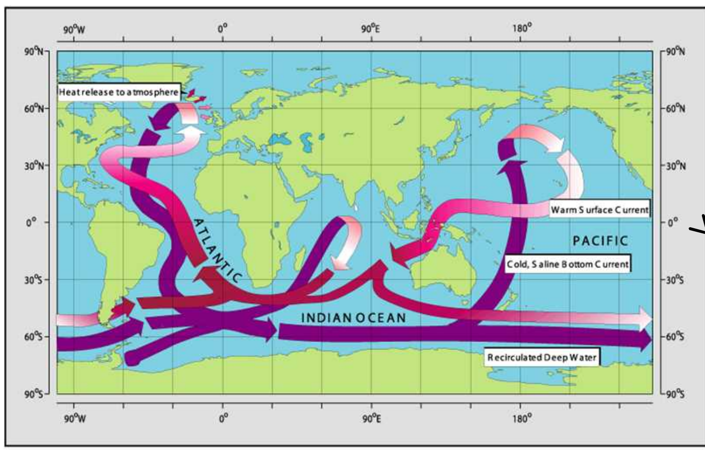
- But how can you predict seasons, years or decades ahead?

- The feature that gives longer potential predictability is forcing given by slow changes on boundary conditions, especially to the Sea Surface Temperature (SST)
  - Atmospheric responds to SST anomalies, especially large scale tropical anomalies
  - **El Nino/Southern Oscillation** is the main mode for controlling the predictability of the interannual variability.

Ocean Circulation

Wind Driven: Gyres, Western Boundary Currents, Upwelling regions (coastal, equatorial), Ekman pumping and subduction





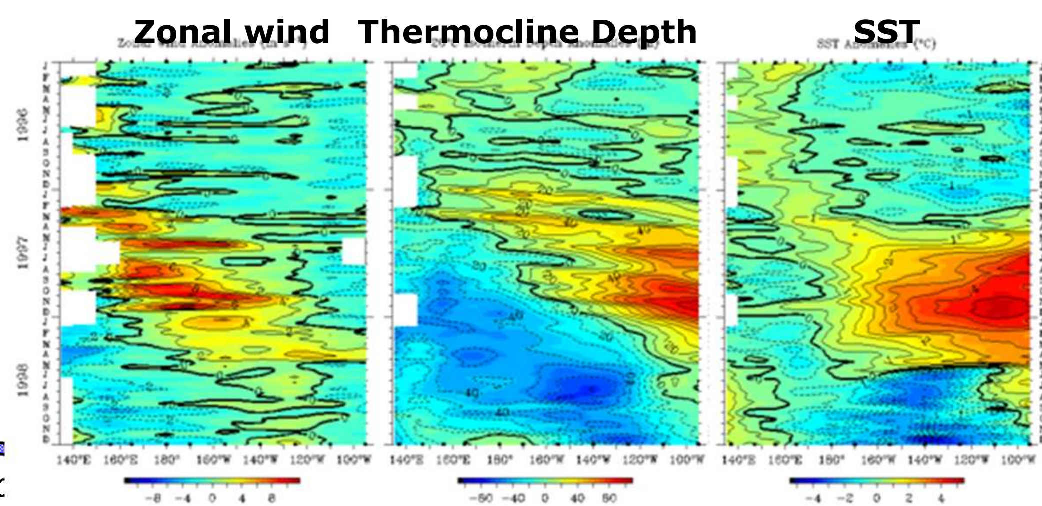
Density Driven:

Thermohaline Circulation

Interannual and Decadal variability: **Adjustment processes**

Equatorial Kelvin waves (c ~2-3m/s) (months). **ENSO**

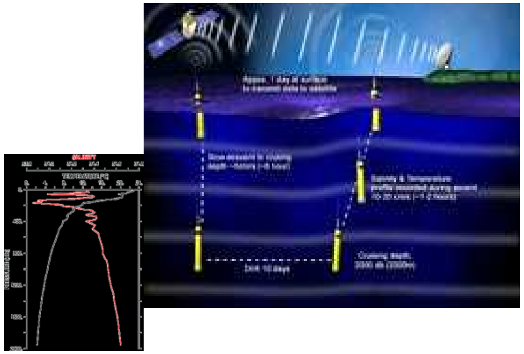
Planetary Rossby waves (months to decades)



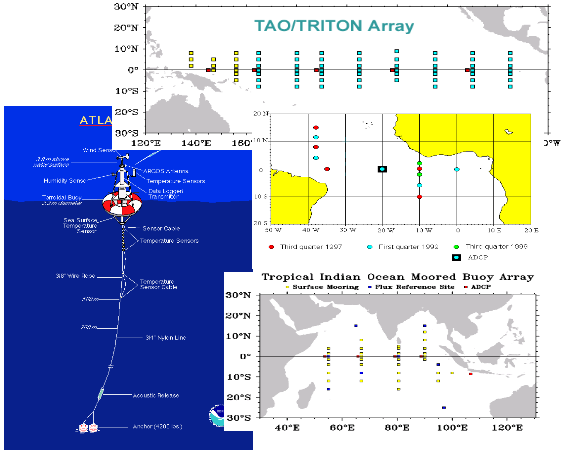
The Ocean Observing system

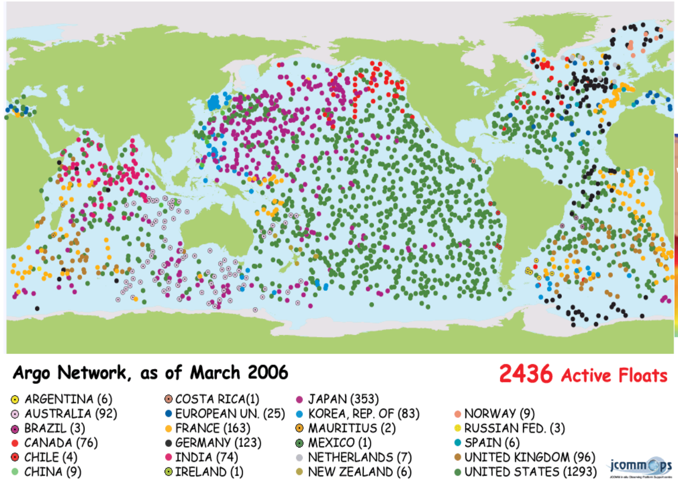
Moorings

ARGO floats

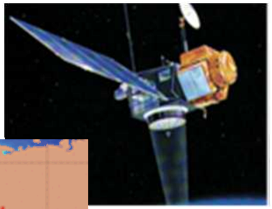


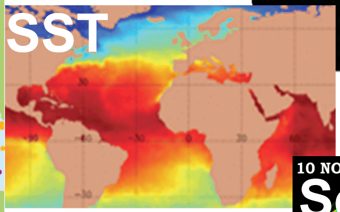
XBT (eXpandable BathiThermograph)

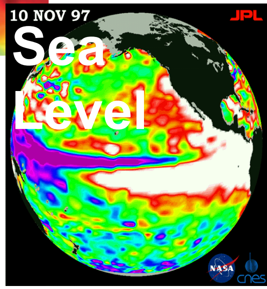




Satellite





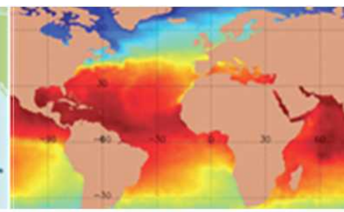


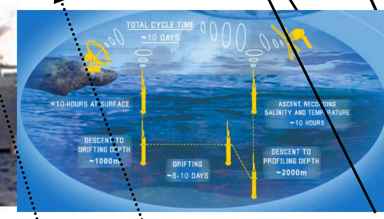
Elephant seals

Time evolution of the Ocean Observing System

1982 1993 2001 2008

XBT's 60's | Satellite SST | Moorings/Altimeter | ARGO





Gravity info:

GRACE

GOCE

TRITON

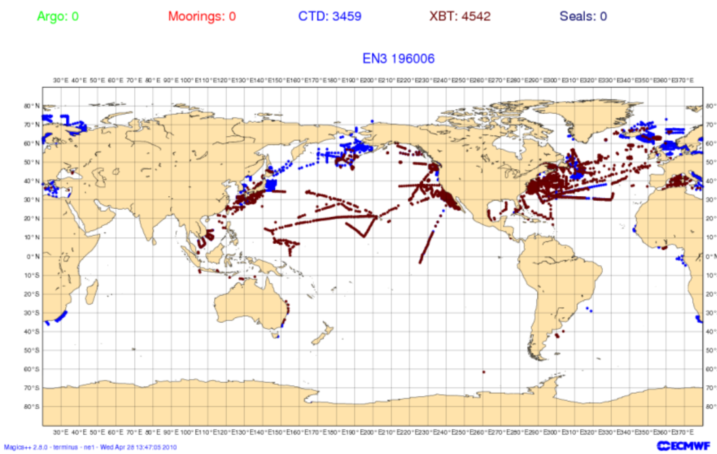
SSS info:

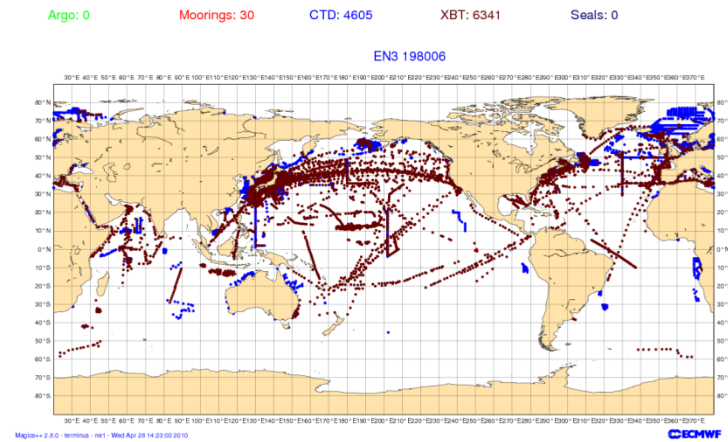
Aquarius

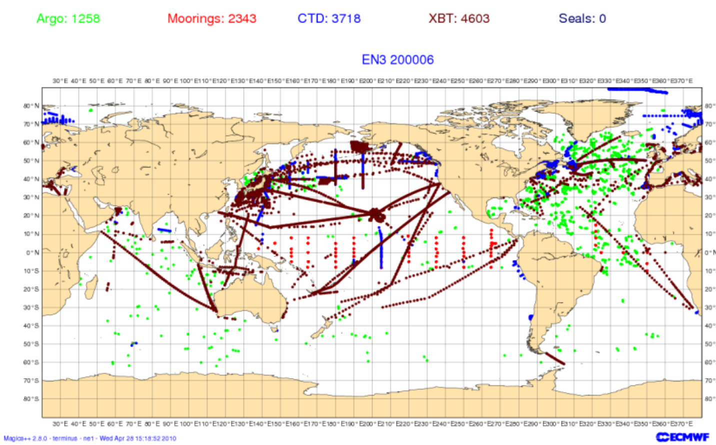
SMOS

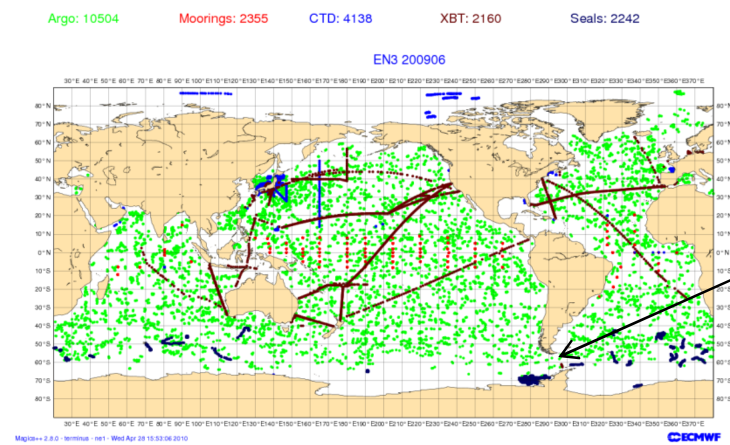
1998-1999
PIRATA

Changes to the T/S obs. network

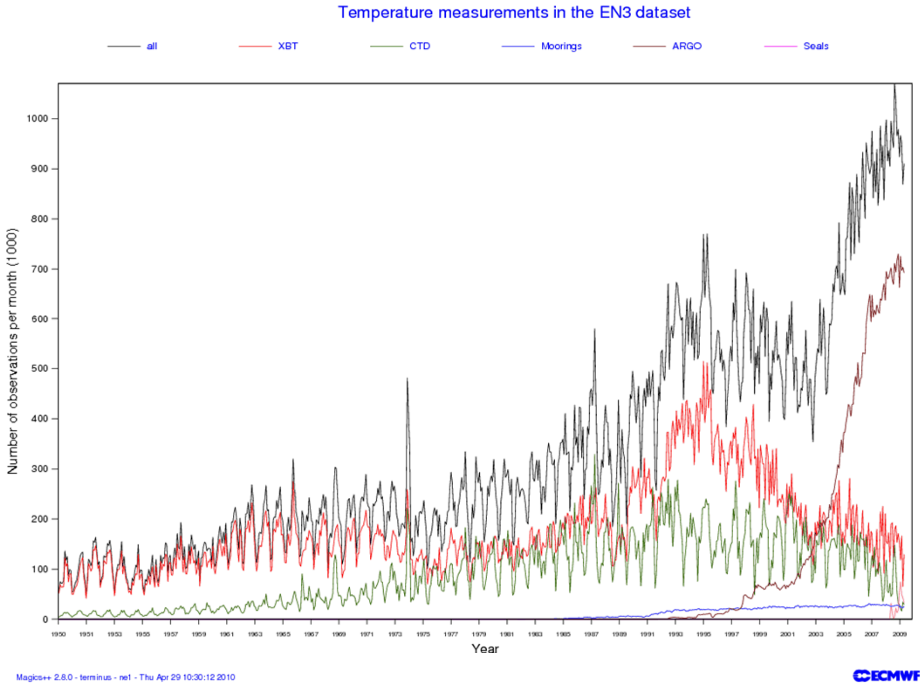




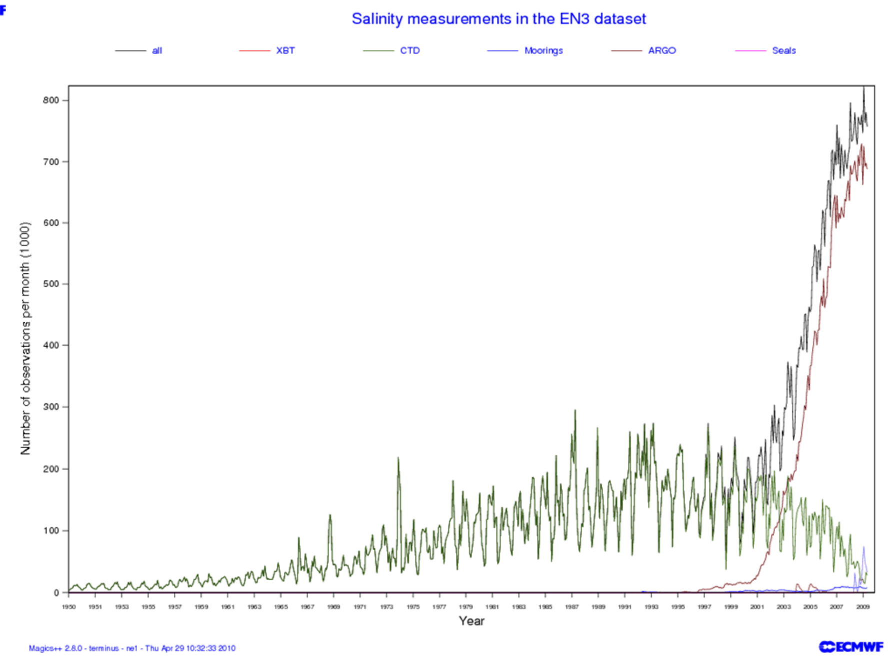




- Very uneven distribution of observations.
- Southern ocean poorly observed until ARGO period.



No. of T obs. as function of time



No. of S obs. as function of time

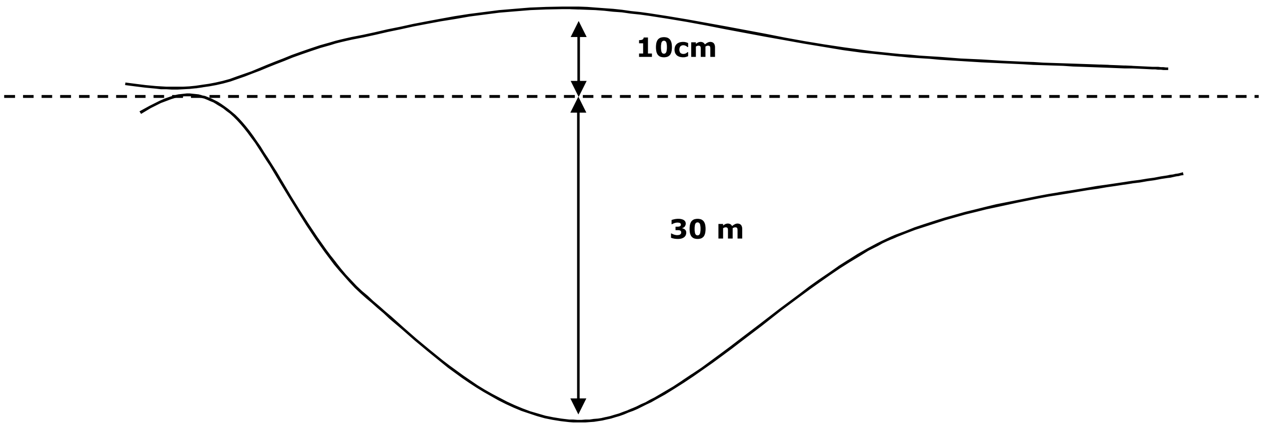
What about altimetry?

Vertical Stratification and Satellite altimetry

- The density of the second layer is only a little greater than that of the upper layer.

Typically g'~g/300

- A 10cm displacement of the top surface is associated with a 30m displacement of the interface (the thermocline).

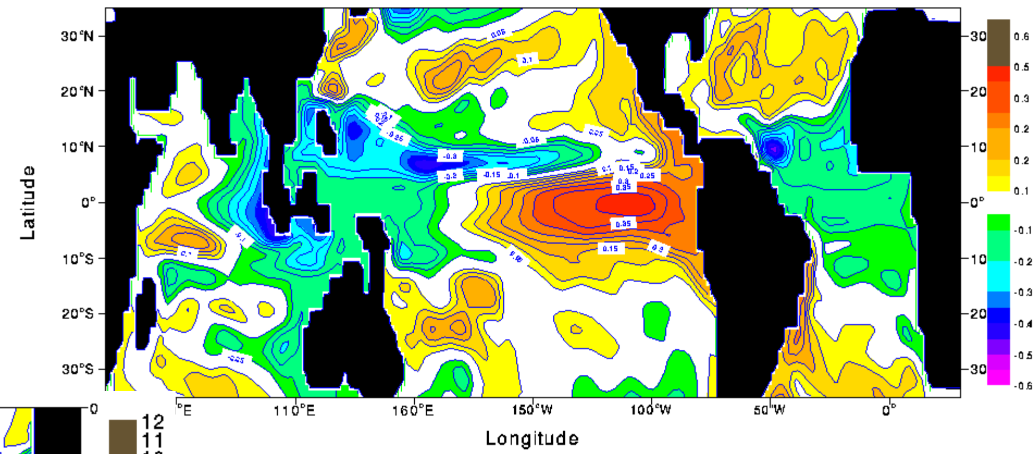


If we observe sea level, one can infer information on the vertical density structure

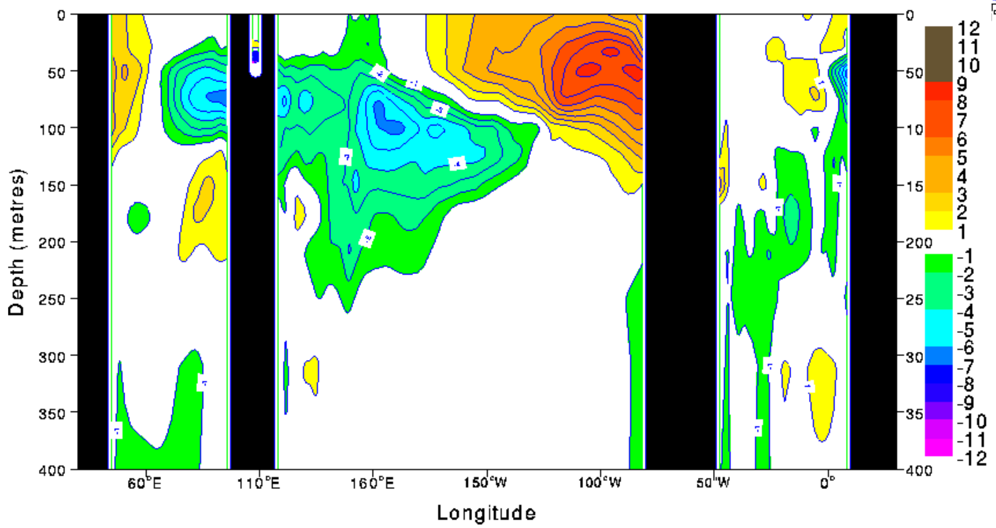
Sea Level Anomaly from Altimetry

El Nino 1997/98

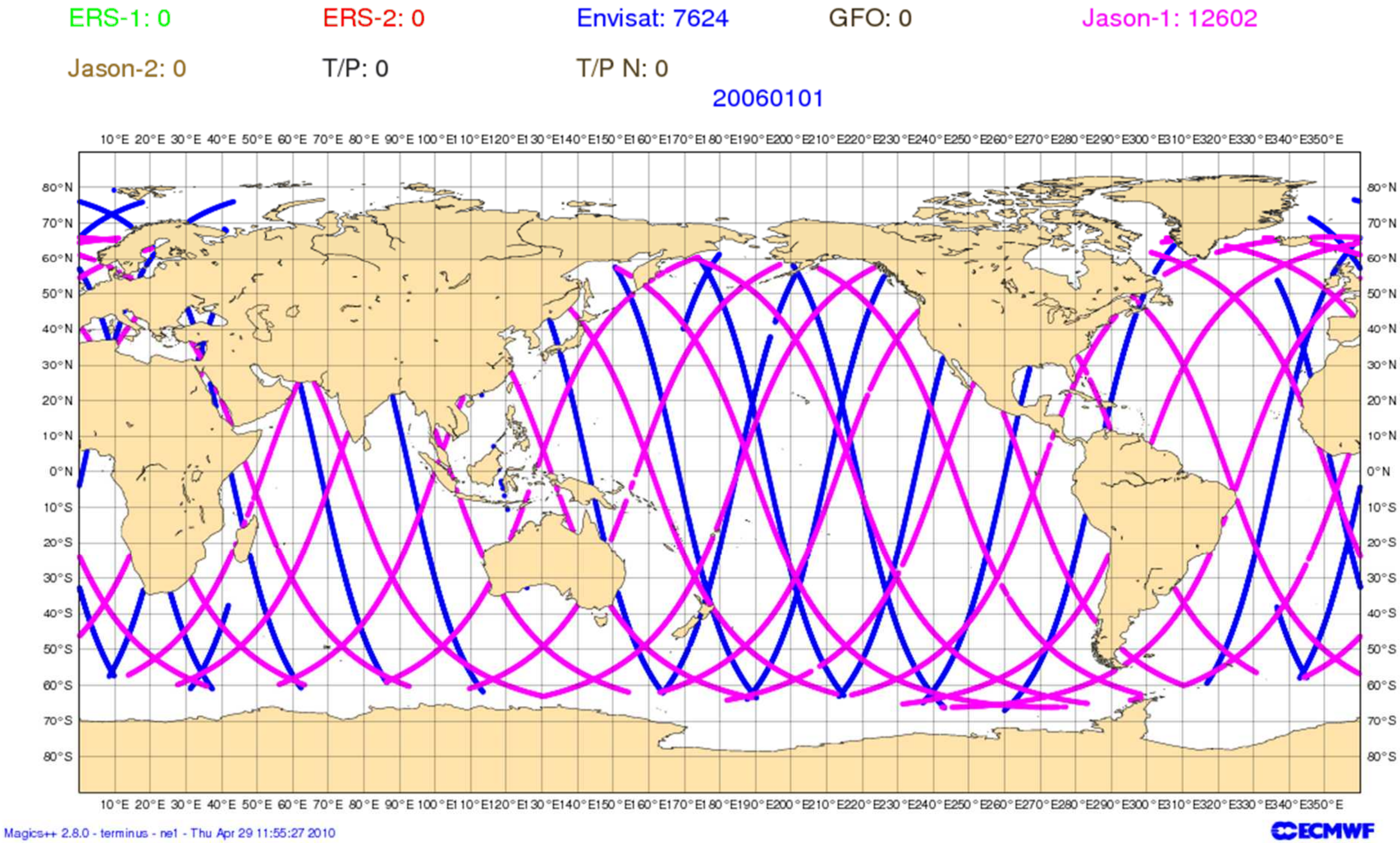
Sea Level anomaly



Equatorial Temperature anomaly



SSH observational coverage 20060101



Ocean assimilation systems

- DA systems based on optimum interpolation (OI), variational techniques (*e.g.* 3D/4D-Var) or various ensemble Kalman filter based methods.
  - Or various hybrid combinations, just like for the atmospheric systems.
- First guess given by an ocean model forced by atmospheric fluxes.
- Usually observations are used to modify Temperature (T), Salinity (S), SSH. Velocities are derived via balance relationships.
- How to deal with coast lines is not trivial.
  - *E.g.* we don't want increments (result of analysis) from the Pacific to propagate to the Atlantic across Panama.
- To avoid initialization shock increments are typically applied via Incremental Analysis Update (IAU) which applies the increments as a forcing term over a period of time.
- Bias correction is very important is very important for reanalyses applications

Example of ocean DA:NEMOVAR

Variational DA system for the NEMO ocean model

- Collaborative project CERFACS, ECMWF, INRIA and the Met Office.
- Solves a linearized version of the full non-linear cost function.
- Incremental 3D-Var FGAT running operationally at ECMWF and Metoffice.
- 4D-Var working on research model
- Uses diffusion operators for background correlation model (not discussed here, quite expensive).
- Uses partition into balance and unbalance components

NEMOVAR algorithm

Weaver et al 2003,2005
Daget et al 2009
Mogensen et al 2012
Balmaseda et al 2013

$$J[\delta \mathbf{w}] = \frac{1}{2}\delta \mathbf{w}^{\mathrm{T}} \mathbf{B}^{-1} \delta \mathbf{w} + \frac{1}{2}(\mathbf{G}\delta \mathbf{w} - \mathbf{d})^{\mathrm{T}} \mathbf{R}^{-1} (\mathbf{G}\delta \mathbf{w} - \mathbf{d})$$

$\mathbf{y}^{\mathrm{o}} = \{(\mathbf{y}_0^{\mathrm{o}})^{\mathrm{T}} \cdots (\mathbf{y}_i^{\mathrm{o}})^{\mathrm{T}} \cdots (\mathbf{y}_N^{\mathrm{o}})^{\mathrm{T}}\}^{\mathrm{T}}$ $\longrightarrow$ 4D observation array

$\delta \mathbf{w} = \mathbf{w} - \mathbf{w}^{\mathrm{b}}$ $\longrightarrow$ **w** is the control vector

$\mathbf{d} = \mathbf{y}^{\mathrm{o}} - G(\mathbf{w}^{\mathrm{b}})$ $\longrightarrow$ Departure vector

$$\mathbf{w}^{\mathrm{b}} \equiv K^{-1}\{\mathbf{x}^{\mathrm{b}}(t_0)\}$$

$$(T, S_{\mathrm{U}}, \eta_{\mathrm{U}}, u_{\mathrm{U}}, v_{\mathrm{U}})^{\mathrm{T}} \longleftarrow (T, S, \eta, u, v)^{\mathrm{T}}$$

$$G(\mathbf{w}) = \begin{pmatrix} \vdots \\ G_i(\mathbf{w}) \\ \vdots \end{pmatrix} = \begin{pmatrix} \vdots \\ H_i[M(t_i, t_0)\{K(\mathbf{w})\}] \\ \vdots \end{pmatrix}$$

In **w** space, **B** is block diagonal, representing the spatial covariance model. The variables are linearly independent.

Question: how to specify the spatial covariances?. In the current version of NEMOVAR, this is done by diffusion operator (Weaver and Courtier 2001)

Solution

$$\delta \mathbf{w}^{\mathrm{a}} \approx \mathbf{B}\,\mathbf{G}^{\mathrm{T}}\left(\mathbf{G}\,\mathbf{B}\,\mathbf{G}^{\mathrm{T}} + \mathbf{R}\right)^{-1}\mathbf{d}.$$

$$\delta \mathbf{x}^{\mathrm{a}} = K\left(\mathbf{w}^{\mathrm{b}} + \delta \mathbf{w}^{\mathrm{a}}\right) - K\left(\mathbf{w}^{\mathrm{b}}\right) \approx \mathbf{K}\,\delta \mathbf{w}^{\mathrm{a}}$$

$$\mathbf{x}^{\mathrm{a}}(t_i) = M(t_i, t_{i-1})\left[\,\mathbf{x}^{\mathrm{a}}(t_{i-1}),\; F_i\,\delta \mathbf{x}^{\mathrm{a}}\right]$$

IAU,Bloom et al 1996

Background errors for ocean assim B.

- Length scales for a typical climate model:
  - ~2 degree at mid latitudes
  - ~15-20 degrees along the eq.
- The background error correlation scales are highly non isotropic to reflect the nature of equatorial waves- Equatorial Kelvin waves which travel rapidly along the equator ~2m/s but have only a limited meridional scale as they are trapped to the equator.
- Complex structures and smaller length scales near coastlines are usually ignored.
- Background errors are correlated between different variables (multivariate formulation) through balance relations (next slides).
  - *E.g.* an temperature observation gives rise to an increment in salinity.
- The background errors can be flow dependent.

Linearized balance operator

- Define the balance operator symbolically by the sequence of equations

Temperature	$\delta T^k = \delta T^k = \delta T^k$
Salinity	$\delta S^k = \mathbf{K}_{ST}^{k-1}\delta T^k + \delta S_U^k = \delta S_B^k + \delta S_U^k$
SSH	$\delta\eta^k = \mathbf{K}_{\eta\rho}^{k-1}\delta\rho^k + \delta\eta_U^k = \delta\eta_B^k + \delta\eta_U^k$
u-velocity	$\delta u^k = \mathbf{K}_{up}^{k-1}\delta p^k + \delta u_U^k = \delta u_B^k + \delta u_U^k$
v-velocity	$\delta v^k = \mathbf{K}_{vp}^{k-1}\delta p^k + \delta v_U^k = \delta v_B^k + \delta v_U^k$

Treated as approximately mutually independent without cross correlations

Density	$\delta\rho^k = \mathbf{K}_{\rho T}^{k-1}\delta T^k + \mathbf{K}_{\rho S}^{k-1}\delta S^k$
Pressure	$\delta p^k = \mathbf{K}_{p\rho}\delta\rho^k + \mathbf{K}_{p\eta}\delta\eta^k$

(Weaver et al., 2005, QJRMS)

Components of the balance operator

Salinity balance
(approx. T-S conservation)

$$\delta S_B^k = \gamma^{k-1}\left(\partial S \big/ \partial z\right)_{S=S^{k-1}}\left(\partial z \big/ \partial T\right)_{T=T^{k-1}}\delta T^k$$

SSH balance
(baroclinic)

$$\left(\nabla \cdot H\nabla\right)\delta\eta_B^k = -\nabla \cdot \int_{z=-H}^{0}\int_{z'=z}^{0}\left(\nabla\delta\rho^k(z')/\rho_0\right)dz'dz$$

u-velocity balance
(geostrophy with
β-plane approx. near eq.)

$$\delta u_B^k = -\frac{1}{\rho_0}\left(\frac{W_f}{f}+\frac{W_\beta}{\beta}\frac{1}{a}\frac{\partial}{\partial\varphi}\right)\frac{1}{a}\frac{\partial\delta\tilde{p}^k}{\partial\varphi}$$

v-velocity
(geostrophy, zero at eq.)

$$\delta v_B^k = \frac{1}{\rho_0}\frac{W_f}{f}\frac{1}{a\cos\varphi}\frac{\partial\delta\tilde{p}^k}{\partial\lambda}$$

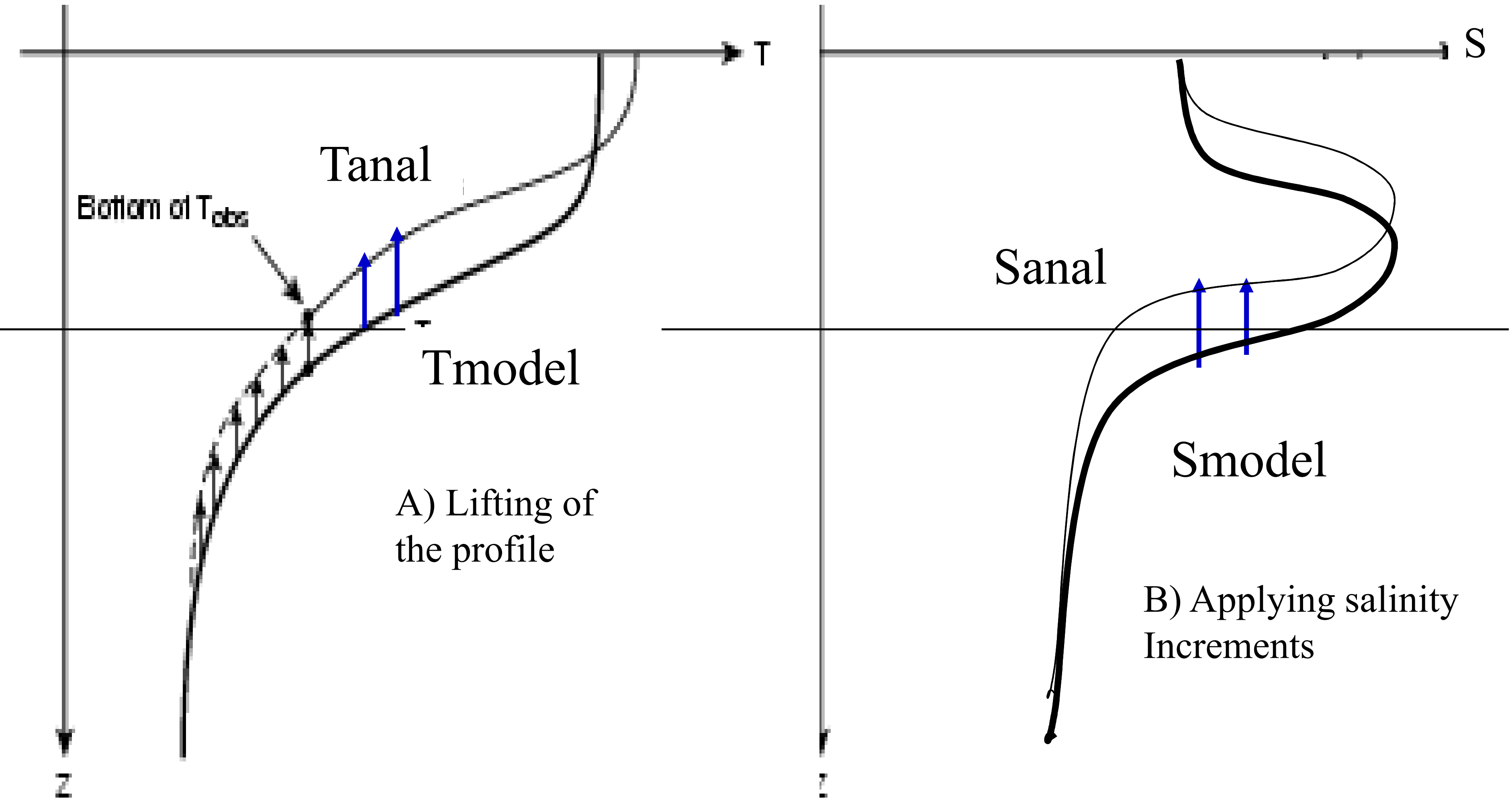
Density
(linearized eq. of state)

$$\delta\rho^k = \rho_0\left(-\alpha^{k-1}\delta T^k + \beta^{k-1}\left(\delta S_B^k + \delta S_U^k\right)\right)$$

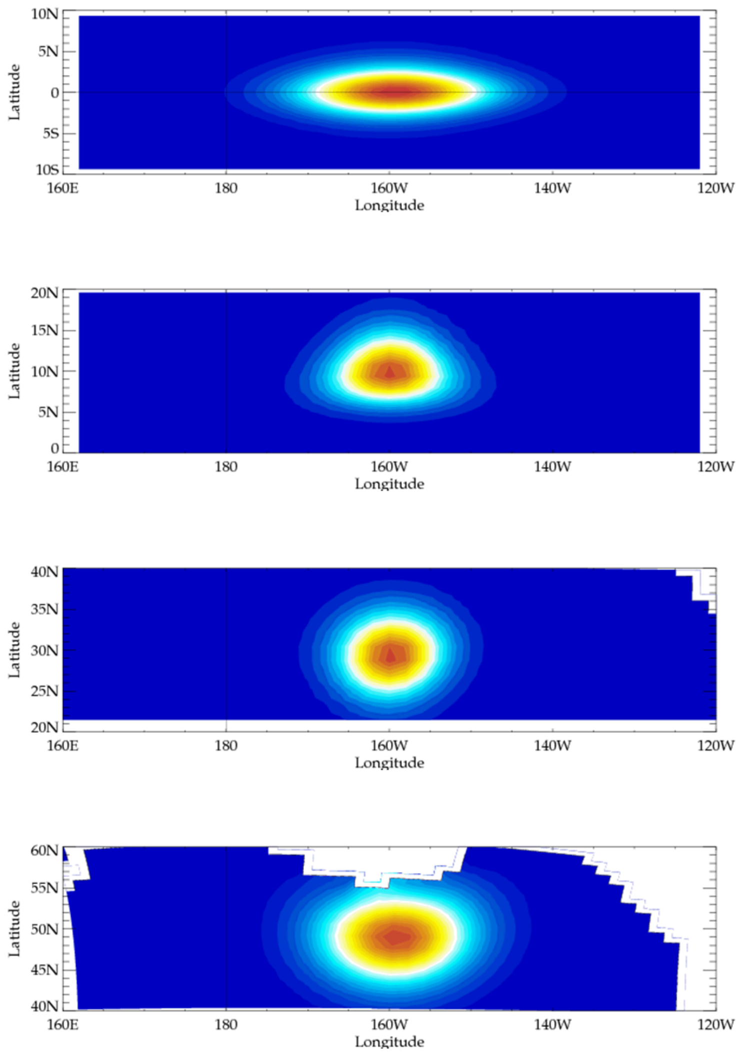
Pressure
(hydrostatic approx.)

$$\delta\tilde{p}^k(z) = \int_{z'=z}^{0}\delta\rho^k(z')\,g\,dz' + \rho_0 g\left(\delta\eta_B^k + \delta\eta_U^k\right)$$

T/S/SSH balance: effective profile vertical displacement

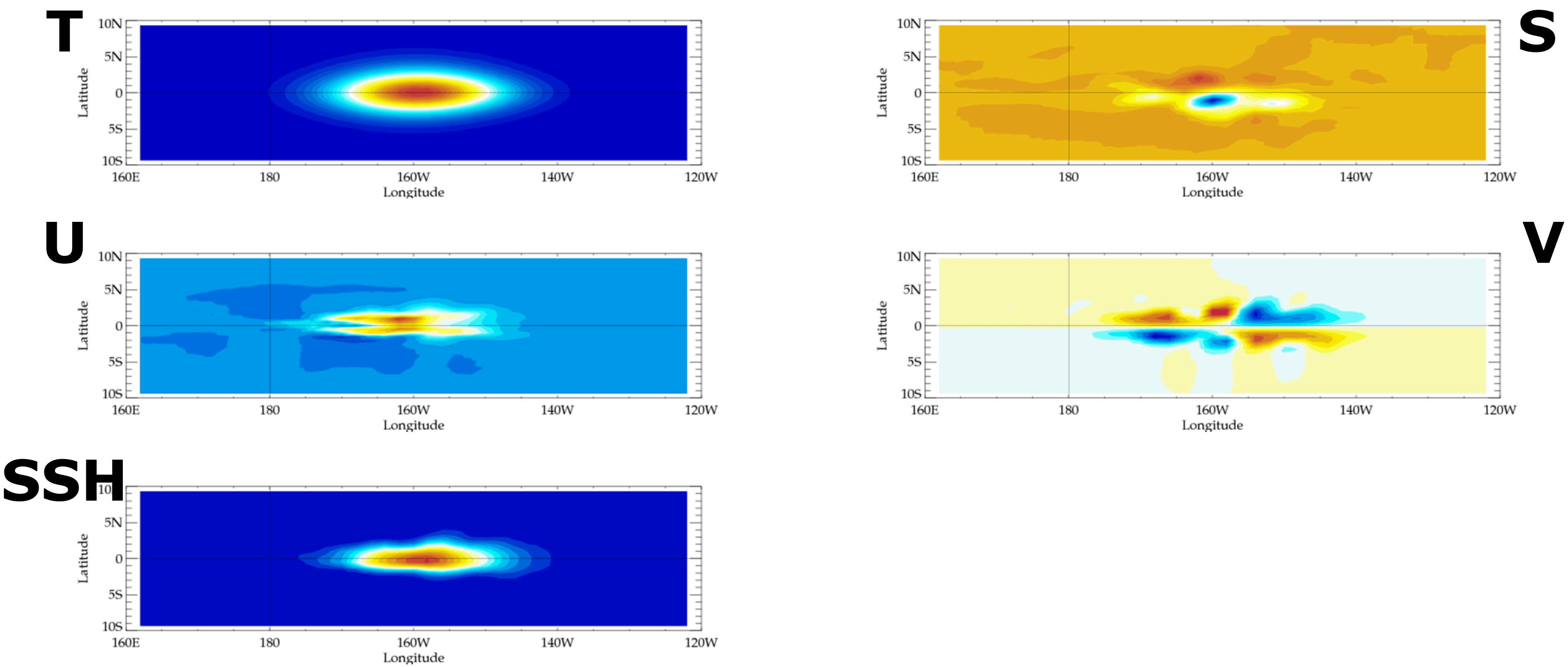


Horizontal correlation of T at 100m



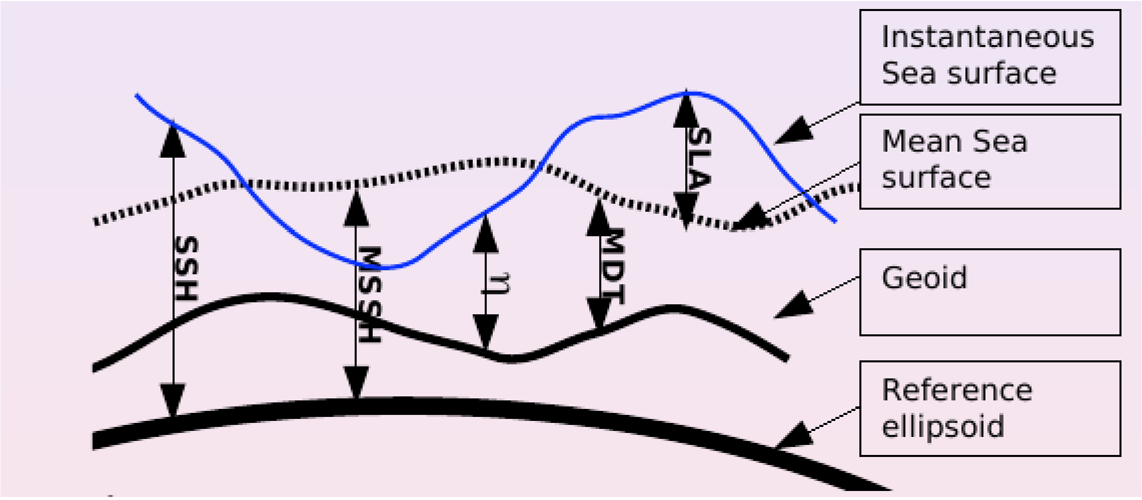
- From single observation of temperature experiment.
- Wider longitudinal length scales at equator.
- At 50 N the coast line comes into play.

Horiz. cross correlation of T at 100m



- From single observation of temperature experiment.
- The specific background determines the shape due to the balance relations.
- S, U, V, SSH increments are from balance with T only.

Assimilation of altimeter data



Altimeter measures SSH (respect reference ellipsoide)
Model represents η (ssh referred to the Geoid)

SSH-Geoid= η

Geoid was poorly known (not any longer, but inertia…) and changes in time (*)

Alternative: Assimilate Sea Level Anomalies (SLA) respect a time mean

Obs: SSH anomalies = SSH-MSSH = Obs SLA

Mod: η anomalies = η – MDT = Mod SLA

Where: MSSH= Mean SSH ; MDT= Mean Dynamic Topography

MSSH – Geoid = MDT

Assimilation of altimeter data

Ingredients: η'_{alt} **Observed SLA (Sea Level Anomaly) from altimeter Respect to 7 year mean of measurements. Provided**

$$\eta'_{\mathrm{mod}} = \eta - \overline{\eta}$$

$\overline{\eta}$ **A Mean Sea Level or MDT respect a similar period**

The choice of MDT for of the reference global mean is not trivial and the system can be quite sensitive to this choice. Active area of research.

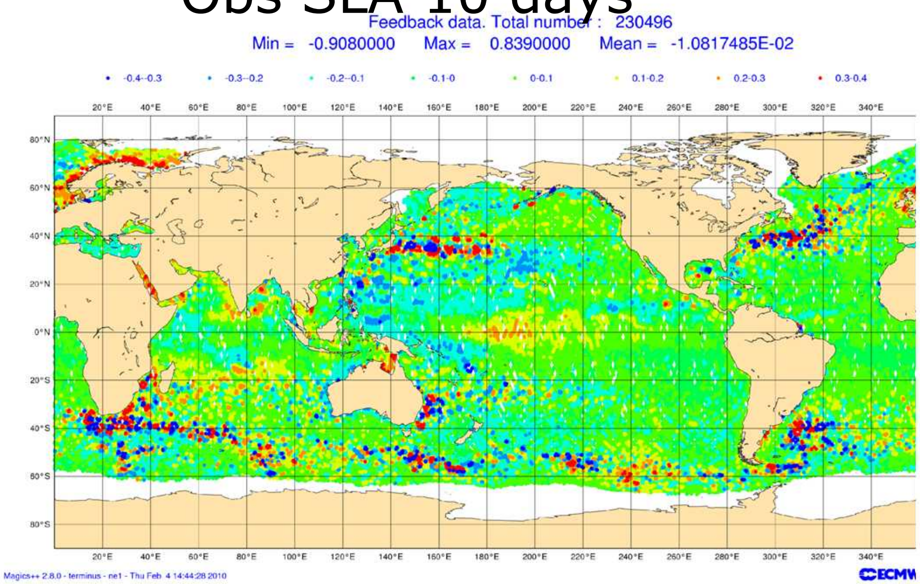
- **The GLOBAL mean sea level (GMSL) needs to be removed prior to Assimilation**
  - Ocean models are volume preserving, and can not represent changes in GLOBAL sea level due to density changes (thermal expansion, ….).
- **GMSL can be assimilated separately:** The difference between

Altimeter GMSL and Model Steric Height is added to the model as a fresh water flux.

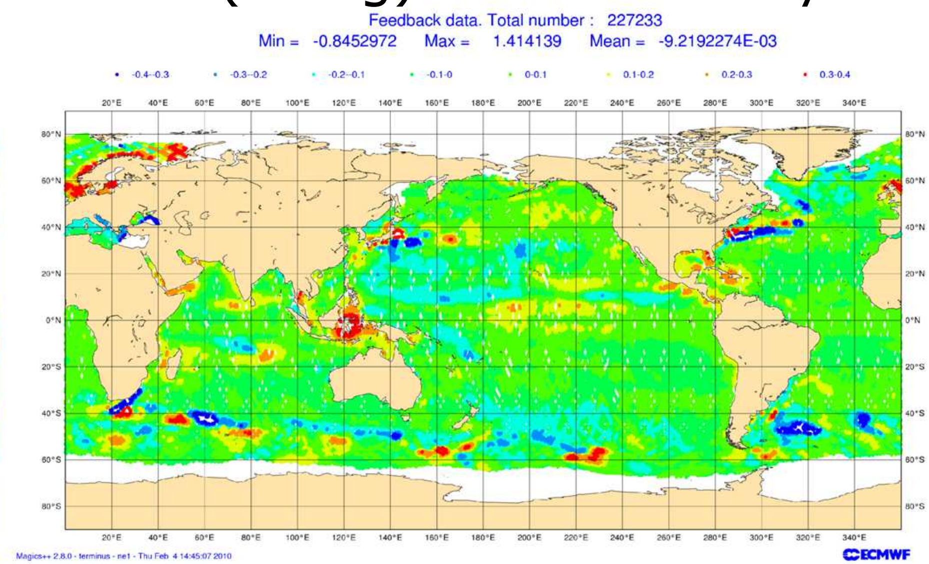
Other SLA issues:

- **The SLA along track data has very high spatial resolution for the 1 degree "class" of ocean assimilation systems.**
  - Features in the data which the model can not represent.
- **This can be dealt with in different ways:**
  - Inflate the observation error to account for non representativeness of the "real" world in the assimilation system.
  - Construction of "superobs" by averaging.
  - Thinning

Obs SLA 10 days



Model (1 deg) SLA in 10 days



Bias Correction Scheme

Why a bias correction scheme?

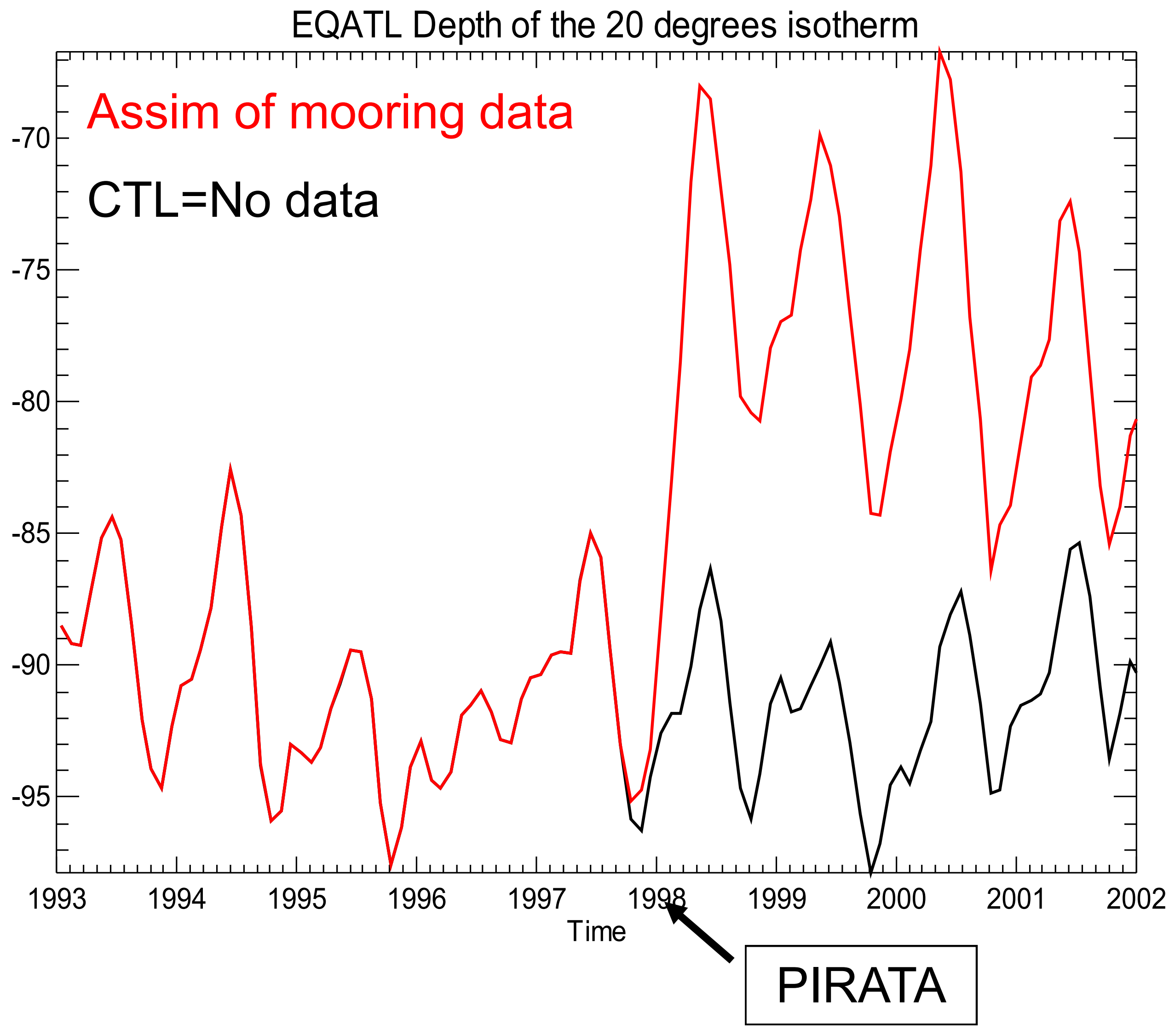
- Models/forcing have systematic error (correlated in time)
- Changes in the observing system can be damaging for the representation of the inter-annual variability.
- Part of the error may be induced by the assimilation process.

What kind of bias correction scheme?

- Multivariate, so it allows to make adiabatic corrections ***(Bell et al 2004)***
- First guess + adaptive component.
- Generalized Dee and Da Silva bias correction scheme

Balmaseda et al 2007

Impact of data assimilation on the mean

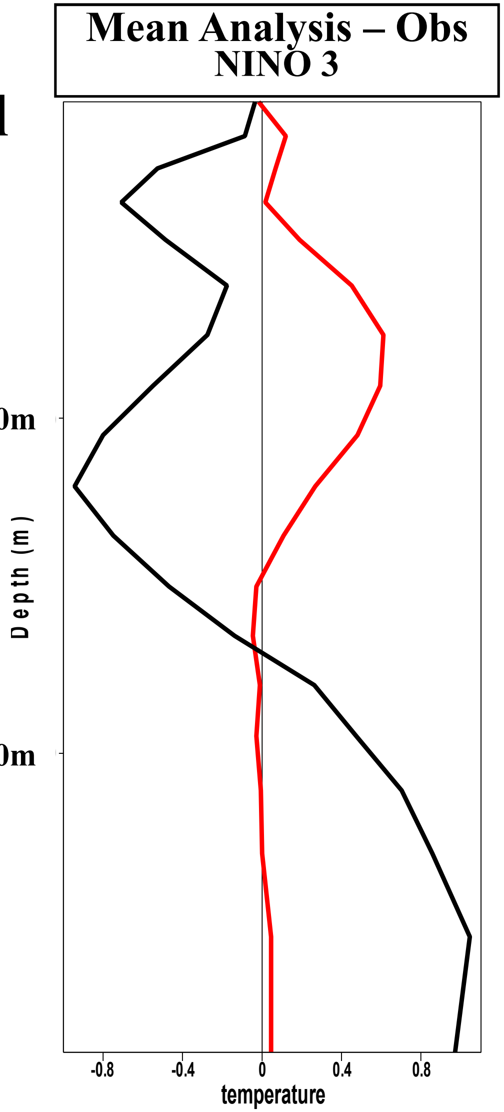


Large impact of data in the mean state: Shallower thermocline

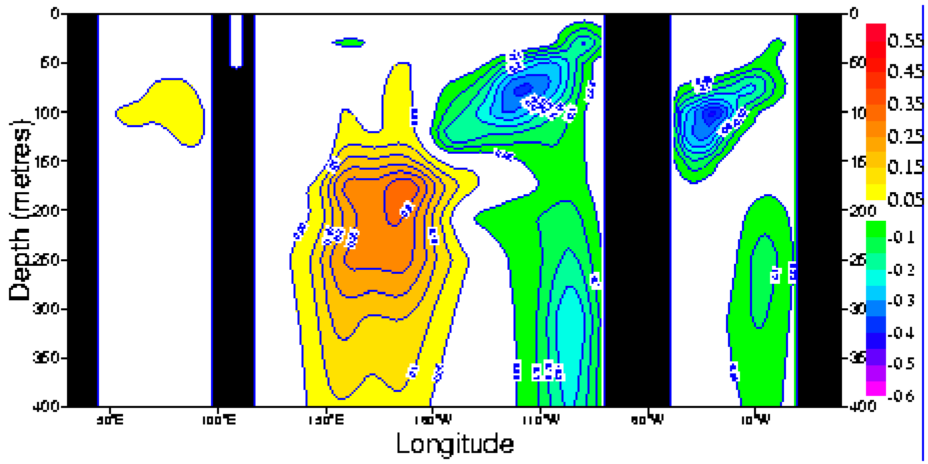
The systematic error may be the result of the assimilation

control

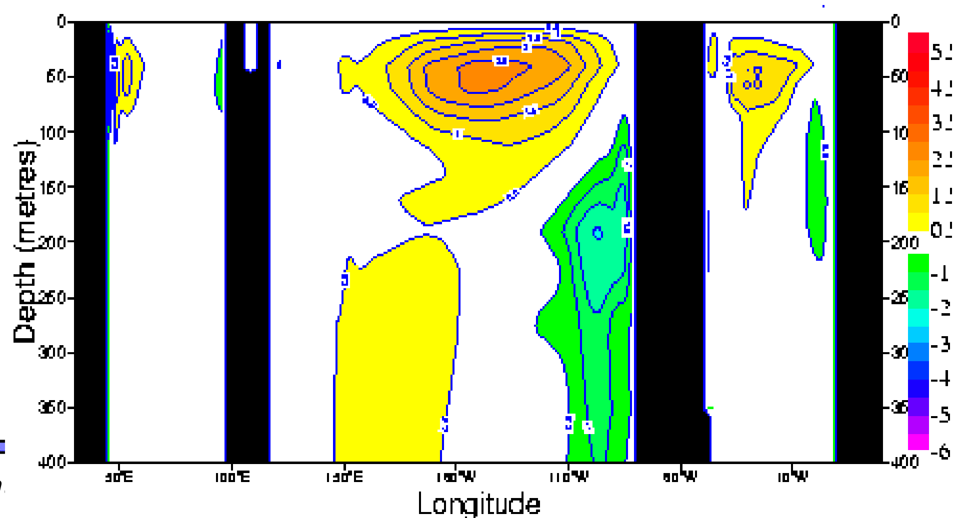
assim



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



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

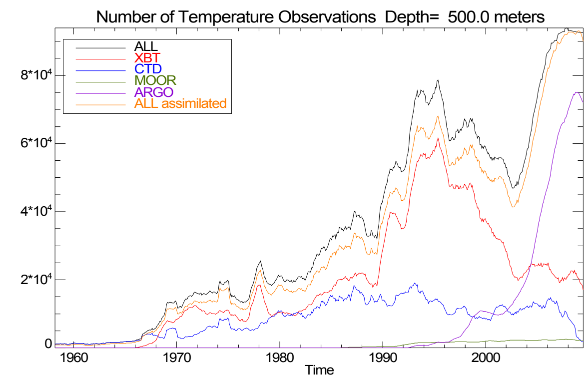


Bias Correction Algorithm

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

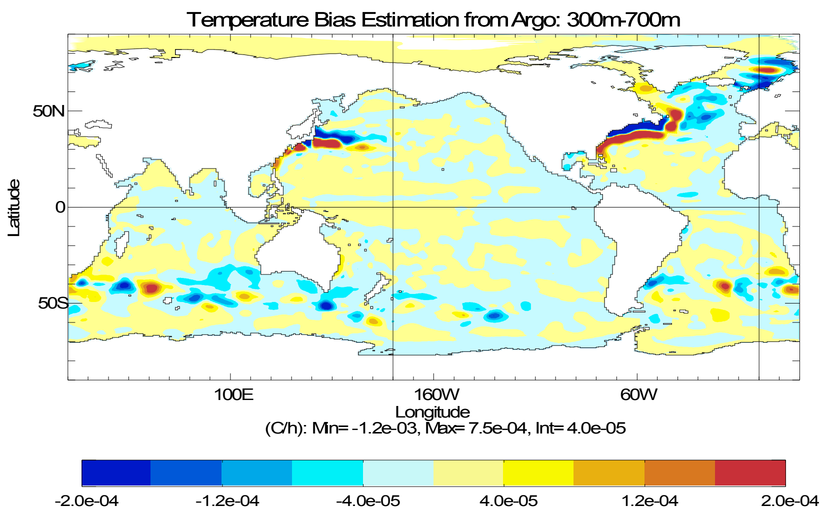
Seasonal term, estimated offline from Argo Period

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



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)

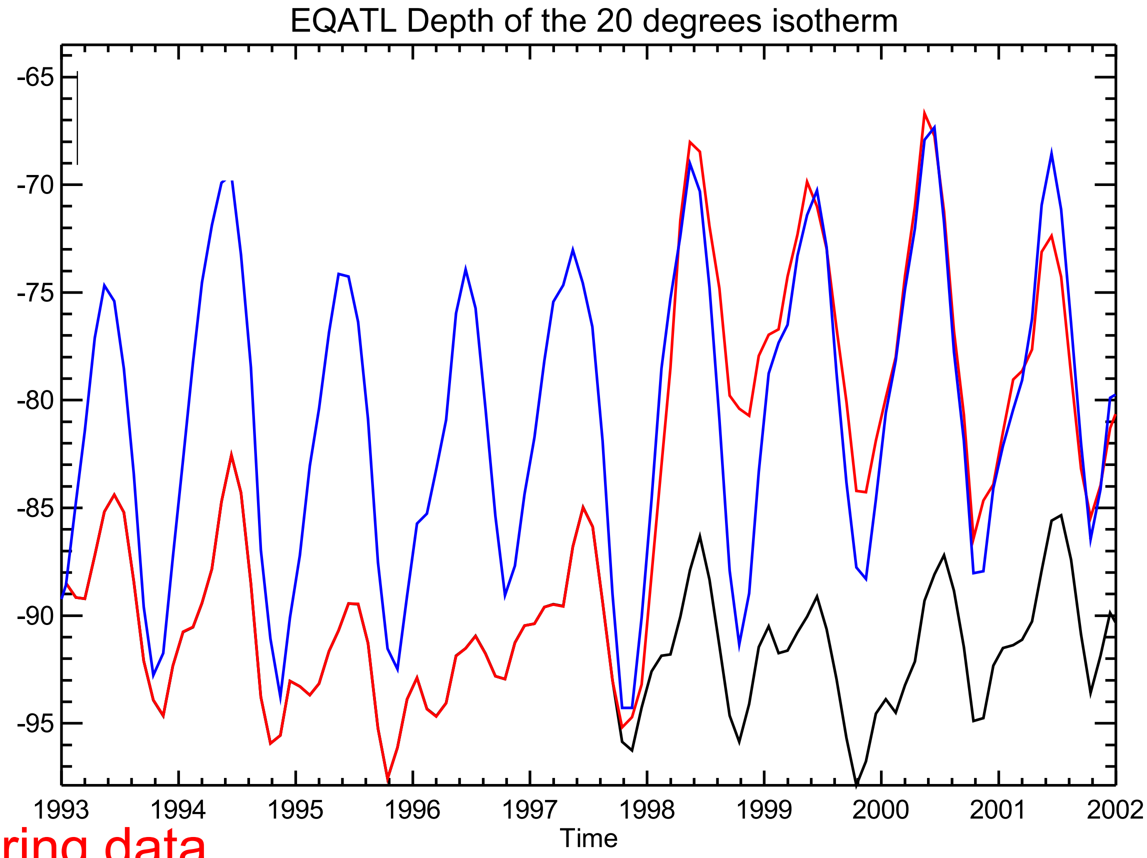
Refinement of Balmaseda et al 2007, Dee 2005, Bell et al 2002

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.

Effect of bias correction on the time-evolution



Assim of mooring data

CTL=No data

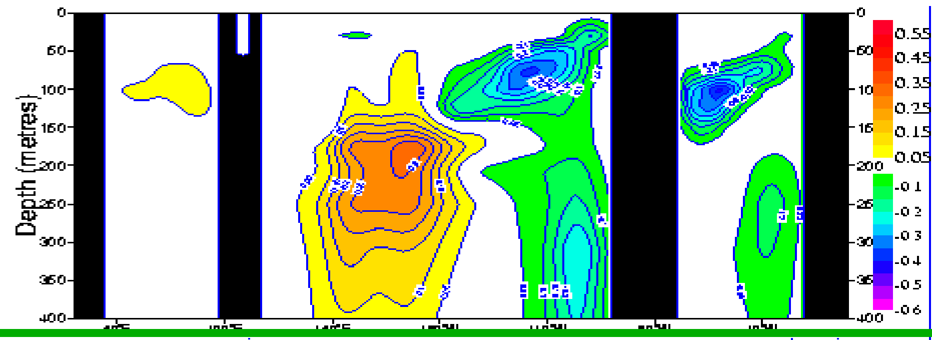
Bias corrected Assim

a)Impact of Balance in Bias

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

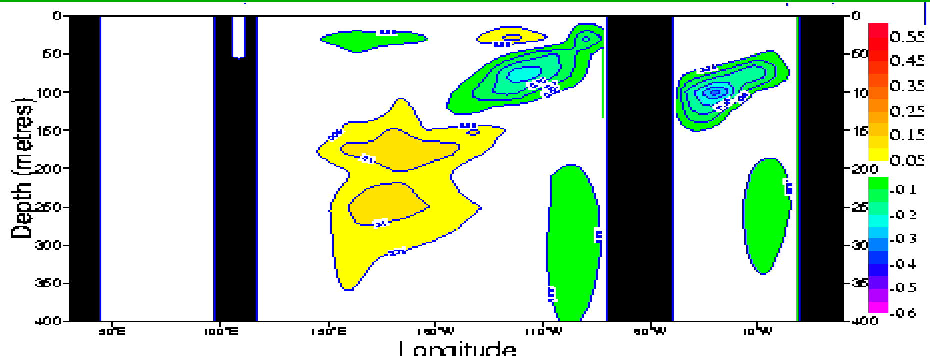
Experiment E0

No bias correction



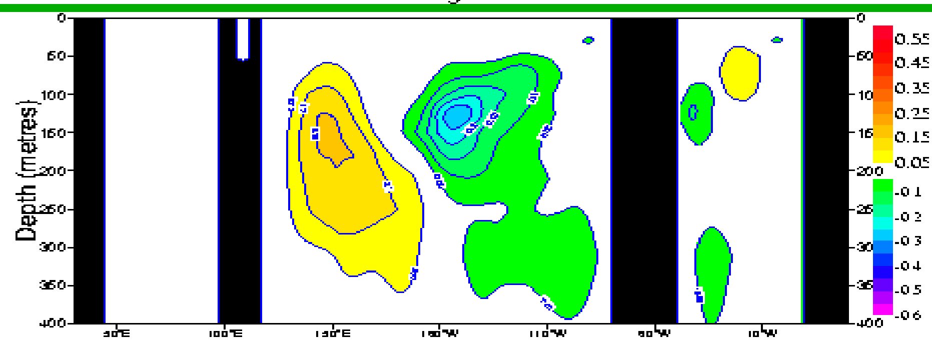
Experiment EP

Correcting bias in pressure gradient



Experiment ET

Correcting bias in Temperature



b)Impact of Balance in Bias

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

Experiment E0

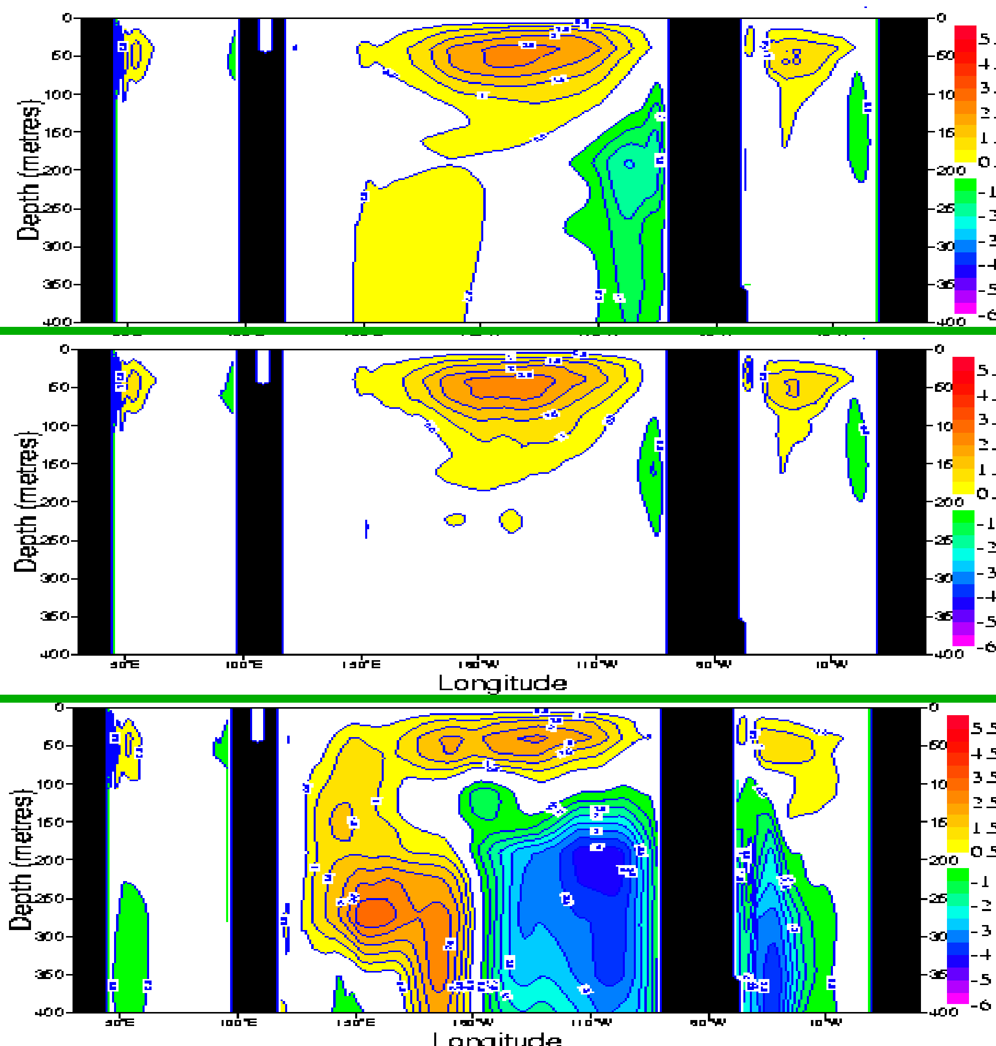
No bias correction

Experiment EP

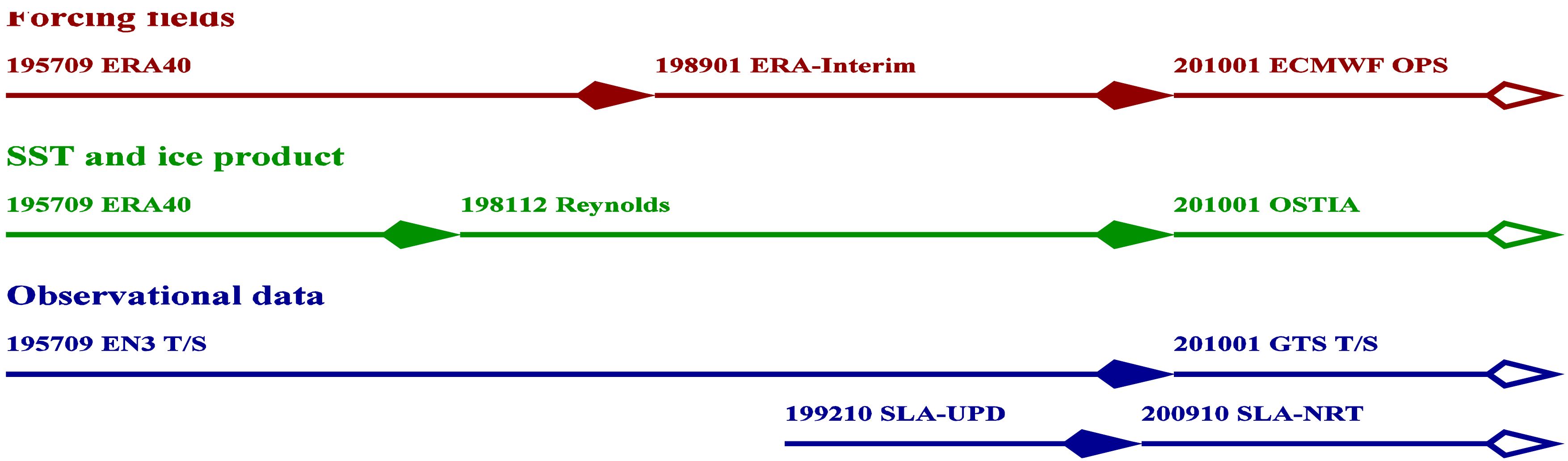
Correcting bias in pressure gradient

Experiment ET

Correcting bias in Temperature



ORAS4: 5 ens members 195709 to present



Main Ingredients

Ocean Model: NEMO. Approx resolution 1x1 deg, 42 levels

Multivariate Data Assimilation: NEMOVAR (3Dvar FGAT)

Data: EN3-XBT corrected. Altimeter, SST as in figure. GTS after 2010

Bias Correction: estimated from Argo period

Forcing: ERA40/ERA-INTERIM/OPS

Ensemble Generation: wind perturbations, observation coverage, deep ocean

Assimilation cycle: 10 days, IAU

Initialization of coupled forecasts

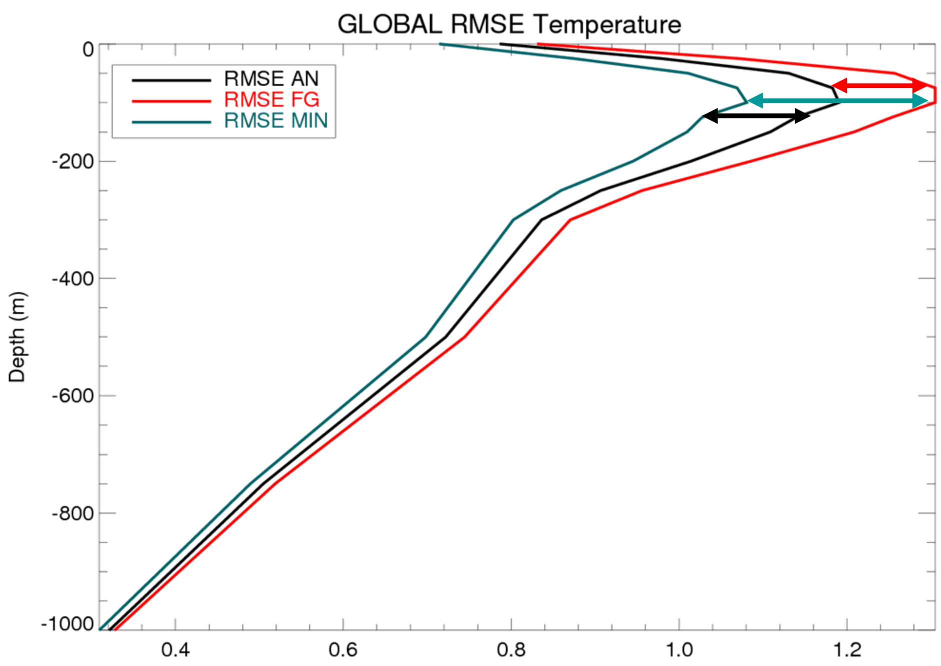
Historical reanalysis brought up-to-date

Assessment of ORAS4

- **Reference CNTL experiment:** Equivalent Ocean Model Simulation with SST/FreshWater corrections. No NEMOVAR nor bias. 5 ens
- **Fit to assimilated data**
- **Comparison with independent data**
  - ADCP Current meters from moorings. Sea Level Gauges. GRACE Bottom Pressure. WOCE transports.
  - RAPID AMOC.
- **Comparison with other estimates**
  - SL altimeter, OSCAR currents, Heat Content
- **Impact on Seasonal Forecasts**
- **Sensitivity Experiments and Observing System Experiments**

Balmaseda et al QJ, 2013

Fit to obs: FG MIN and AN (IAU)

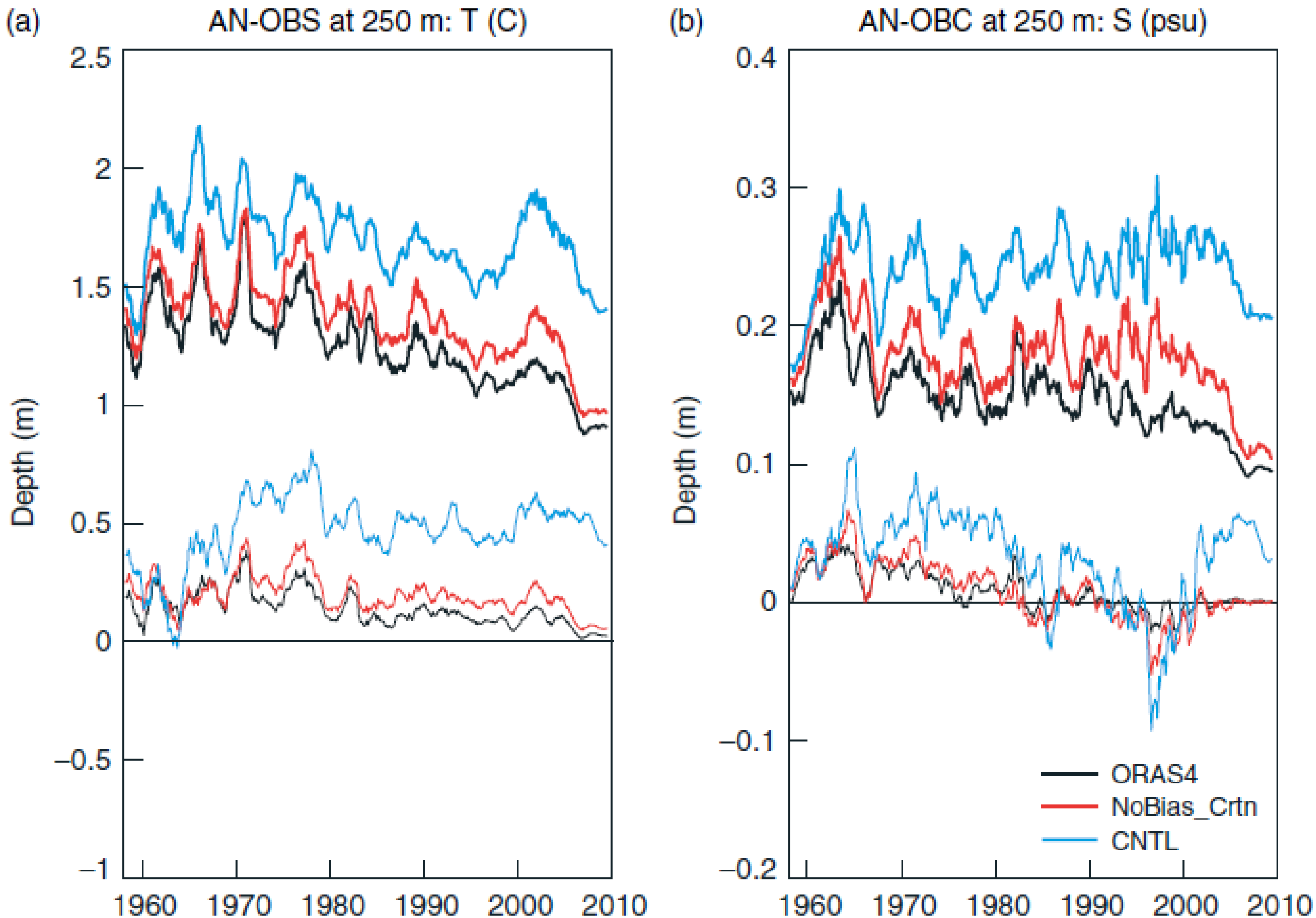


Reduction of Error by direct initialization: Assim Incr

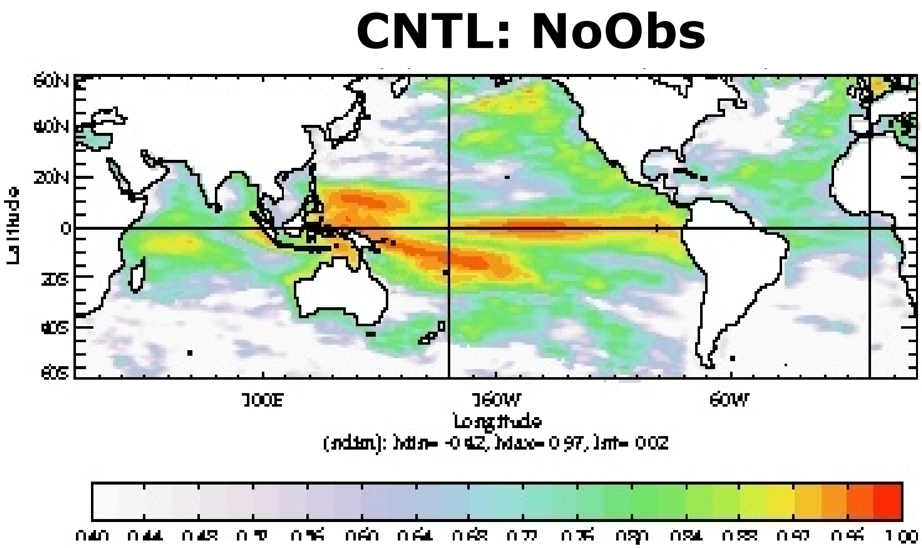
IAU approximation

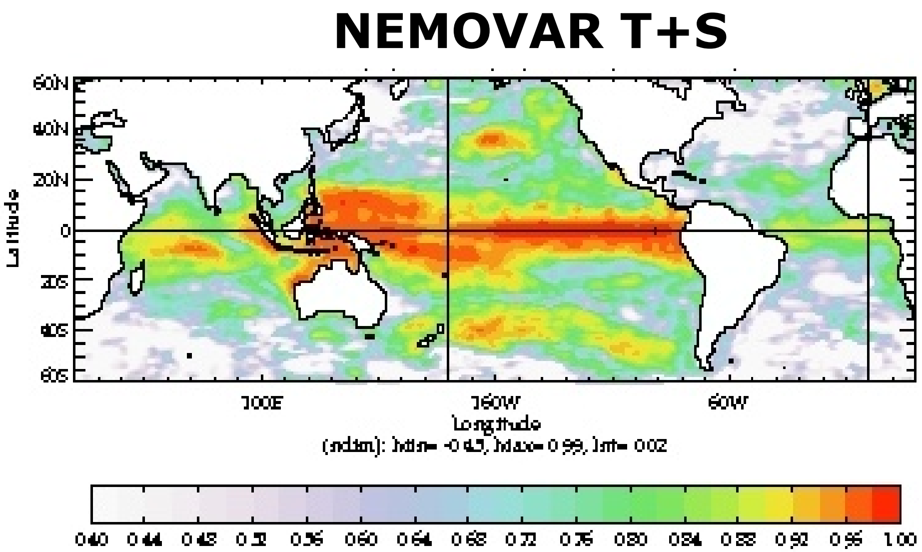
Effective error reduction (or error growth)

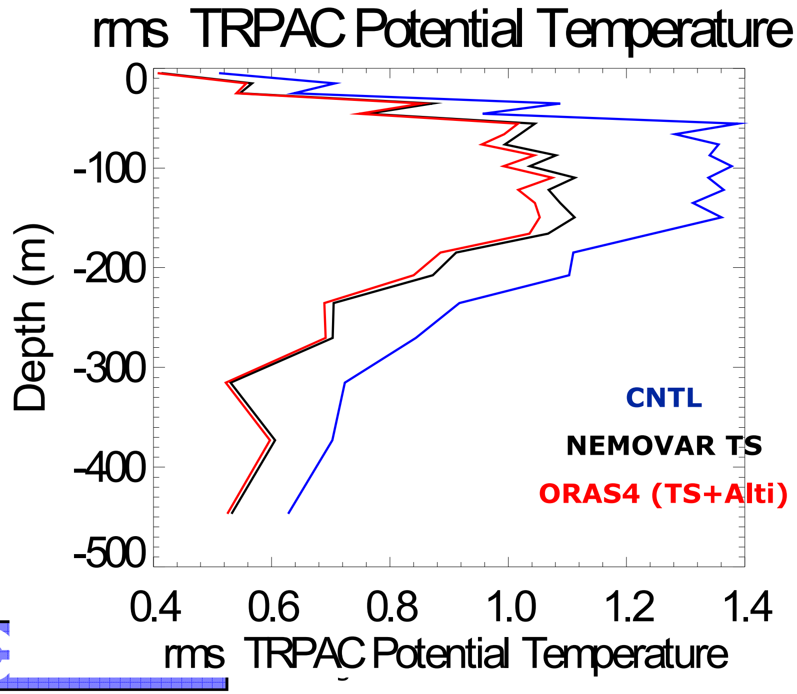
Fit to Observations

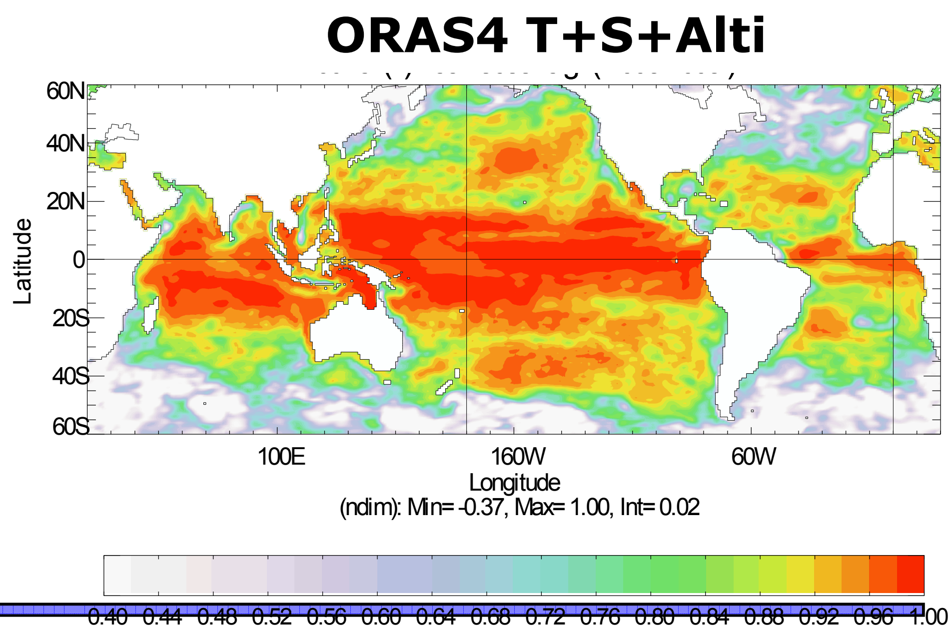


Time correlation with altimeter SL product

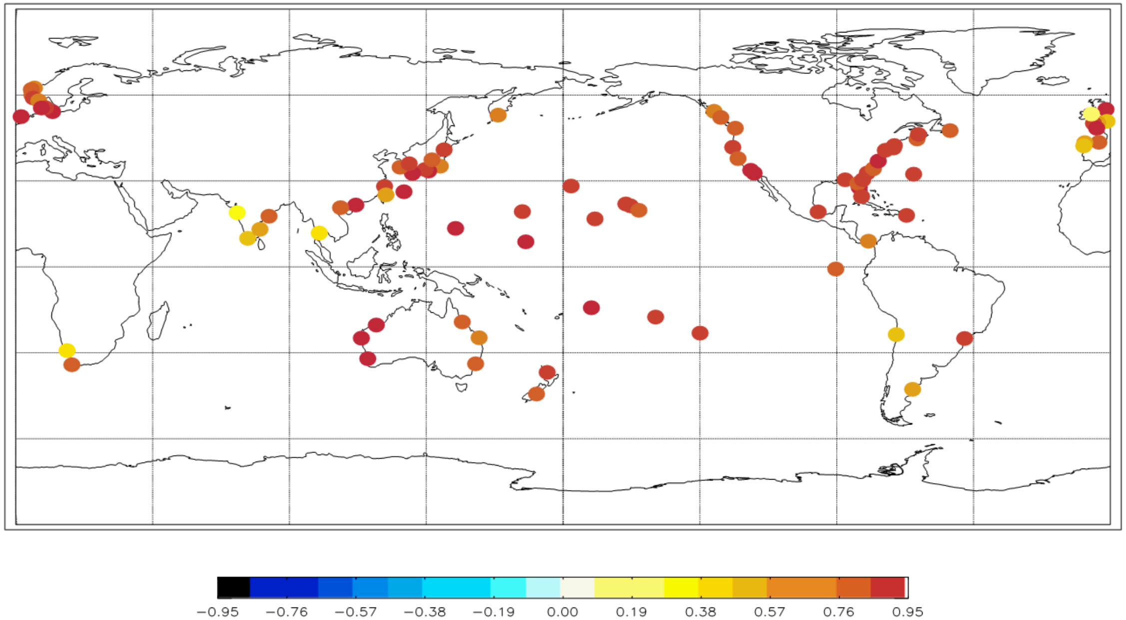








ORAS4 (mean 0.72). 1960-2009

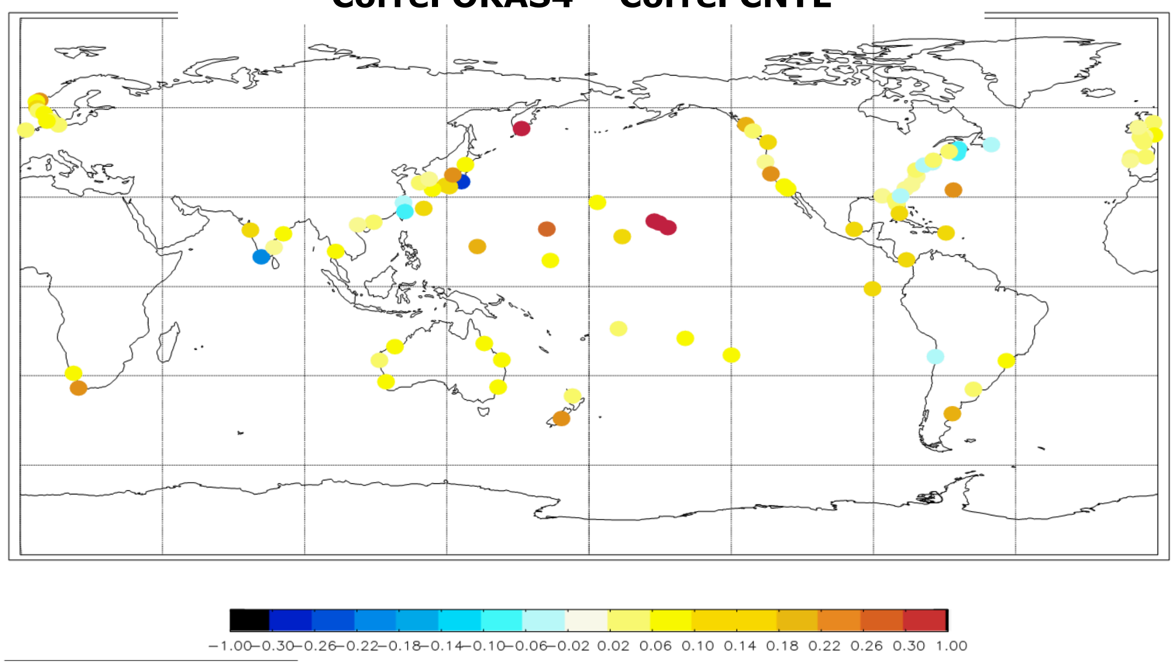


Time Correlation

Sea Level from Tide Gauges.

Independent data

Correl ORAS4 – Correl CNTL

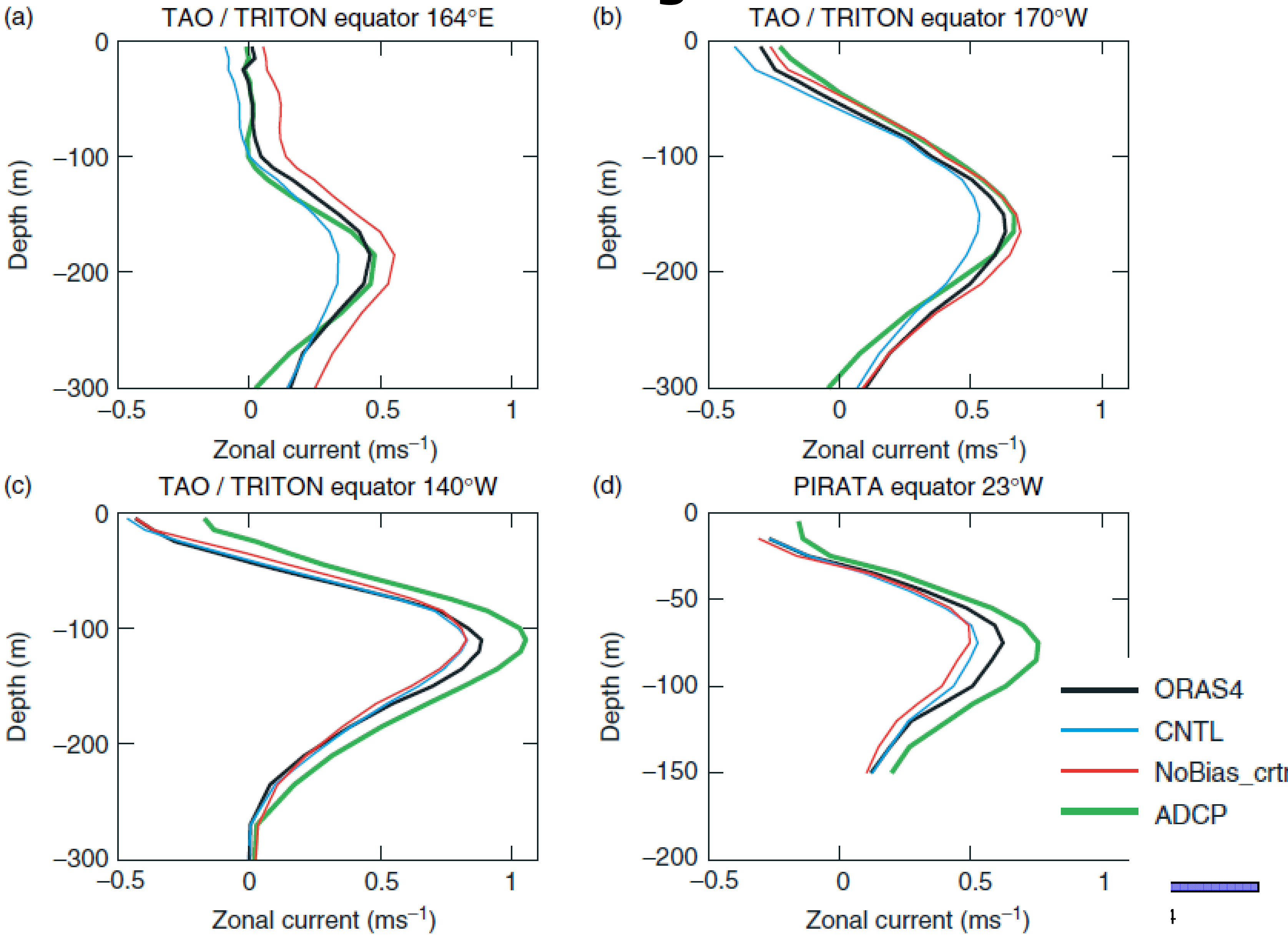


Overall improvement, problems at some locations

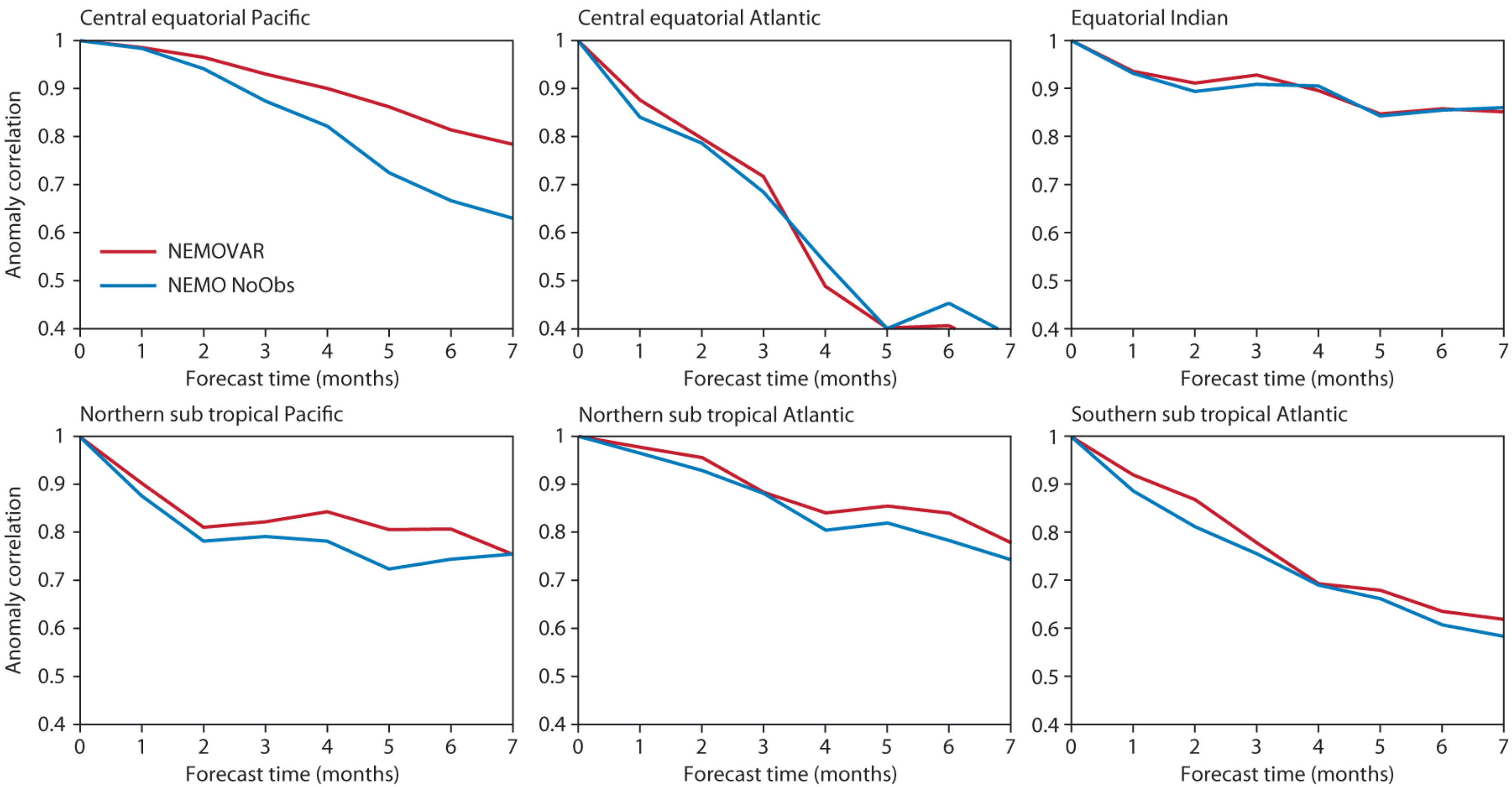
(usually in rich data areas, possibly related to the treatment of coastal observations)

Data courtesy of Anny Cazenave's group

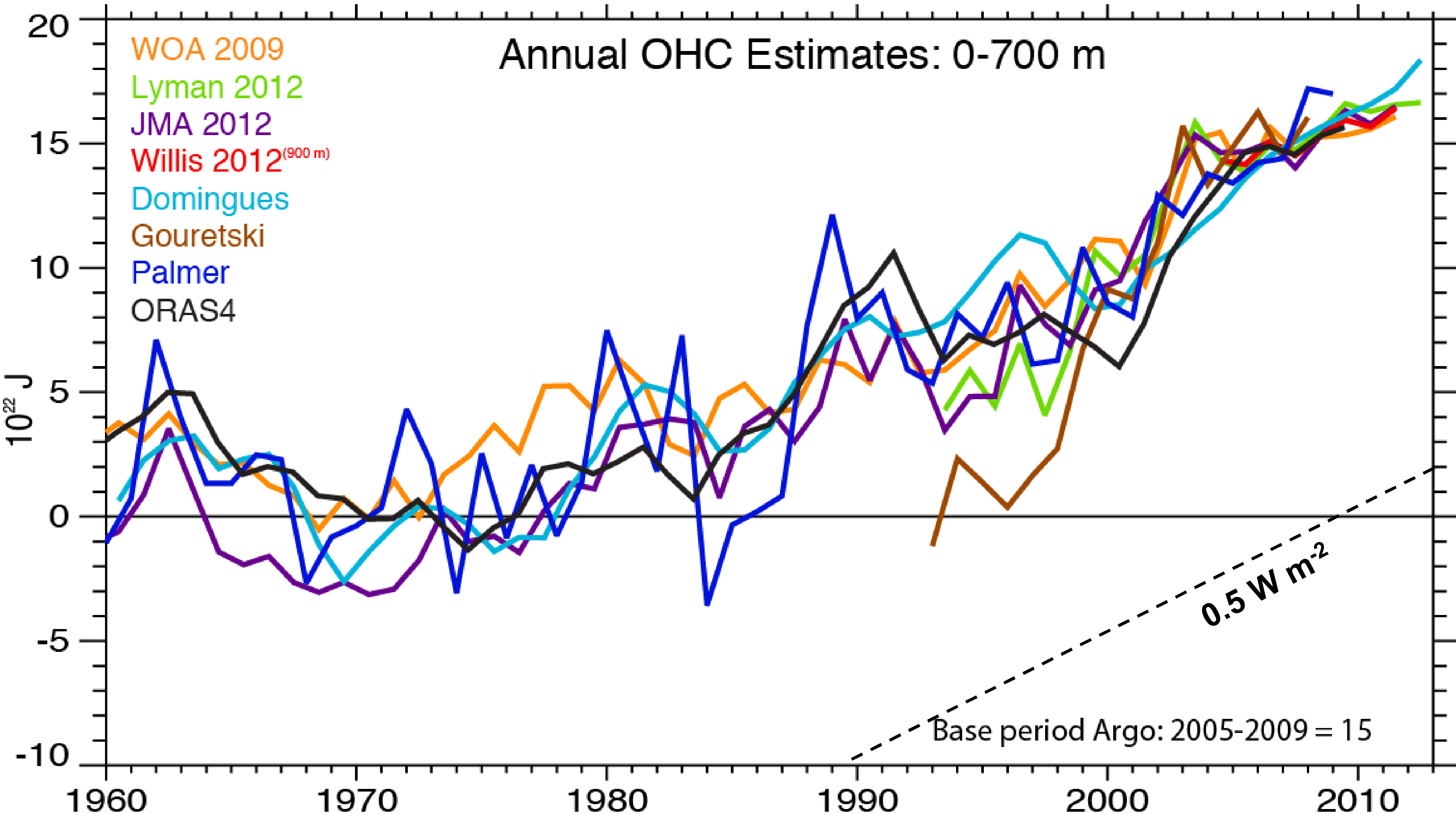
Comparison with ADCP currents from Moorings



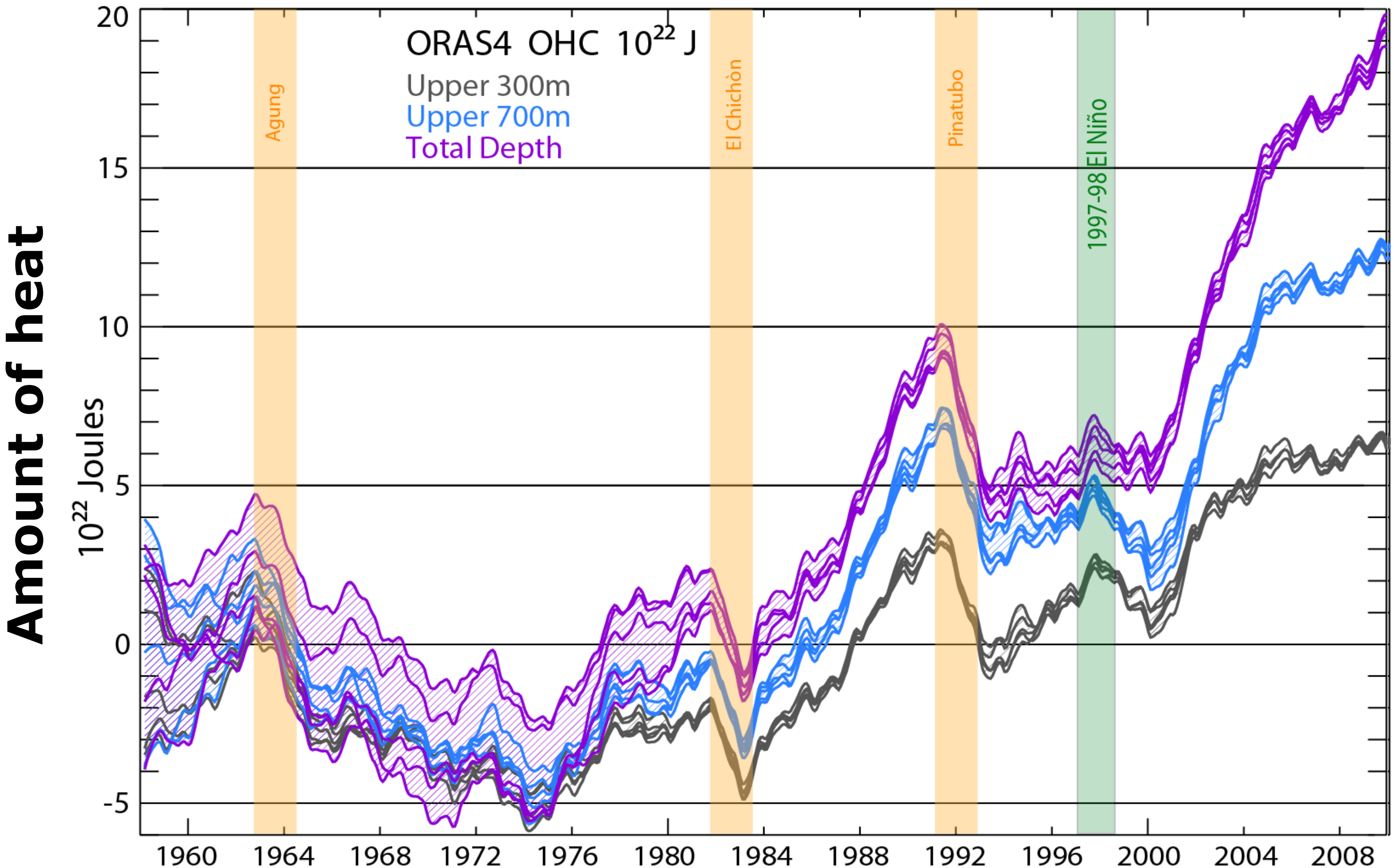
Impact on ECMWF-S4 SST Seasonal Forecast Skill



Ocean Re-analysis heat content: comparison with obs-only estimates



Global Ocean Heat Content



Balmaseda, Trenberth and Källén 2013

Room for improvements

- **Choice of control variable**
  - Separate assimilation of T and S can be problematic.
  - Use density instead?

- **Difficult to parameterize covariance structure. Flow dependence**
  - Coordinate transformation (isopycnal diffusion)
  - Hybrid methods (ens + var)

- **Different spatial/time scales**
  Include bias as control vector (weak constrain)

- **What if error is in the forcing fields?**
  - Coupled data assimilation?

Motivations for coupled data assimilation

- Basically:
  - Ocean models need improved surface fluxes
  - Atmospheric models need improved sea surface temperature, sea-ice

- Coupled data assimilation should:
  - improve the use of near-surface observation data
  - improve the ocean/atmosphere balance
  - improve the prediction of extreme air-sea flux events
  - reduce coupling shocks in coupled forecasts

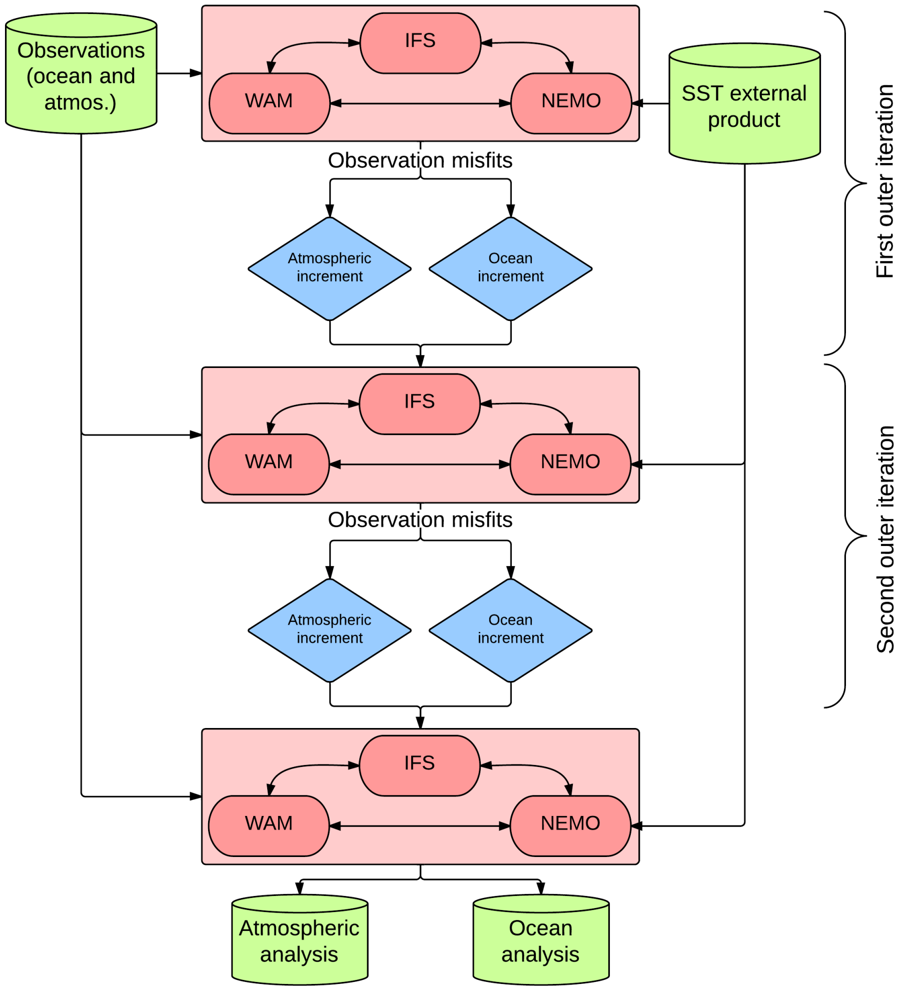
Coupled assimilation schemes

- Fully coupled assimilation
  - ➢ coupled model for the nonlinear trajectories
    - o balanced fields
  - ➢ one analysis calculated by one minimization process
    - o balanced analysis
    - o coupled adjoint for a 4D-VAR approach
    - o modelisation of covariances between atmosphere and ocean

- Weakly coupled assimilation
  - ➢ coupled model for the nonlinear trajectories
    - o balanced fields
  - ➢ two analysis computed in parallel by two minimization processes
    - o avoid the development of new adjoint codes
    - o covariances between atmosphere and ocean are not required
    - o **possible information exchange during the minimizations**
    - o Balance between ocean-atmos analyses is not guaranteed

The CERA system

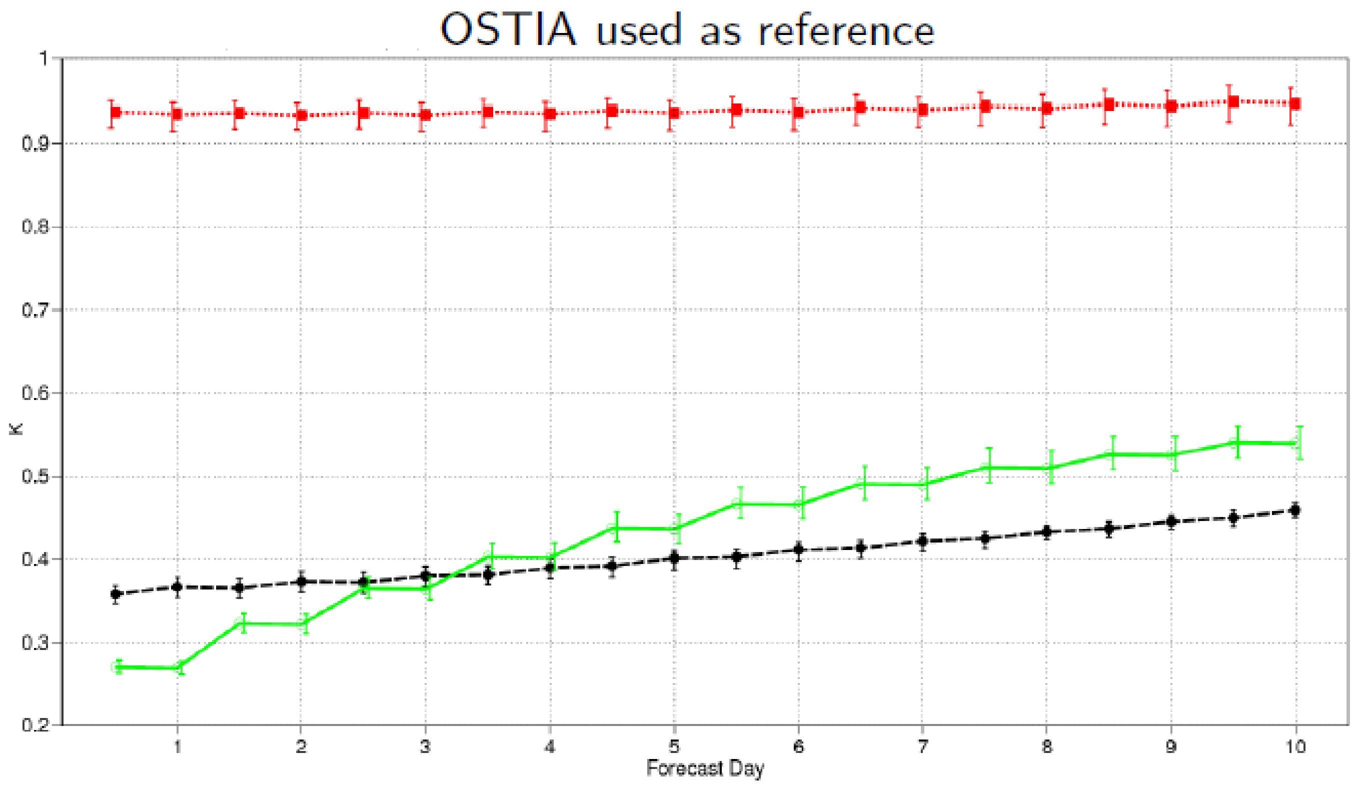
- Weakly coupled data assimilation system initially intended for the reanalysis.
- The atmosphere (IFS) runs coupled to the ocean (NEMO) in the "outer" loops (trajX).
- The minimization of the cost function is done separately for the ocean and the atmosphere.



Laloyaux et al QJMS, submitted

Slower Error growth in tropics

RMSE of the SST forecast in the Tropics for September 2010



Climatology

Operational-like IFS system

CERA

Courtesy of Patrick Laloyaux

Summary

- **Data assimilation in the ocean serves a variety of purposes**, from climate monitoring to initialization of coupled model forecasts and ocean mesoscale prediction.
- This lecture dealt mainly with ocean DA for initialization of coupled forecasts and reanalyses. Global Climate resolution. NEMOVAR as an example.
- Compared to the atmosphere, **ocean observations are scarce**. The main source of information are temperature and salinity profiles (ARGO/moorings/XBTs), sea level from altimeter, SST from satellite/ships and geoid from gravity missions.
- Assimilation of ocean observations reduces the large uncertainty(error) due to the forcing fluxes. It also improves the initialization of seasonal forecasts and decadal forecasts and it can provide useful reconstructions of the ocean climate.
- **Data assimilation changes the ocean mean state**. Therefore, consistent ocean reanalysis requires an explicit treatment of the bias. More generally, we need a methodology that allows the assimilation of different time scales.
- The separate initialization of the ocean and atmosphere systems can lead to initialization shock during the forecasts. A **more balance "coupled" initialization** is desirable, but it remains challenging.

Some references related to ocean data assimilation at ECMWF

- Evaluation of the ECMWF ocean reanalysis system ORAS4, Balmaseda, M. A., Mogensen, K. and Weaver, A. T. (2012),. Q.J.R. Meteorol. Soc.. doi: 10.1002/qj.2063
- The NEMOVAR ocean data assimilation system as implemented in the ECMWF ocean analysis for System 4, Mogensen et al 2012. ECMWF Tech-Memo 668.
- The ECMWF System 3 ocean analysis system, Balmaseda et al 2008. MWR. See also ECMWF Tech-Memo 508.
- Three and four dimensional variational assimilation with a general circulation model of the tropical Pacific. Weaver, Vialard, Anderson and Delecluse. ECMWF Tech Memo 365 March 2002. See also Monthly Weather Review 2003, 131, 1360-1378 and MWR 2003, 131, 1378-1395.
- NEMOVAR: A variational data assimilation system for the NEMO ocean model. Mogensen et al. ECMWF newsletter No. 120 Summer 2009.
- Balanced ocean data assimilation near the equator. Burgers et al. J Phys Ocean, 32, 2509-2519.
- Salinity adjustments in the presence of temperature adjustments. Troccoli et al., MWR..
- Comparison of the ECMWF seasonal forecast Systems 1 and 2. Anderson et al ECMWF Tech Memo 404.

Some references related to ocean data assimilation at ECMWF 2

- Sensitivity of dynamical seasonal forecasts to ocean initial conditions. Alves, Balmaseda, Anderson and Stockdale. Tech Memo 369. Quarterly Journal Roy Met Soc. 2004. February 2004
- A Multivariate Treatment of Bias for Sequential Data Assimilation: Application to the Tropical Oceans. Q. J. R. Meteorol. Soc., 2007. Balmaseda et al.
- A multivariate balance operator for variational ocean data assimilation. Q.J.R.M.S, 2006, Weaver et al.
- Salinity assimilation using S(T) relationships. K Haines et al Tech Memo 458. MWR, 2006.
- Impact of Ocean Observing Systems on the ocean analysis and seasonal forecasts, MWR. 2007, Vidard et al.
- Impact of ARGO data in global analyses of the ocean, GRL,2007. Balmaseda et al.
- Historical reconstruction of the Atlantic Meridional Overturning Circulation from the ECMWF ocean reanalysis. GRL 2007. Balmaseda et al.