Ocean Data Assimilation for Seasonal Forecasting

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Outline

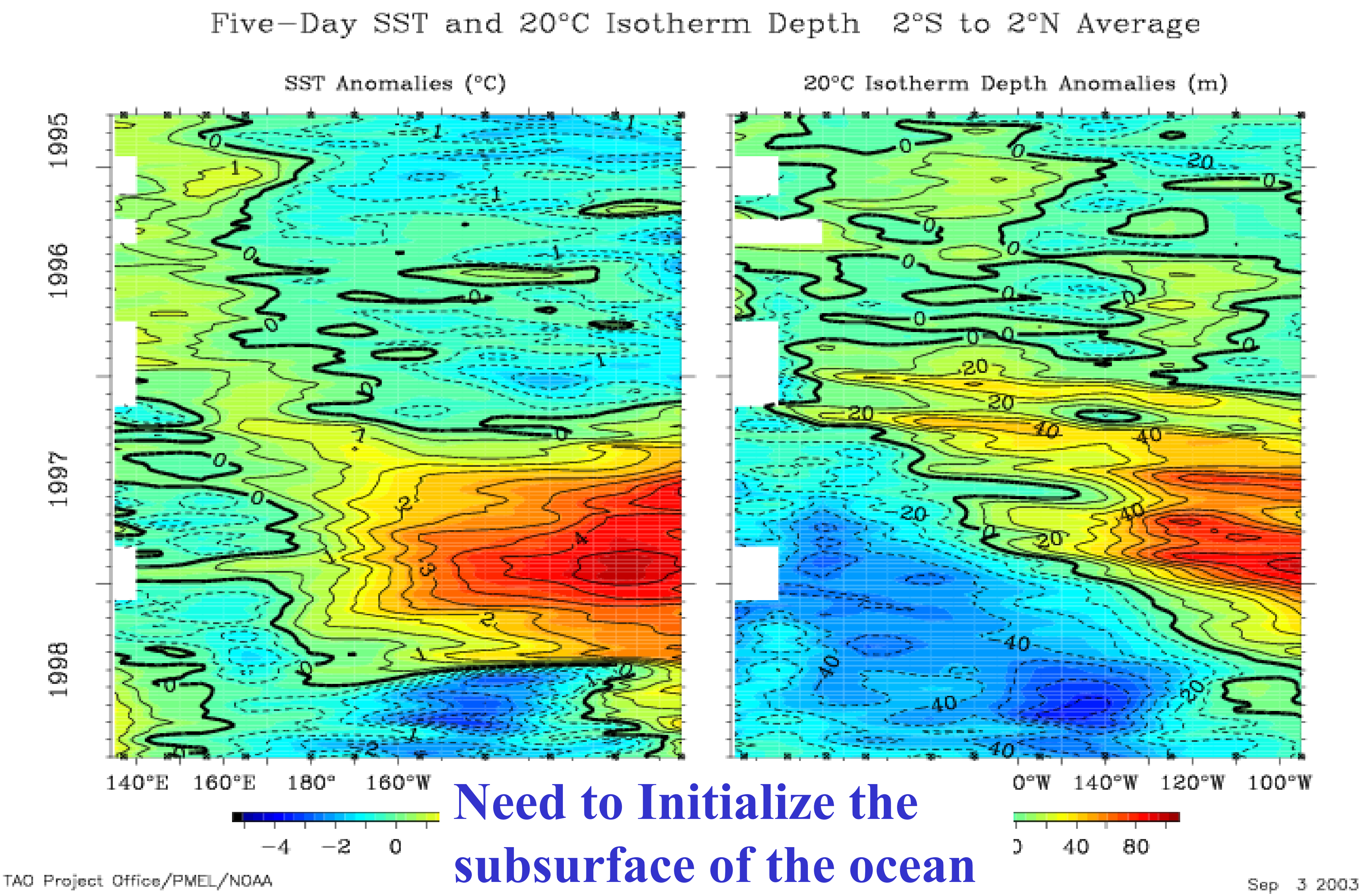
- Why Ocean Data Assimilation?
- The Operational Ocean Analysis System
  - Main ingredients
  - Systematic error
  - Impact of data assimilation
- What next?
  - Future plans for seasonal forecasts
  - The challenge of decadal variability (ENACT)
  - Ocean analysis for shorter range forecasts (?)
- Summary

The Basis for Seasonal Forecasts

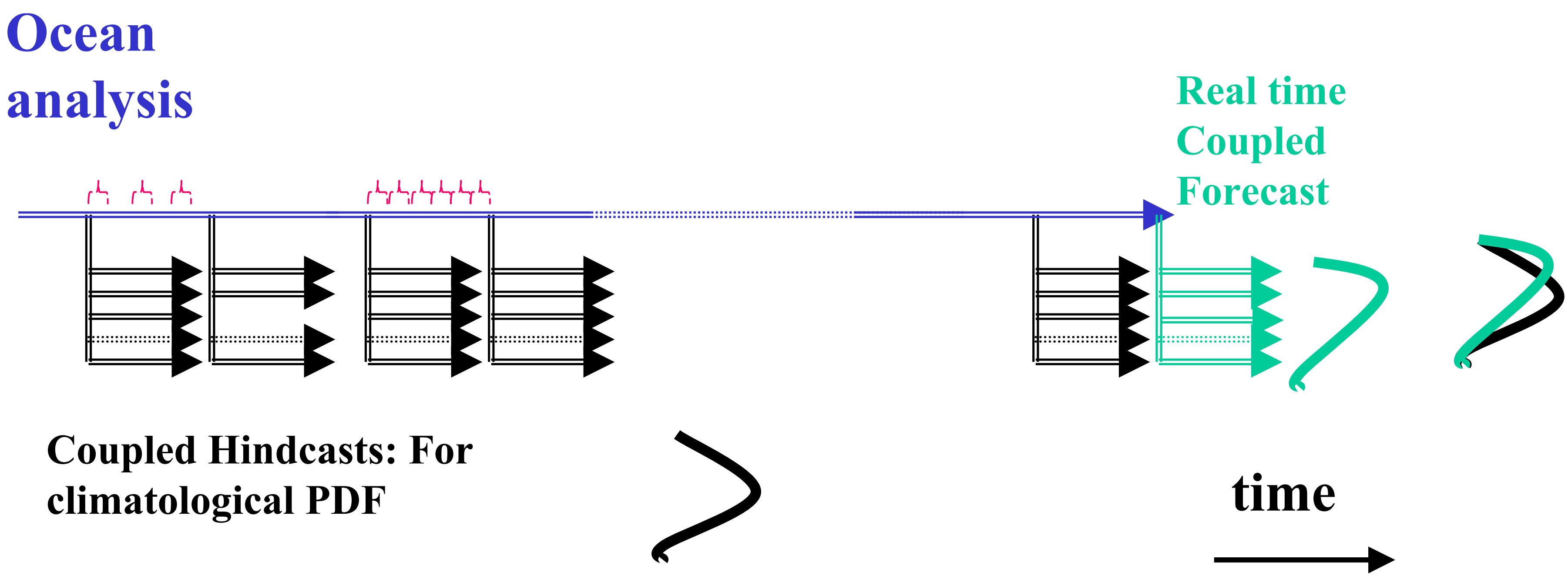
- *Atmospheric point of view: Boundary condition problem*
  - Forcing by lower boundary conditions changes the PDF of the atmospheric attractor

"Loaded dice"

  - The lower boundary conditions (SST, land) have longer memory
    - Higher heat capacity (Thermodynamic argument)
    - Predictable dynamics
- *Oceanic point of view: Initial value problem*
  - *Prediction of tropical SST*



Need to Initialize the subsurface of the ocean



The seasonal forecasts need the model climatological PDF

=>Need for several years of ocean (re-)analysis

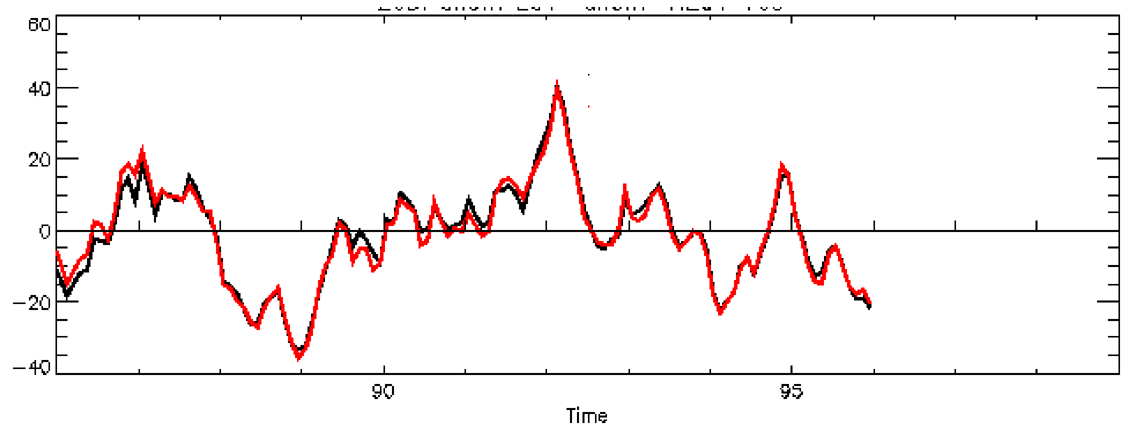
Creation of Ocean Initial conditions:

- A) Ocean model driven by surface fluxes :
  - Momentum,
  - Heat (short and long wave)
  - PME
- B) Daily Atmospheric Fluxes
- C) Real time: from the NWP
- D) Calibration Period: Reanalysis products.

Oceanic Initial conditions

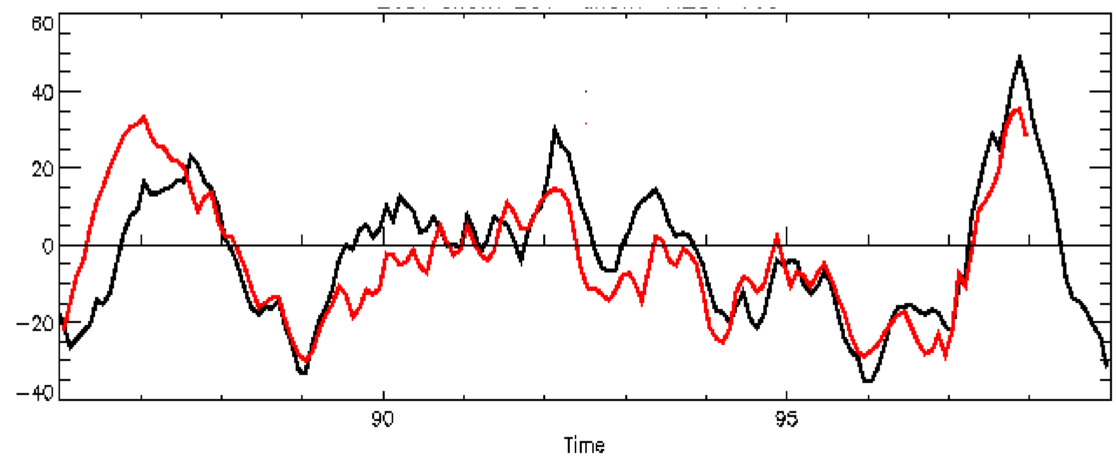
- A) The state of the upp
  ocean is largely
  determined by the win
  forcing

D20 anomaly (with data assimilation)



- B) Large uncertainty in wind products.

D20 (thermocline depth) anomaly (EasternPacific)

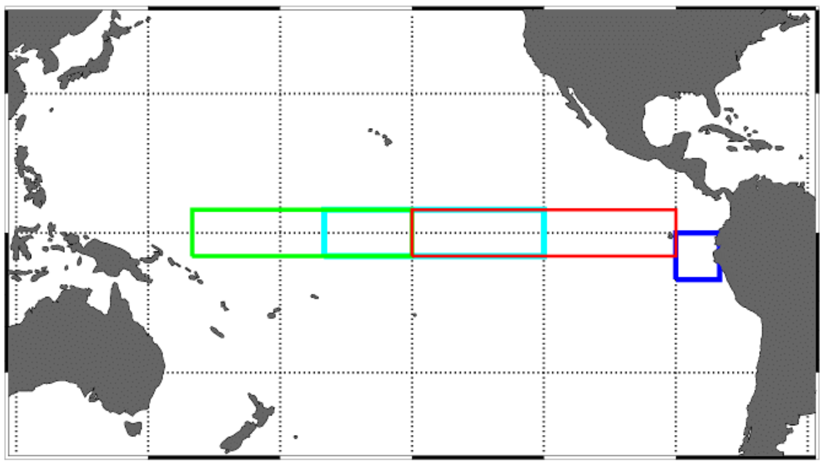


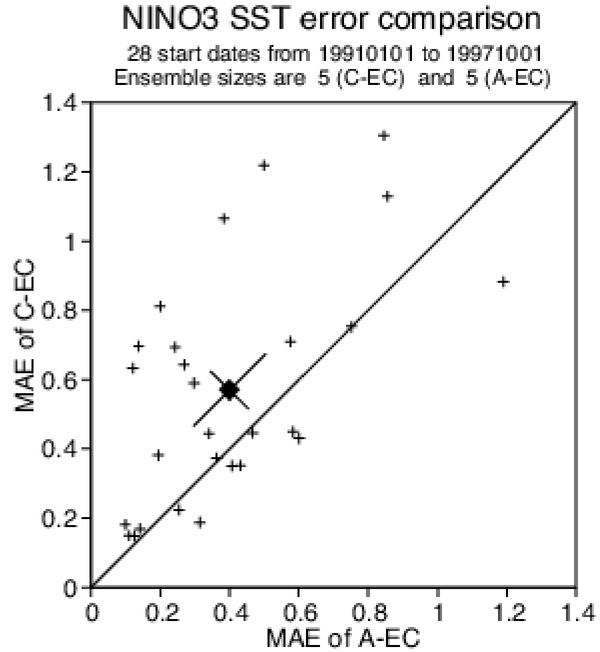
- D) Need Data assimilation to constrain the ocean state.

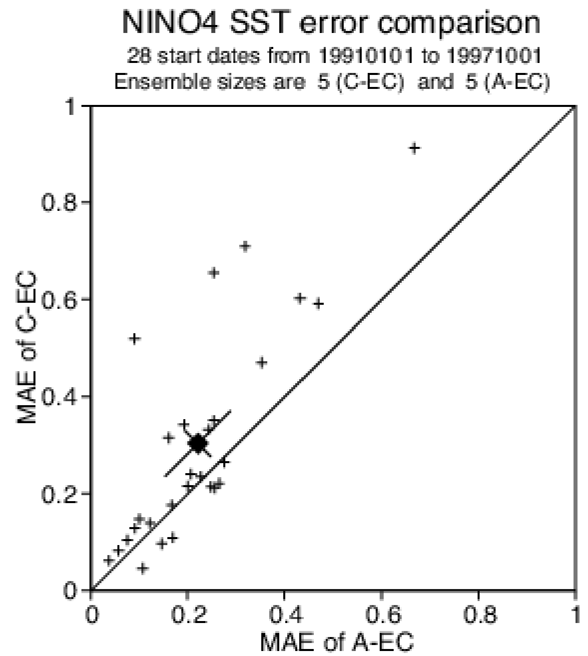
Ocean data assimilation also improves the forecast skill

(Alves et al 2003)

Nino3.4, Lon = [-170, -120], Lat = [-5, 5]
Nino12, Lon = [-90, -80], Lat = [-10, 0]
Nino4, Lon = [160, -150], Lat = [-5, 5]
Nino3, Lon = [-150, -90], Lat = [-5, 5]







January 1997: Seasonal Forecast System 1

- The Coupled model
  - Atmosphere (IFS-15r8) + Ocean (HOPE ~2x2)
- Ocean Analysis: OI
- Ensemble: "Lag average" (1 fc per day to 6 months)
- The Calibration Period: 1991-1996

January 2002: Seasonal Forecast System 2

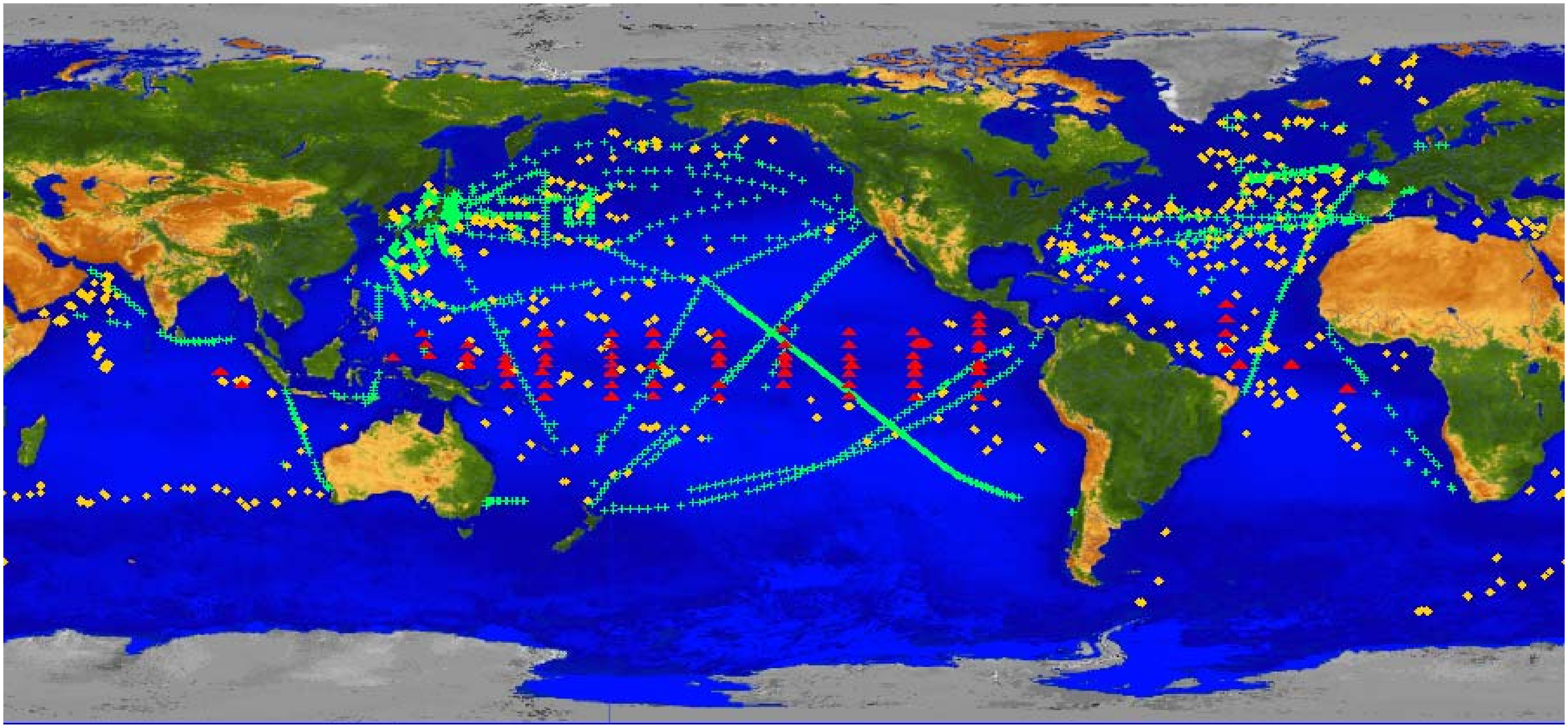
- The Coupled model
  - Atmosphere (IFS-23r4) +Ocean (HOPE 1x1)
- Ocean Analysis: (OI)
  - 5-member ensemble of ocean analysis (wind pertub.)
- Ensemble: "*BURST MODE*"
  - 40 forecasts made on 1st of month to 6 months
- The Calibration Period: From 1987-2001, using ERA15

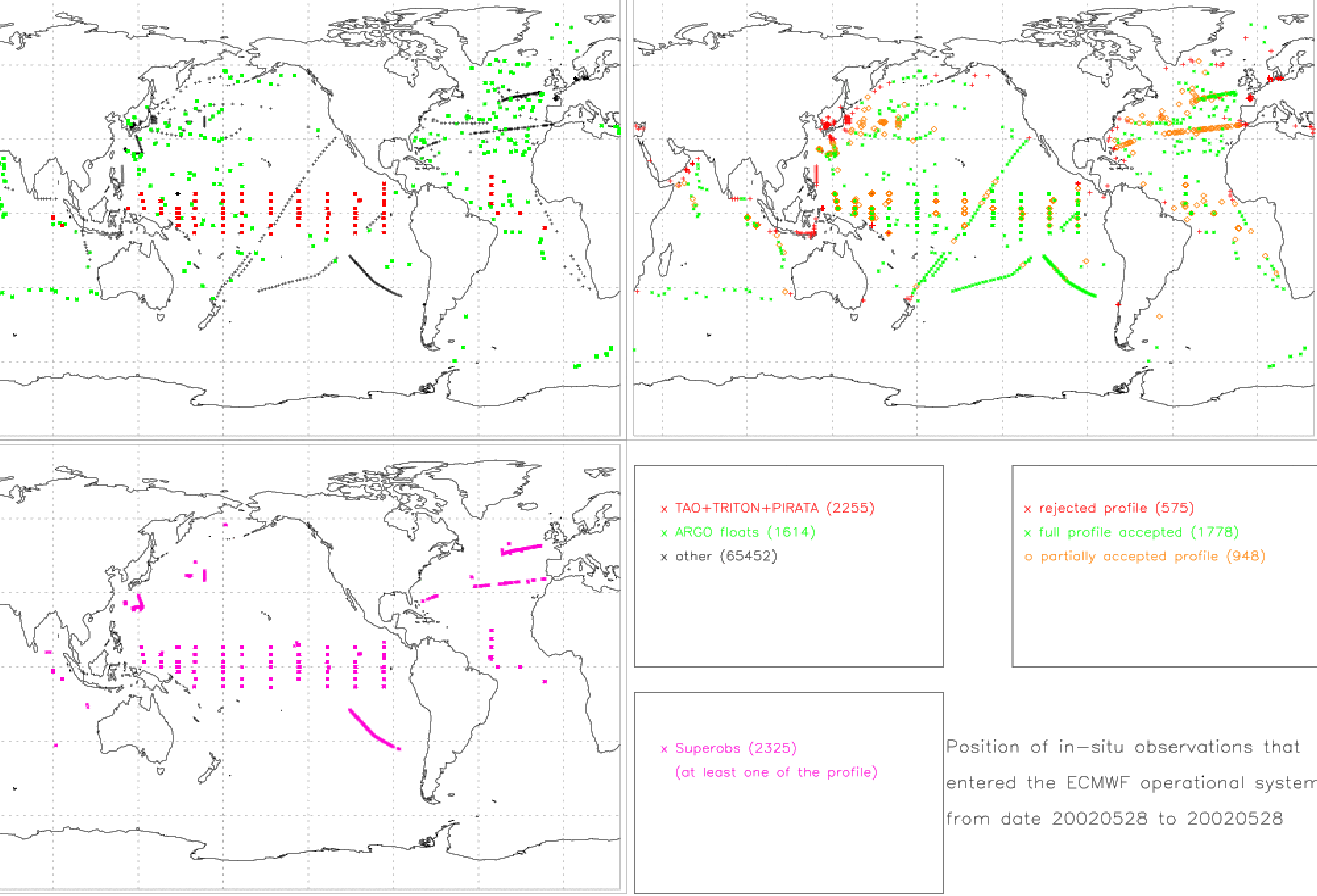
OCEAN INITIALIZATION

- **Strong Relaxation to Reynolds OIv2 SST (~2 days)**
- **OI of subsurface T, every 10 days**
- **10 days assimilation window**
- **Salinity Updates (T-S scheme)** *New*
- **Velocity Updates (geostrophy)** *New*
- **Subsurface 3D relaxation to T and S Levitus 98 (~18 months).** *New*
- **Ensemble of 5 analysis** *New*
- **Daily forcing for mass, momentum, and heat from NWP**
- **Wind perturbations (SOC-ERA, monthly values)**
- **11 days behind real time**

Data coverage for May 2002

- XBT, MOORINGS, ARGO floats

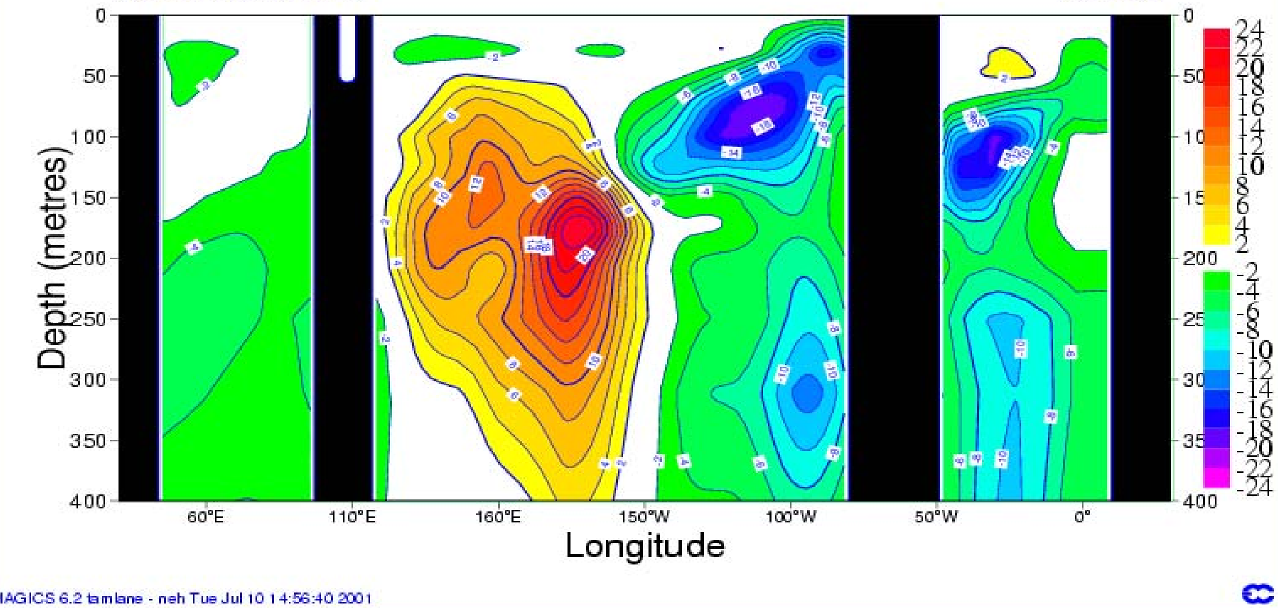




From A. Vidard

Assimilation Increments

<Analysis-Background> **(8 year average)**



C.I: 2 C/year

Why worry about systematic error?

- Suboptimal use of observations:

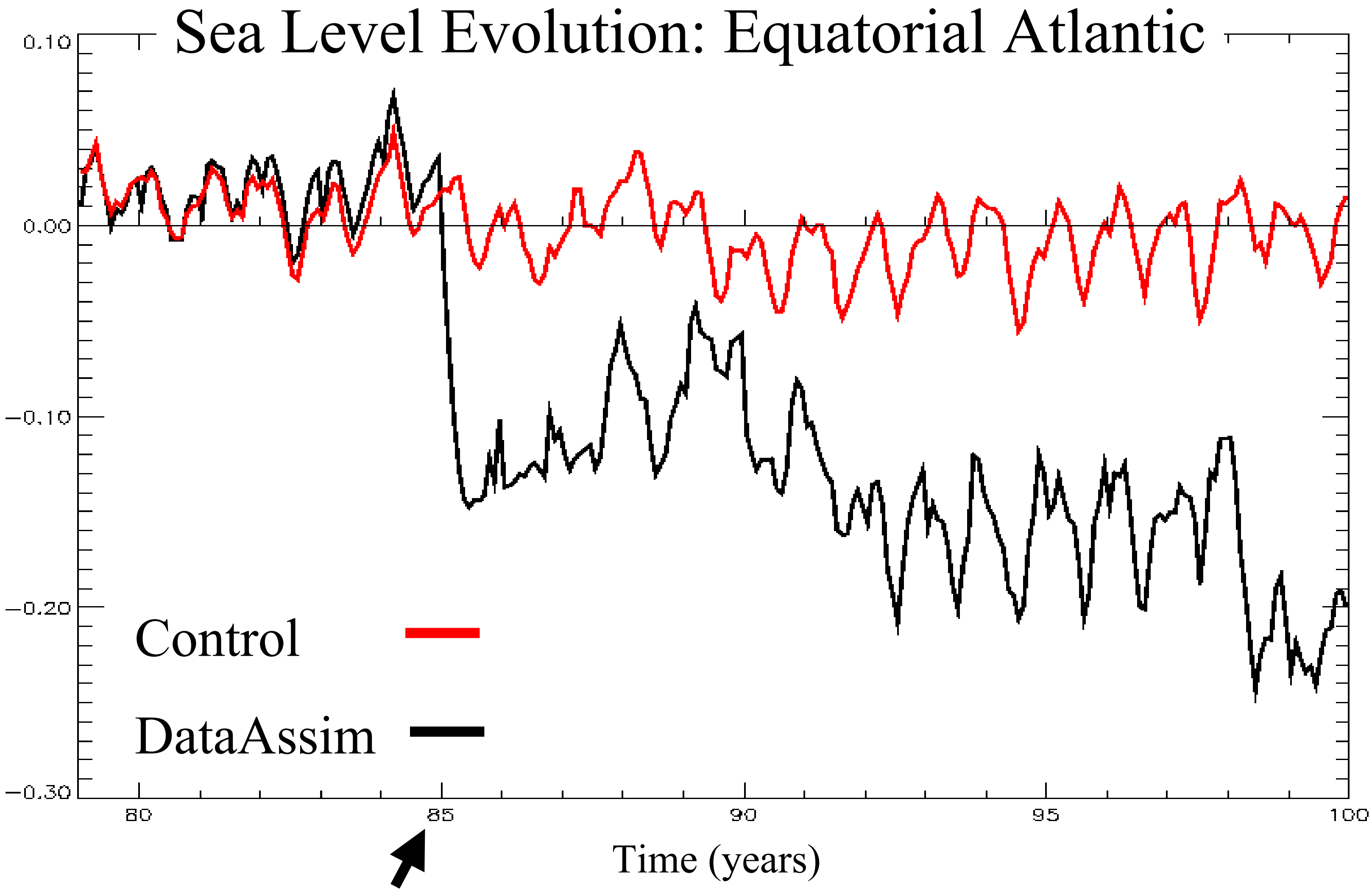
  Increased variance in the analysis, convergence, etc…

- Practical considerations:

  -spurious time variability: If observation are not homogeneous in time

  -Systematic error in “unconstrained” variables

SYSTEM 1



1985

OCEAN INITIALIZATION

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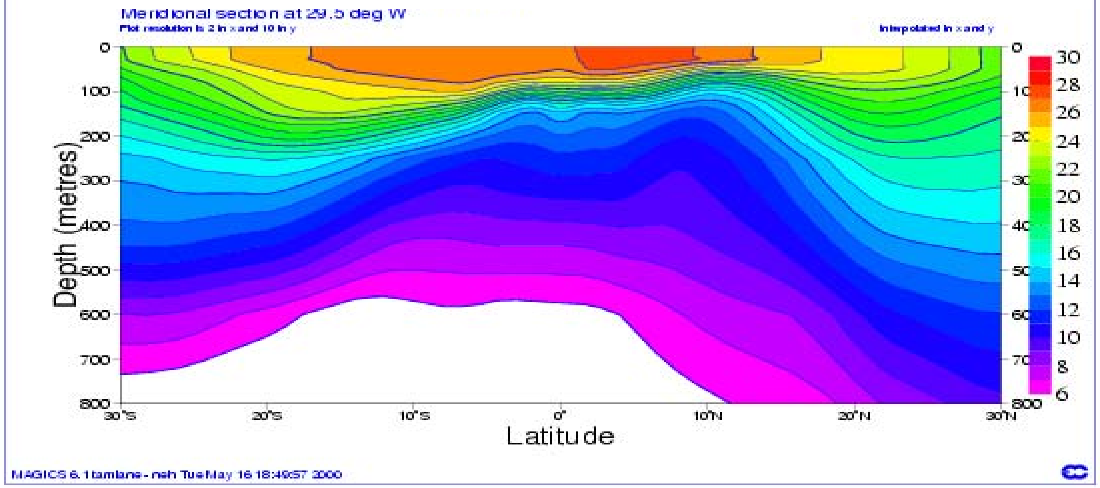
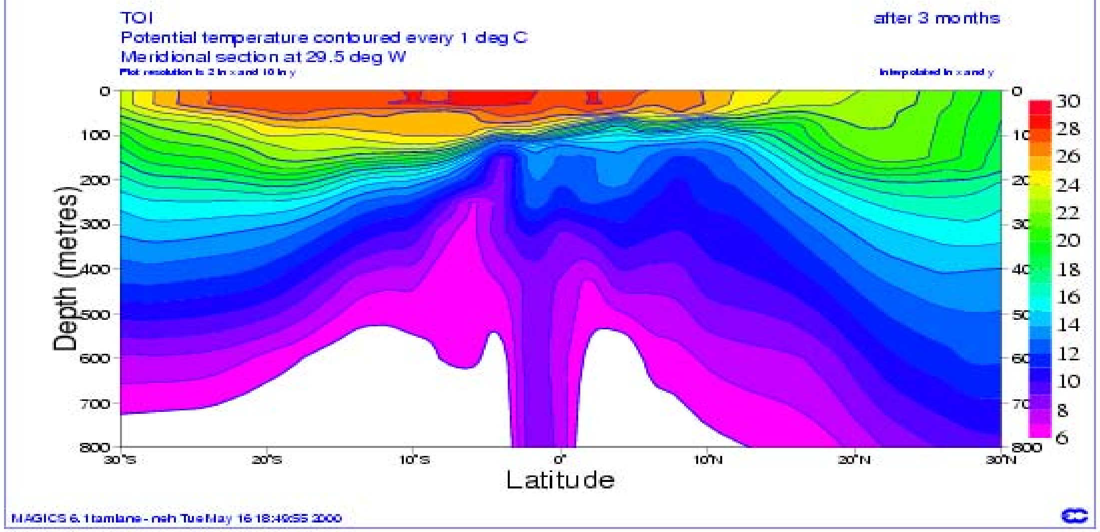
Temperature Section 30 W



Initial Conditions :

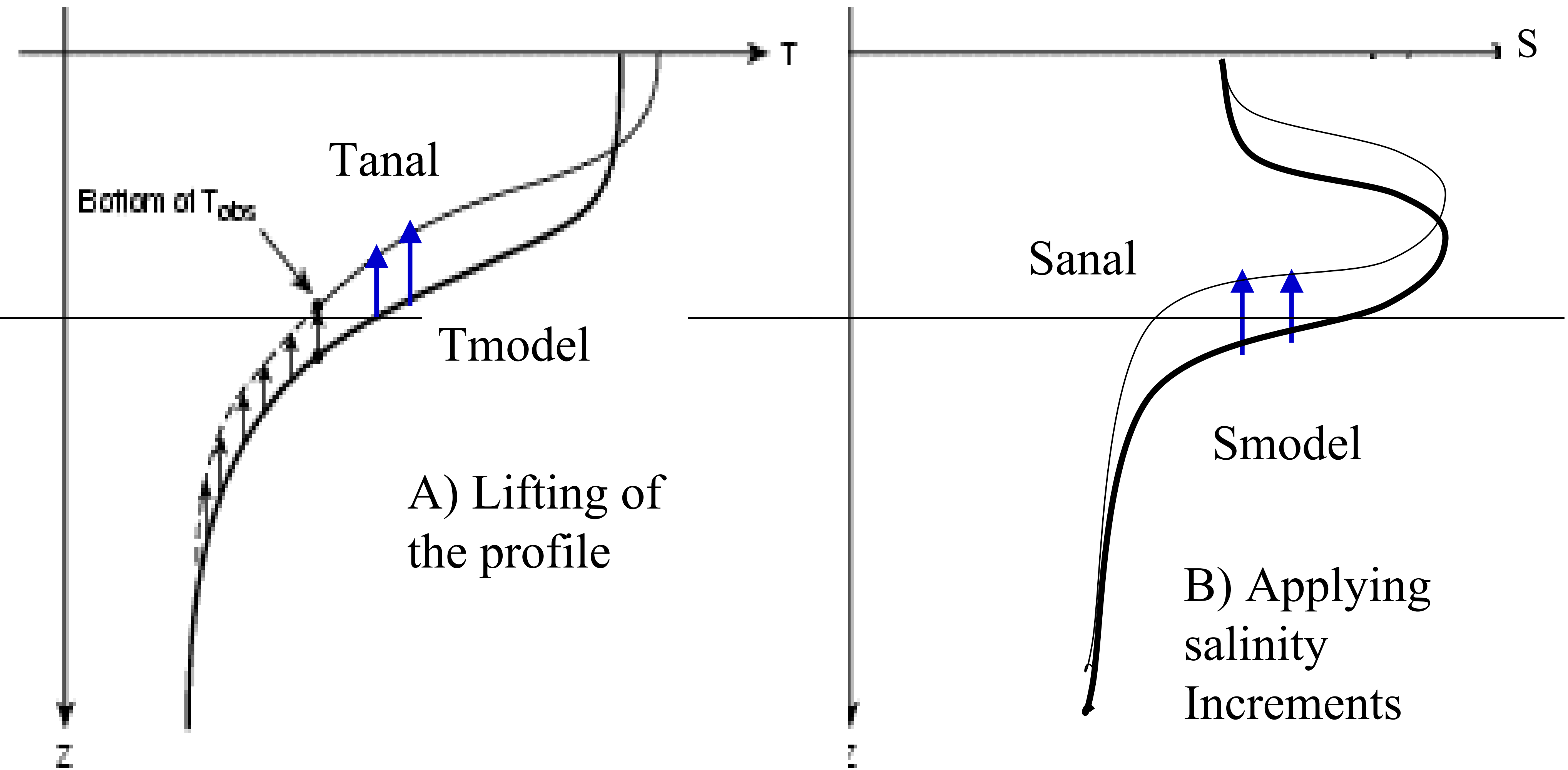
Stratified water column



3 months into the assimilation of Subsurface temperature:

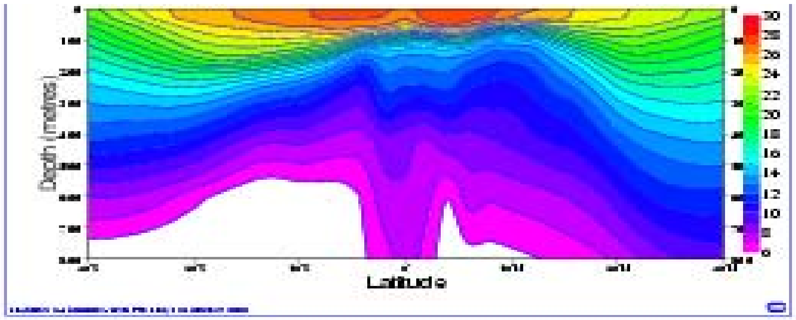
Convection occurs at the Equator. Broken stratification

Updating Salinity: S(T) SCHEME

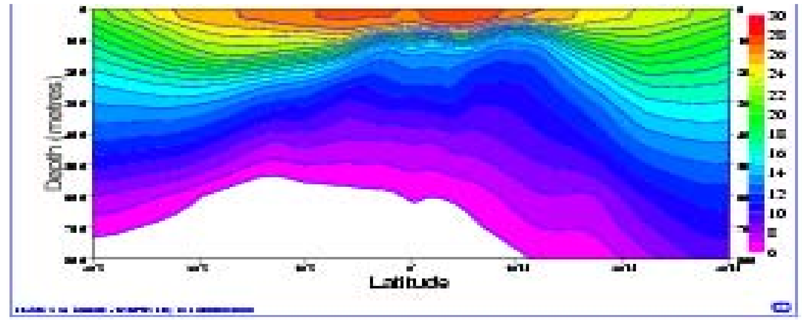


Troccoli et al, MWR 2002, Weaver Lecture

Temperature : No S(T)



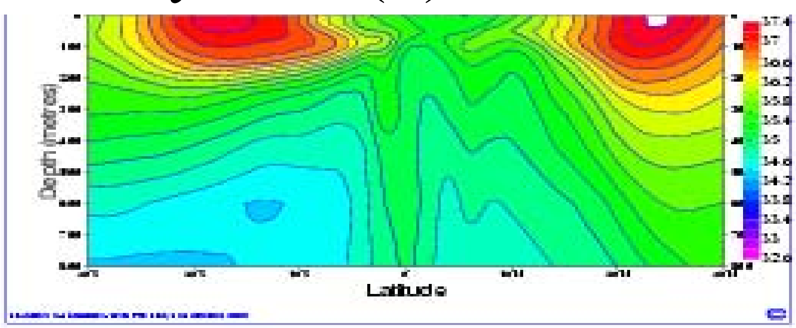
Temperature: S(T)



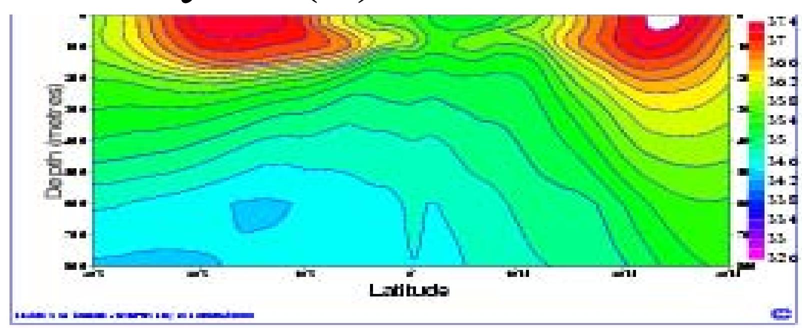
Spurious Convection

S(T) prevents convection

Salinity: No S(T)



Salinity: S(T)



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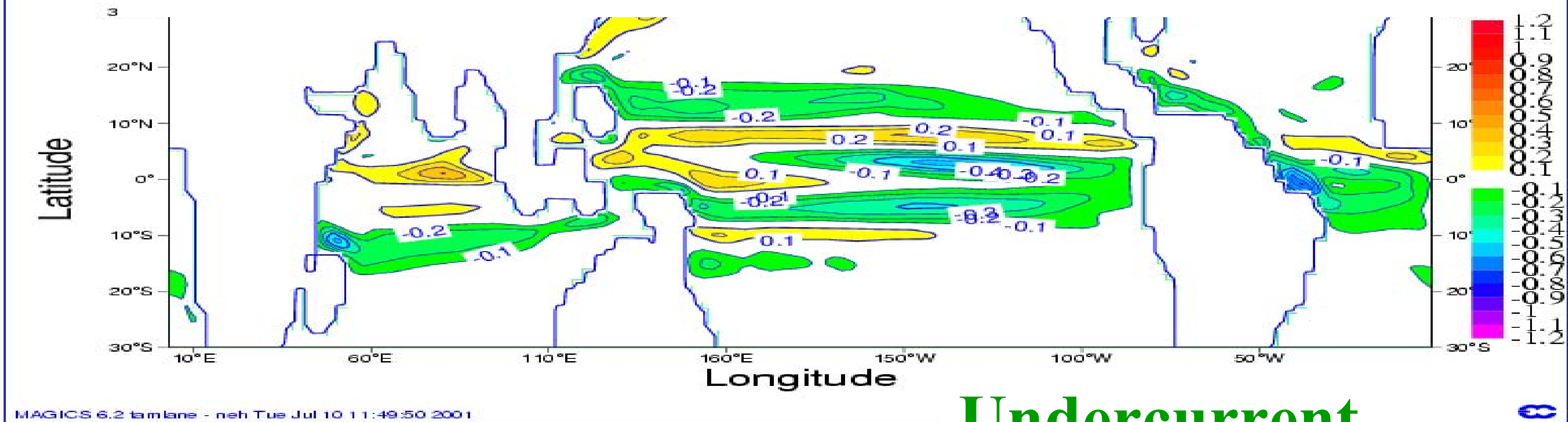
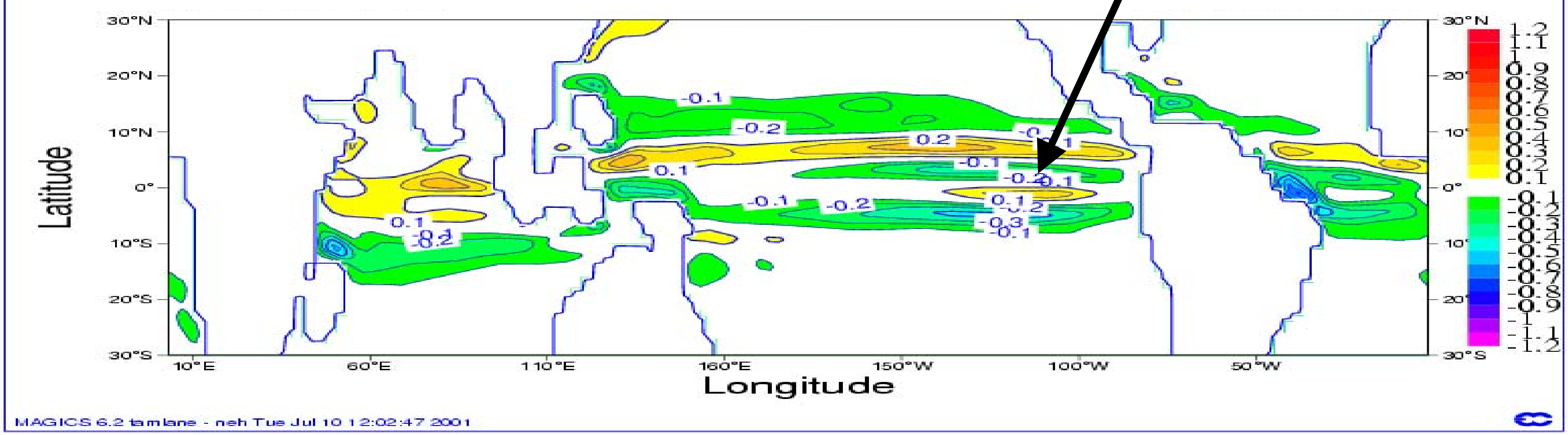
Surface Zonal Velocity

Control



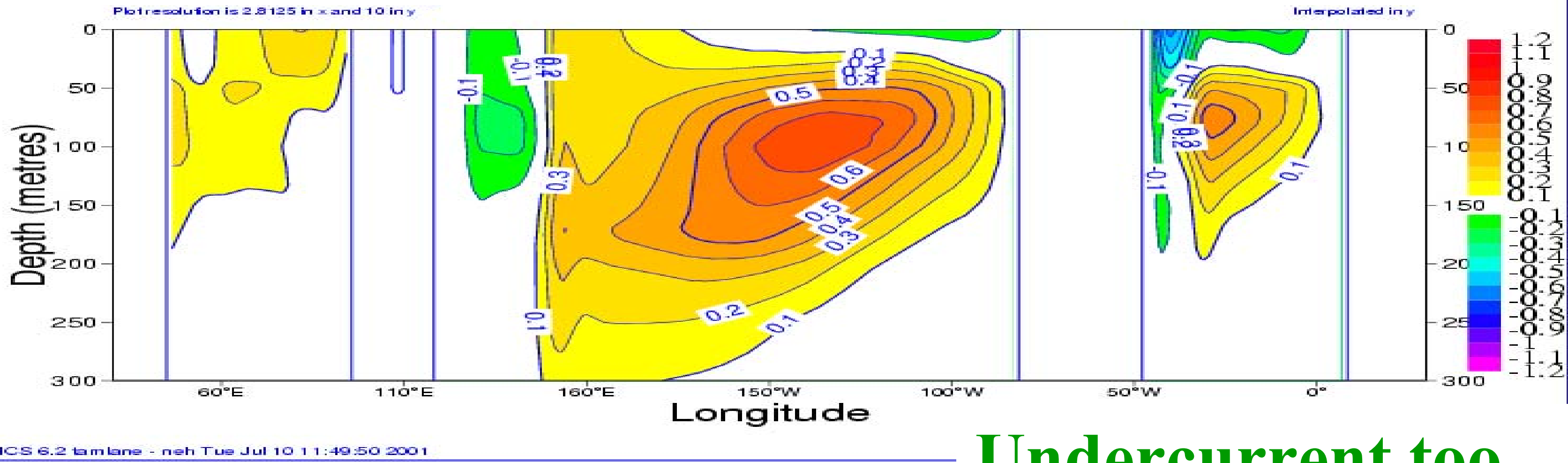
Undercurrent Surfaces

Assimilation



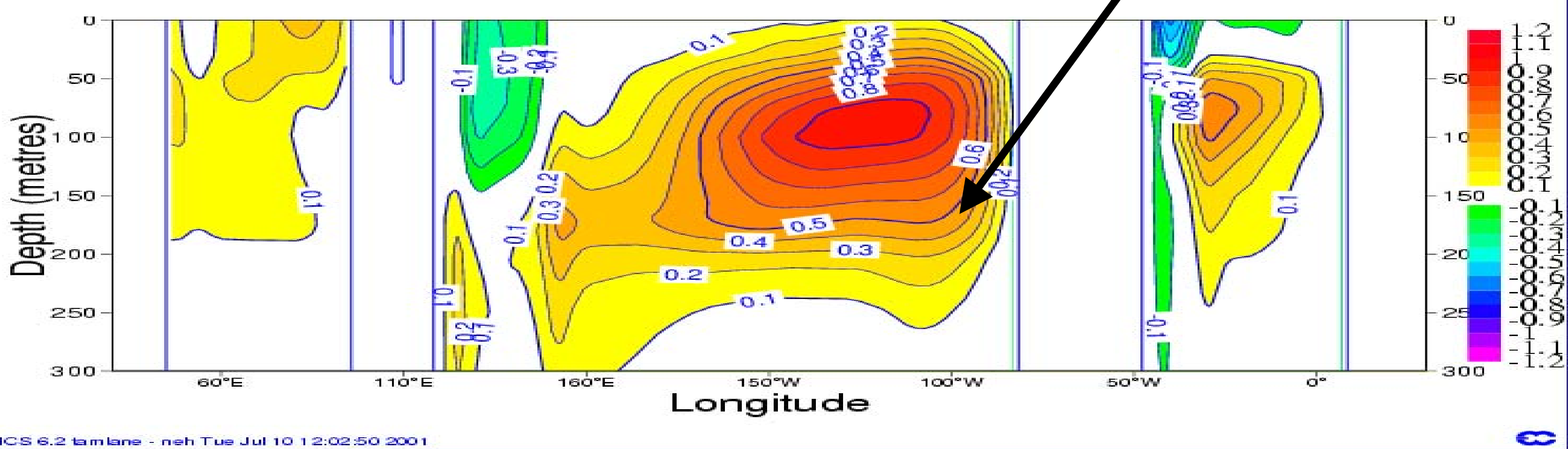
Equatorial Zonal Velocity

Control Run



Undercurrent too strong and deep

Assimilation Run

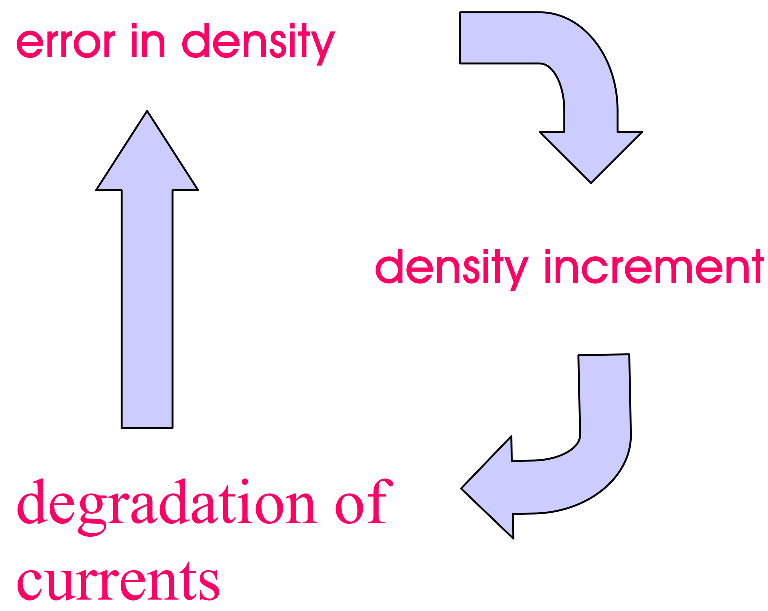


Problem with Equatorial Currents

Equatorial currents degrade when assimilating density information (temperature /salinity)

The currents get worse as the constraint to the density data is increased

- Possibility of feedback :



- Strategy 1: to introduce dynamical constraints *(Burgers et al, JPO 2002)*
  - Error Induced by the assimilation process by disruption of dynamical balances

- Strategy 2: to estimate and correct error *(Bell, Martin,Nichols,2001)*
  - It assumes that the source of error lies on the momentum equation

Balanced Currents Method

- To update currents / the velocity increment is partially in geostrophic balance with the density increments:

$$\eta_a = \eta_b + \delta\eta \, ; \vec{u}_a = \vec{u}_b + \delta\vec{u}$$

$$\delta\eta = \delta\eta_\eta + \delta\eta_e ; \delta\eta_e = \alpha\delta\eta ; 0 \le \alpha \le 1$$

$$\delta u = -\frac{g}{f}\frac{\alpha\partial\delta\eta}{\partial y} \quad ; \delta v = \frac{g}{f}\frac{\alpha\partial\delta\eta}{\partial x}$$

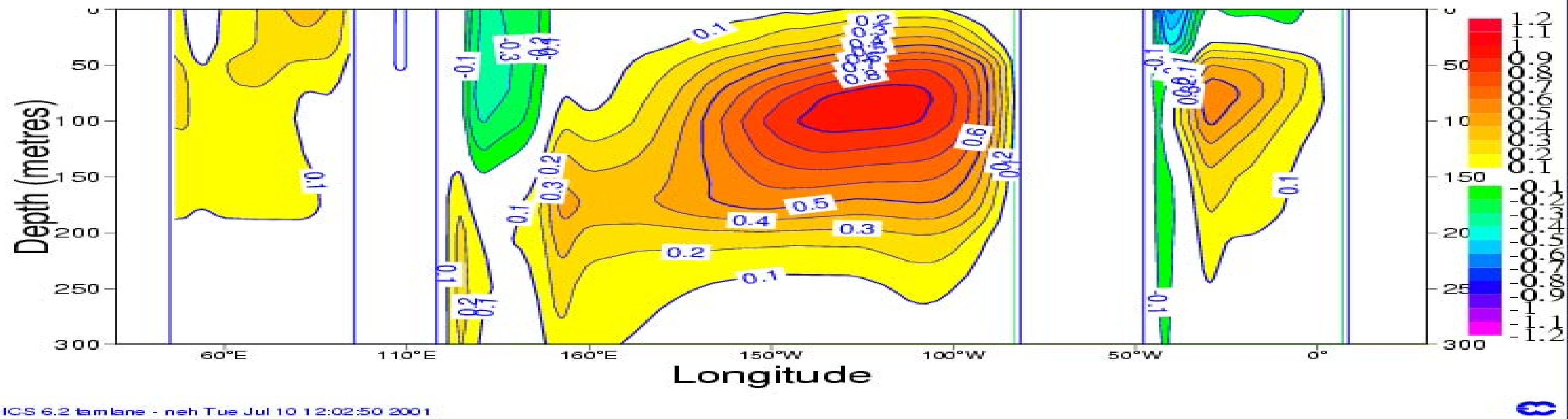
- At the Equator:

$$\delta u = -\frac{g}{\beta}\frac{\alpha\partial^2\delta\eta}{\partial y^2} \; ; \delta v = 0$$

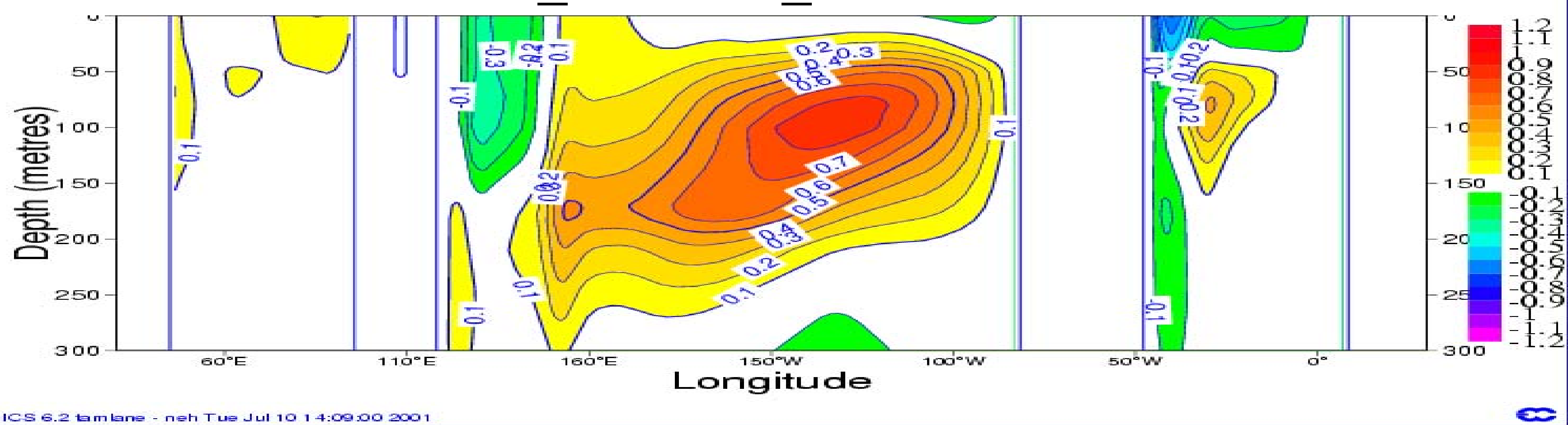
α may depend on z

Equatorial Section: Zonal Velocity

Assimilation

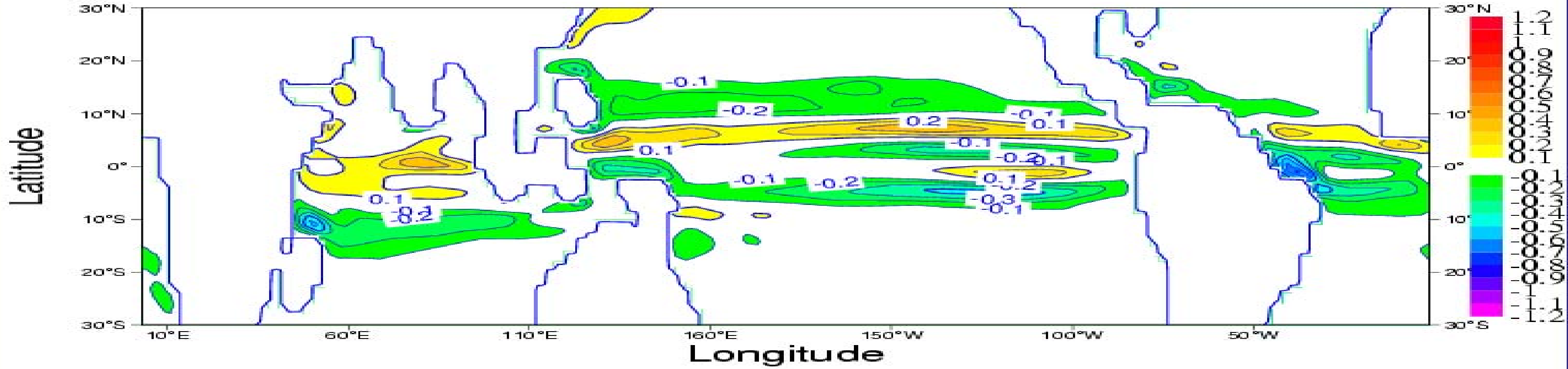


Assimilation + Geos_Balanced_currents

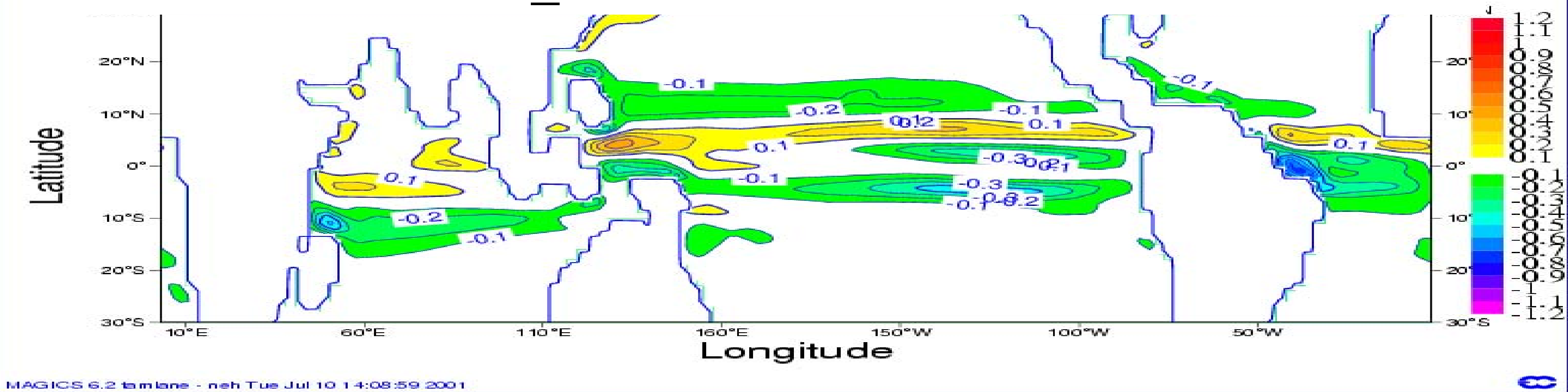


Surface Zonal Velocity

Assimilation

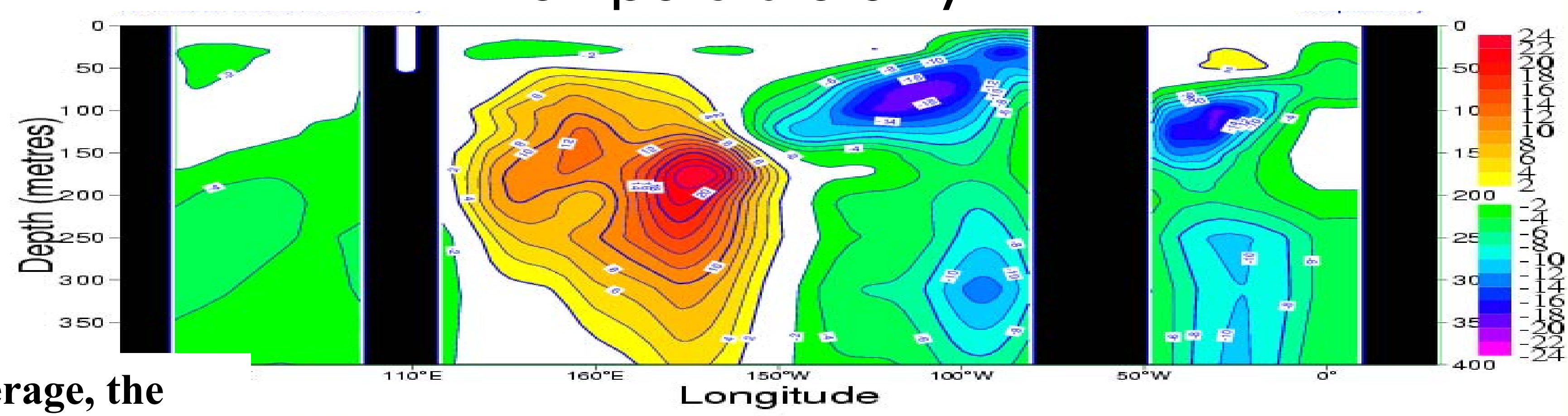


Assimilation +Geos_balanced



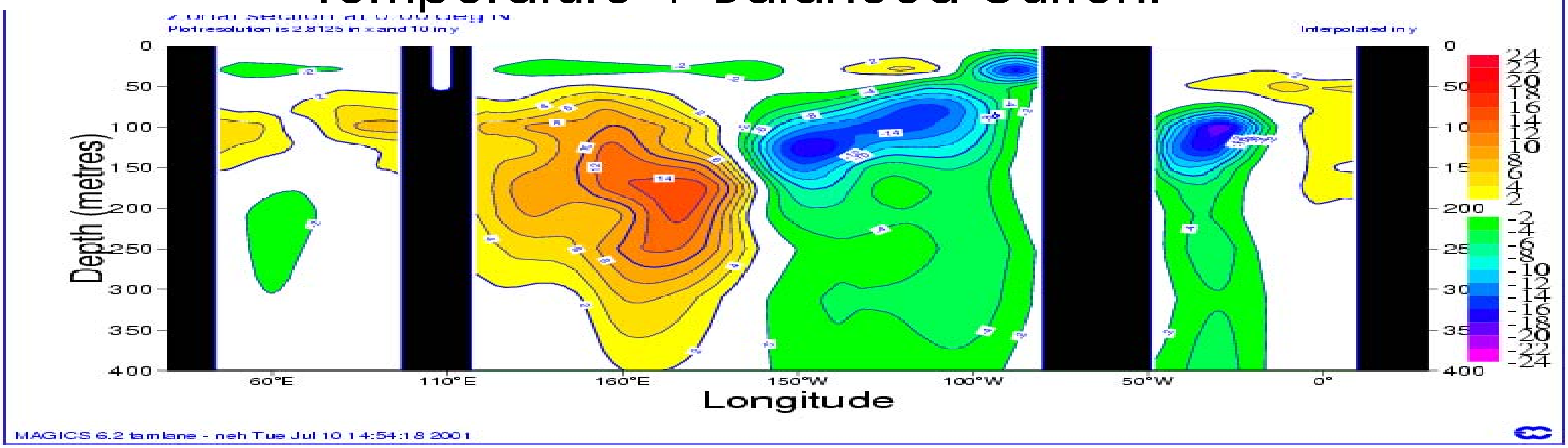
Temperature Increments

Temperature only

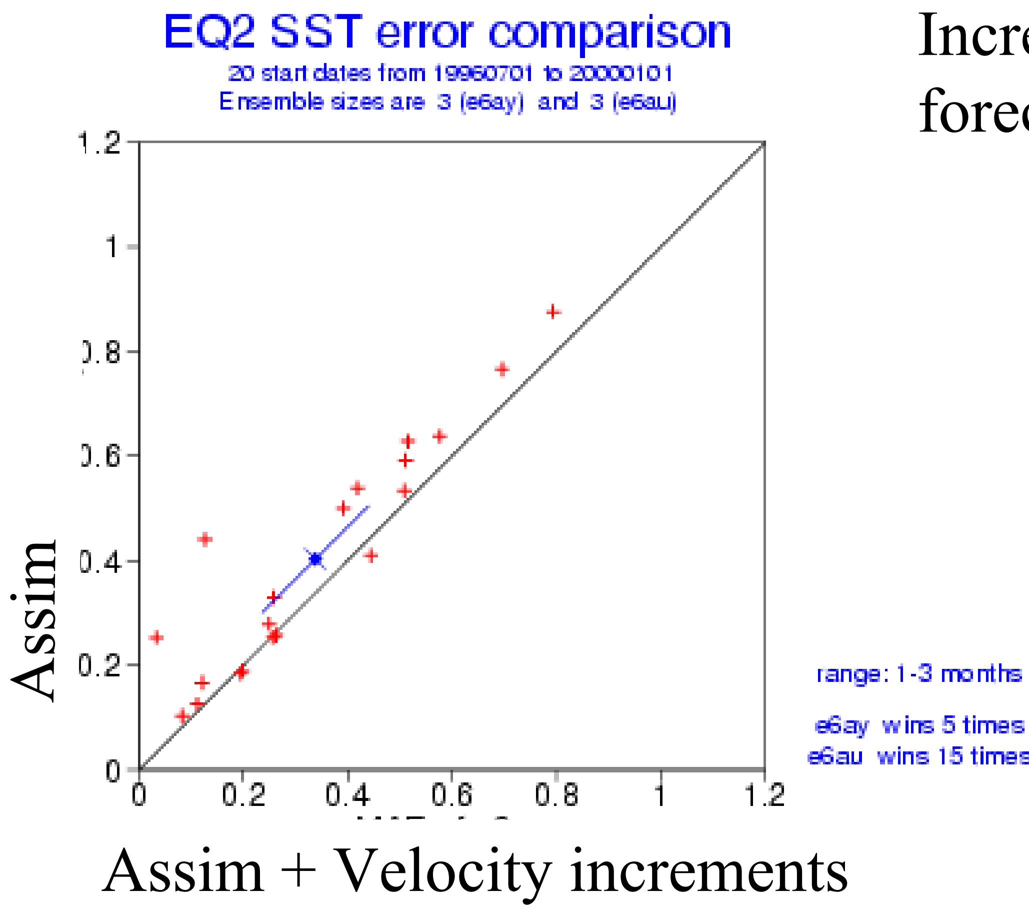


On average, the averaged assim increment decreases by ~20%

Temperature + Balanced Current



Velocity
Increments help
forecast statistics



Dealing with Model Error

- More general solution
- Estimation problem:
  - Time dependency?
  - Which equations are in error?
  - Uncertainty in the bias estimate
- Sequential Methods(Dee and Da Silva, 1998,Bell et al,2001…): they use only past information
- Adjoint methods (Derber 1989, Bonekamp et al,2001, Vidard et al,2003): they use also future information

Bias Correction Methods

- Data assim system:

$$x(t_0) = x_b + \varepsilon(t_0)$$

$$\frac{dx}{dt} = \mathbf{M}(x(t)) + \eta(t)$$

$$\mathbf{H}(x(t_0)) = y_o + \delta(t_0)$$

with

$$\langle \varepsilon(t) \rangle = 0; \ldots \quad \langle \varepsilon | \varepsilon \rangle = \mathbf{B}$$

$$\langle \delta(t) \rangle = 0; \ldots \quad \langle \delta | \delta \rangle = \mathbf{R}$$

$$\langle \eta(t) \rangle = \mathbf{b}; \ldots \quad \langle \eta | \eta \rangle = \mathbf{Q}$$

$$d = (\mathbf{H}x_b - y)$$

$$x_a = x_b + \mathbf{K}d$$

State Augmentation

$$x(t_0) = x_b + \varepsilon(t_0)$$

$$\frac{dx}{dt} = \mathbf{M}(x(t)) + \mathbf{T}(\eta(t))$$

$$\eta(t_0) = \eta_b$$

$$\frac{d\eta}{dt} = \mathbf{\Phi}(\eta(t)) + \mu(t)$$

$$x_a = x_b + \mathbf{K}_b d$$

$$\eta_a = \eta_b - \mathbf{K}_\eta d_\eta$$

T : Which model variables are biased?

M: **how does the model error evolve in time?**

$\mathbf{K}_\eta$ **: what is the gain matrix of the bias term?**

Bell et al, 2001: systematic error in momentum equations

M: **how does the model error evolve in time?**

$\mathbf{K}_\eta$: **what is the gain matrix of the bias term?**

T : **Which model variables are biased?**

$\Phi = \mathbf{I}$; **constant**

$$\eta_b(t+1) = \eta_b(t)$$

$$\mathbf{K}_\eta = \alpha \mathbf{K}_b$$

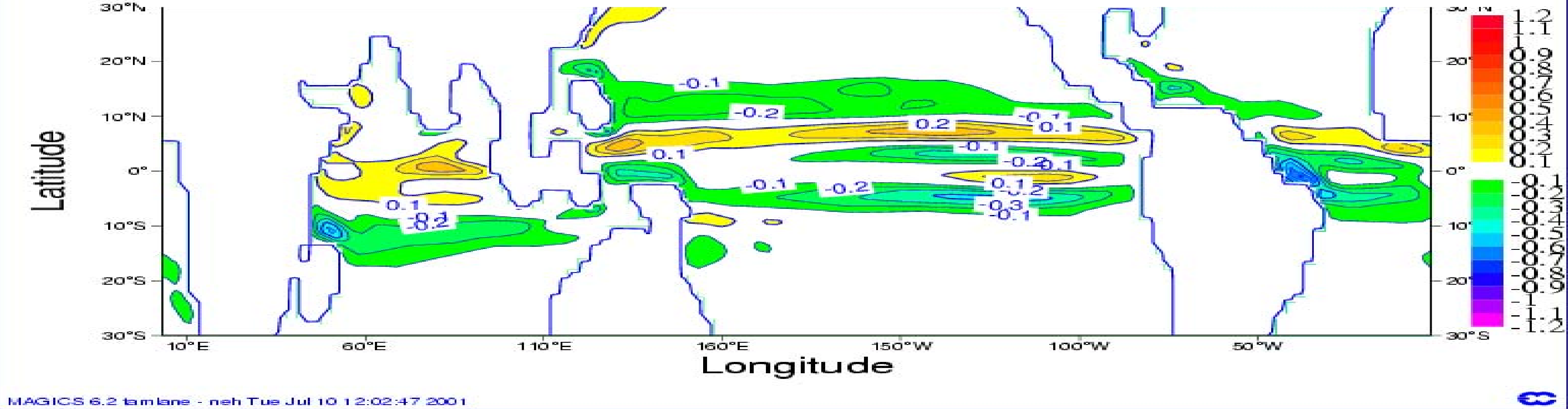
$$\eta_a = \eta_b - \alpha \mathbf{K}_\eta d$$

$$T = (X, Y)$$

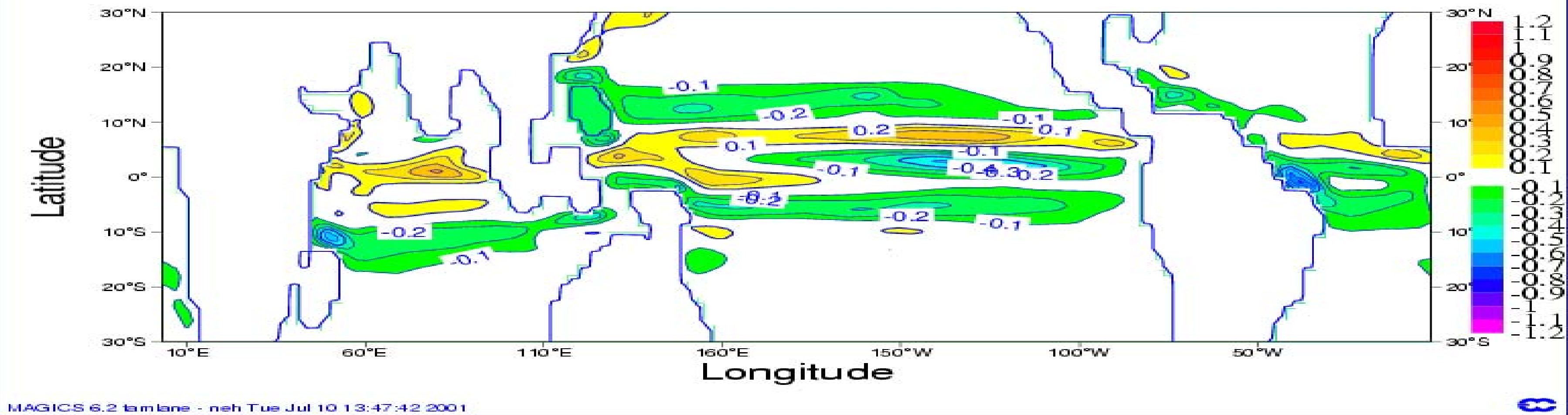
$$X = -g \frac{\partial(\eta)}{\partial x} \quad ; Y = -g \frac{\partial(\eta)}{\partial y}$$

Surface Zonal velocity

Assimilation

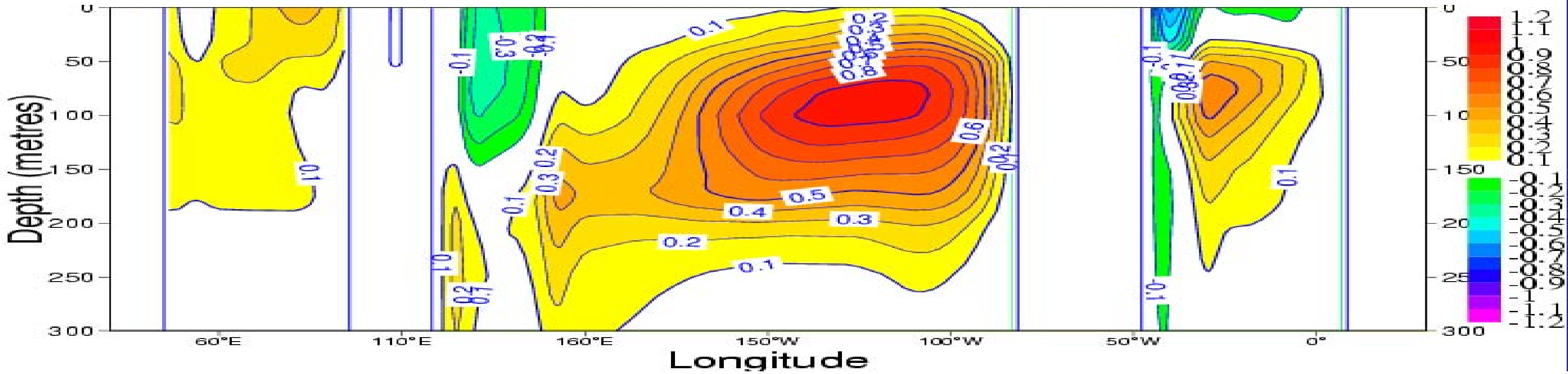


Assimilation + Bias correction



Equatorial Section of Zonal velocity

Assimilation



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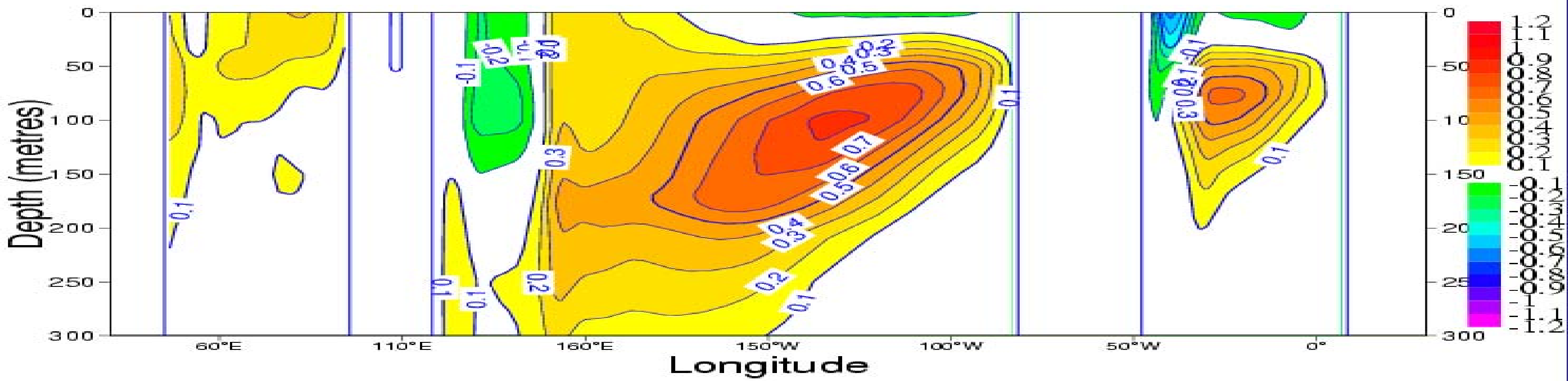


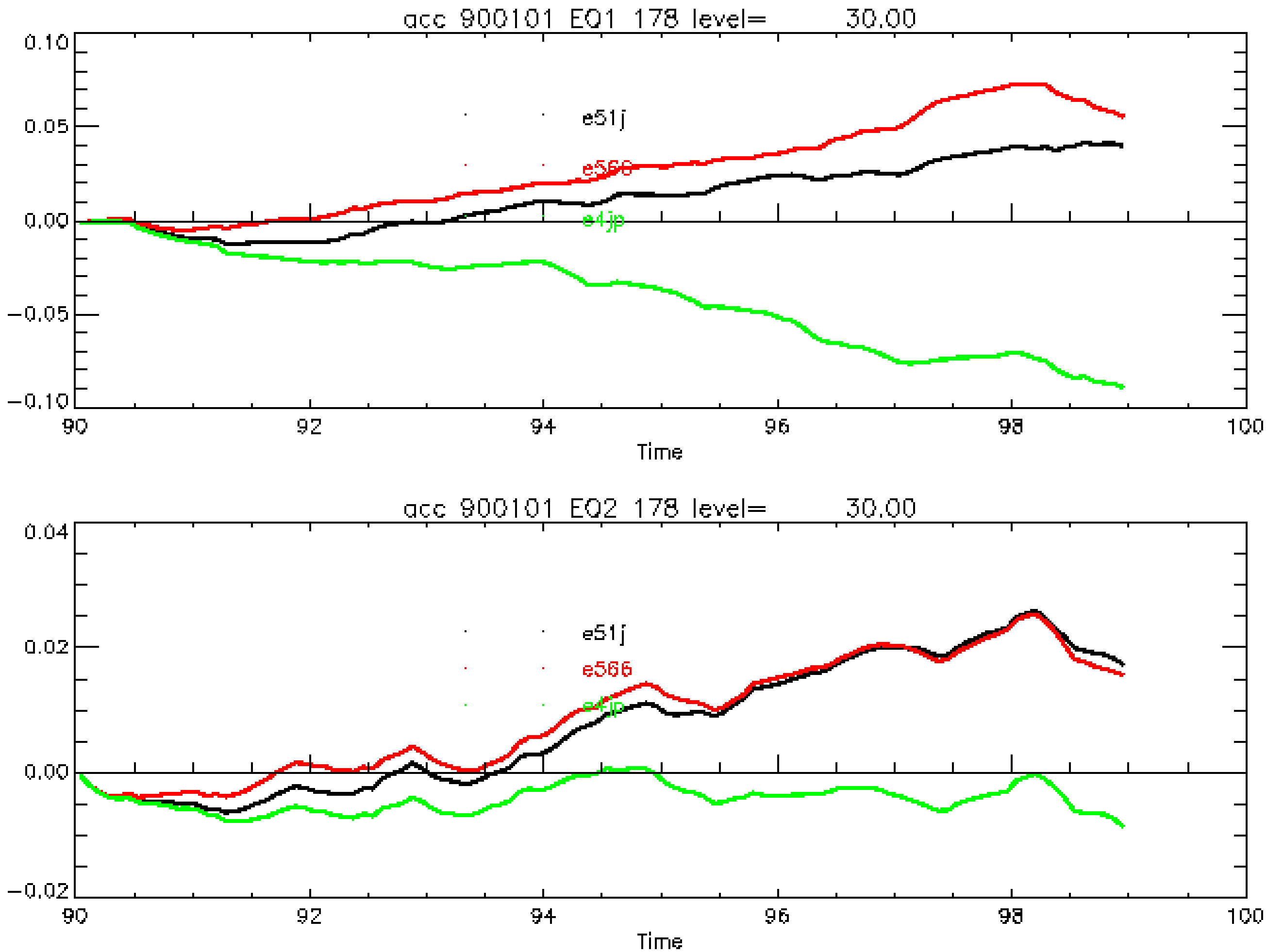
MAGICS 6.2 tamlane - neh Tue Jul 10 13:47:43 2001

Accumulated Assimilation Increment

Standard

Bias $\beta = 0.1$

Bias $\beta = 0.3$



Eastern Pacific

Bias correction works

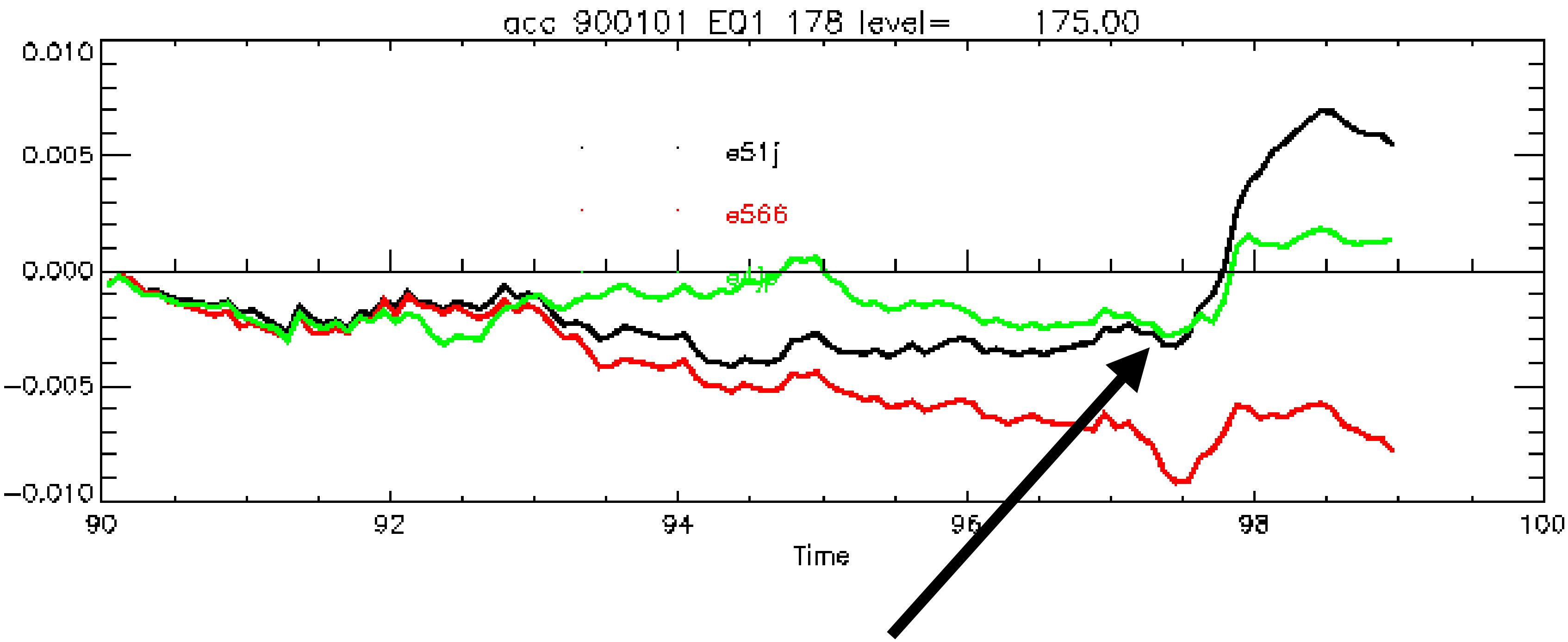
Central Pacific

~

Standard

Bias $\beta = 0.1$

Bias $\beta = 0.3$



Bias is not constant

There is Interannual variability

Bias correction method

- It prevents the degradation of the velocity

  By maintaining the balance between wind and pressure gradient

- Results are sensitive to the prescribe time evolution β

  Errors may be flow dependent.

  Introduce memory term? Or different slow evolving error terms (Dee lecture)

- Useful methodology for error diagnosis (passive)
- Online error correction requires robust estimates of model error
  - Adjoint methods may do better than sequential methods

In S2, it was decided to "control" the bias by a weak relaxation to Levitus climatology (T and S). It is not a definitive solution, and more work is needed on bias detection/correction.

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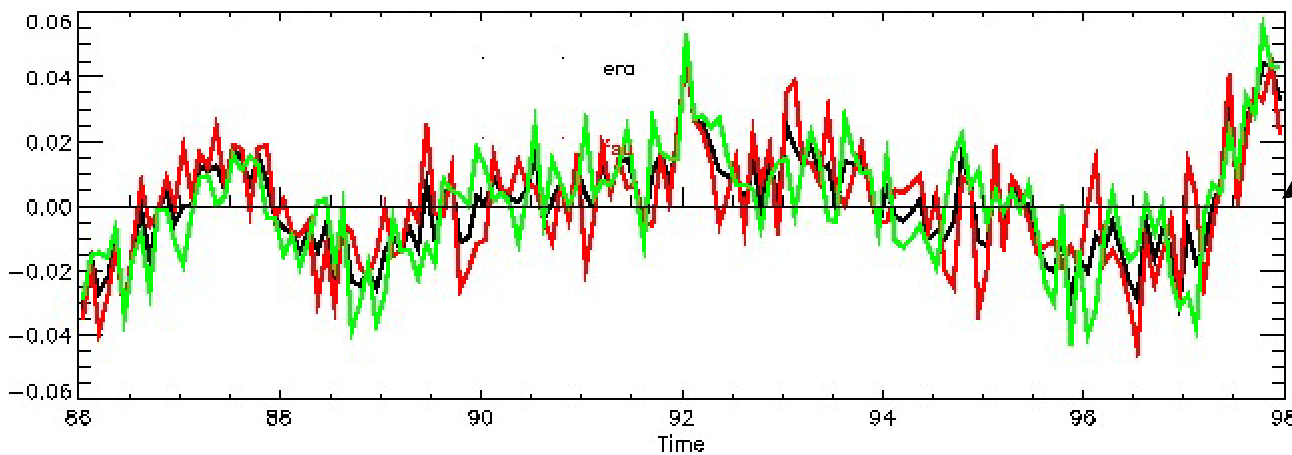
Ensemble of Ocean Analysis

The ensemble of forecasts is created by sampling the uncertainty on the <u>Ocean Initial Conditions</u> + uncertainty in sub-grid processes

Ocean Initial Conditions: Surface + Subsurface

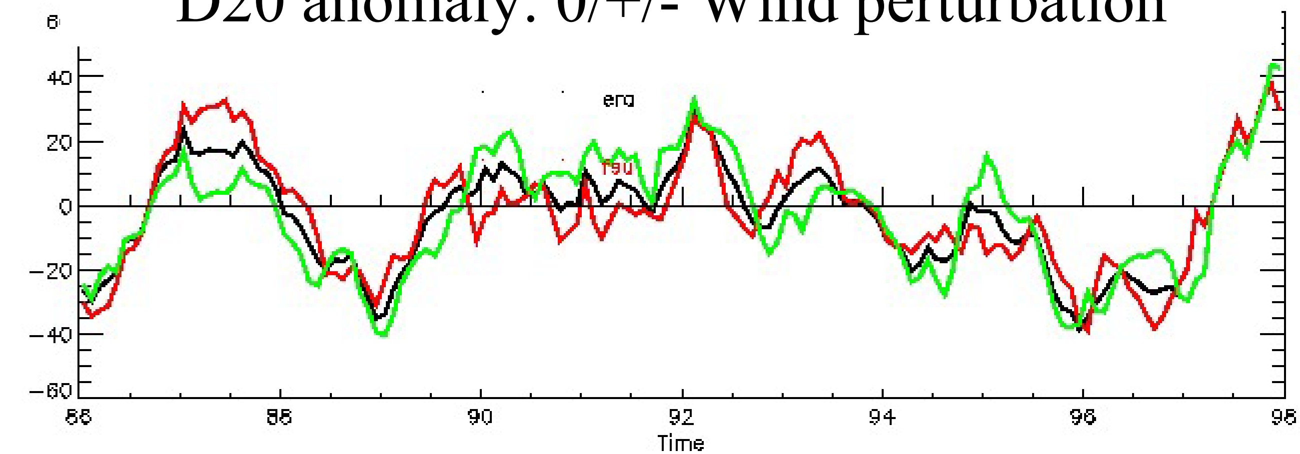
- **The ensemble of ocean analysis is created to represent uncertainties in the subsurface, by adding perturbations to the wind stress forcing:**
  - **SOC - ECMWF monthly means (1980-2000)**
  - **1 month de-correlation scale**
- **Applied during ocean analysis**
  - **They affect the subsurface structure of the ocean**
- **Not actively used in the estimation of error covariances**

Taux anom: 0/+/- Wind perturbation



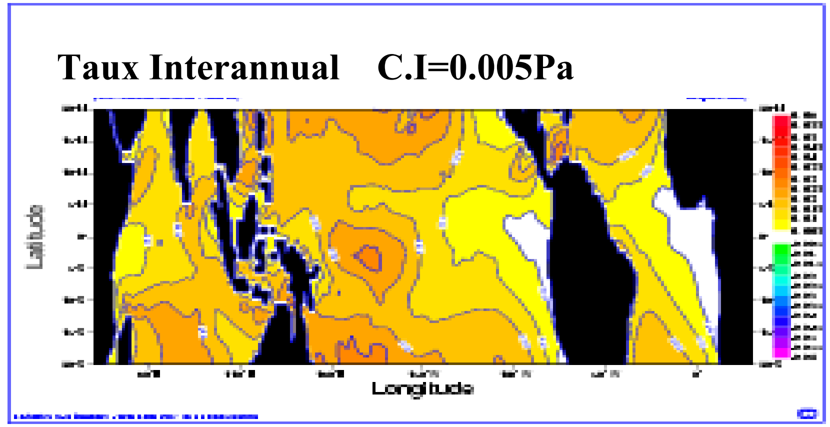
1month decorrelation time

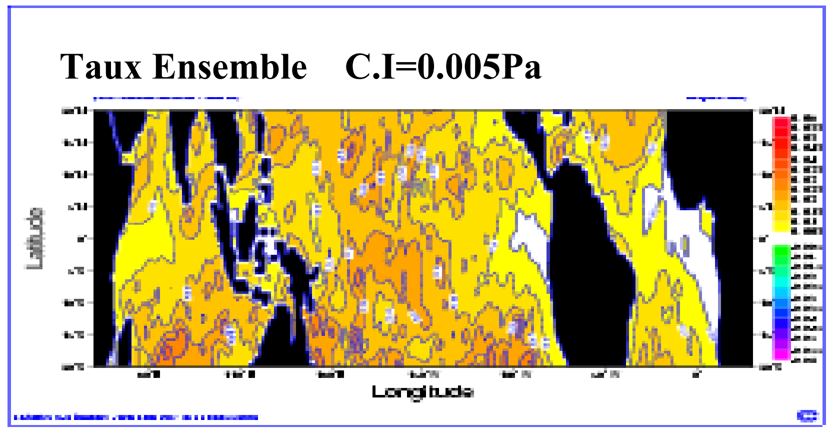
D20 anomaly: 0/+/- Wind perturbation



~6 months decorrelation time

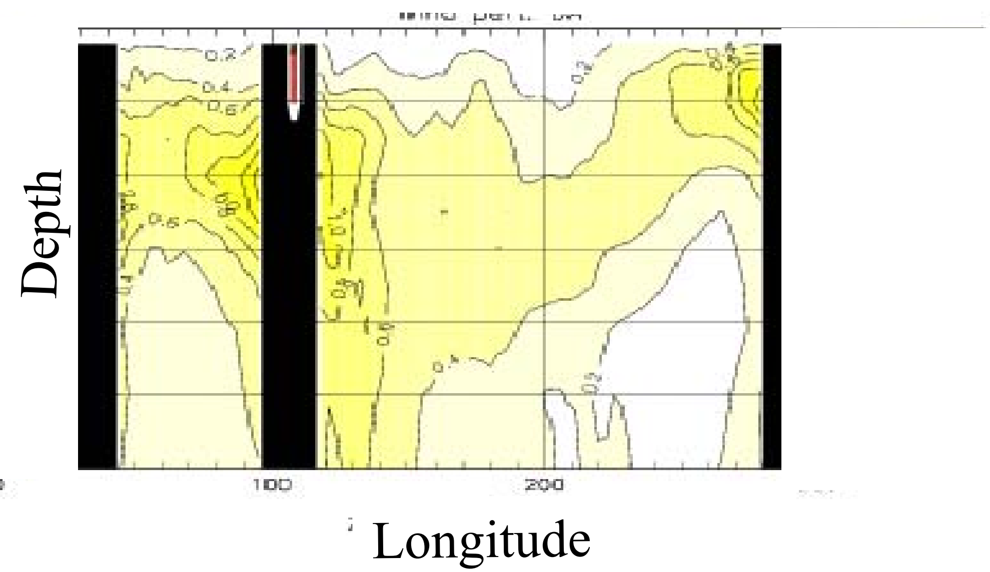
Ensemble spread ~ Interannual variability



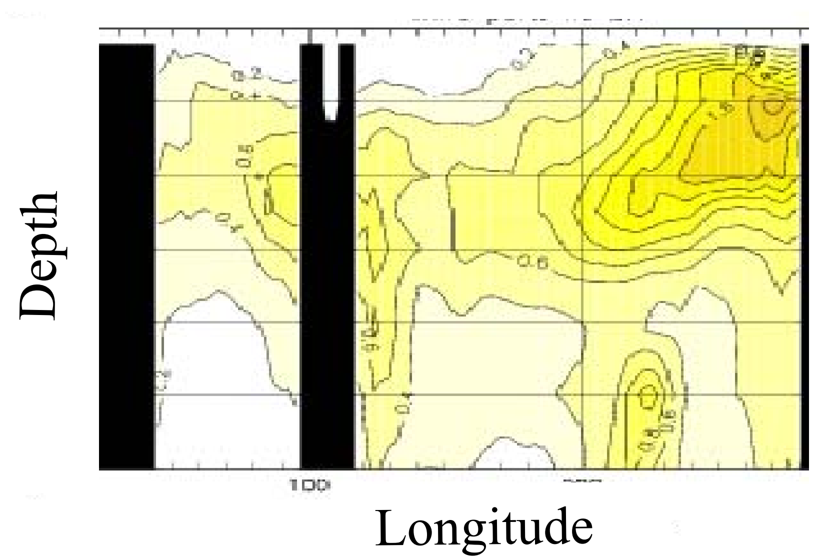


Uncertainties in ocean initial conditions due to wind stress errors

With
data assimilation



Without
data assimilation



Quality of the Analysis

A) Data assimilation

versus

No Data assimilation

B) New System (S2)

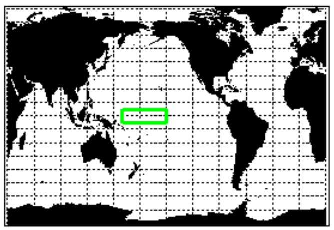
versus

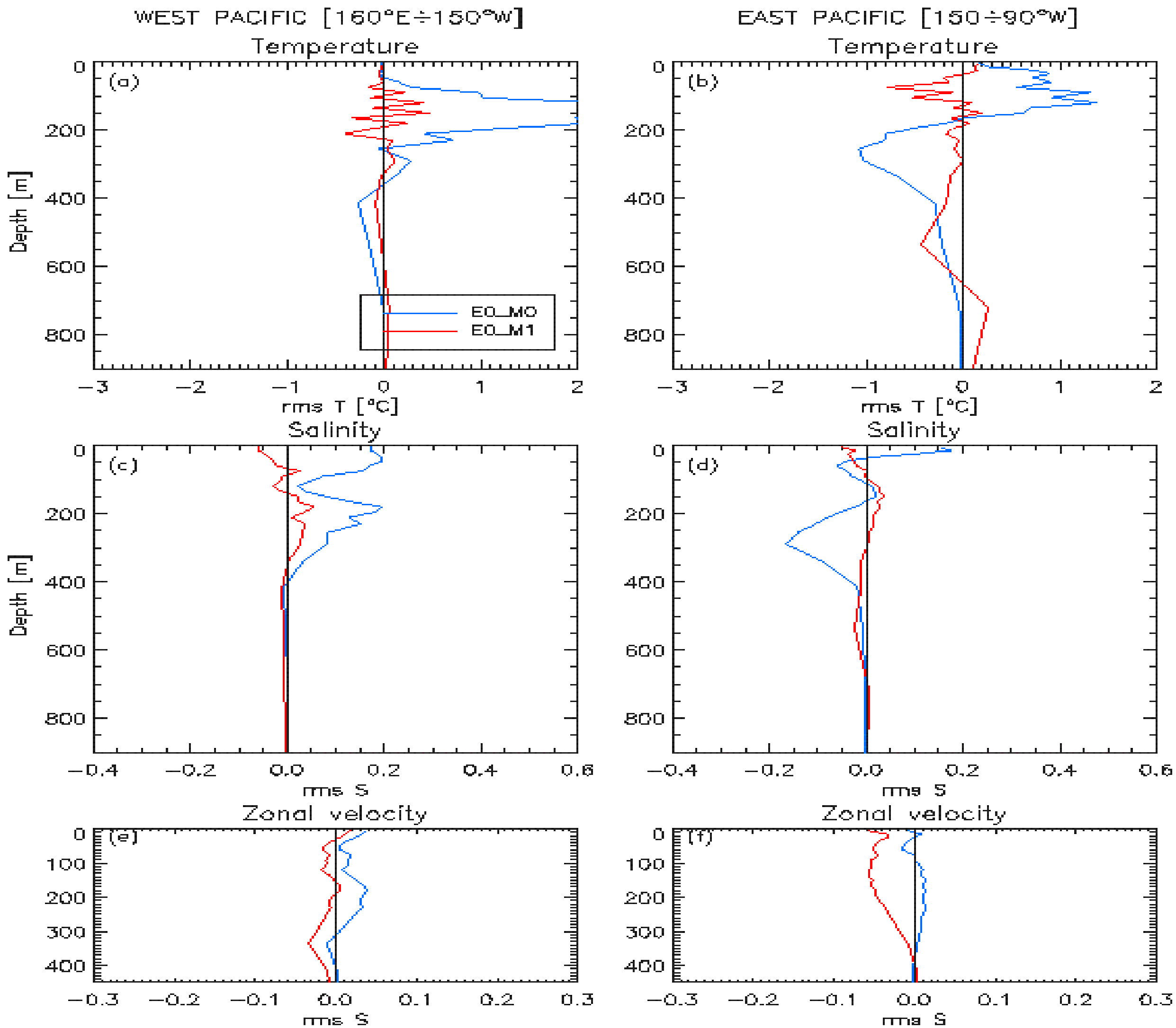
Old System (S1)

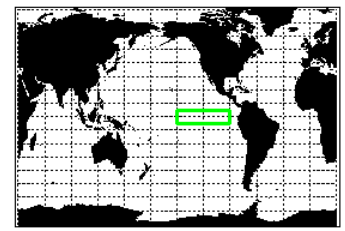
State Estimation

Comparison with Observations: mean Obs - Anal

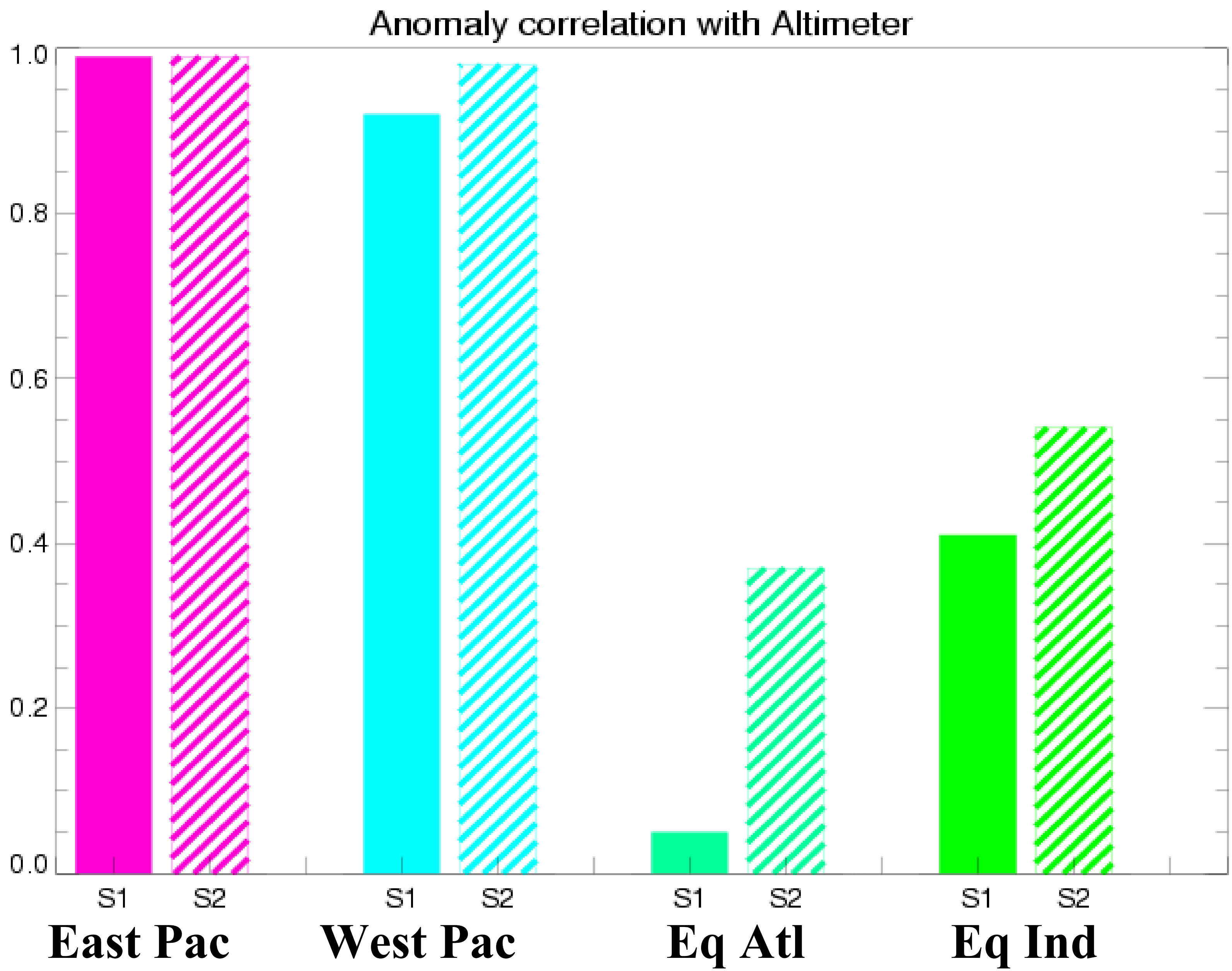
Johnson et al, JGR (2000), Johnson et al, Progr. Ocean. (2002),







Produced by Alberto Troccoli


Anomaly correlation with Altimeter
1.0
0.8
0.6
0.4
0.2
0.0
S1
S2
S1
S2
S1
S2
S1
S2
East Pac
West Pac
Eq Atl
Eq Ind

Quality of the Analysis

A) Data assimilation

versus

No Data assimilation

As Initial conditions for seasonal forecasts

B) New System (S2)

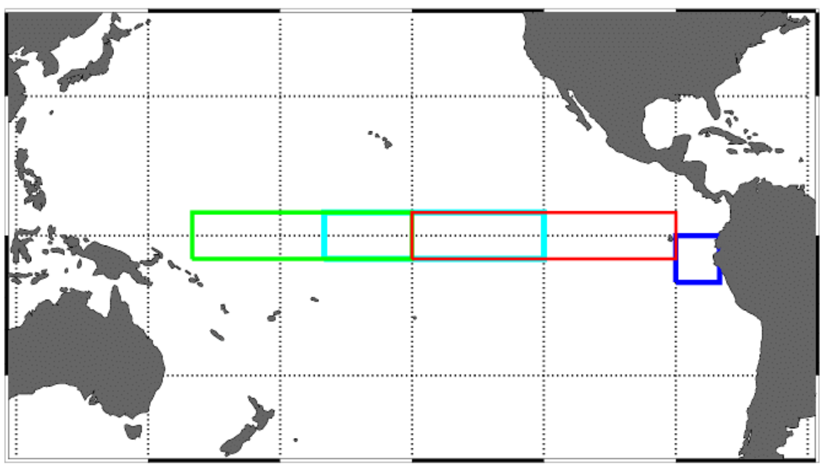
versus

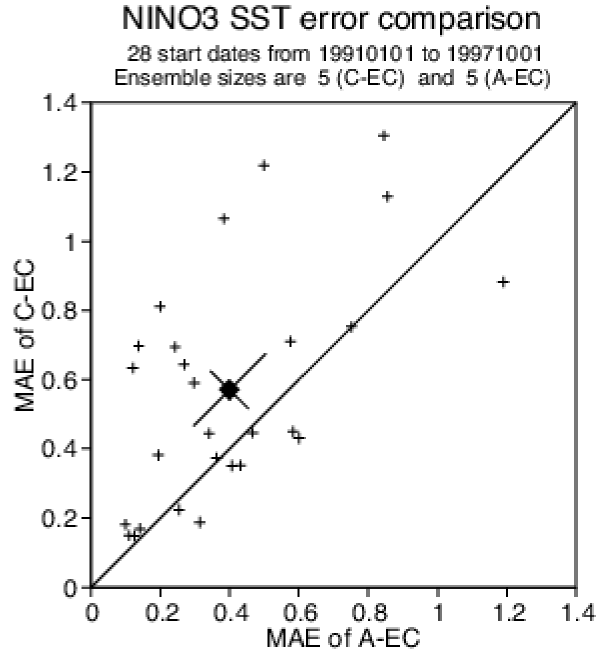
Old System (S1)

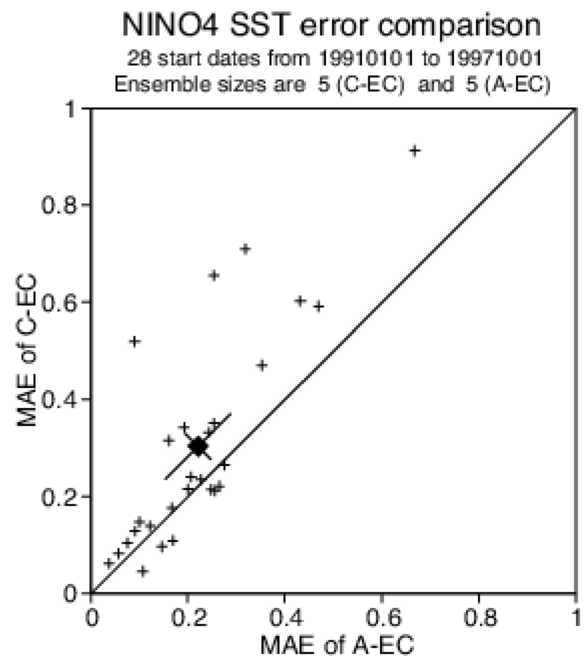
Previously, it was shown that ocean data assimilation improves the forecast skill

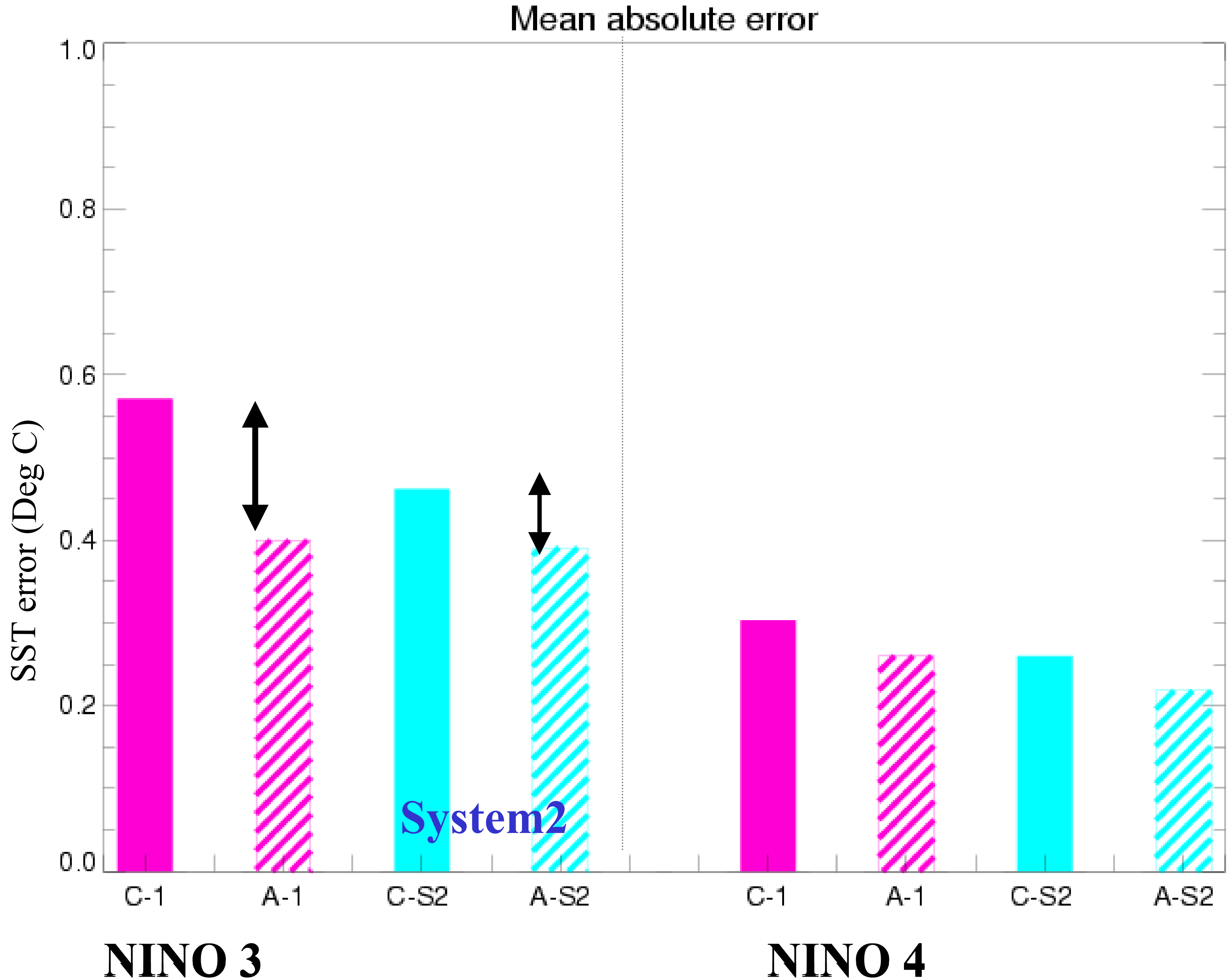
(Alves et al 2003)

Nino3.4, Lon = [-170, -120], Lat = [-5, 5]
Nino12, Lon = [-90, -80], Lat = [-10, 0]
Nino4, Lon = [160, -150], Lat = [-5, 5]
Nino3, Lon = [-150, -90], Lat = [-5, 5]









Mean absolute error
SST error (Deg C)
1.0
0.8
0.6
0.4
0.2
0.0
System2
C-1
A-1
C-S2
A-S2
C-1
A-1
C-S2
A-S2
NINO 3
NINO 4

Some results

State Estimation

- Data assimilation corrects the mean state of the ocean model
  - Temperature
  - Currents?
  - Salinity
- S2 ocean analysis shows better interannual variability than S1

Initial Conditions

- S2 forecasts have smaller errors than previous system
- Data assimilation improves the forecasts skill
- The impact of data assimilation is reduced
  - Need for better DA methods?
  - Need for better coupled models?

Developments

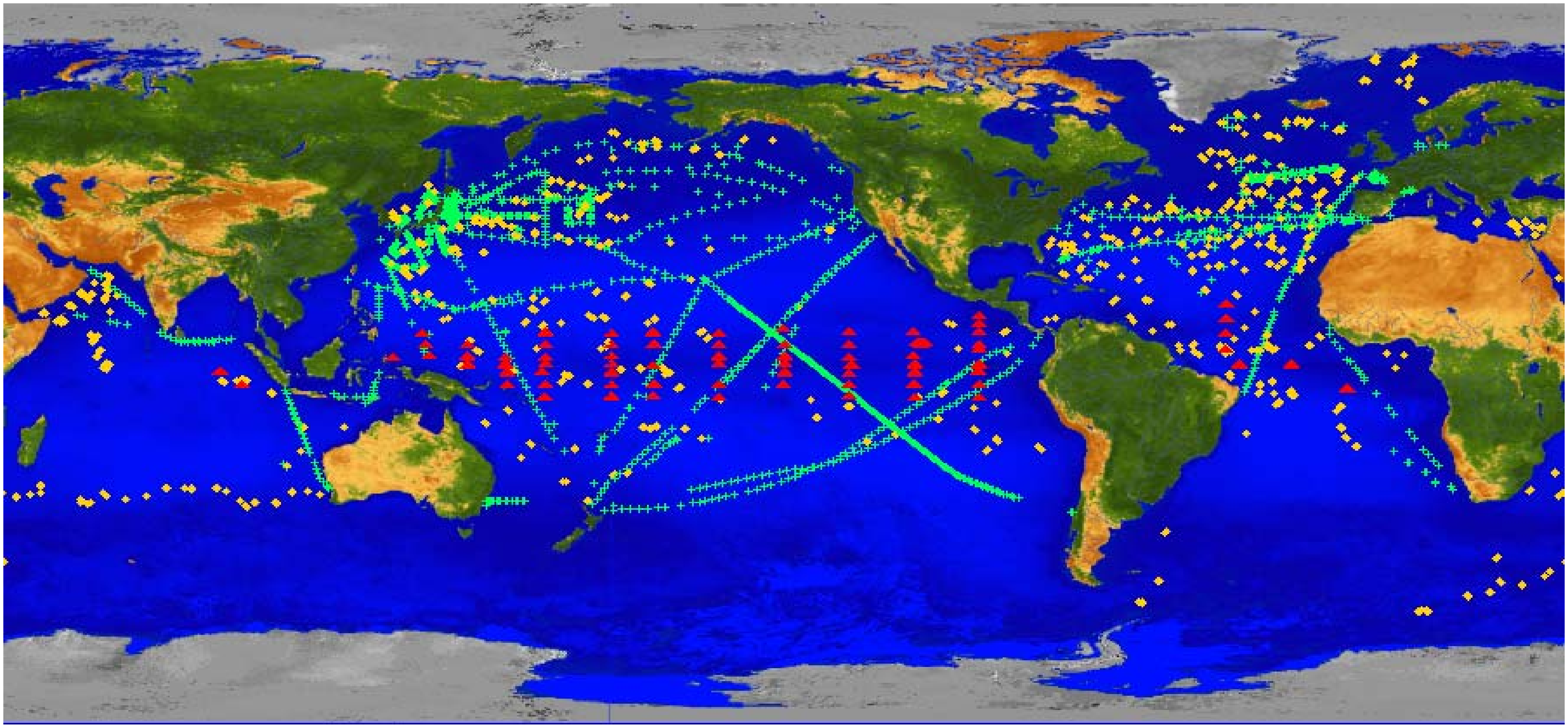
HOPE + OI

- **Different methods for combining SL with InSitu Data**
- **OSE experiments**
- **Assimilation of Salinity data**
- **Dealing with model error**

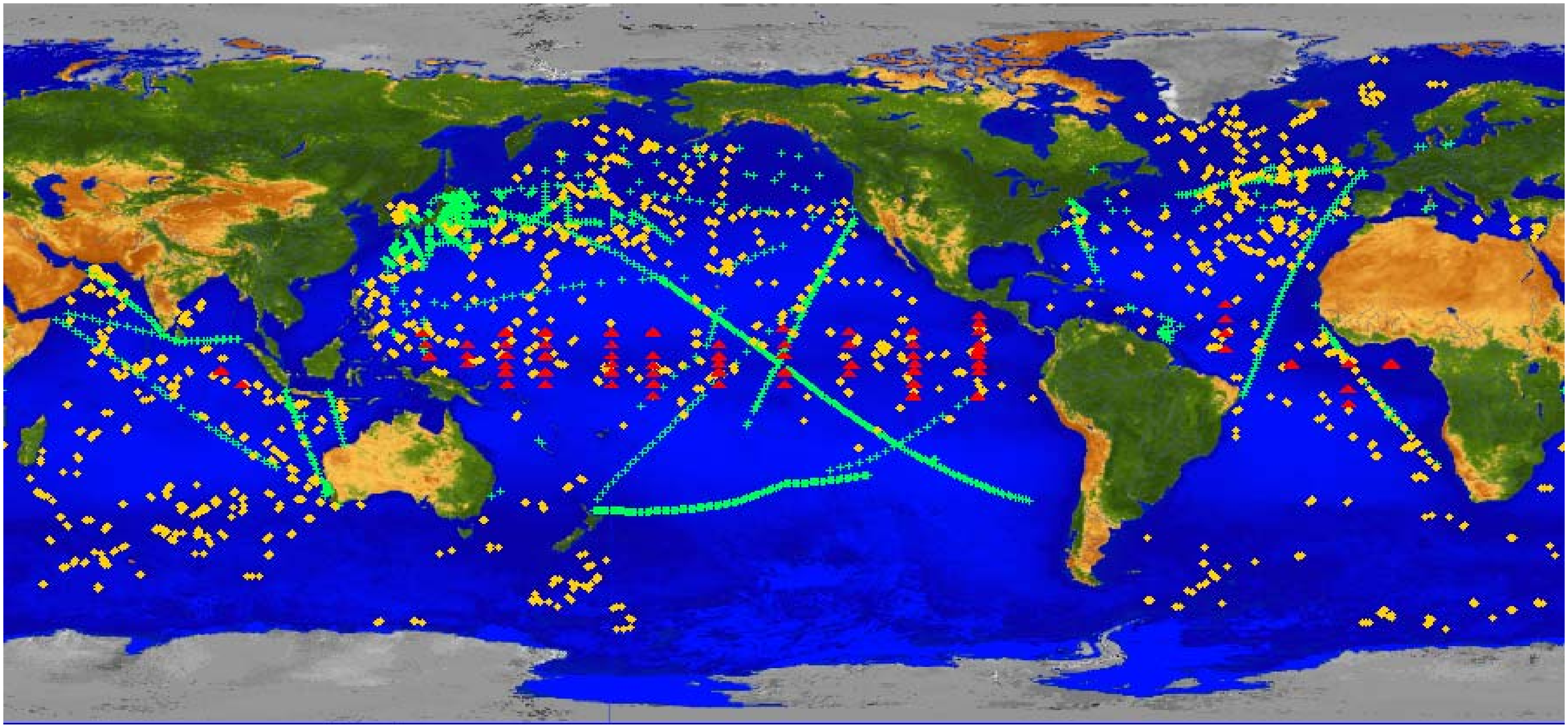
OPA-VAR

- **Installing the ocean model (ongoing)**
- **Installing (& integrating) the variational system (Weaver lecture)**

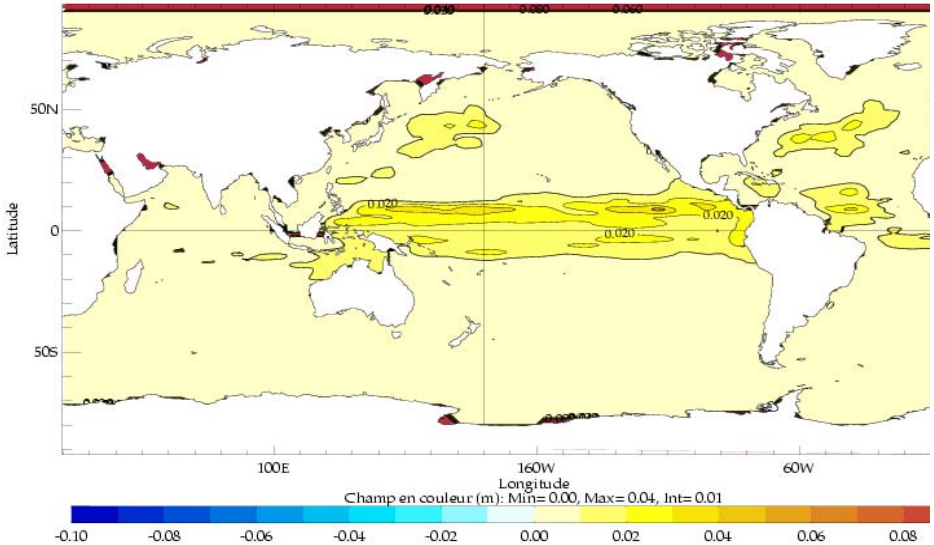
Data coverage for May 2002



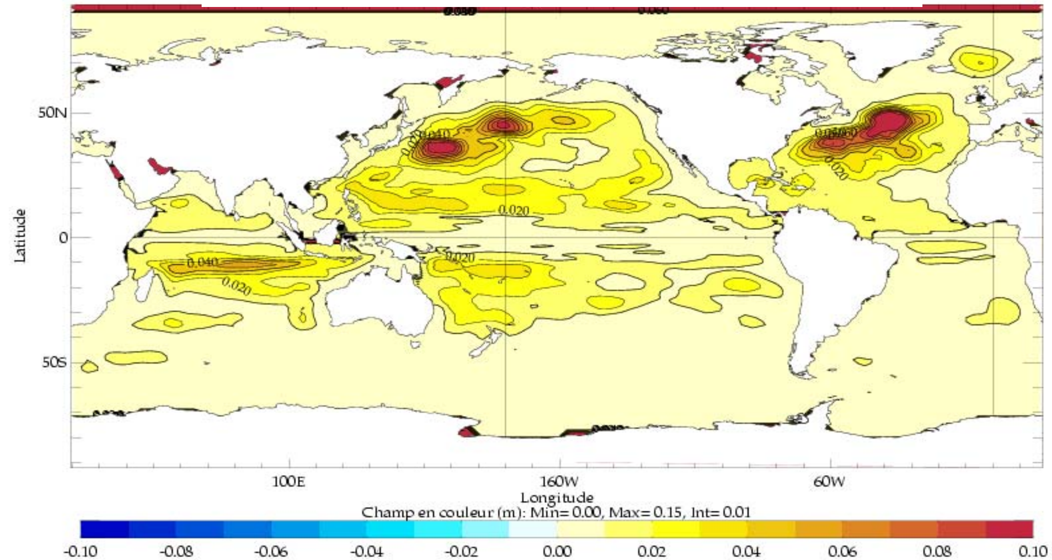
Data coverage for May 2003



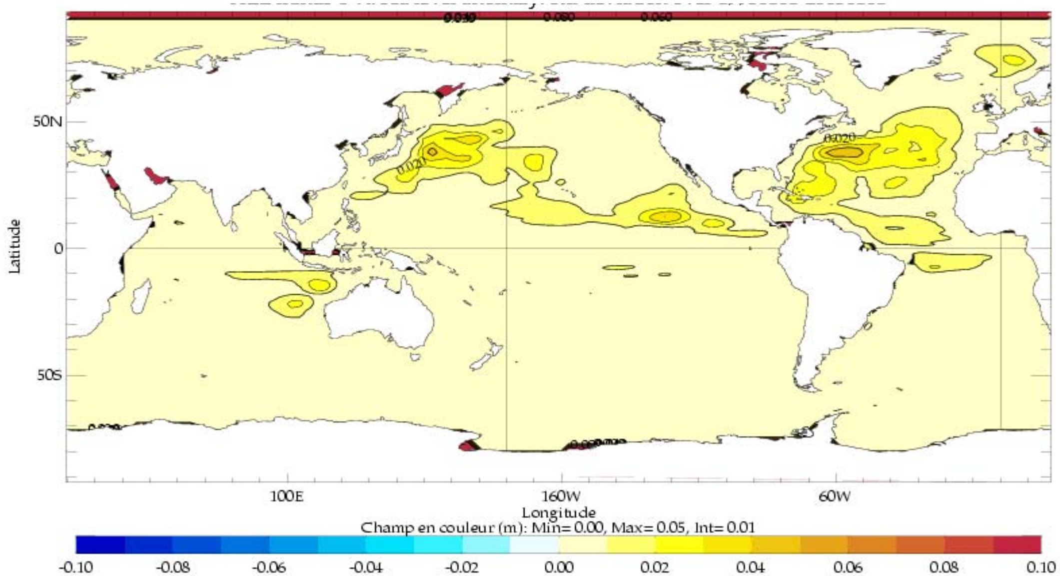
RMS: ALL - Moorings



RMS: ALL - XBT



RMS: All-ARGO



Impact of Different Data types

Variable: Surface Elevation

Time Period: 1998-2003

From A. Vidard

What Next?

Longer time scales

- Era40 offers the possibility of longer ocean Reanalysis:

  a) Calibration for Seasonal Forecasts

  b) Decadal Predictions

- Decadal variability is an issue:
  - Controlling model error
  - Assimilation in the deep ocean

Shorter time scales

- Monthly Forecasts already requires a more timely ocean analysis

  Accelerated ocean analysis

- Possibility of using a coupled model for Medium Range Forecast

  How to initialize the ocean component?

ENACT:
ENhance ocean data Assimilation and ClimaTe

- (A). Improve and extend ocean data assimilation systems, and apply them to produce global ocean analyses over a multi-decadal period.

- B). Quantify the benefits of the enhanced assimilation systems through retrospective seasonal and multi annual climate forecasts and through analysis of ocean behaviour in a multi-model framework

ENACT

- Forcing fields from ERA40
- Comprehensive Ocean Obs data set + QC procedure (provided by the UKMO)
- Development and Implementation of different Ocean Data assimilation Methods

  (3D-var,4-Dvar,EnKF…)

It will allow the comparison of assimilation methods

- Development of diagnostics for Ocean D-A
- First trial of decadal forecasts with coupled models

ENACT: Framework of ODA systems

OGCM	scheme	partner
OPA	4d-var 3d-var	CERFACS/LODYC
OPA	generic EnKF	NERSC/ECMWF
OPA	OI-type (SOFA)	INGV
C-HOPE	4d-var	MPIM
C-HOPE E-HOPE	generic EnKF 4d-var	KNMI
E-HOPE	OI-type	U-READING/ECMWF
GLOSEA	OI-type	Met Office

Summary

- Ocean data assimilation improves the state estimate of the tropical ocean
- Initialization of ocean models by means of data assimilation improves the forecast of ENSO
- The existence of model/forcing error in ocean data assimilation can not be ignored.
- The importance of balance relationships has been illustrated
  - The operational environment is ideal to spot problems
- The choice of a data assimilation method can not be independent of the application

Future Directions

Method:

- Implementation of OPA-VAR at ECMWF
  - Treatment of model error
  - Comparison of 4Dvar/EnKF
  - Development of internal diagnostics

Observations:

•Assimilate in Situ Temperature/ SL /Salinity

• OSE experiments

•Further diagnostics

Questions:

1. Feedback to the atmospheric community?
   Should the atmospheric reanalysis include an ocean model in the future?
2. Different methods for different problems?
   Initializing the ocean for NWP versus Seasonal