Initialization of Coupled Models for climate Forecasts

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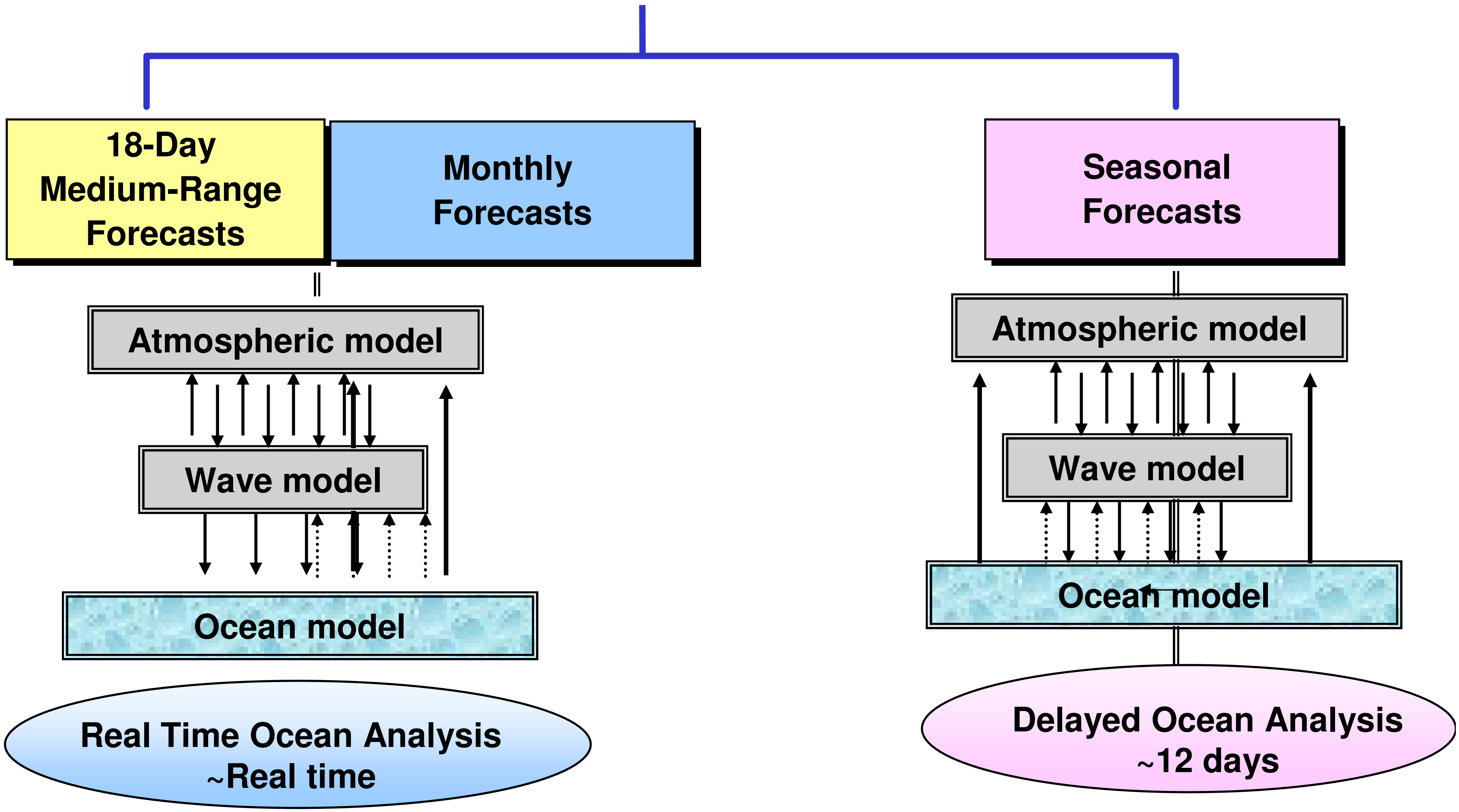
ECMWF

ECMWF:
Weather and Climate Dynamical Forecasts



Outline

- The importance of the ocean initial conditions in long range forecasts
  - A well established case: ENSO in the Equatorial Pacific and Seasonal Forecasts
  - A tantalizing case: decadal forecasting
- Ocean Model initialization in Seasonal Forecasting
  - Ocean initialization: requirements
  - Standard practice: assessment
  - Role of ocean initialization into context
- Different Initialization strategies
  - Assessment of initialization strategies
  - Comments on coupled data assimilation.

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 (ocean, snow cover, sea ice, soil moisture...).
  - ➢ Here we focus on the ocean

Basis for long-range predictability

- Ocean is responsible for the slow time scales
  - The ocean has a large heat capacity and slow adjustment times relative to the atmosphere.
- Atmospheric response to ocean forcing: very sensitive to the structure, location, and amplitude of the ocean forcing.
  - The atmosphere responds more readily to large-scale spatial forcing.
  - Conventional idea : In the mid-latitudes, the atmosphere is not sensitive to SST anomalies less than about 1C. Thus, the atmospheric response to ocean forcing is very weak. This idea is being revisited.
  - However, in the tropics, the atmosphere is quite sensitive to SST anomalies, implying a stronger response to a given temperature anomaly.
- Without any atmospheric response to boundary forcing, there can be no interannual-decadal atmospheric variability, due to the short time scale of intrinsic atmospheric variability.

Hasselmann 1976, Saravanan et al 2000,
Latif et al 2002, Timmermann 2005…

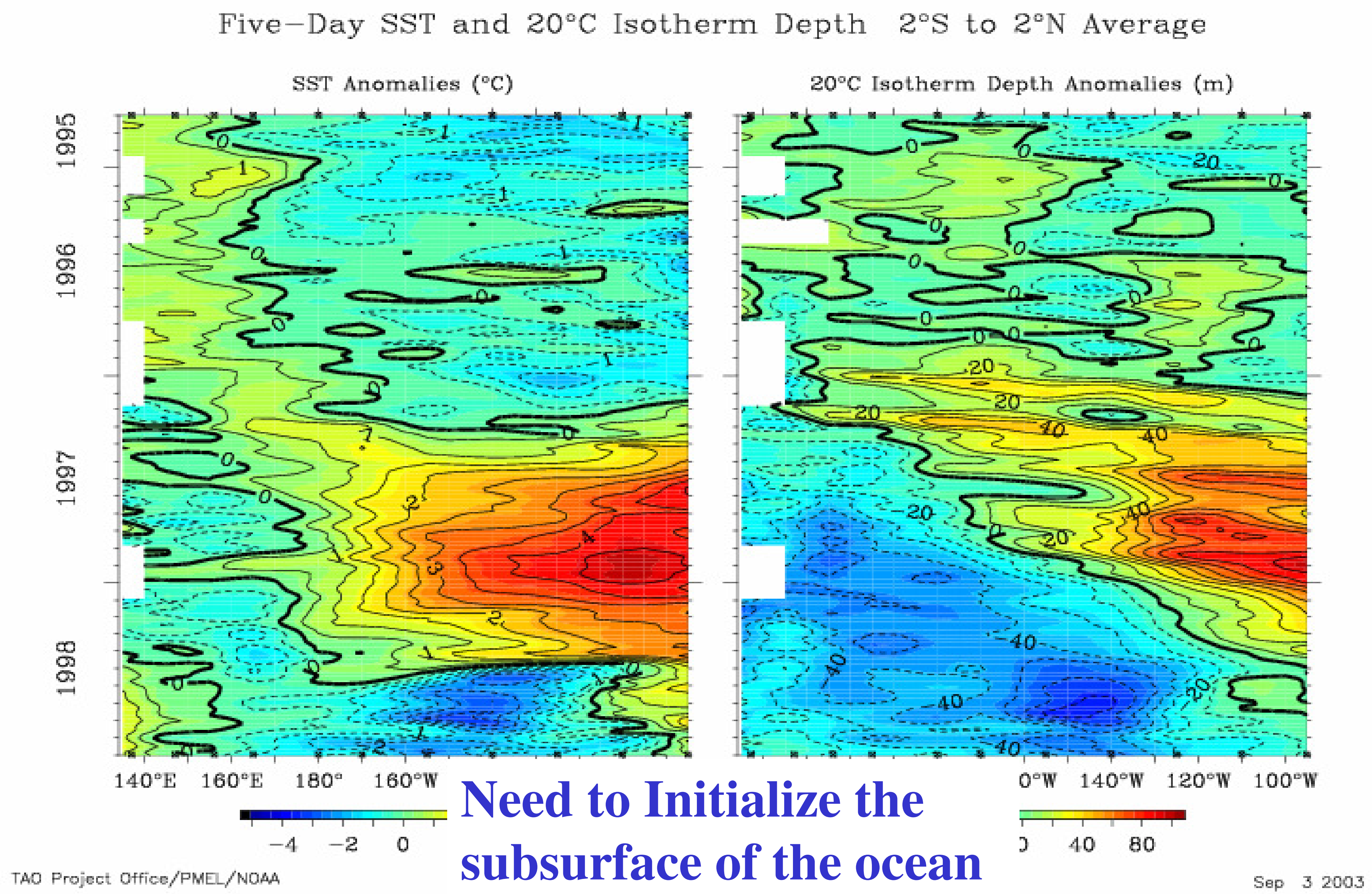
The Basis for Extended Range Forecasts

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

"Loaded dice"

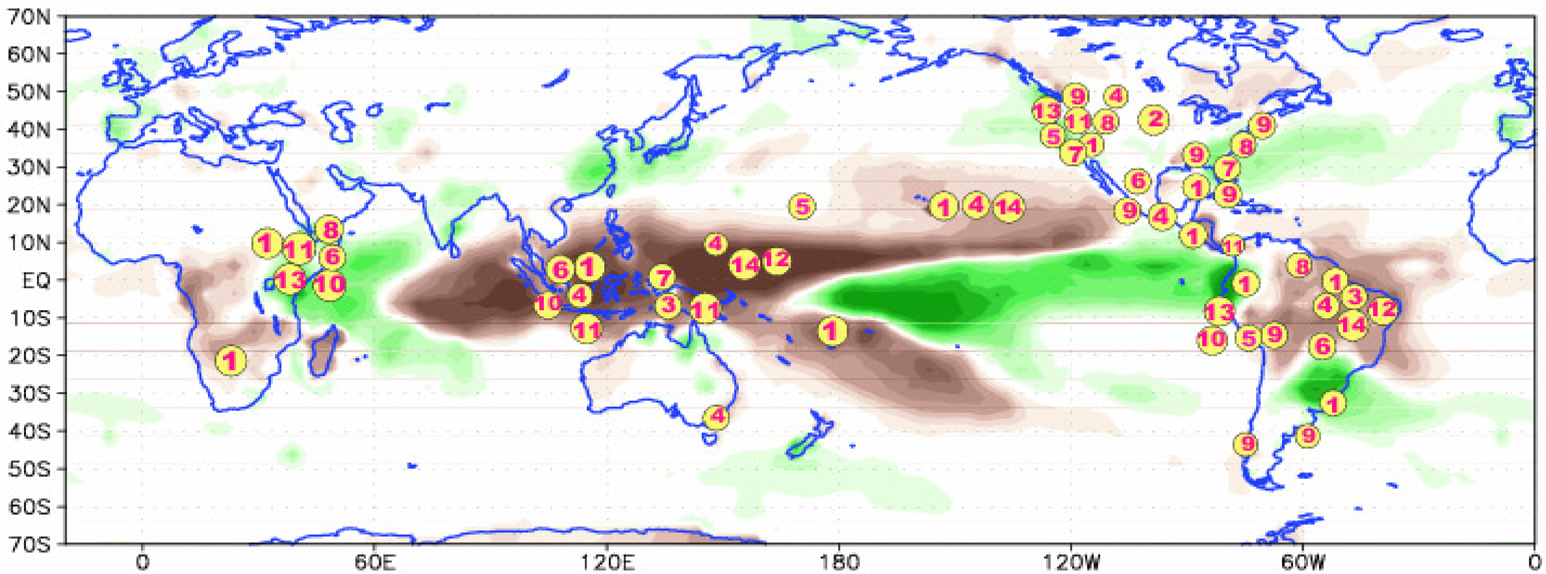
  - The lower boundary conditions (SST, land) have longer memory
    - **Higher heat capacity (Thermodynamic argument)**
    - **Predictable dynamics**

- *Oceanic point of view: Initial value problem*
  - *Prediction of <u>tropical</u> SST: need to initialize the ocean subsurface.*
  - *Examples:*
    - *A well established case is ENSO*
    - *A more tantalizing case is the importance of the ocean initial conditions for decadal forecasts.*



Need to Initialize the subsurface of the ocean

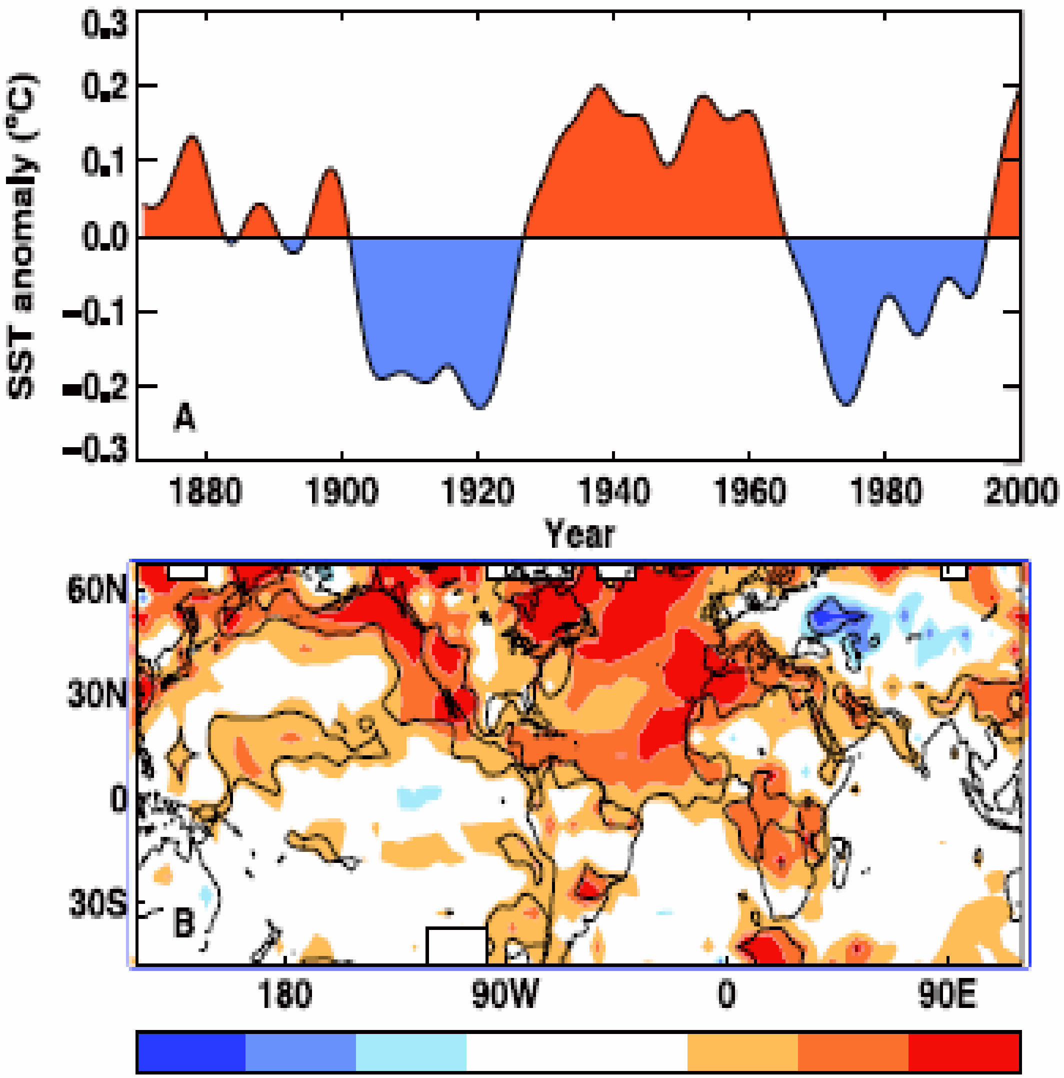
Societal Impacts from 1997/98 El Niño



1. Crop/Stock Damage
2. Energy Savings
3. Famine
4. Fires
5. Fisheries Disruption
6. Health Risks
7. Human Fatalities
8. Pests Increased
9. Property Damage
10. Tourism Decreased
11. Transportation Problems
12. Social Disruptions
13. Wildlife Fatalities
14. Water Rationing

Climate Prediction Center

Atlantic Multidecadal Oscillation: AMO



From King et al 2005

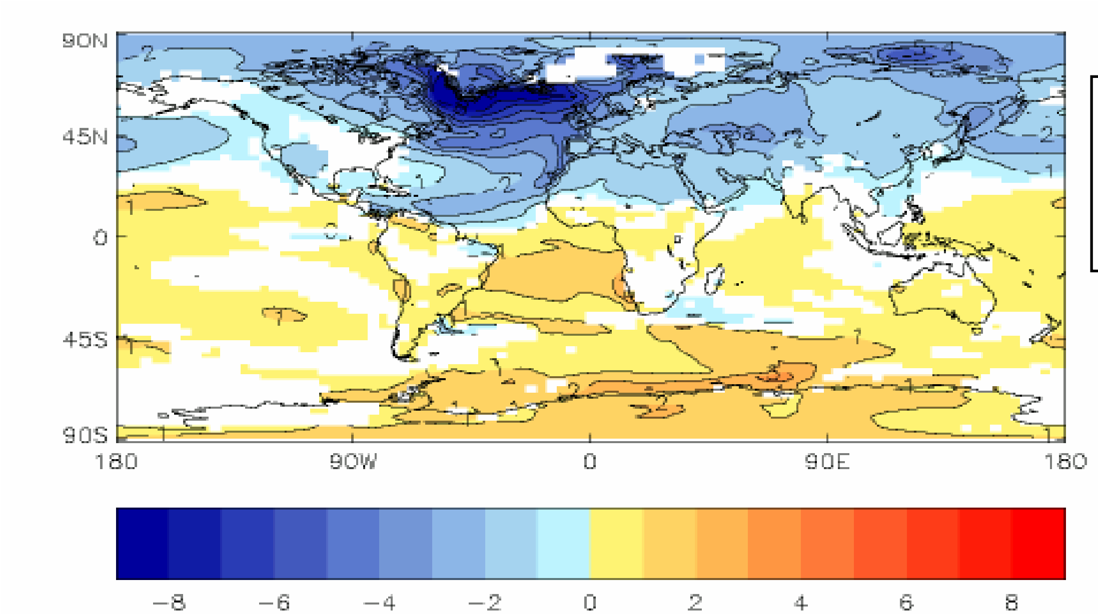
- **Changes in the AMO linked to NE Brazil and Sahel rainfall, North Atlantic hurricane frequency, European and North American climate**

  Warm AMO phase during the 40-50's associated to decreased NE Brazil rainfall, increased Sahel rainfall, increased hurricane frequency

- **Evidence from observations and model studies**.

- Is it predictable? **Do ocean initial conditions play a role? Is it connected with the AMOC (Atlantic Meridional Overturning circulation)?**

Atlantic Variability and Climate Change

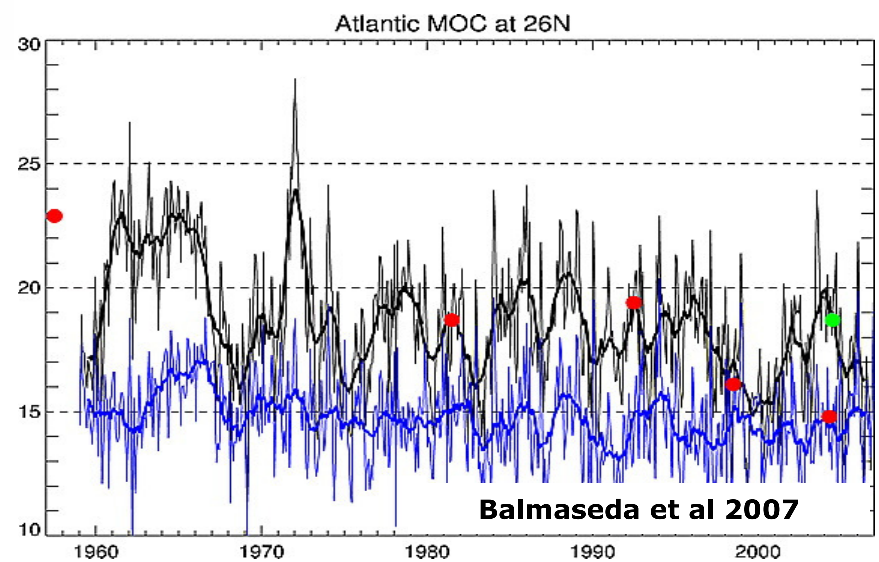


Vellinga and Wood 2002:

Surface Air Temperature change 20-30 years after the THC slowdown by large fresh water input. The THC recovers after 120 years

Assimilating ocean data (black line, right panel) influences the MOC. Without assimilation the MOC is weaker? Does it matter for the decadal forecasts?

Atlantic MOC



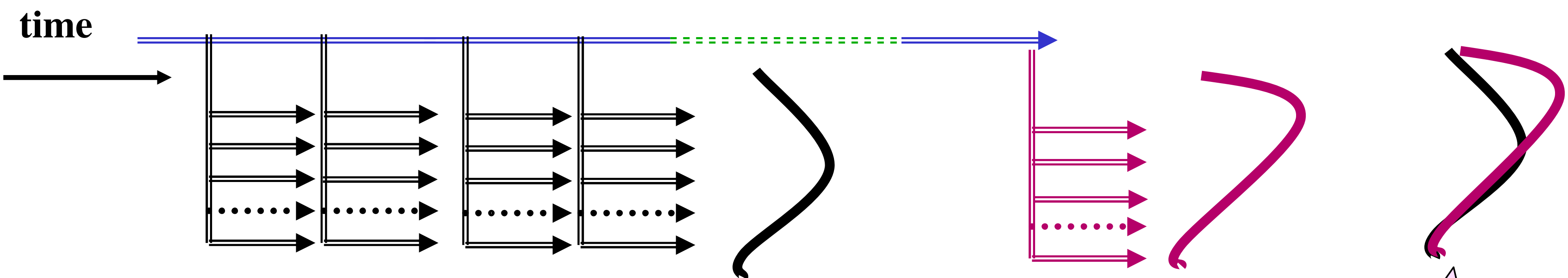
The Example of Seasonal Forecasting

- **Initial Conditions**
- Ensemble generation
- Coupled integrations
- **A-posteriori Calibration**
- **Skill Assesement**

Main Objective: to provide ocean Initial conditions for coupled forecasts

Ocean reanalysis

Real time Probabilistic Coupled Forecast



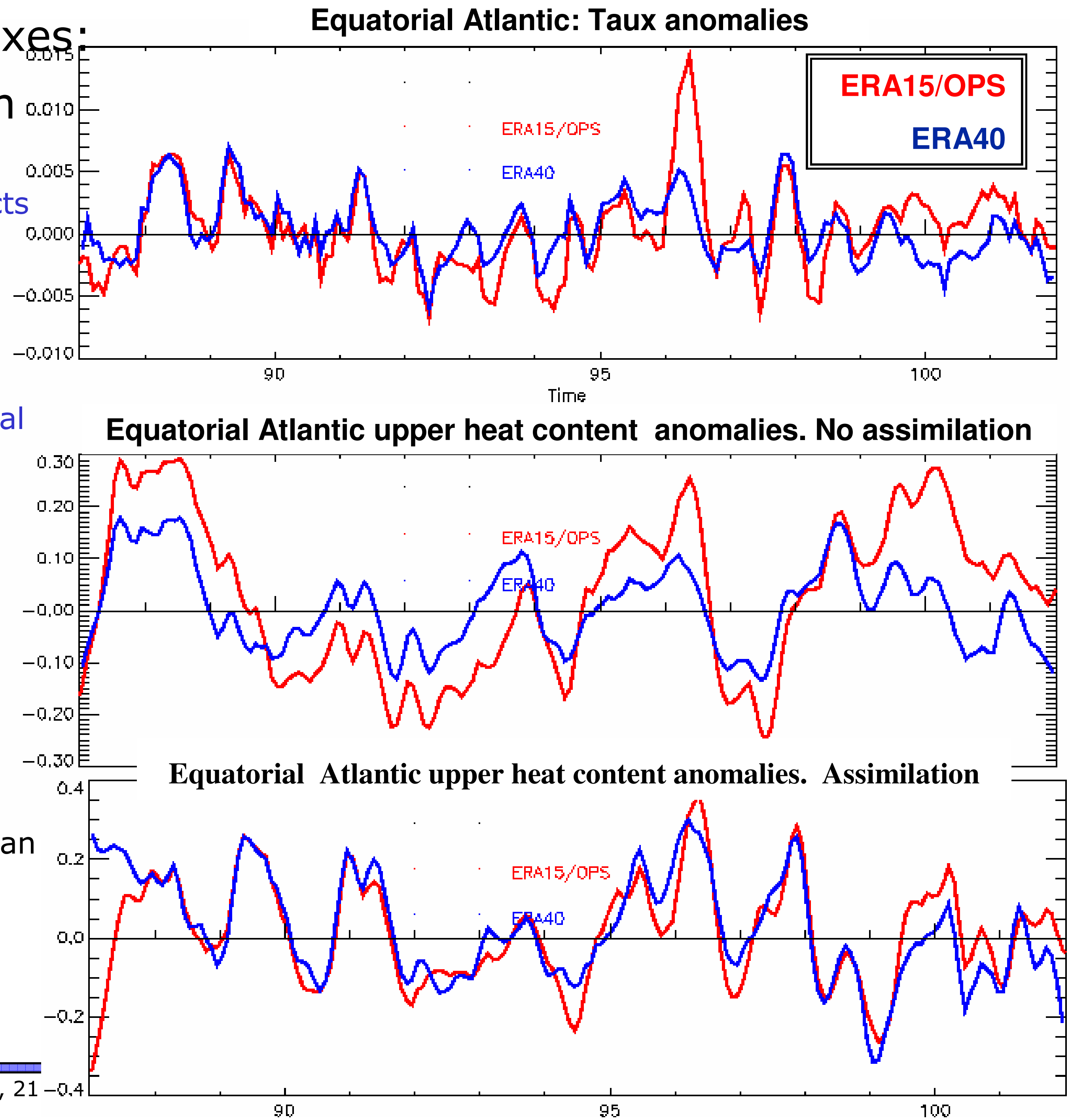
Coupled Hindcasts, needed to estimate climatological PDF, require a **historical ocean reanalysis**

Quality of reanalysis affects the climatological PDF

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

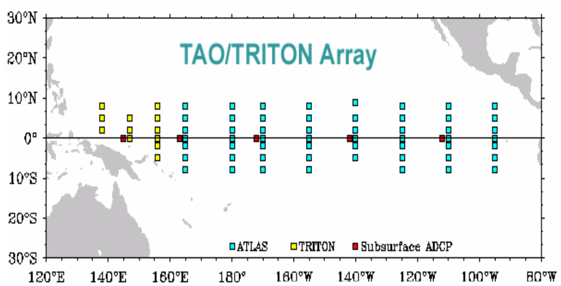
Uncertainty in Surface Fluxes: Need for Data Assimilation

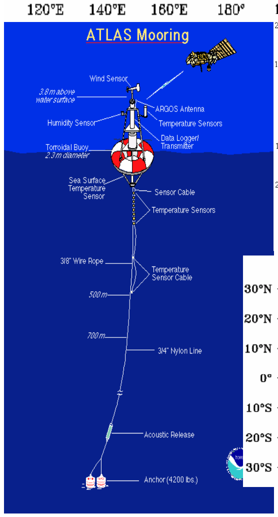
- Large uncertainty in wind products lead to large uncertainty in the ocean subsurface
- The possibility is to use additional information from ocean data (temperature, others…)
- Questions:
  1. Does assimilation of ocean data constrain the ocean state?
  2. Does the assimilation of ocean data improve the ocean estimate?
  3. Does the assimilation of ocean data improve the seasonal forecasts

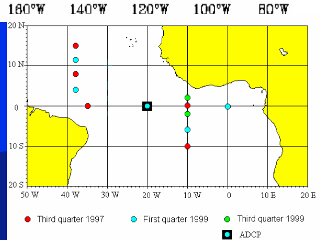


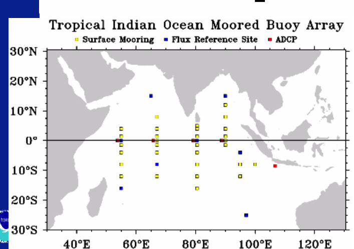
Real Time Ocean Observations

Moorings

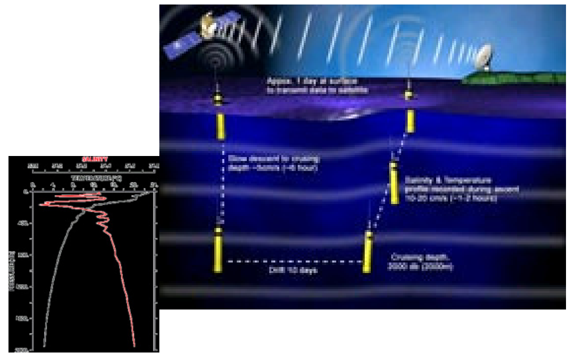


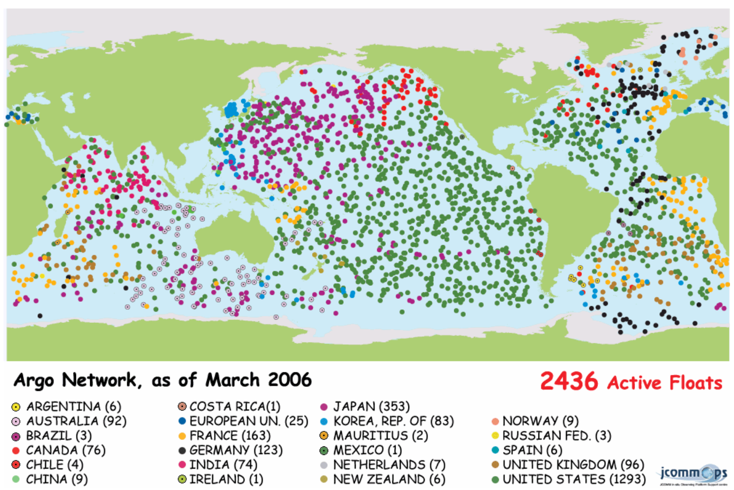




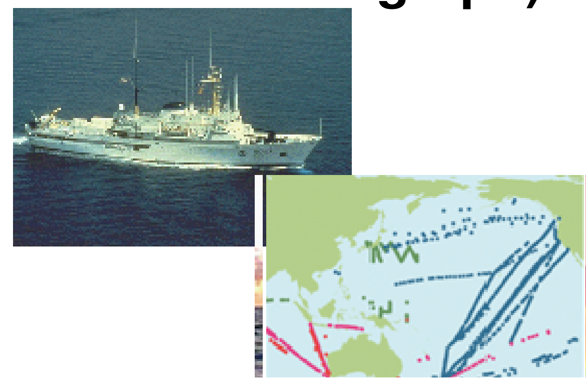


ARGO floats

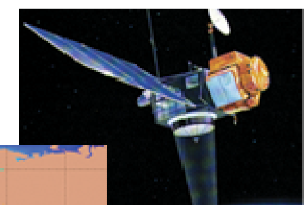


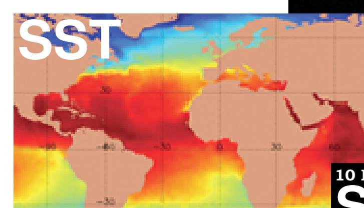


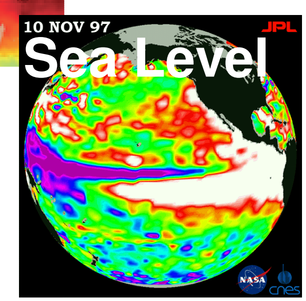
XBT (eXpandable BathiThermograph)



Satellite







ECMWF Ocean Re-Analysis S3 (ORA-S3)

- Main Objective: Initialization of seasonal forecasts
  - ➢ Historical reanalysis brought up-to-date (11 days behind real time)
  - ➢ Source of climate variability

Main Features

•ERA-40 daily fluxes (1959-2002) and NWP thereafter

•Retrospective Ocean Reanalysis back to 1959

•Multivariate on-line Bias Correction (pressure gradient)

•Assimilation of temperature, salinity, altimeter sea level anomalies an global sea level trends.

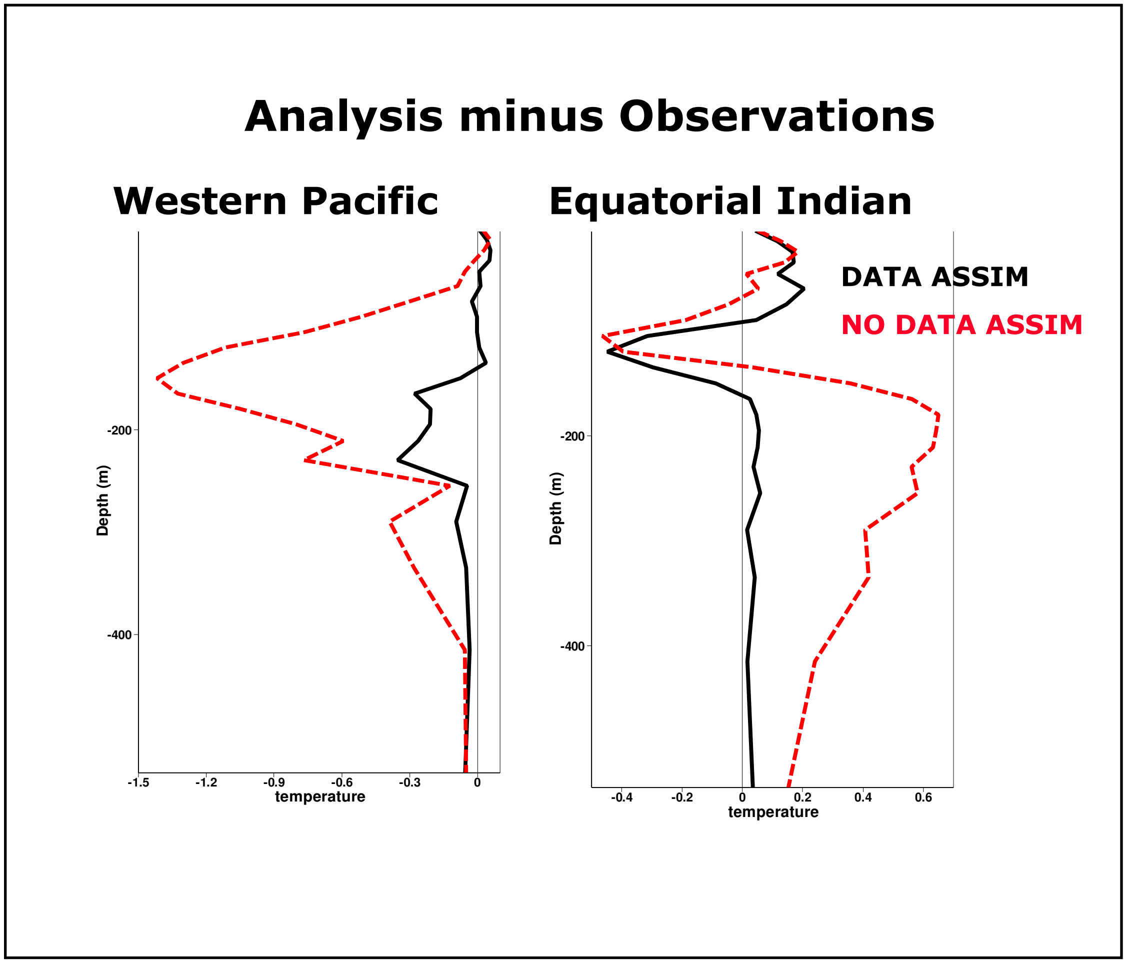
•3D OI, Salinity along isotherms

•Balance constrains (T/S and geostrophy)

•Sequential, 10 days analysis cycle, IAU

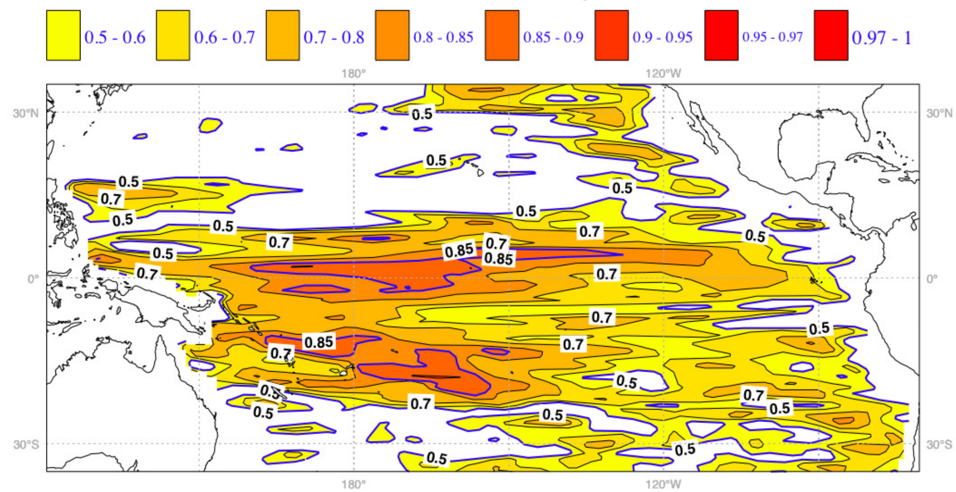
Balmaseda etal 2008

The Assimilation corrects the ocean mean state

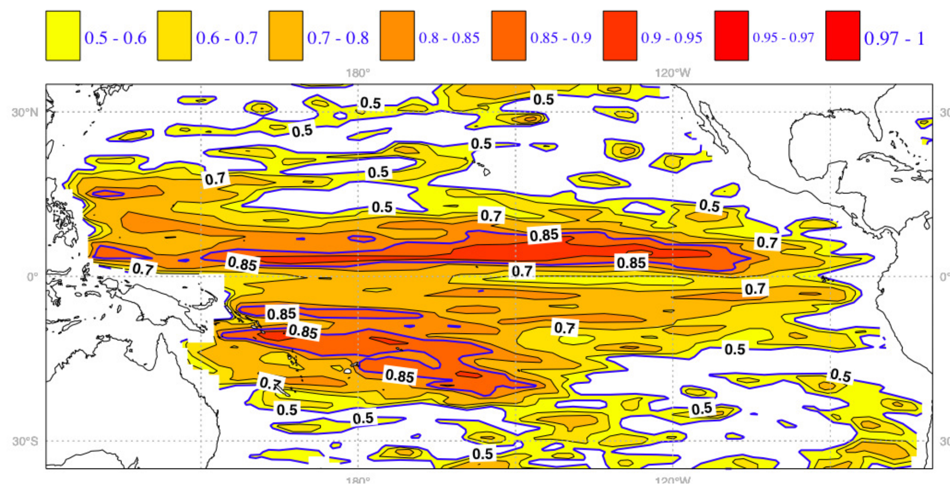


Data Assimilation improves the interannual variability of the ocean analysis

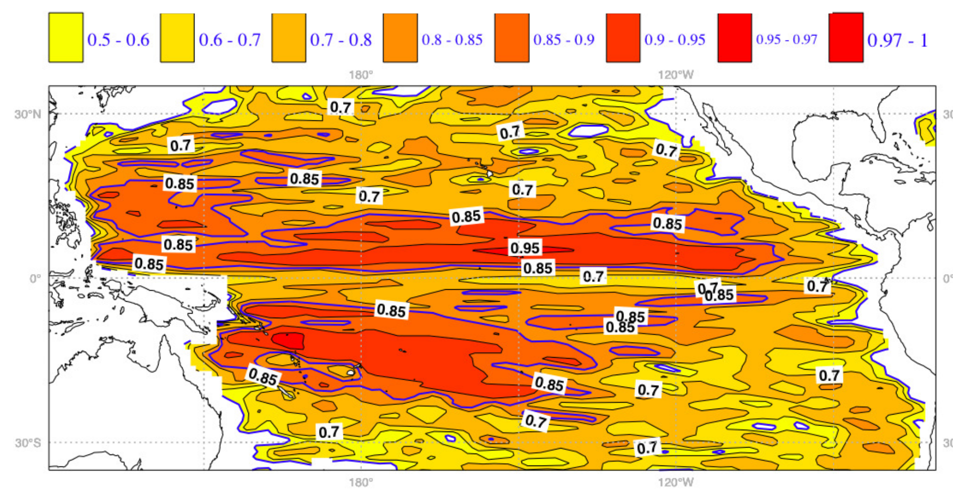
No Data Assimilation



Assimilation:T+S



Assimilation:T+S+Alt



Correlation with OSCAR currents

Monthly means, period: 1993-2005

Seasonal cycle removed

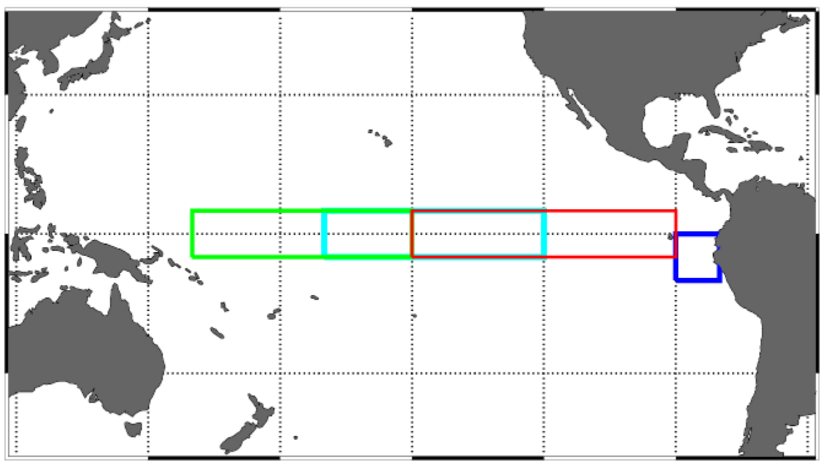
Impact of Data Assimilation

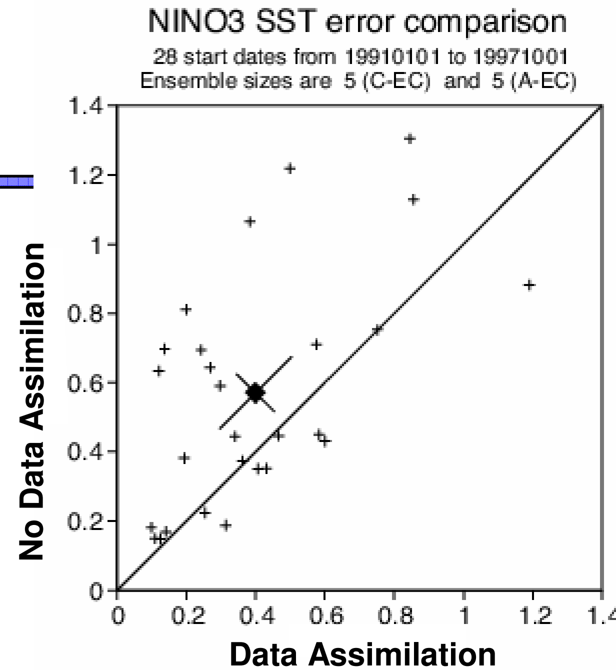
Forecast Skill

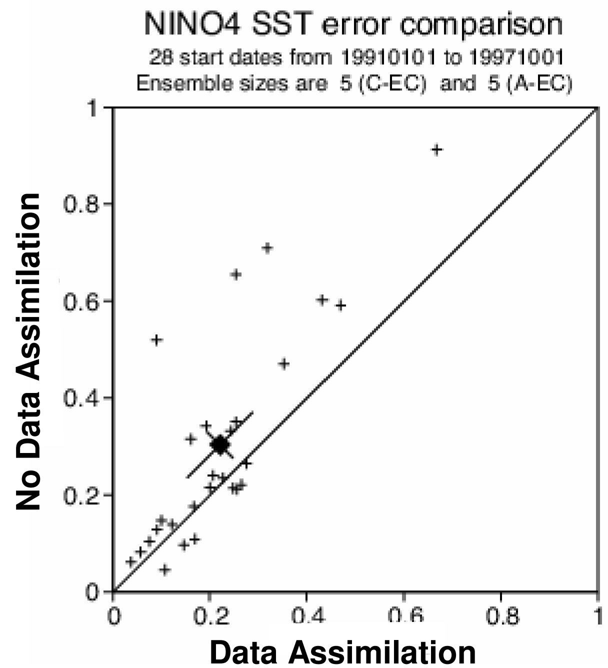
Ocean data assimilation also improves the forecast skill

(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]





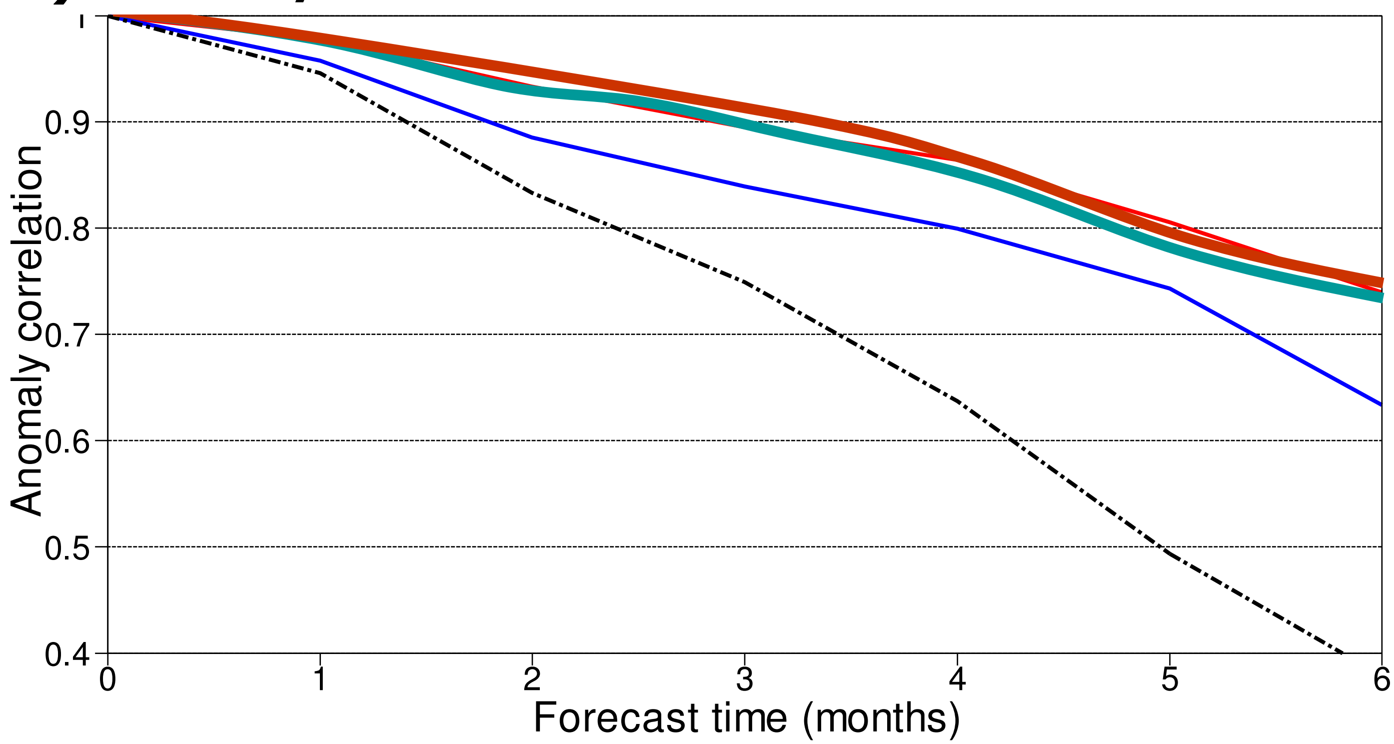


So far so good, but:

- Progress is not monotonic:
  - ➢ Need good coupled models to gauge the quality of initial conditions

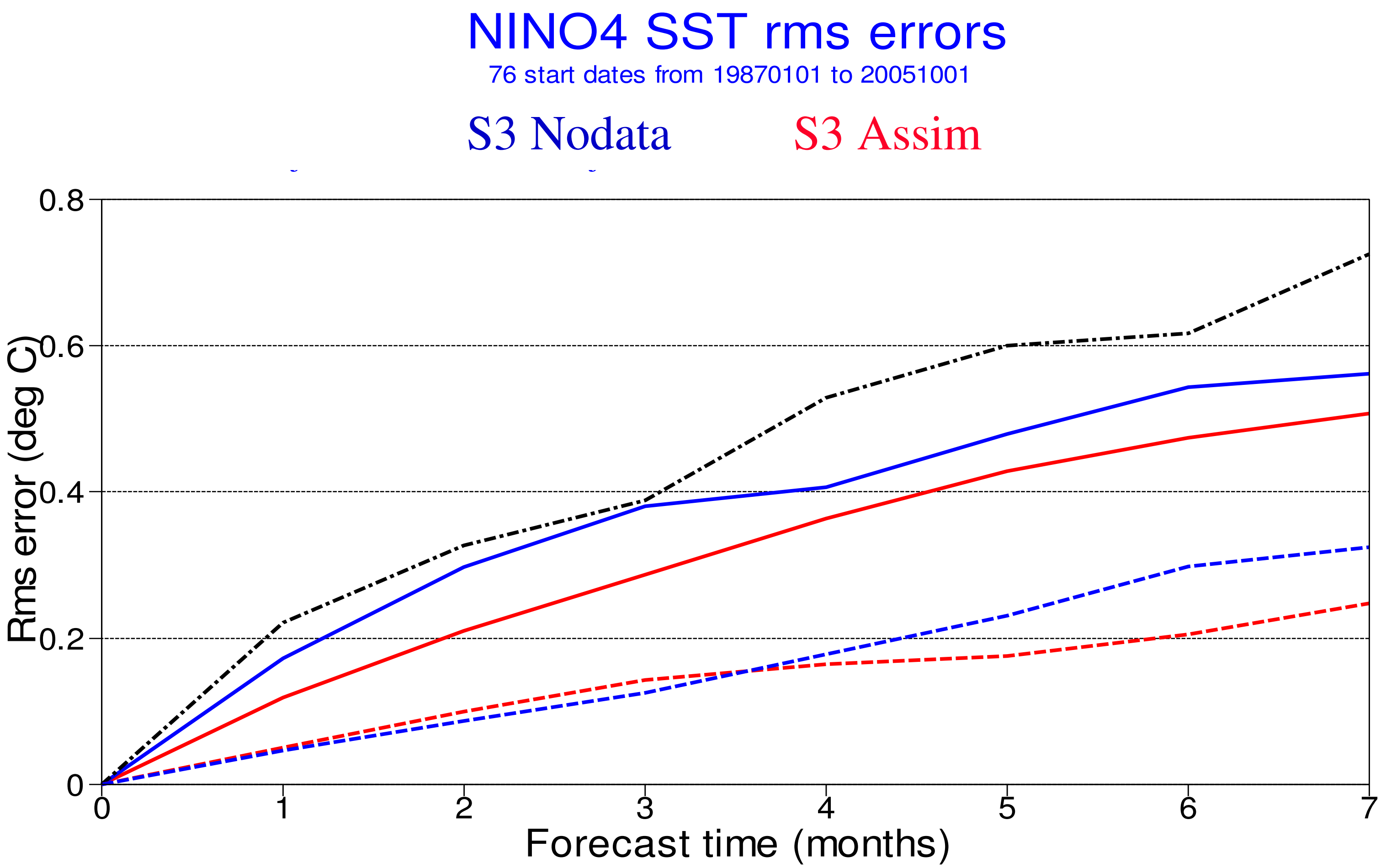
a) ERA15/OPS fluxes S2 NO Asim S2 Assim

b) ERA40/OPS fluxes DEM NO Assim DEM Assim



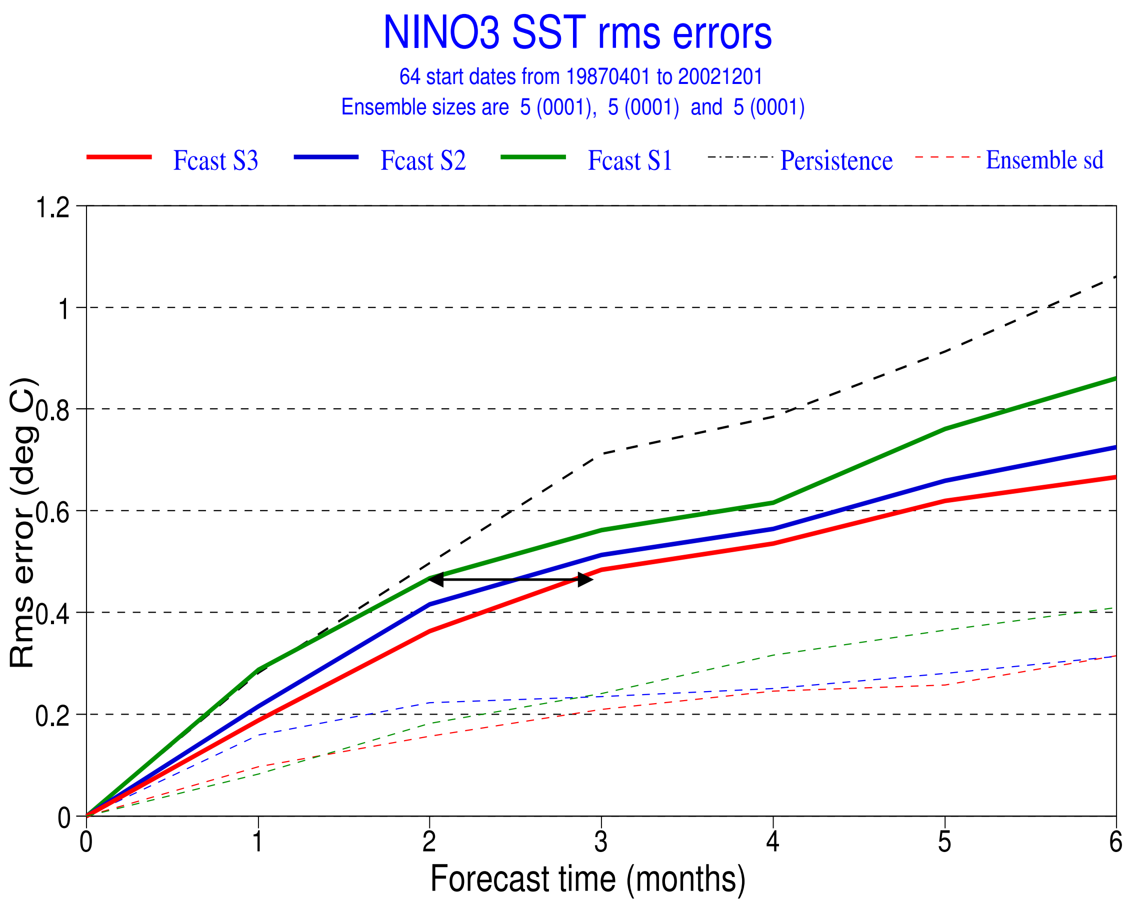
Skill can be limited by the quality of the coupled model

Impact on ECMWF-S3 Seasonal Forecast Skill



Progress on ENSO forecast

Past 10 years (ECMWF)



- In the last 10 years there have been 3 operational SF at ECMWF (S1,S2,S3)
- Slow but Steady progress: ~1 month/decade skill gain
- The improvement is due to both improvement in the coupled model and ocean initial conditions

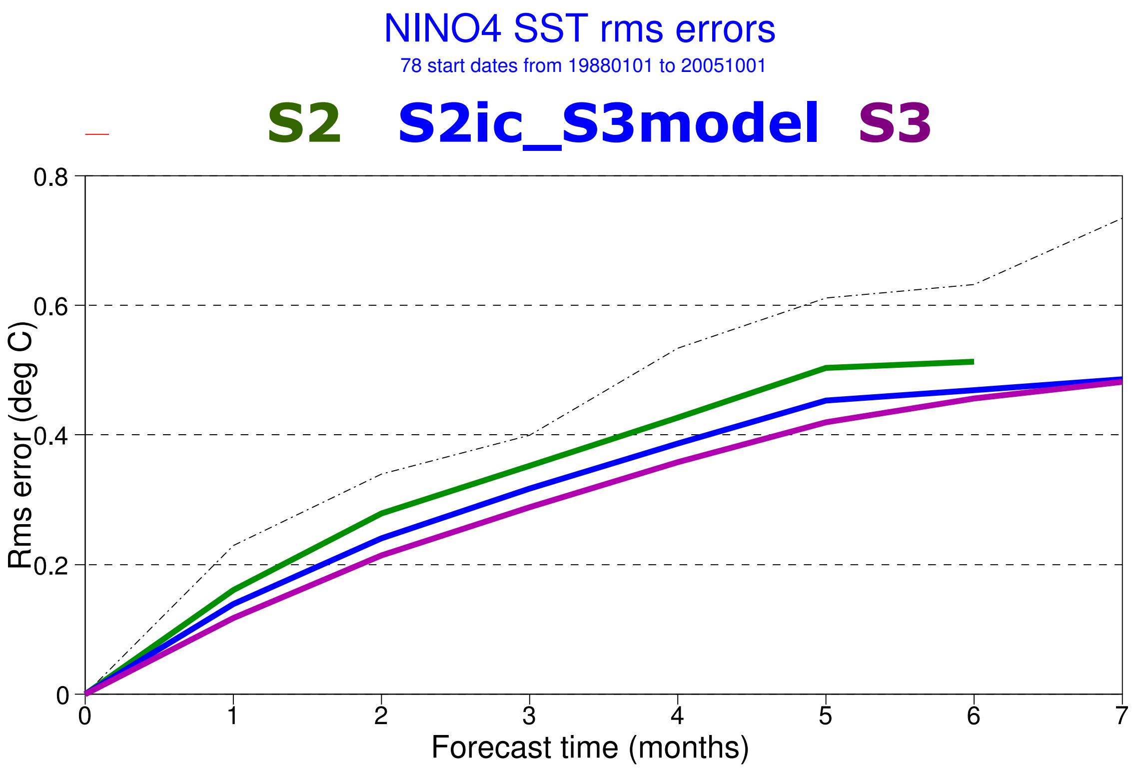
S1 S2 S3

Initialization into context

Ocean Initial Conditions

Versus

Coupled Model



Some general considerations on initialization

Initialization Problem: Production of Optimal I.C.

- Optimal Initial Conditions: those that produce the best forecast.
  - Need of a metric: lead time, variable, region (i.e. subjective choice)
  - In complex non linear systems there is no “objective searching algorithm” for optimality. The problem is solved by subjective choices.
- Theoretically:
  - I.C. should represent accurately the state of the real world.
  - I.C. should project into the model attractor, so the model is able to evolve them.

    In case of model error the above 2 statements may seem contradictory
- Practical requirements:
  - If forecasts need calibration, the forecast I.C. should be “consistent” with the I.C. of the calibrating hindcasts. ***Need for historical ocean reanalysis***
- Current Priorities:
  - Initialization of SST and ocean subsurface.
  - Land/ice/snow potentially important. Not much effort so far …
  - Atmospheric initial conditions play a secondary role.

We choose a metric, forecasts of SST from 1-6 months.

Perceived Paradigm for initialization of coupled forecasts

Real world **Model attractor**

<u>Medium range</u>

Being close to the real world is perceived as advantageous. Model retains information for these time scales.

Model attractor and real world are close?

<u>Seasonal?</u>

<u>Somewhere in the middle**?**</u>

<u>Decadal or longer</u>

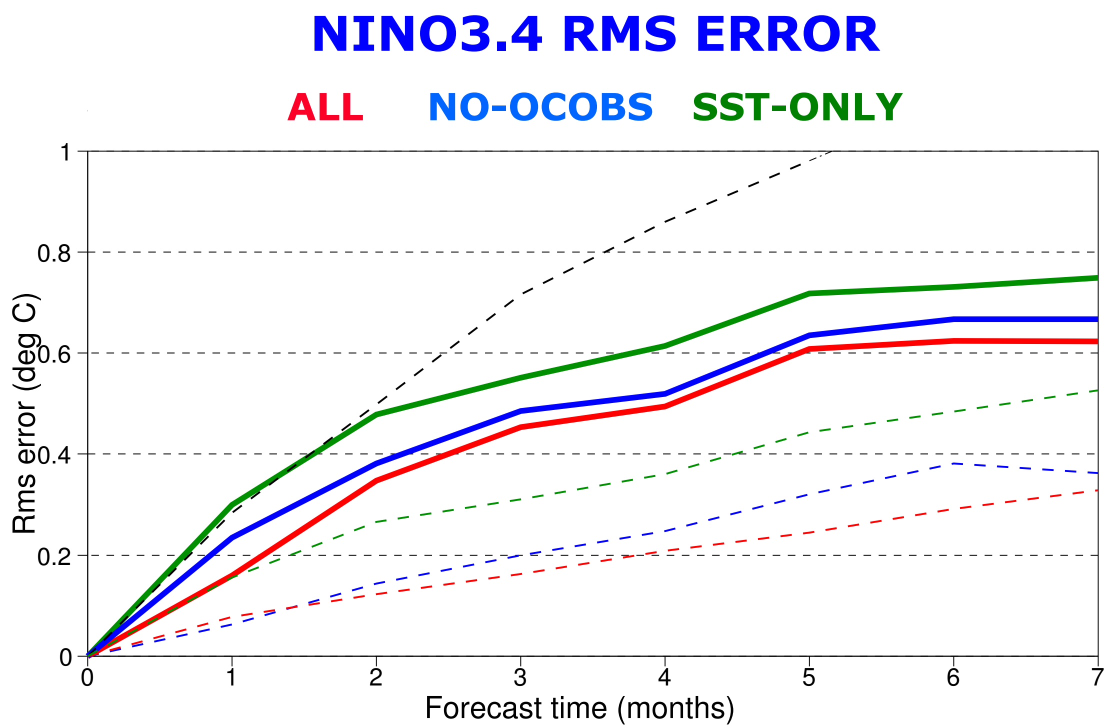
Need to initialize the model attractor on the relevant time and spatial scales.

Model attractor different from real world.

<u>At first sight, this paradigm would not allow a seamless prediction system.</u>

- **Experiments:**
  - **Uncoupled SST + Wind Stress + Ocean Observations (ALL)**
  - **Uncoupled SST + Wind Stress (NO-OCOBS)**
  - **Coupled SST (SST-ONLY)** **(Keenlyside et al 2008, Luo et al 2005)**

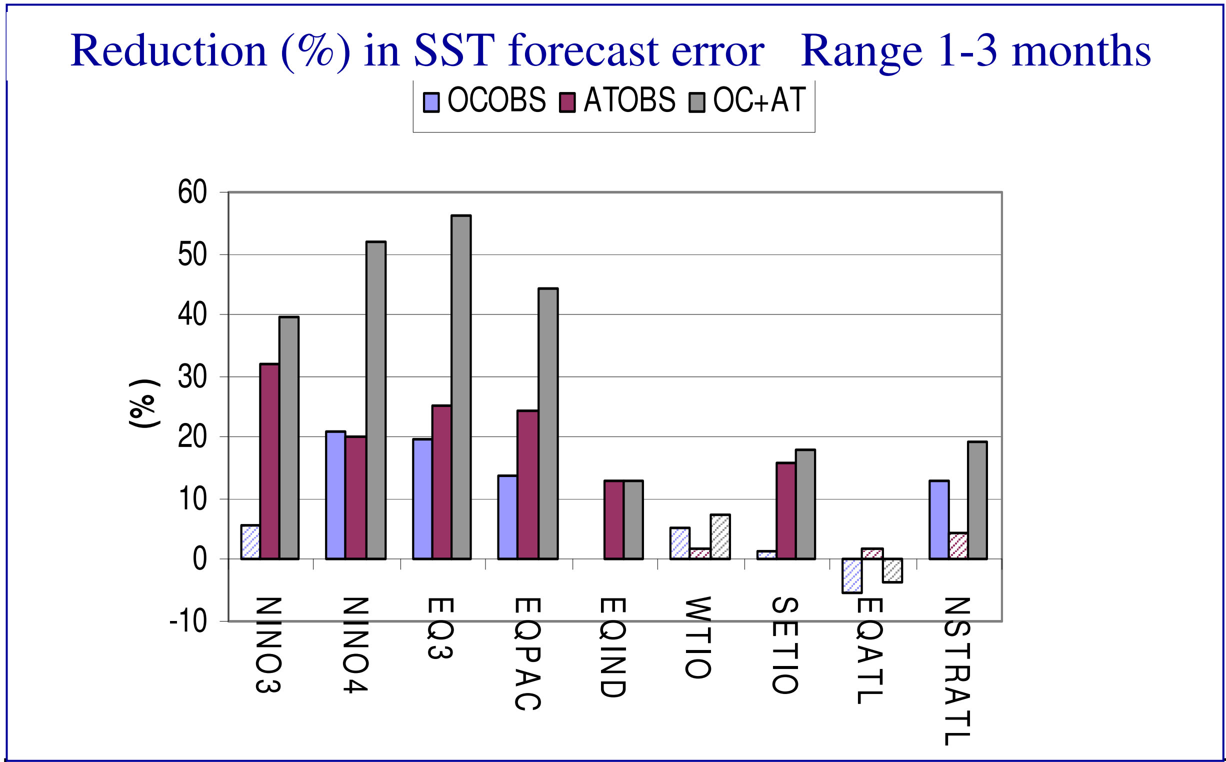
Impact of "real world" information on skill:

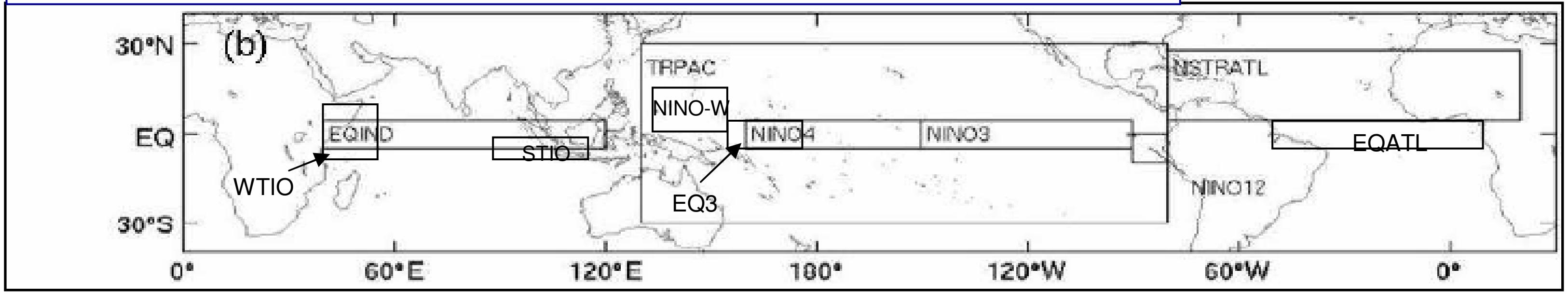


Adding information about the real world improves ENSO forecasts

From Balmaseda and Anderson 2009

Impact of "real world" information on skill:





In Central/Western Pacific, up to 50% of forecast skill is due to atmos+ocean observations.

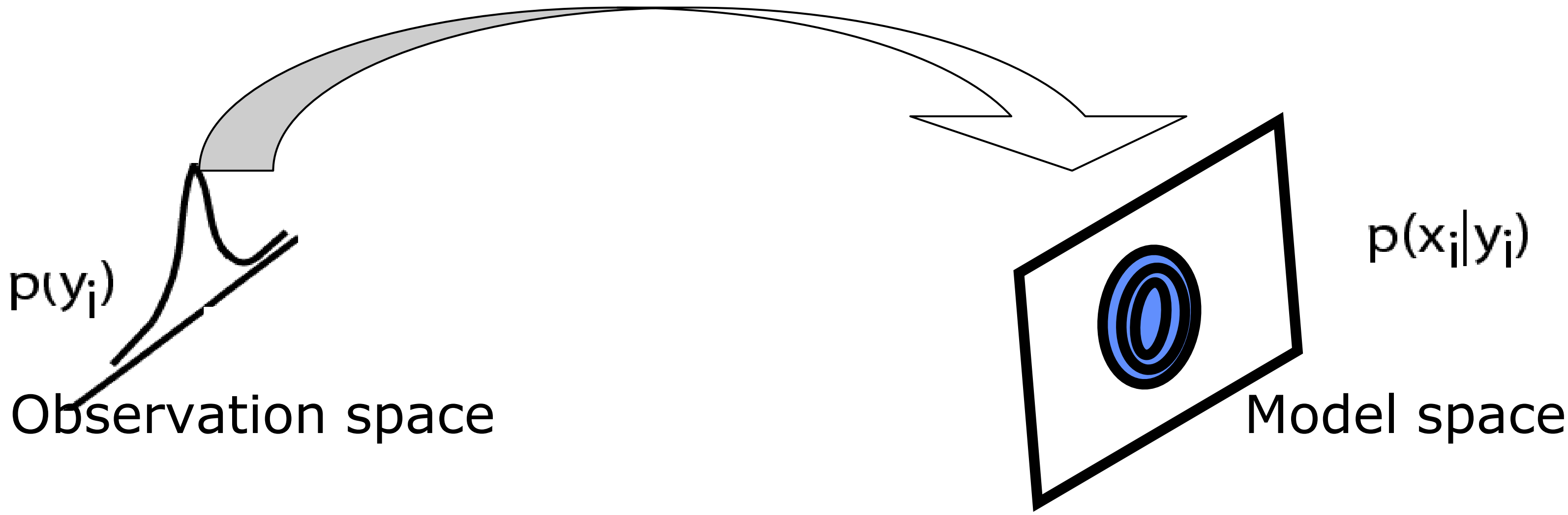
Sinergy: > Additive contribution

Ocean~20%

Atmos ~25%

OC+ATM~55%

Initialization of the model attractor does not mean neglecting observations.



Data Assimilation

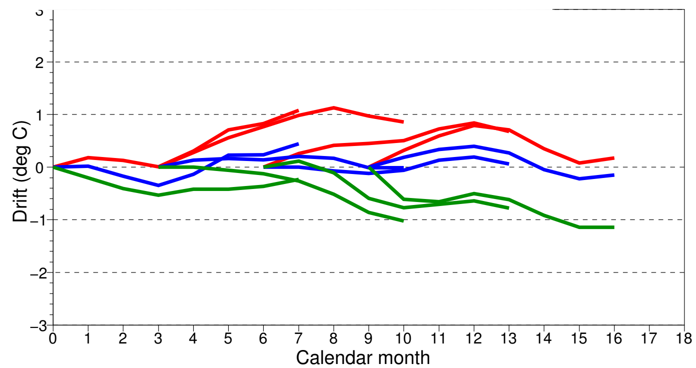
$$p(x_i \mid y_i) = \frac{p(y_i \mid x_i)\,p(x_i)}{p(y_i)}$$

The transformation from observation to model space should be scale dependent.

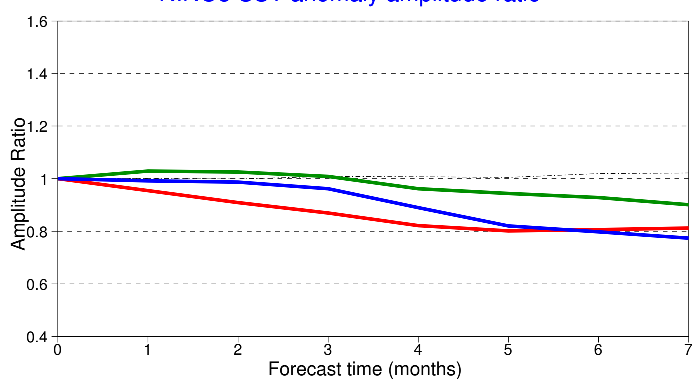
<u>The challenge for a seamless prediction system is the consistent/simultaneous initialization of the different time scales.</u>

Impact of Initialization

Eastern Pacific



NINO3 SST anomaly amplitude ratio



ALL

NO-OCOBS

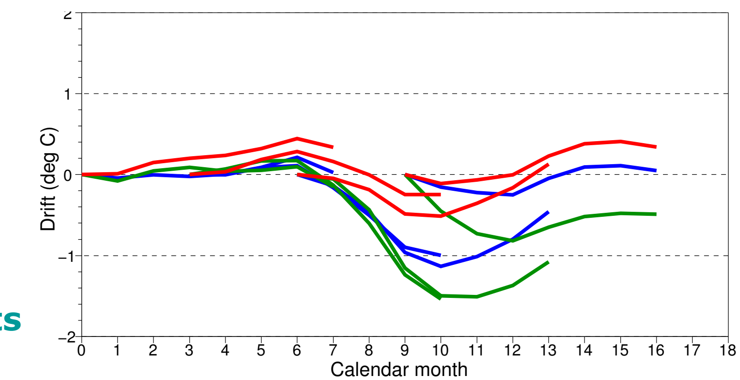
SST-ONLY

DRIFT

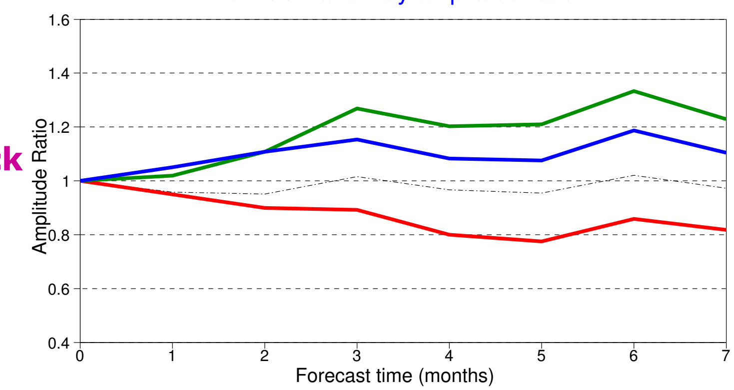
- **Drift and Variability depend on Initialization !!**
- **More information corrects for model error, and the information is retained during the fc.**
- **Need "more balanced" initialization methods to prevent initialization shock hitting non linearities**

VARIABILITY

Western Pacific



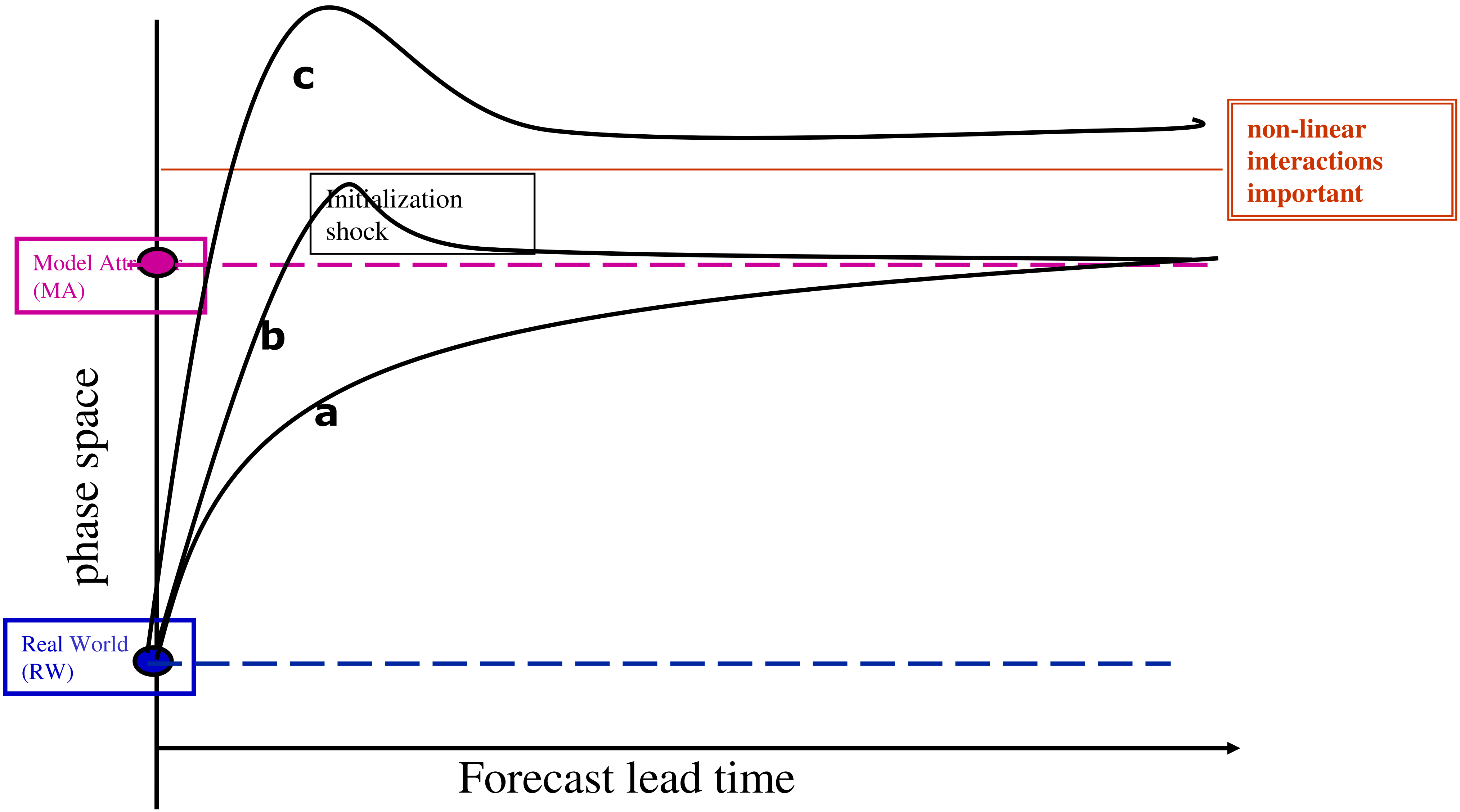
NINO4 SST anomaly amplitude ratio



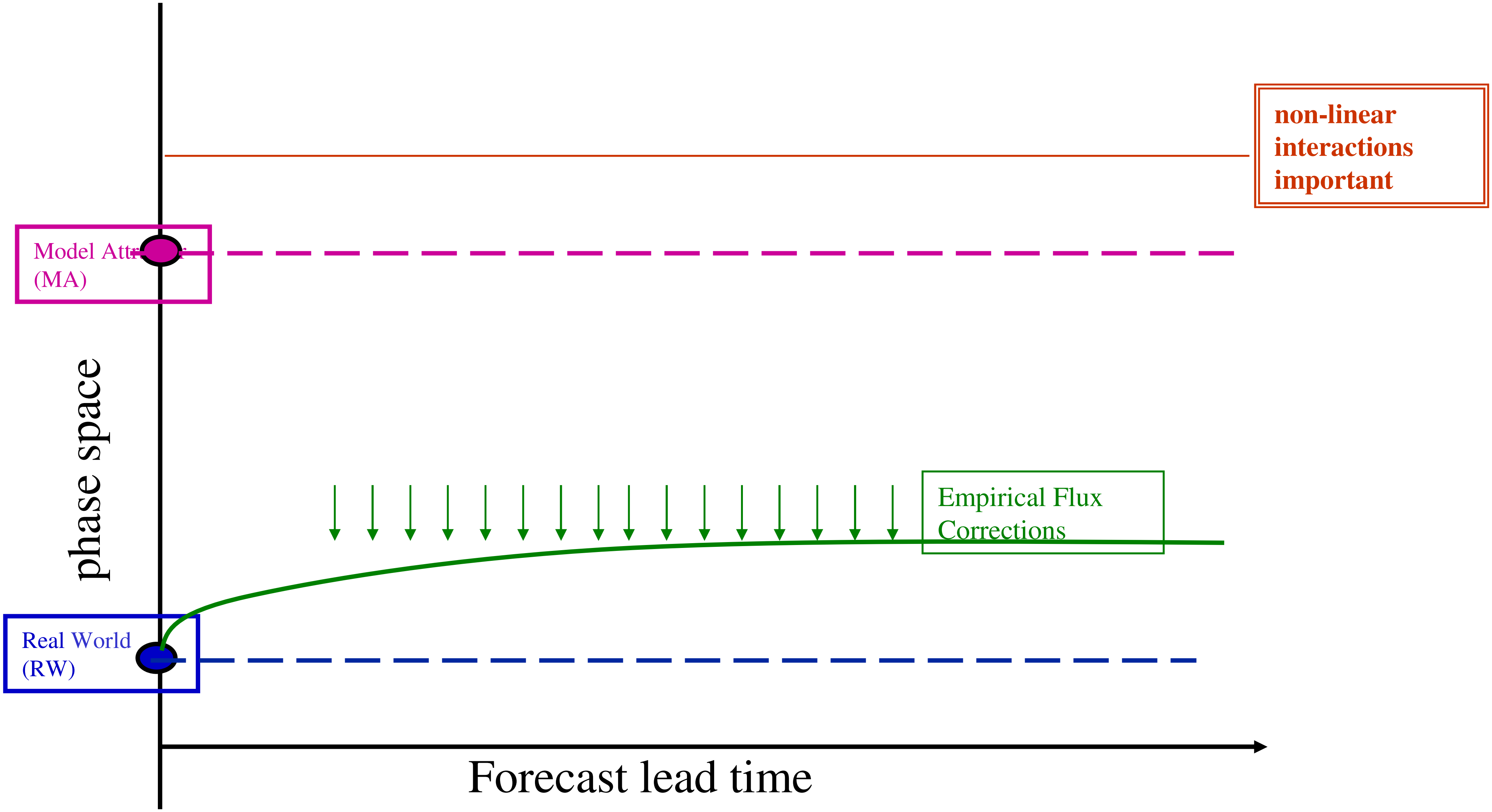
- **Relation between drift and Amplitude of Interannual variability.**
  - **Possible non linearity: is the warm drift interacting with the amplitude of ENSO?**

- **Relation between drift and Amplitude of Interannual variability.**
  - **Upwelling area penetrating too far west leads to stronger IV than desired.**

Initialization Shock and non linearities



Initialization shock and non linearities



Initialization: uncoupled versus coupled

Uncoupled: Most common

- Advantages:
  - ***It is possible***
  - **The systematic error during the initialization is small(-er)**
- *Disadvantages:*
  - **Model is different during the initialization and forecast**
  - **Possibility of initialization shock**
  - ***No synergy between ocean and atmospheric observations***

Other Strategies

- Full Coupled Initialization:
  - **No clear path for implementation in operational systems**
  - **Need of a good algorithm to treat systematic error. Problem with different time scales**
- Weakly-coupled initialization
  - **Atmosphere initialization with a coupled model**
  - **Ocean initialization with a coupled model.**
  - **Ocean initialization in anomaly mode with a coupled model (DePreSyS)**

Different time scales: from Days to Decades

More coupling for shorter forecast?

- There is growing evidence that the representation of ocean process is important for the medium range forecasts and for the atmospheric (re-)analysis.
  - Representation of the diurnal warm layer
  - Interaction in tropical cyclones
  - Coupling of the currents in the waves.
  - Tropical precipitation, monsoon systems
  - Response to sharp SST fronts

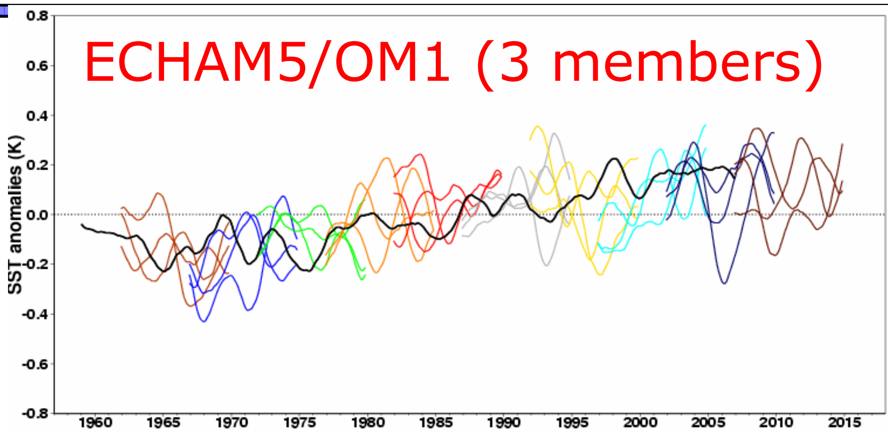
- The complexity of the ocean model required to represent the above processes needs to be established.
  - High vertical resolution in the ocean mixed layer.
  - What horizontal resolution?
  - Full dynamical GCM or 1D mixed layer model?
  - How important is the initialization of the ocean component?

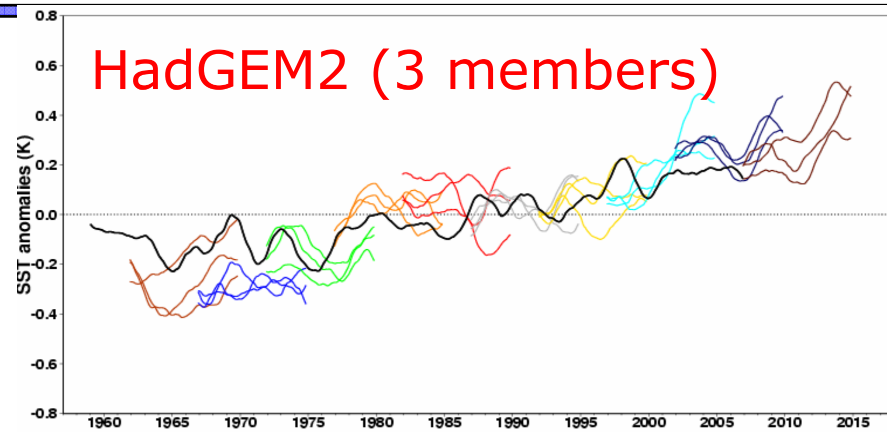
Decadal Predictions

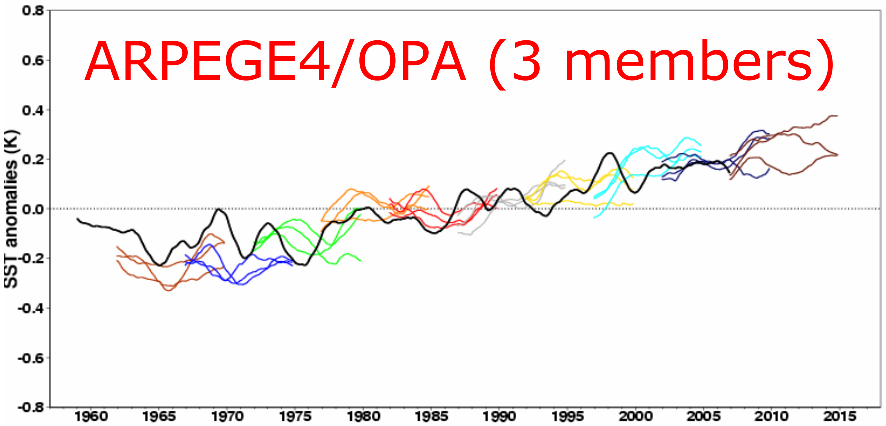
EXPLOITATION OF THE ENSEMBLES DATA SET

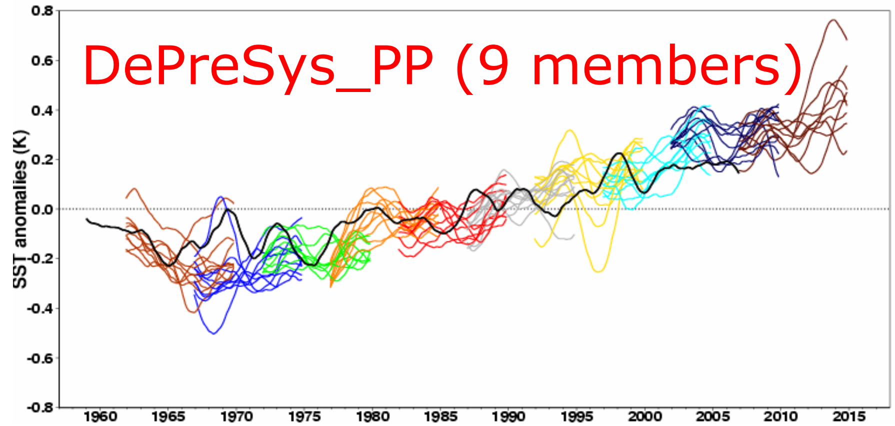
- In preparation for the CMIP5 integrations…
- There is a good set of MULTI-MODEL decadal integrations.
- Data on a OpenDap server (common grid, CF compliant):
  - http://ensembles.ecmwf.int/thredds/catalog.html
  - http://www.ecmwf.int/research/EU_projects/ENSEMBLES/data/index.html
- Output from Ocean and Atmosphere predictions and Ocean Initial Conditions (ocean reanalysis)
- Opportunity to investigate Pacific Decadal Predictability/Prediction?..ENSO behaviour…

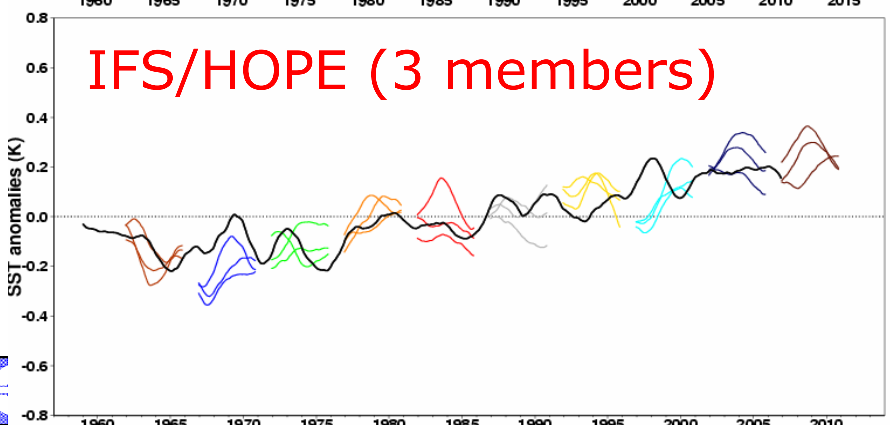
Example: forecast anomalies of ocean temperature









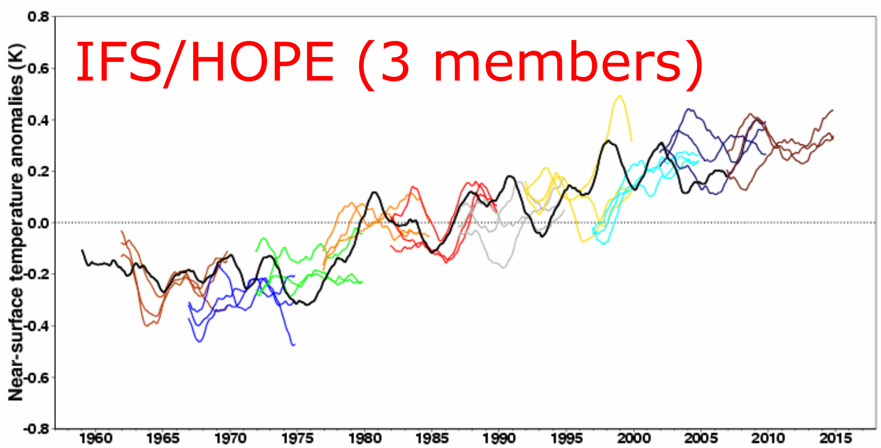


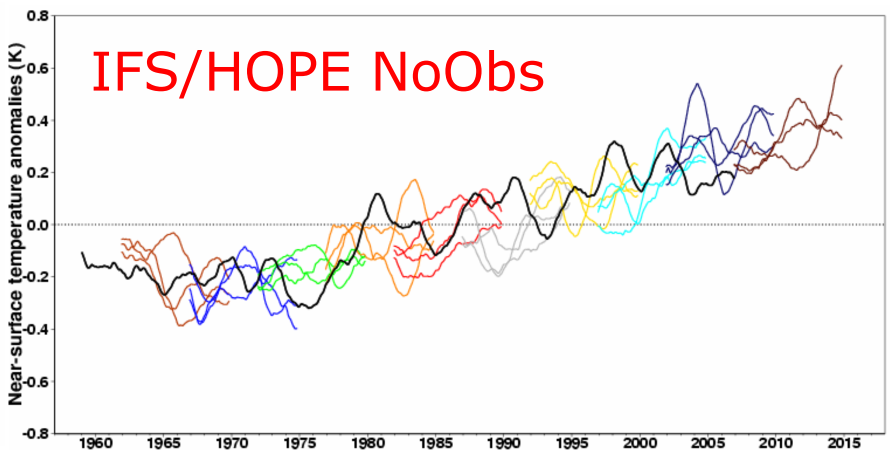
Results from the ENSEMBLES decadal integrations.

Courtesy of F. Doblas -Reyes

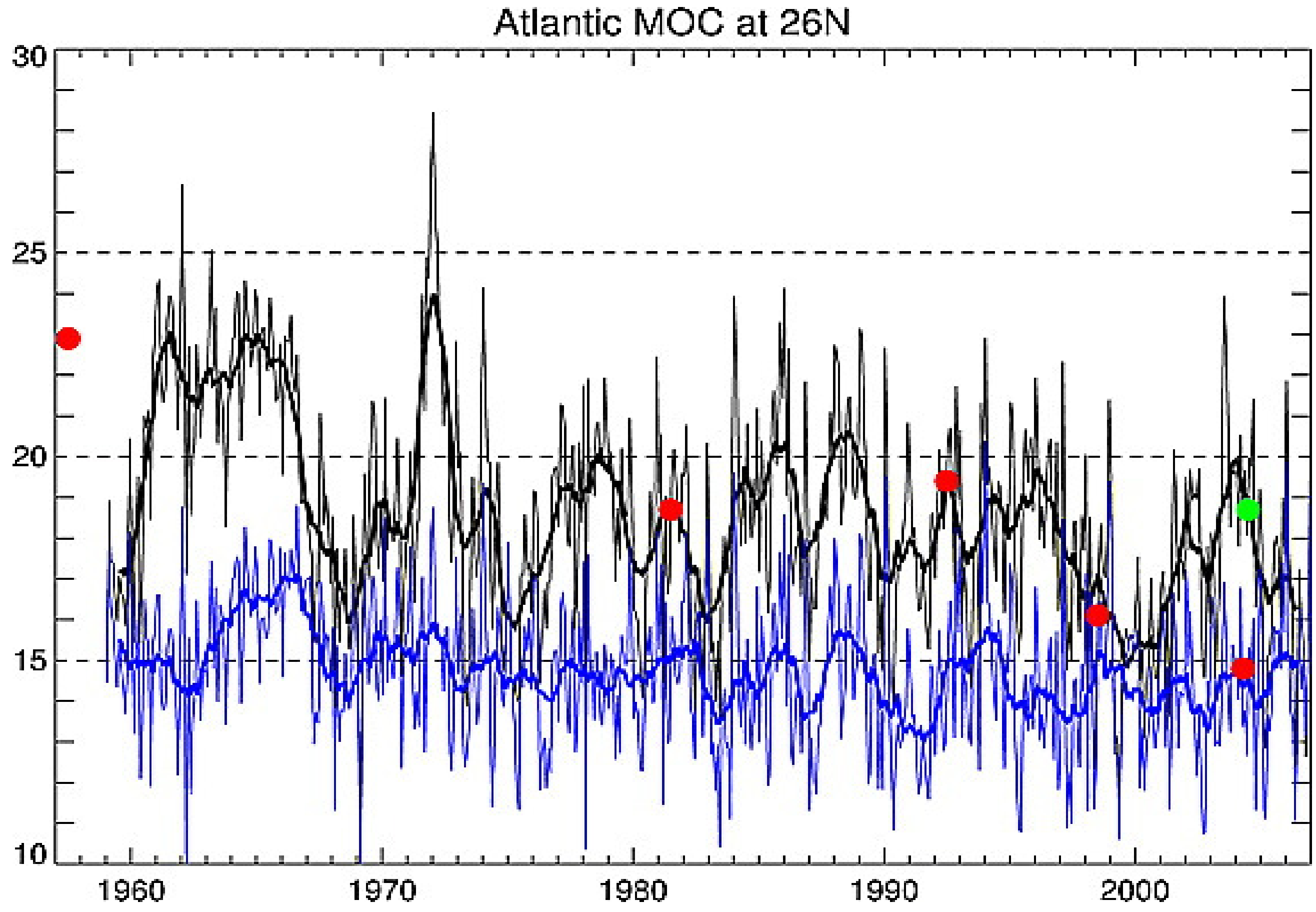
IFS/HOPE: impact of ocean observations

Global mean near-surface air temperature anomaly (2-year running mean applied) from the ECMWF re-forecasts. ERA40/OPS is used as a reference. The mean systematic error has been removed over the period 1960-2005.





Atlantic MOC: Initial Conditions for Decadal forecasts



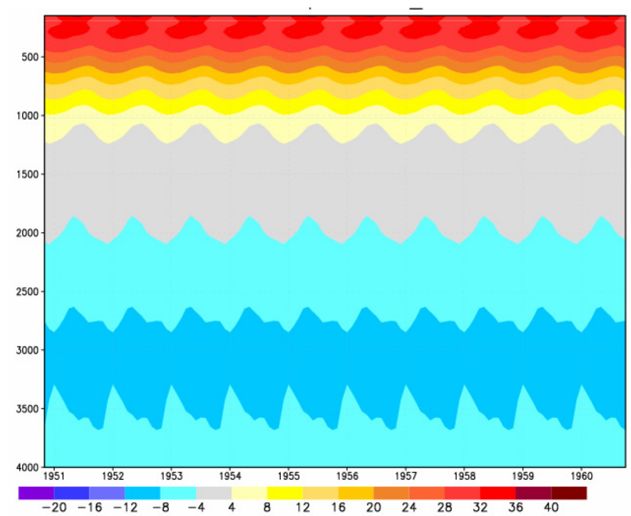
Assimilation No-Data Bryden etal 2005 Cunningham etal 2007

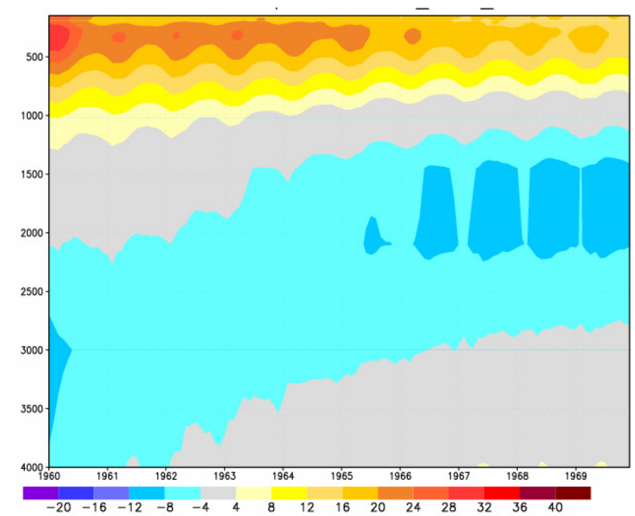
From Balmaseda etal 2007

IFS/HOPE: impact of ocean observations

Zonally integrated (Atlantic) meridional velocity (10^3 m^2/s) at 36N
Mean of 10 cases from the period 1960-2005

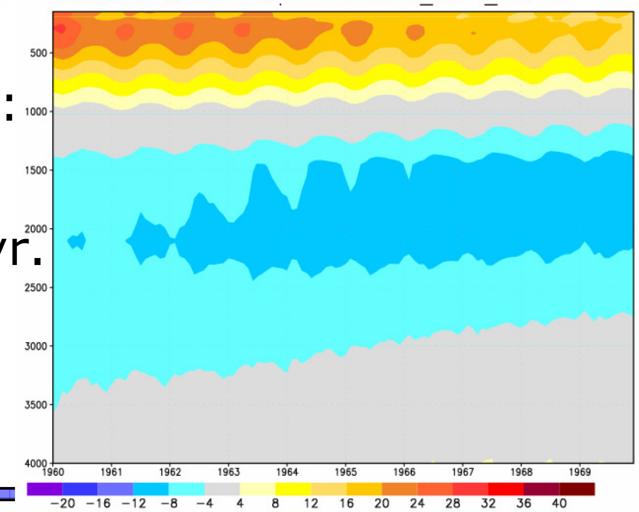
ECMWF ocean reanalysis





FC (ASSIM)

- The MOC drifts in the coupled model: shallower
- The MOC memory lasts for about 5 yr.



FC

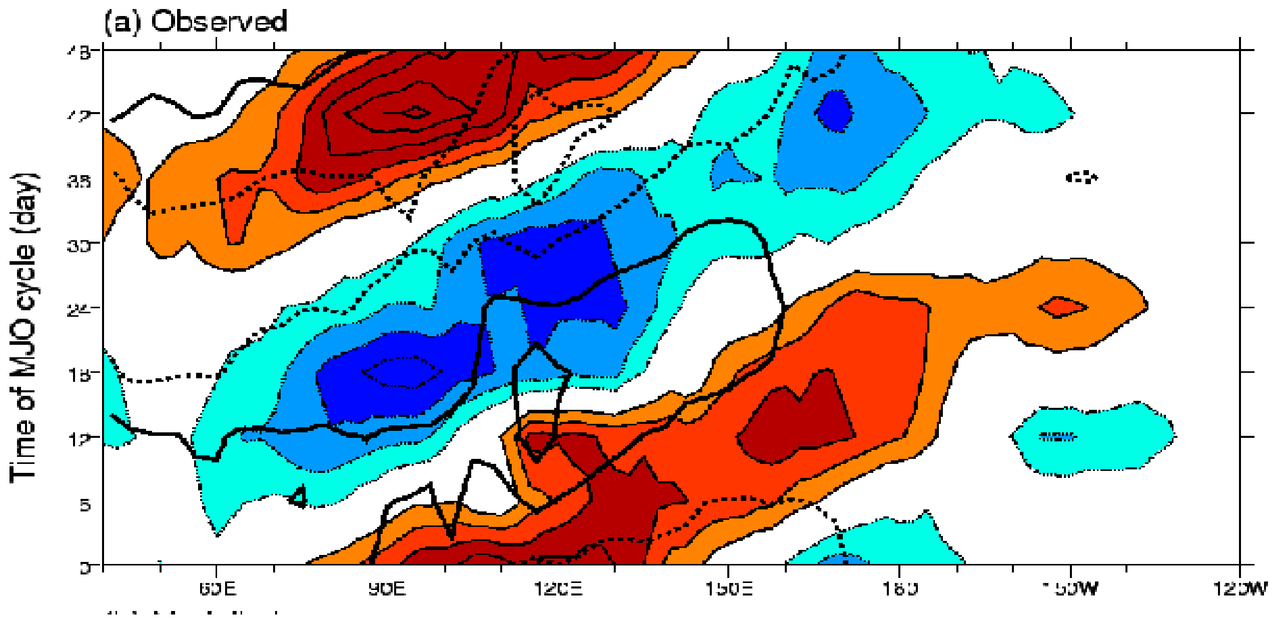
(No-Obs)

Thanks to F. Doblas-Reyes

Summary

- Most common ocean initialization strategy is the uncoupled initialization:
  - Ocean observations are assimilated into an ocean model forced by atmospheric fluxes.
  - In general, this strategy improves the forecast skill in the prediction of SST (if the coupled model is good/discerning enough).
  - If there are serious model errors this strategy can lead to large initialization shocks and degradation of the skill (Equatorial Atlantic).
- The skill of seasonal forecasts of SST is steadily improving due to:
  - Improved quality of coupled models
  - Improved quality of atmospheric reanalysis
  - Improved ocean observing system (contribution of ARGO and Altimeter add to the moorings)
  - Improved ocean assimilation systems.
- More sophisticated assimilation methods are needed
  - A balanced "initialization" does not mean using less information about the real world, but adequate mapping between the observed state and the model state.
- Challenge ahead: to initialize the different time scales simultaneously

Example: Phase between SST and tropical convection

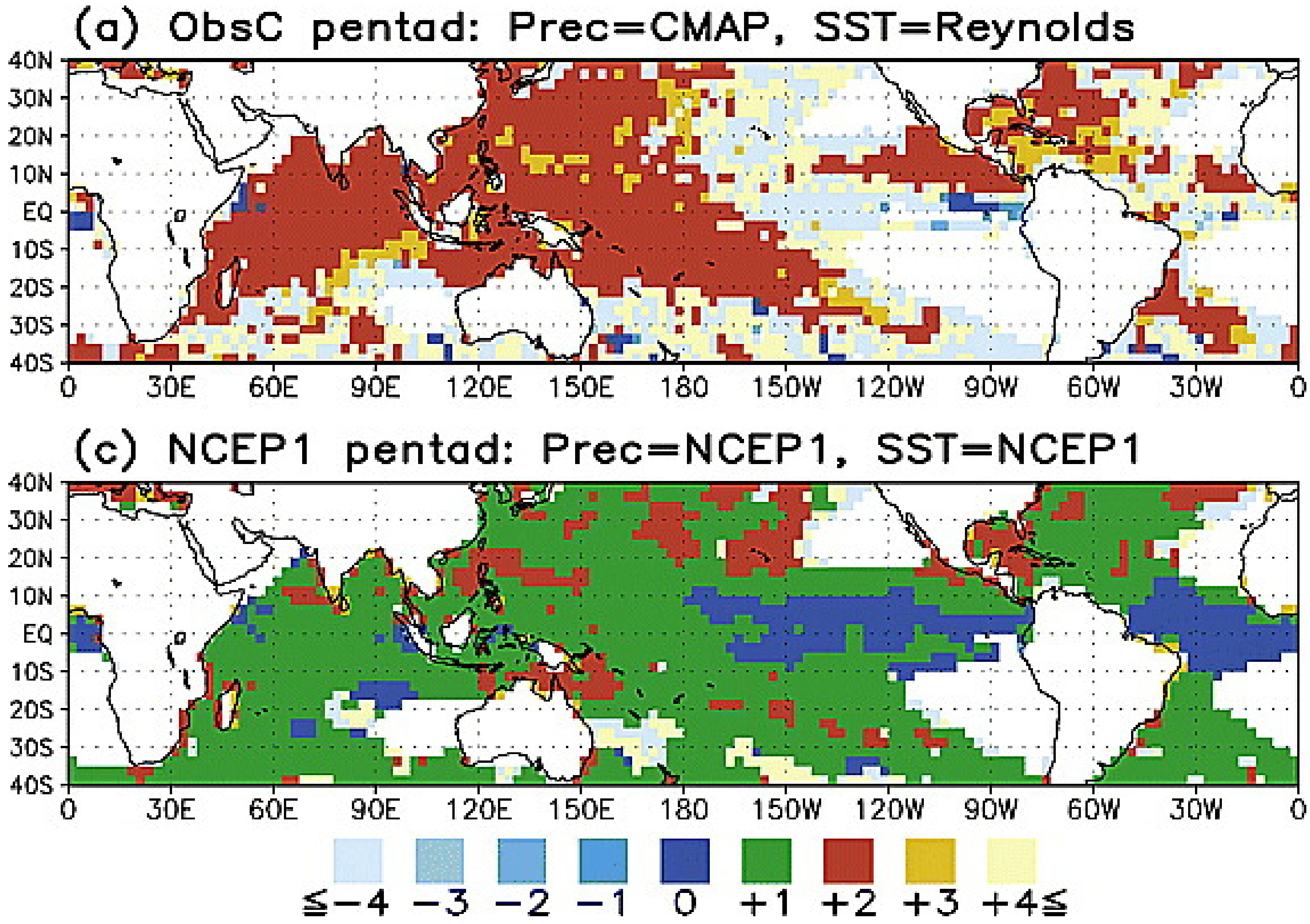


Composites of SST anomalies (contours) and OLR (colours) of MJO events. SST and convection are in quadrature.

The lead-lag relationship between SST and deep convection seems instrumental for setting the propagation speed of the MJO.

A two way coupling is required, but may not be enough. Thin ocean layers are needed to represent this phase relationship.

The SST/Precip relationship is not reproduced by atmospheric re-analysis



Arakawa and Kitoh 2003

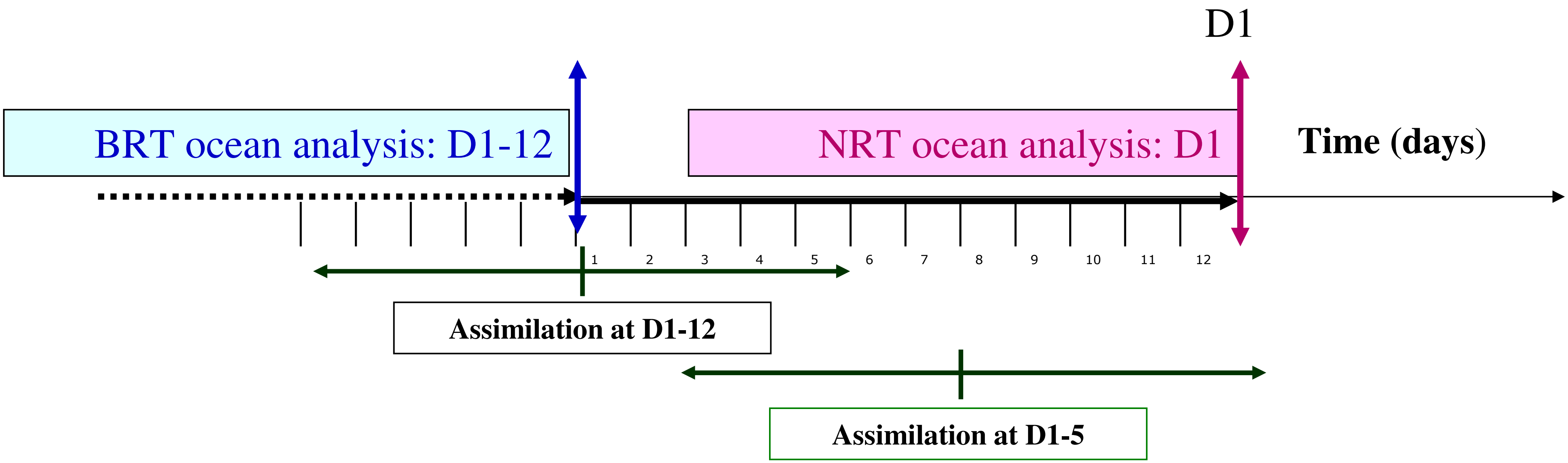
Air-Sea Interaction in Tropical Cyclones

Two U.S. operational hurricane prediction models are coupled with ocean models: GFDL (since 2001) and HWRF (since 2007)

Ocean Initial Conditions may be important

From Ginis 2008

Operational Ocean Analysis Schedule



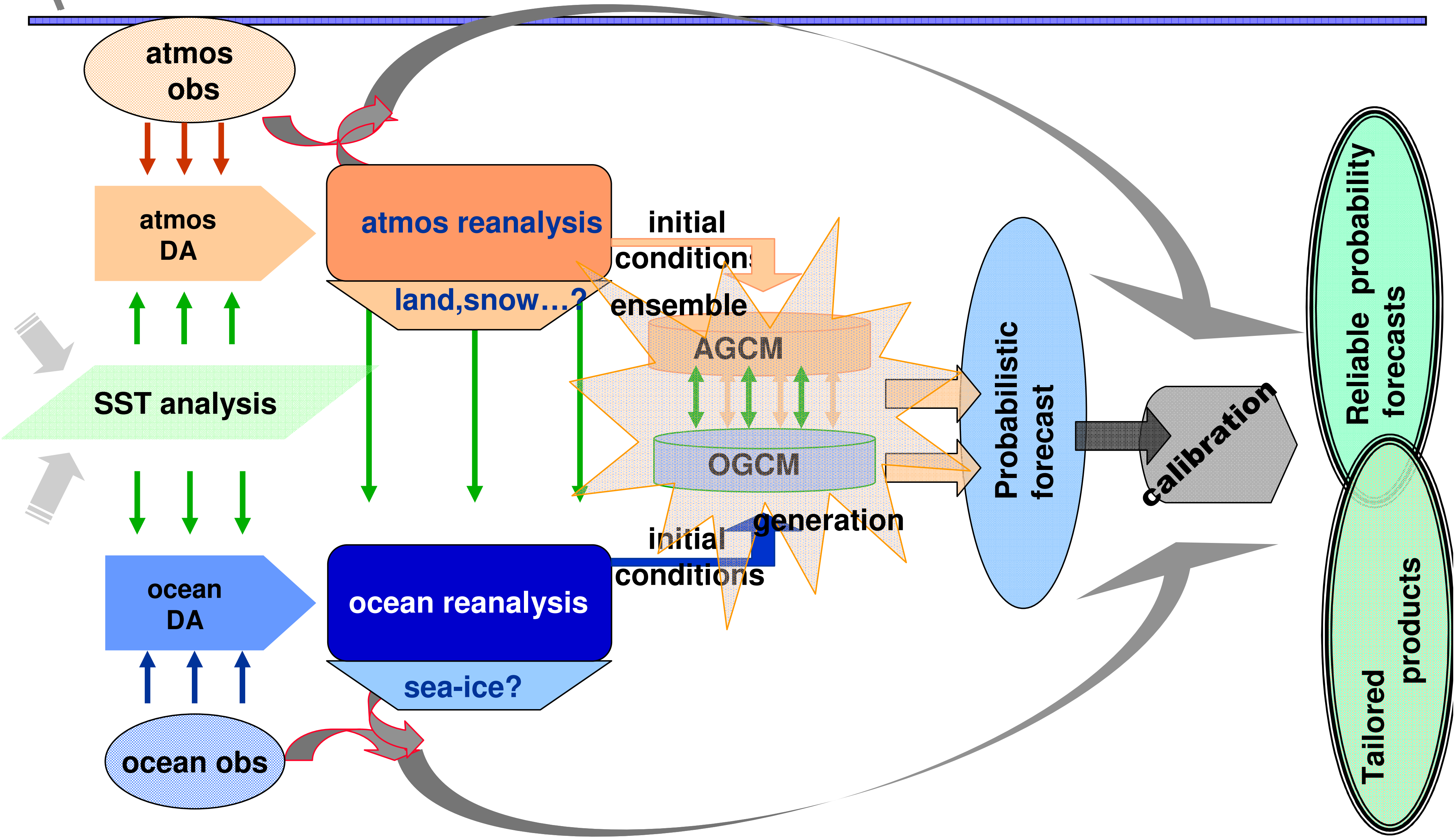
- **BRT (Behind real time ocean analysis): ~<u>12 days delay</u> to allow data reception**

  For seasonal Forecasts.

  Continuation of the historical ocean reanalysis

- **NRT (Near real time ocean analysis):~ For Var-EPS/Monthly forecasts**

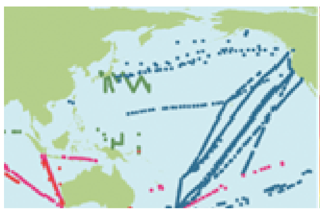
End to End Forecasting System

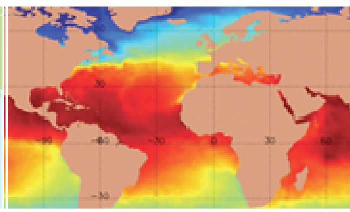


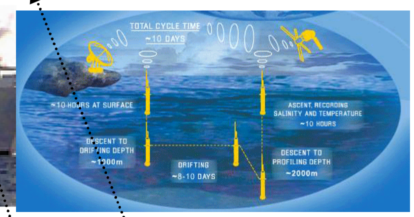
Time evolution of the Ocean Observing System

1982 1993 2001

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





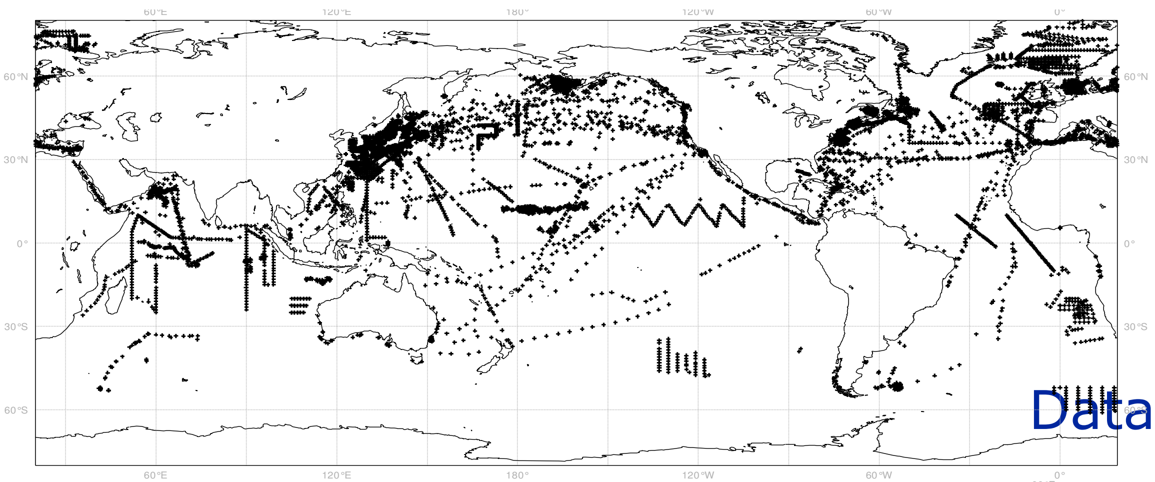


TRITON

1998-1999
PIRATA

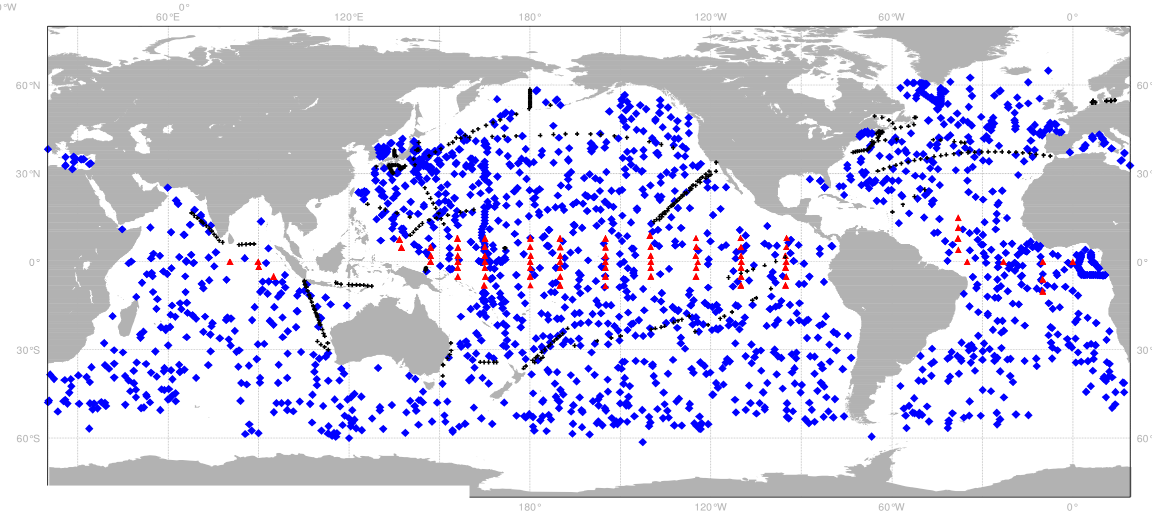
Ocean Observing System

Data coverage for June 1982



Changing observing system is a challenge for consistent reanalysis

Data coverage for Nov 2005



Today's Observations will be used in years to come

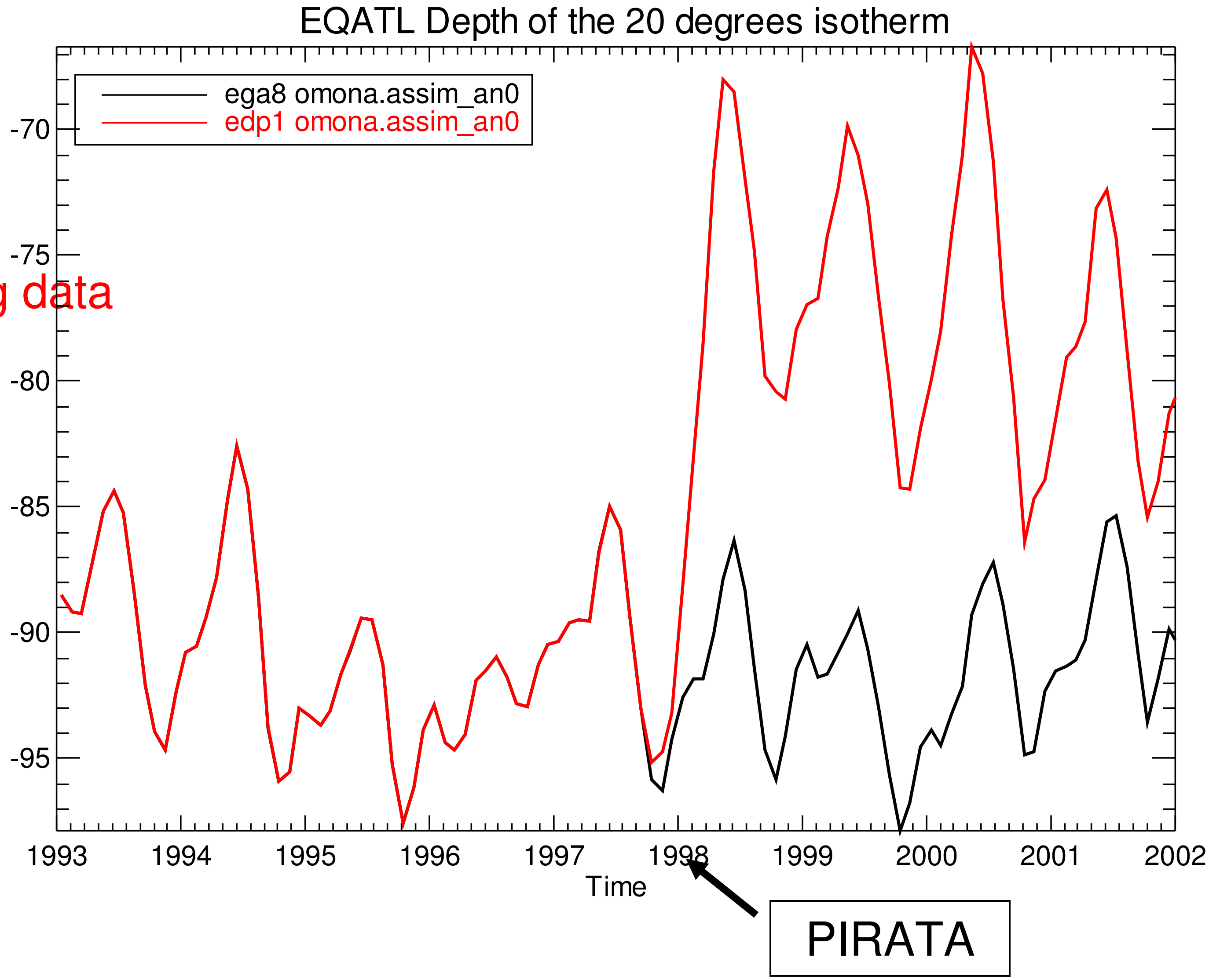
▲Moorings: SubsurfaceTemperature

◊ ARGO floats: Subsurface Temperature and Salinity

+ XBT : Subsurface Temperature

's...

Impact of data assimilation on the mean



Assim of mooring data

CTL=No data

Large impact of data in the mean state: Shallower thermocline

ORA-S3

- Main Objective: Initialization of seasonal forecasts
  - Historical reanalysis brought up-to-date (11 days behind real time)

Main Features

•ERA-40 daily fluxes (1959-2002) and NWP thereafter

•Retrospective Ocean Reanalysis back to 1959

•Multivariate on-line Bias Correction (pressure gradient)

•Assimilation of temperature, salinity, altimeter sea level anomalies an global sea level trends.

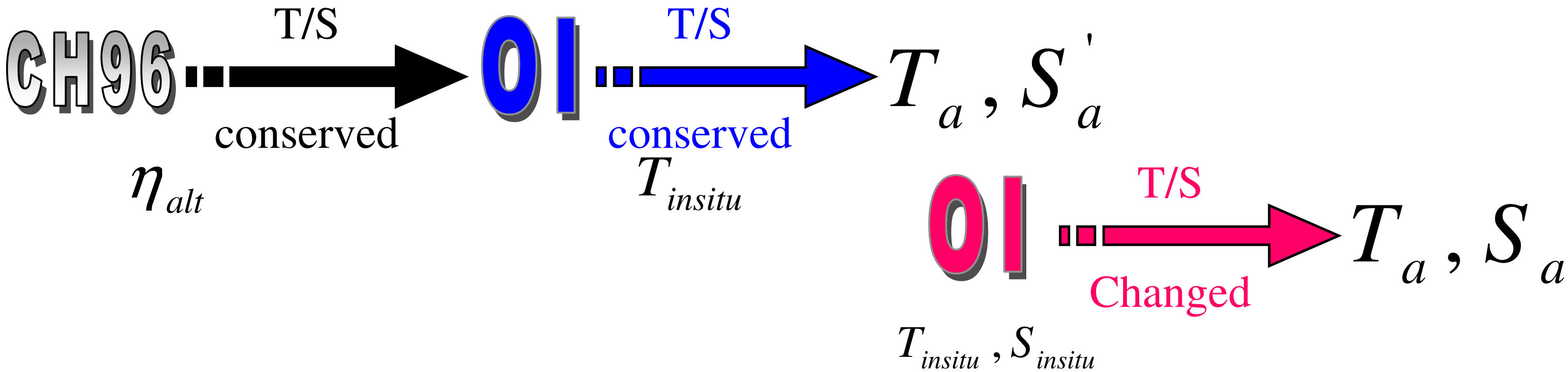
•3D OI, Salinity along isotherms

•Balance constrains (T/S and geostrophy)

•Sequential, 10 days analysis cycle, IAU

Balmaseda etal 2007/2008

System 3: Assimilation of Temperature, Salinity and Sea Level

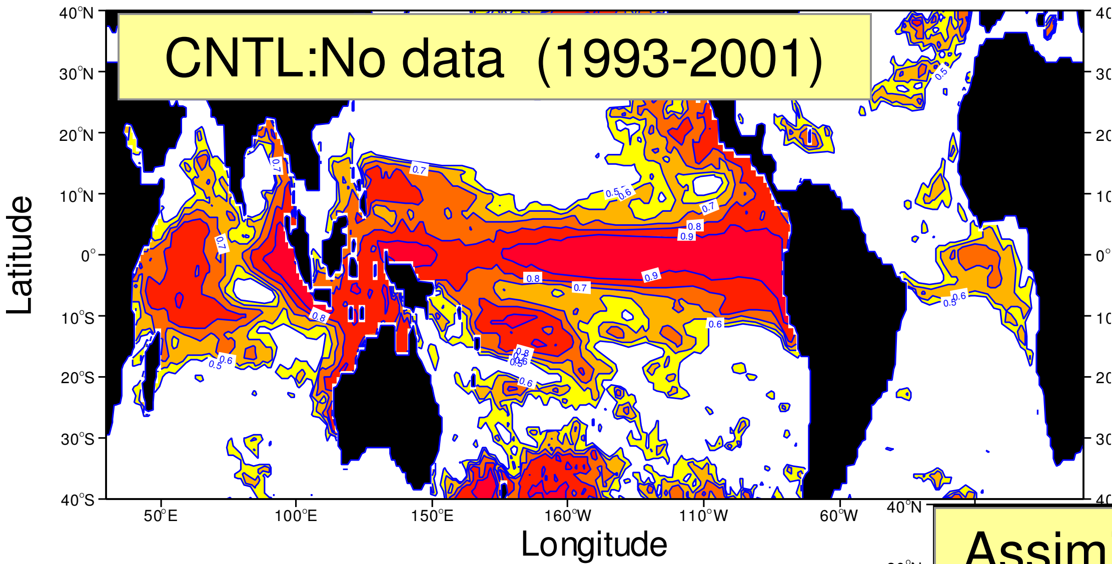


Assimilation of S(T) not S(z)

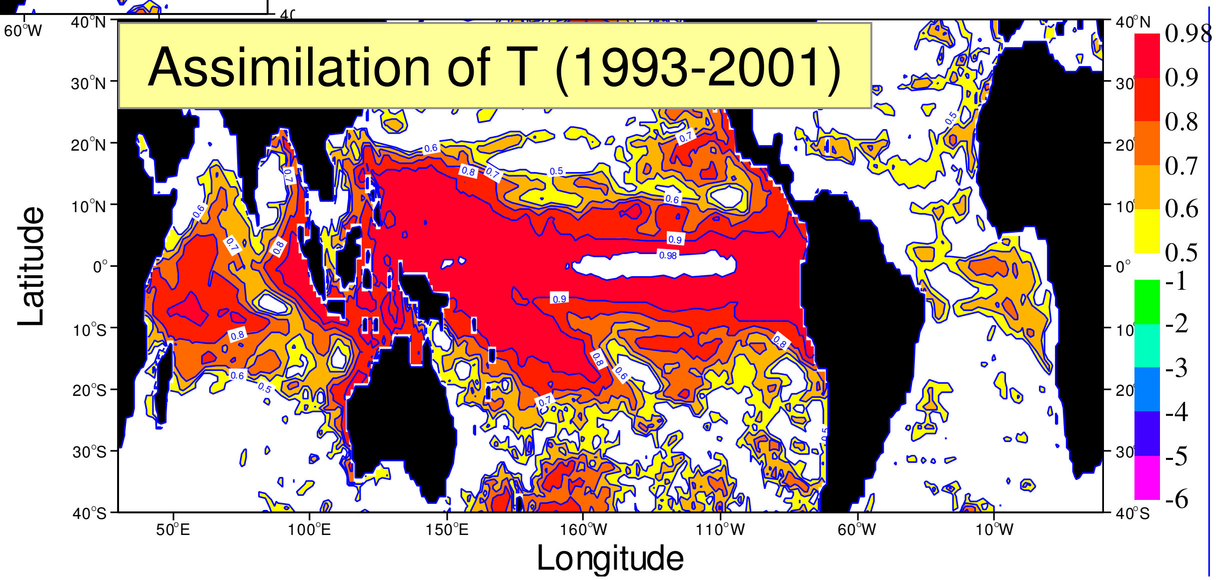
$$S_a(T_a) = S'_a(T_a) + \mathrm{K}'(S_o(T_o) - \mathrm{H}S_b(T_o))$$

$$\mathrm{K}' \approx e^{-\frac{r^2}{R^2}} \cdot e^{-\frac{(T_a - T_o)^2}{T_R{}^2}}$$

Data Assimilation Improves the Interannual variability of the Analysis



Correlation of SL from System2 with altimeter data (which was not assimilated)



IFS/HOPE: impact of ocean observations

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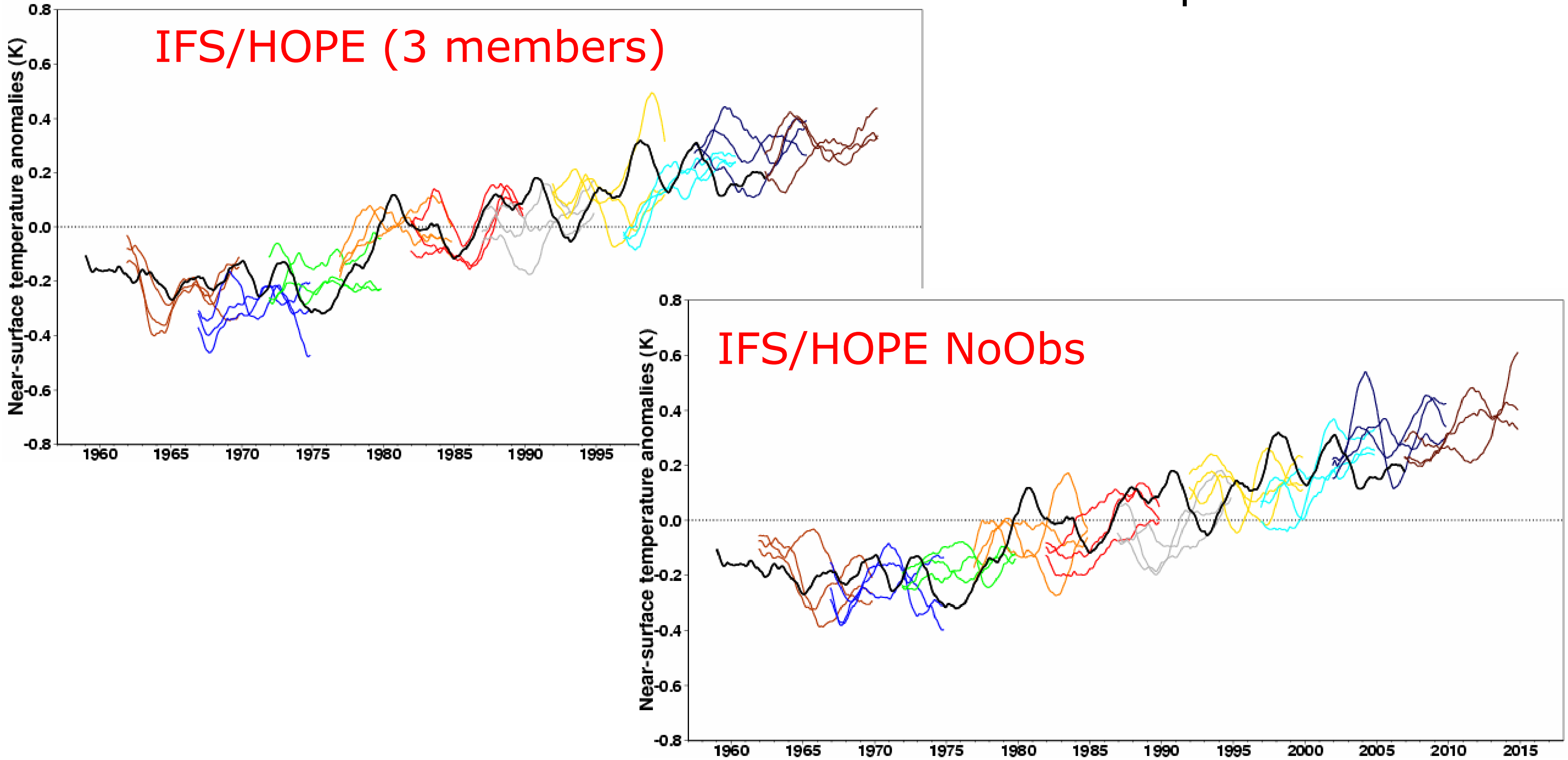

ECMWF: Weather and Climate Dynamical Forecasts