Multi-Decadal Climate Variability : Combining observations and models to investigate predictability and initialization for predictions

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Key Questions

- What decadal predictability exists in the climate system, and what are the mechanisms responsible for that predictability?
- To what degree is the identified predictability (and associated climatic impacts) dependent on model formulation?
- Are current and planned initialization and observing systems adequate to initialize models for decadal prediction?
- Is the identified decadal predictability of societal relevance?

Crucial points:

- Robust predictions will require **sound theoretical understanding** of decadal-scale climate processes and phenomena.

- Assessment of predictability and its climatic relevance **may have significant model dependence**, and thus may evolve over time (with implications for observing and initialization systems).

But … even if decadal fluctuations are not predictable, it is still important to understand them to better understand and interpret observed climate change.

Components of decadal variability and predictability

1. <u>Forced climate change</u>

- **Predictability arising from estimates of future changes in radiative forcing agents, and the climate system response to those changes.**
- **“Committed warming” from past radiative forcing**

2. <u>Internal variability</u>

- **Decadal-scale fluctuations are an important part of climate variability**
- **Is there “meaningful” decadal-scale predictability in the climate system?**
- **Can we realize that predictability?**
- **Is the “internal” variability altered by changing radiative forcing?**

What is the mechanism behind Atlantic multidecadal variability?

Two different, but not mutually exclusive, ideas:

1. **Atlantic Multidecadal Variability is a product of internal variability of the climate system through multidecadal scale strengthening and weakening of the Atlantic Meridional Overturning Circulation (AMOC).**

2. **Atlantic Multidecadal Variability is a product of changing radiative forcing (greenhouse gases and aerosols) in the 20th century.**

OUTLINE

- Seasonal/Interannual Forecast Lessons
- Observing system issues
- Introduction to GFDL’s Coupled Ensemble Filter Assimilation System (ECDA)
- Perfect Model Studies (OSSE) to assess AMOC initialization Predictability
- High Resolution Coupled Model Activities
- Remarks

S/I Prediction Lessons

1. **The initialization problem is different from the state estimation problem**
   - **The best analysis may not be the best initialization**
   - **Overspecification as in the close fit to the ocean data can introduce a lot of noise. Balance constraints between variables**
   - **Particularly for the decadal initialization their may be an argument not to correct the mean state - but perhaps only correct the slowly varying component of the system eg. Large scale water mass properties**
   - **Spurious inter-annual variability due to non-stationary nature of observing system**

S/I Prediction Lessons

2. Need good coupled models to assess the quality of initial conditions

- **Model errors rather than initial errors dominate SF performance**
- **For teleconnections, circulation changes, the performance of the model is even more critical**
- **Improvements in coupled models also translate on the ability of using SF as evaluation of ocean initial conditions.**

S/I Prediction Lessons

3. Initializing from the assimilation analysis

- To the extent that things are linear, the climatology of the forecasts may be subtracted thus removing the drift. ***Can this method be used for decalal predictions?***

- Non-linearities could hurt- but starting close to reality lessens the problem.

- With the current generation of ocean data assimilation systems and coupled models it is possible to demonstrate the benefits of assimilating ocean data for the seasonal forecast skill

Coordinated Decadal Prediction for AR5

Basic model runs:

1.1) **10 year integrations** with initial dates towards the end of 1960, 1965, 1970, 1975, 1980, 1985, 1990, 1995 and 2000 and 2005 (see below).

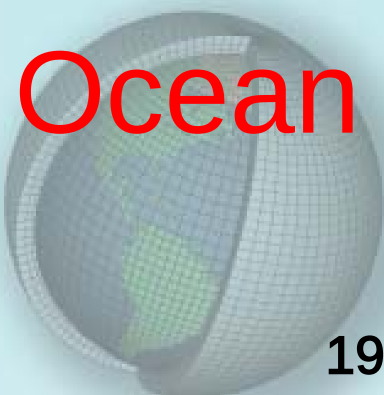
Is the historical ocean observing system up to the task?

- Ensemble size of 3, optionally increased to O(10)
- Ocean initial conditions should be in some way representative of the observed anomalies or full fields for the start date.
- Land, sea-ice and atmosphere initial conditions left to the discretion of each group.

1.2) **Extend integrations** with initial dates near the end of 1960, 1980 and 2005 **to 30 yrs**.

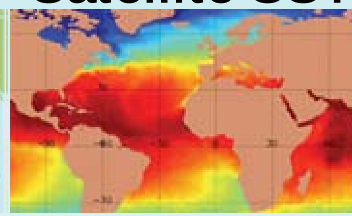
- Each start date to use a 3 member ensemble, optionally increased to O(10)
- Ocean initial conditions represent the observed anomalies or full fields.

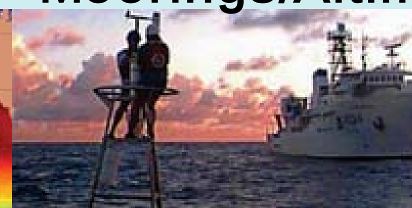
Ocean observations assimilated

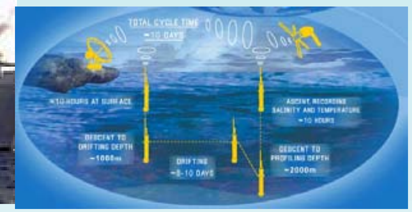


1982 1993 2001

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



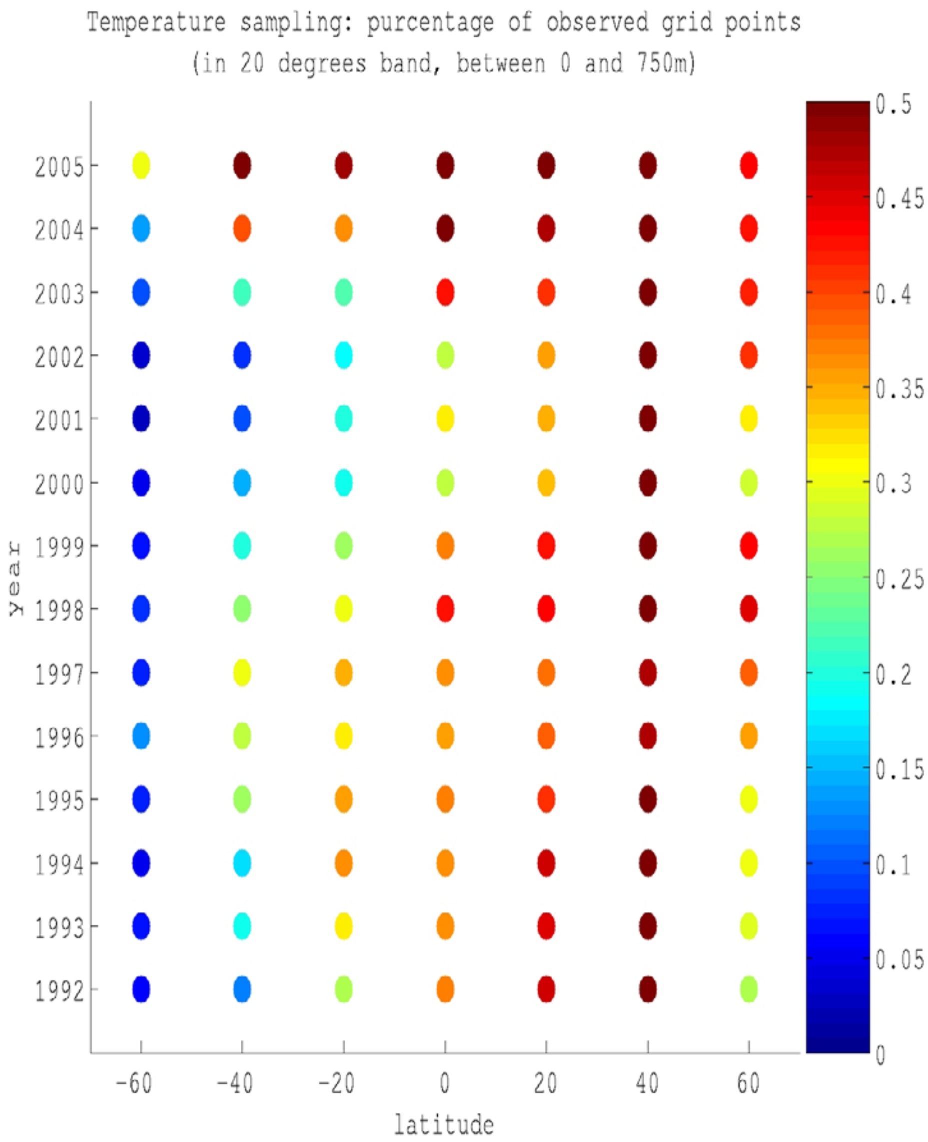


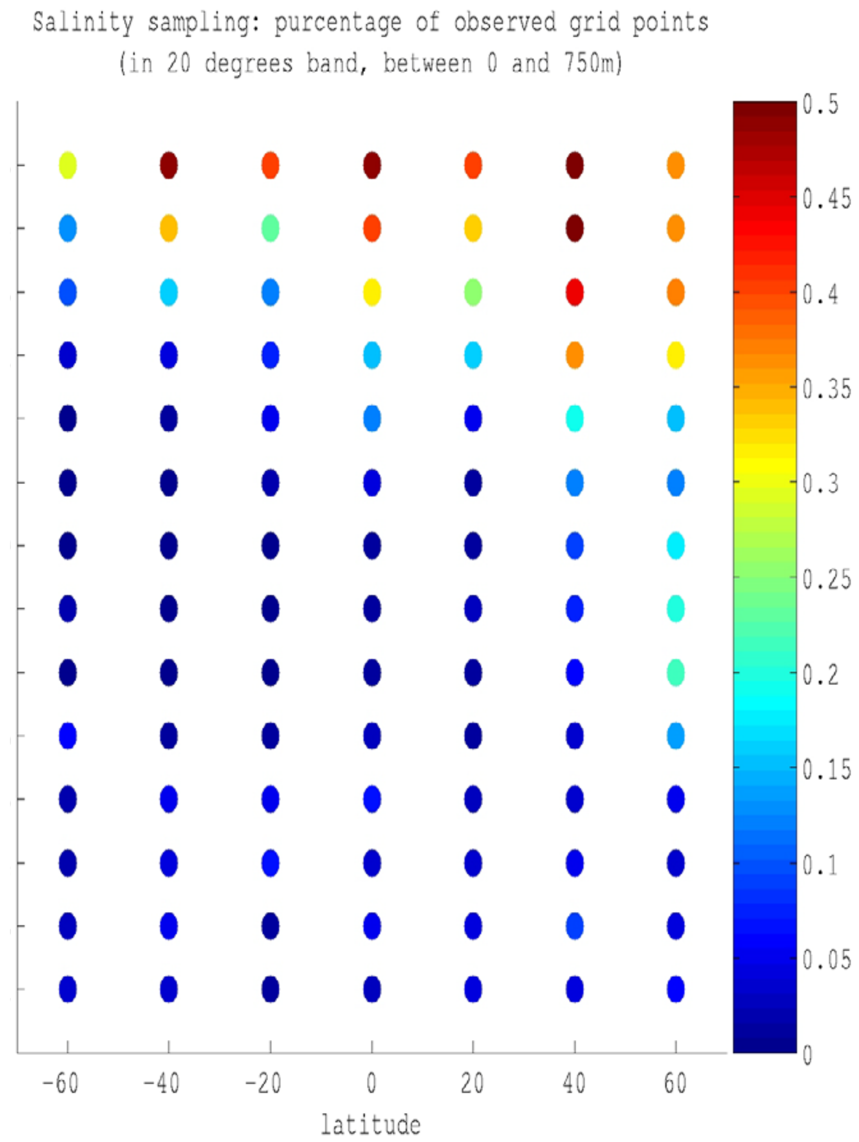


The ocean observing system has slowly been building up…

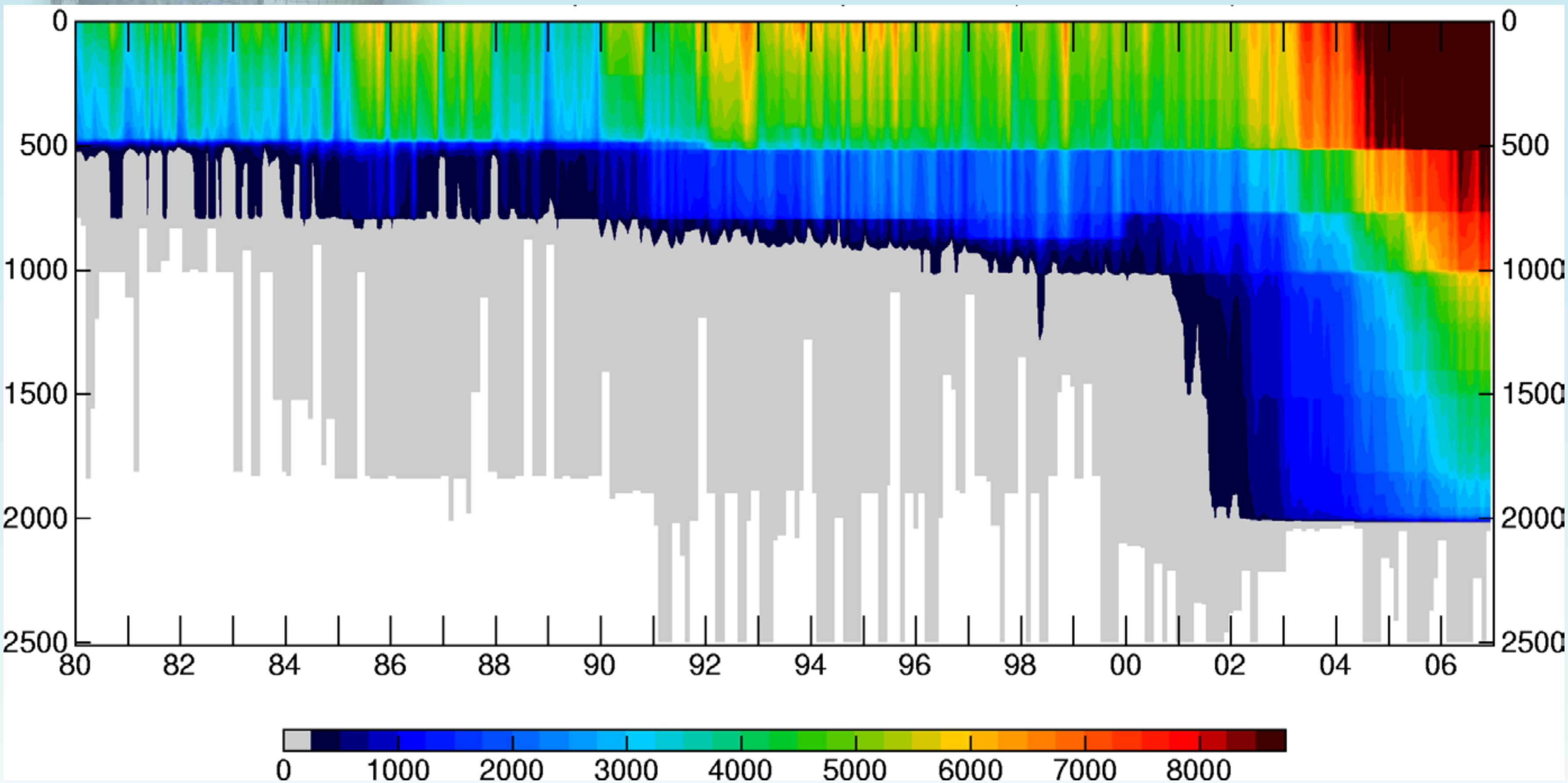
Its non-stationary nature is a challenge for the estimation of decadal variability

Sampling


Temperature sampling: purcentage of observed grid points
(in 20 degrees band, between 0 and 750m)
year
2005
2004
2003
2002
2001
2000
1999
1998
1997
1996
1995
1994
1993
1992
-60
-40
-20
0
20
40
60
latitude
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0

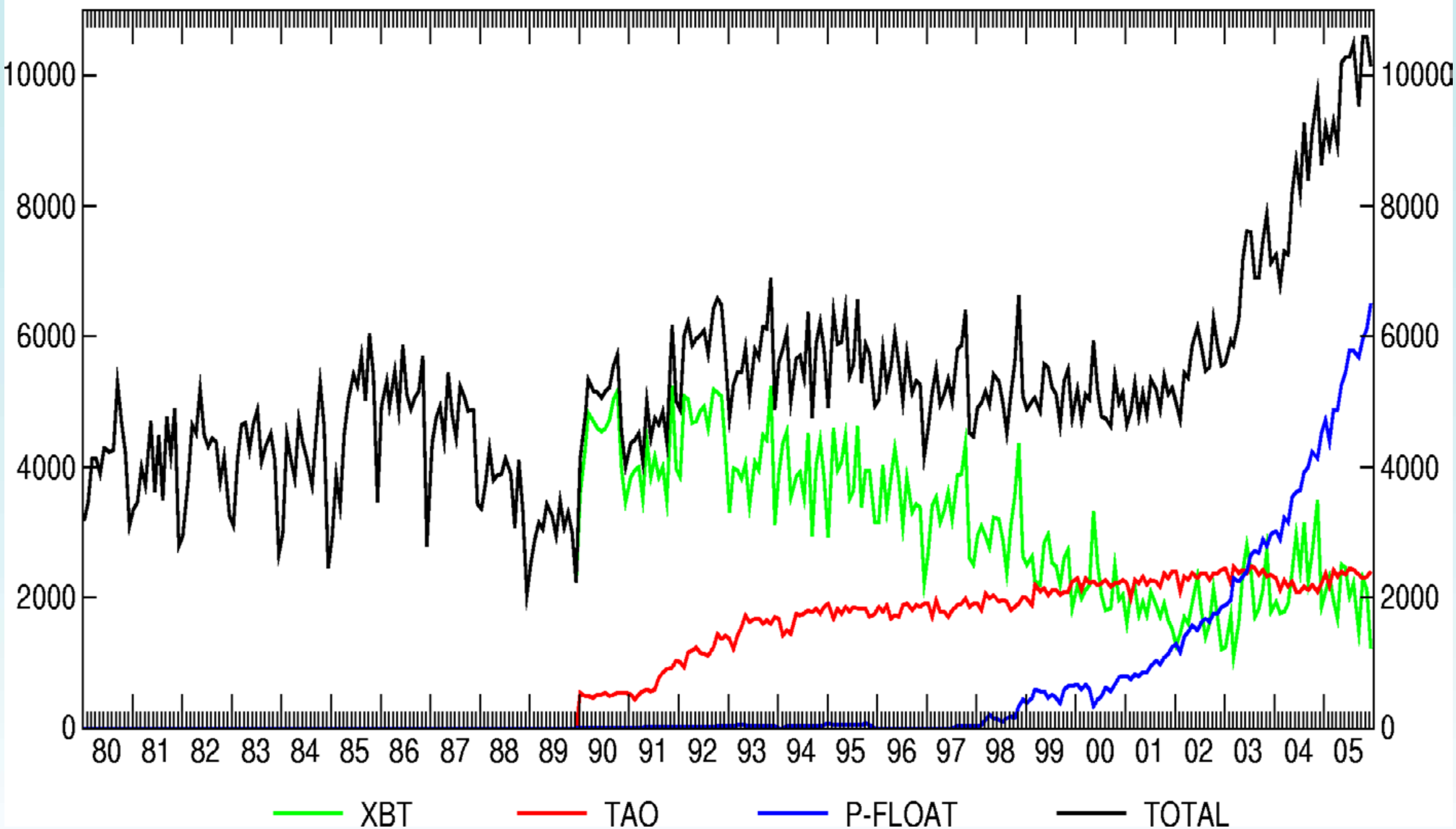

Salinity sampling: purcentage of observed grid points
(in 20 degrees band, between 0 and 750m)
-60
-40
-20
0
20
40
60
latitude
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0

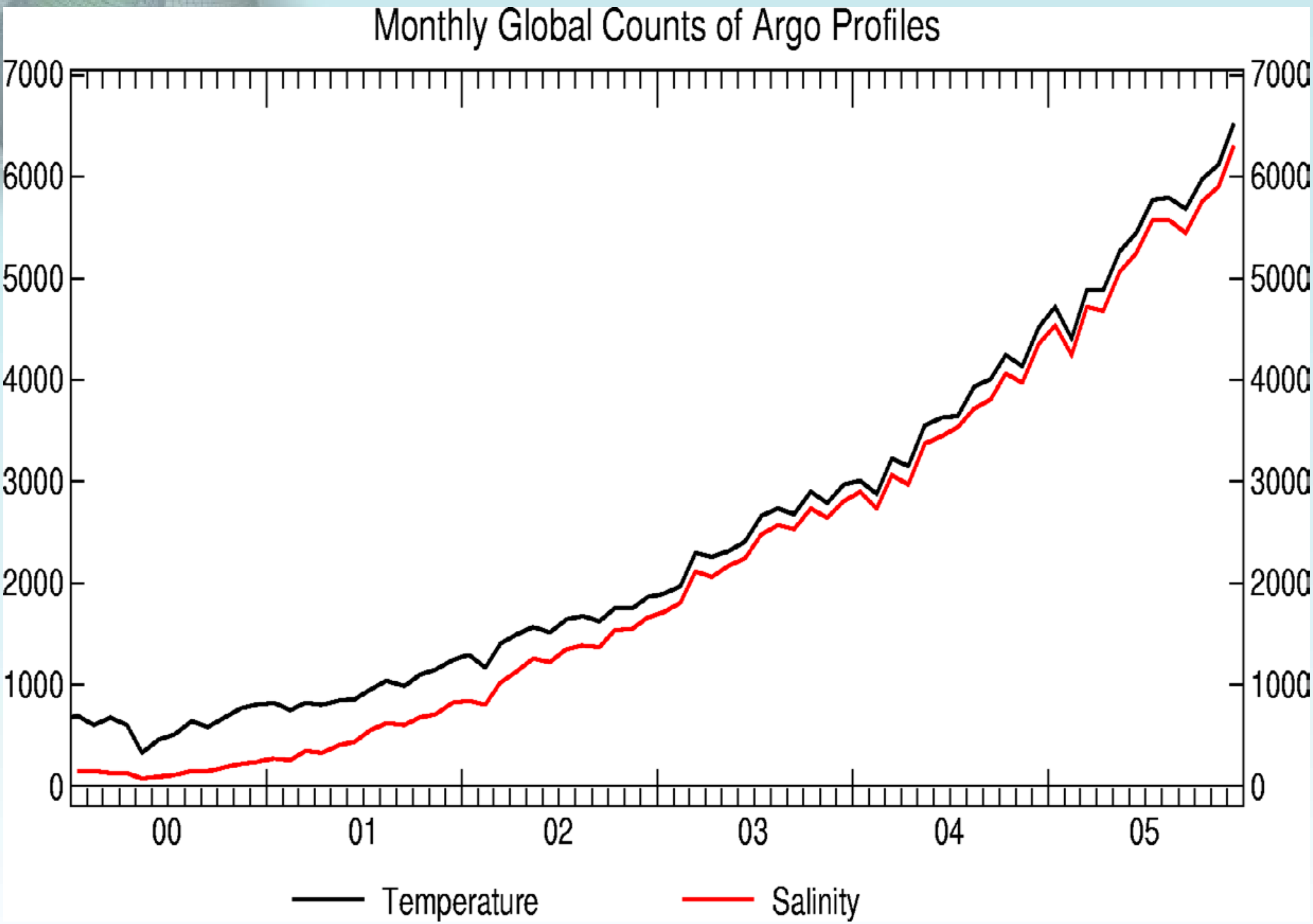
Number of Temperature Observations per Month as a Function of Depth



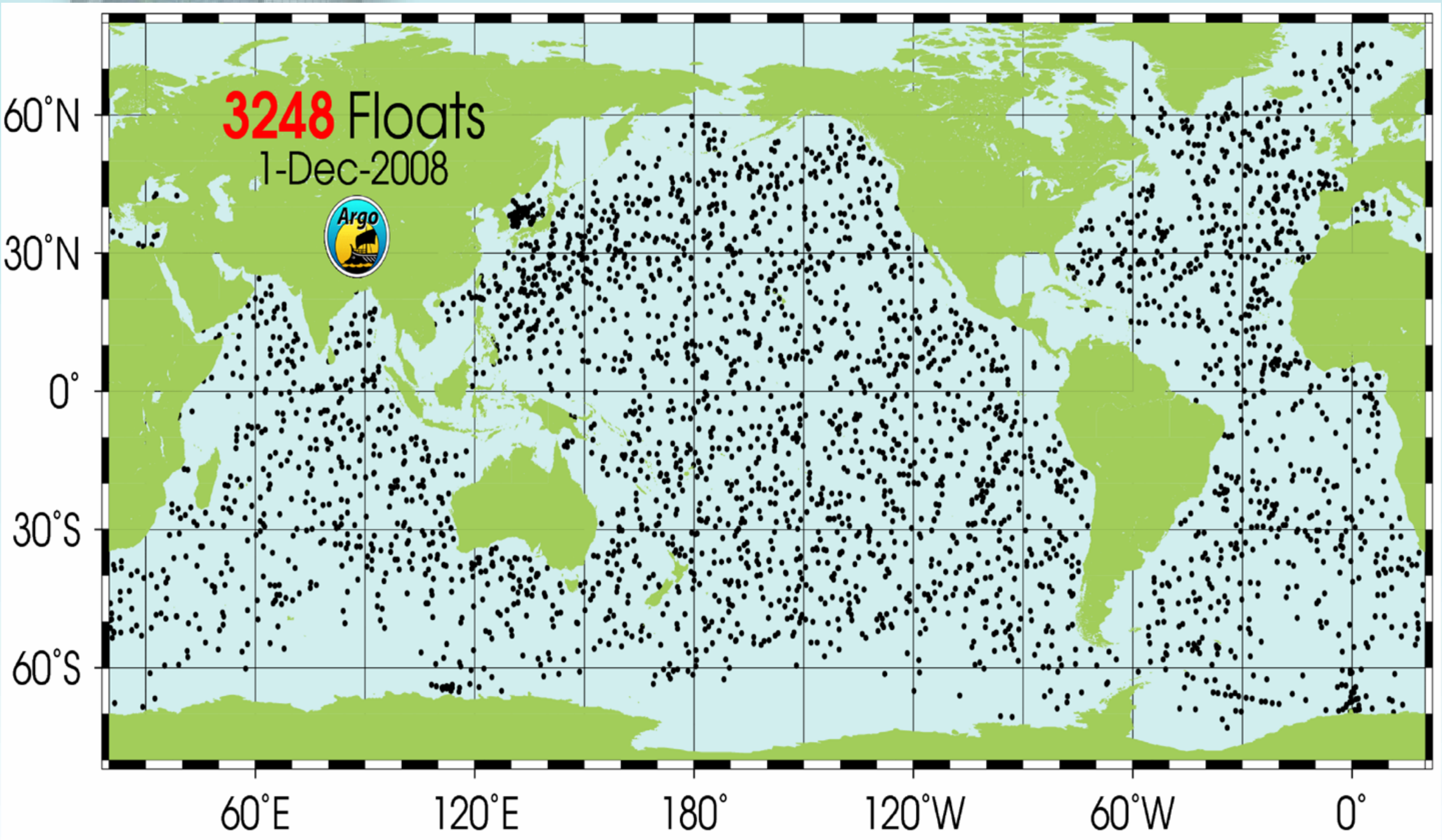
D. Behringer

Number of Temperature Profiles per Month (NODC:1980-89; MEDS:1990-Present)

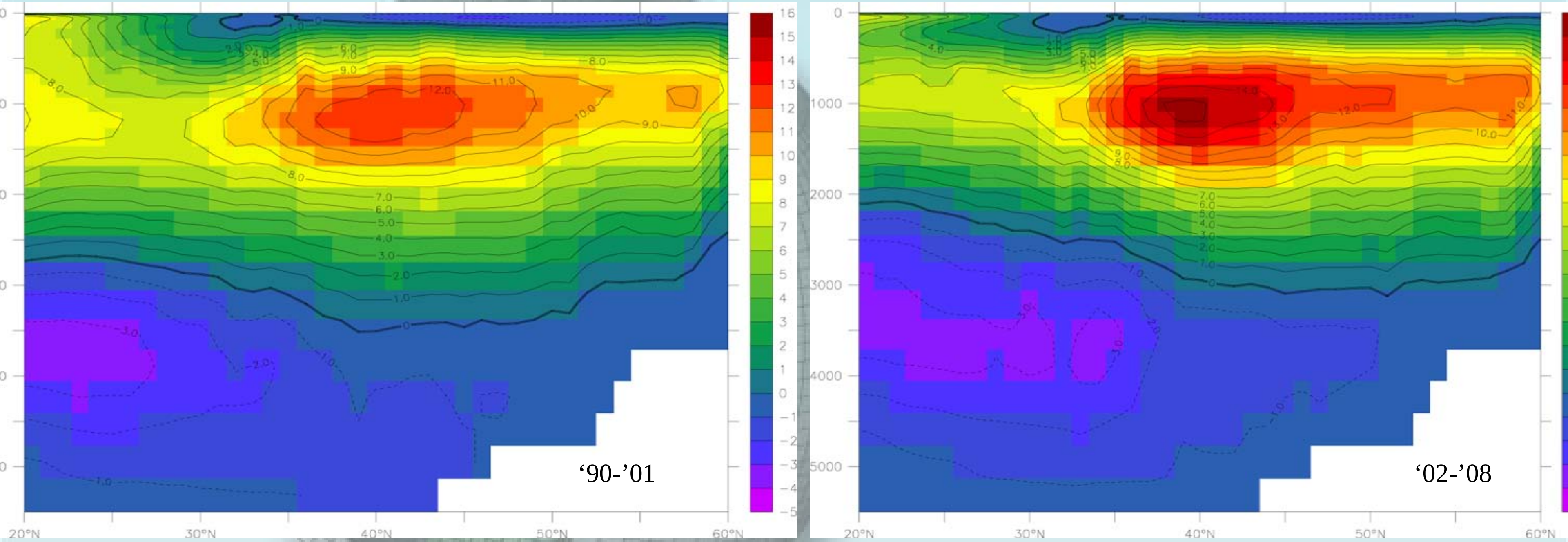


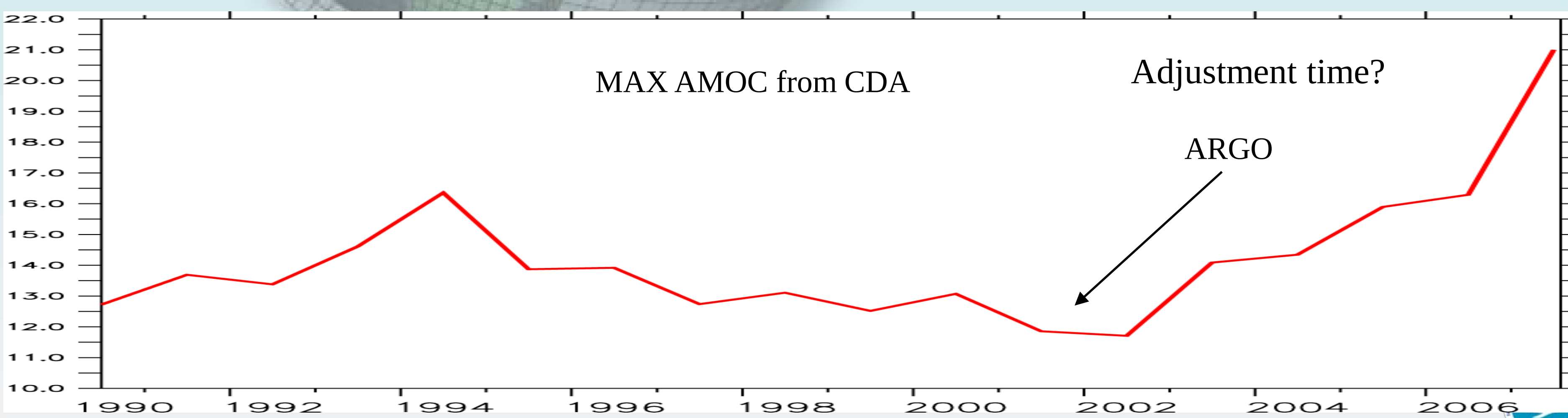

Monthly Global Counts of Argo Profiles
7000
6000
5000
4000
3000
2000
1000
0
00
01
02
03
04
05
Temperature
Salinity

ARGO deploy: 3000 autonomous profiling floats



Is the increase in overturning real or is it due to the onset of ARGO data in the assimilation ?

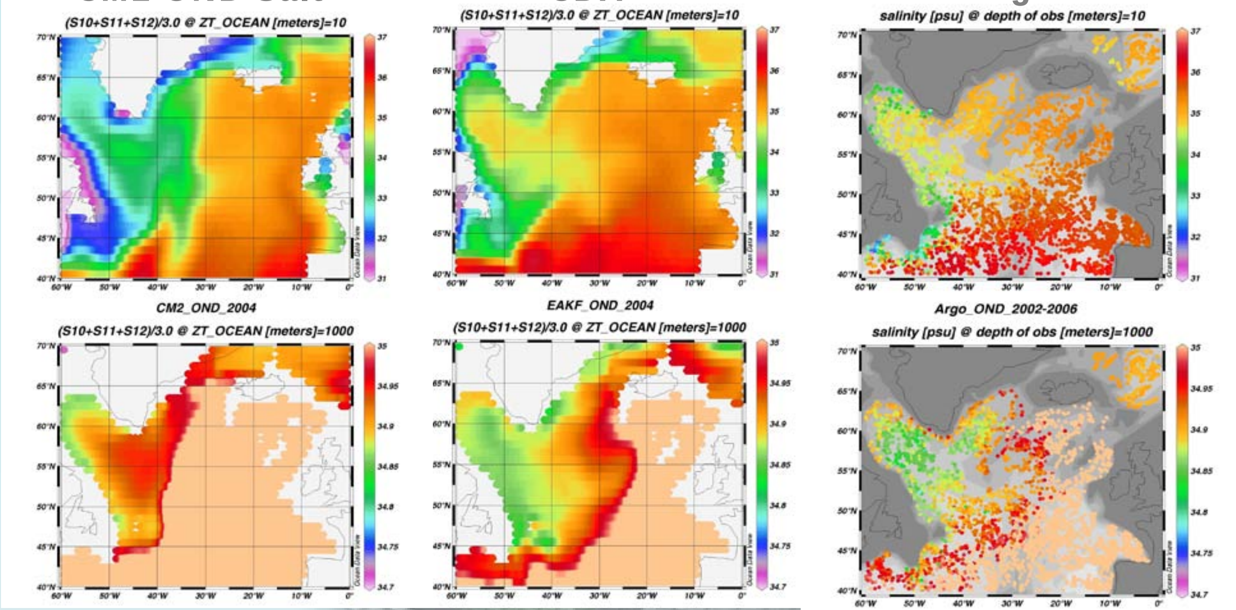




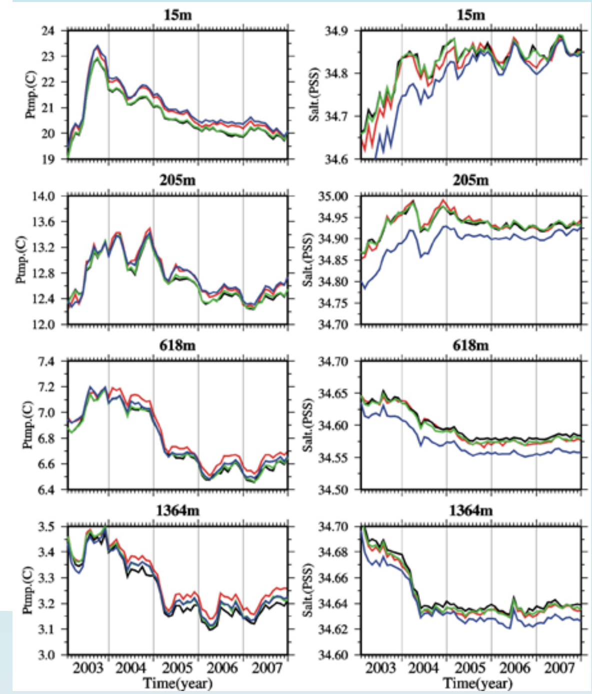
Argo Application

[Model Verification]

CM2 OND Salt | CDA | Argo

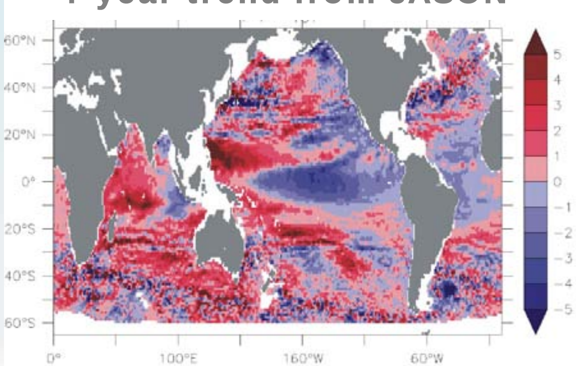


World Ocean T,S
Matching points with Argo
[CDA, Argo, WOA01, WOA05]

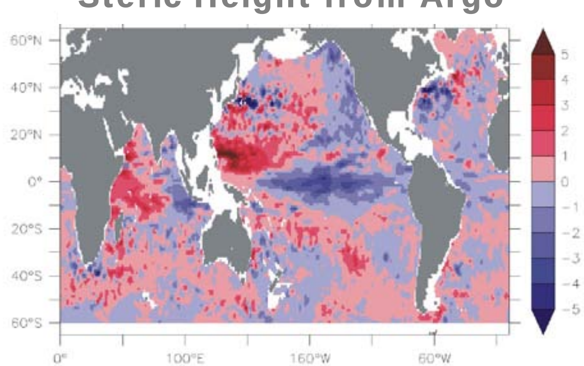


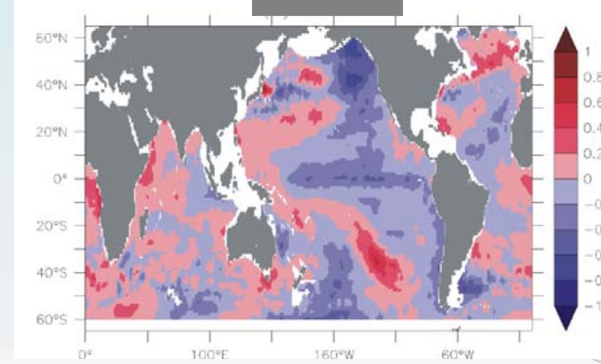
[Sea Level Diagnostic]

4-year trend from JASON



Steric Height from Argo





Coordinated Decadal Prediction for AR5

Additional model runs:

1.3) **10 year integrations** each year in Argo era from near end of 2001, 2002, 2003, 2004, 2006 (2007, ..)

1.4) For models w/ 20th century runs, run additional ensemble members that extend to 2035. These runs form a “control” against which the value of initializing short-term climate and decadal forecasts can be measured.

1.5) For models which do not have 20th century and other standard runs, suggest making a 100 year control integration, and a 70 year run with a 1% per year increase in CO_2. These integrations will allow an evaluation of model drift, climate sensitivity and ocean heat uptake, and give some idea of the natural modes of variability of the model.

2) Further studies which would be of interest

- Comparison of initialization strategies
- Repeat of the 1.1 2005 forecast with a high and/or low anthropogenic aerosol scenario
- Repeat of the 1.1 2005 forecast with an imposed “Pinatubo” eruption in 2010
- Impact of Interactive Ozone chemistry
- Air quality

Decadal Prediction

Challenges with Ocean Initialization

Large uncertainty in climate signals

What is happening now?

Forcing fluxes and analysis methods are largest source of uncertainty

Data assimilation does not always collapse the spread, but there are are good and bad methods

At least 20 current analyses: maybe more?

Not all from models. Ultimately needs to be done using coupled models

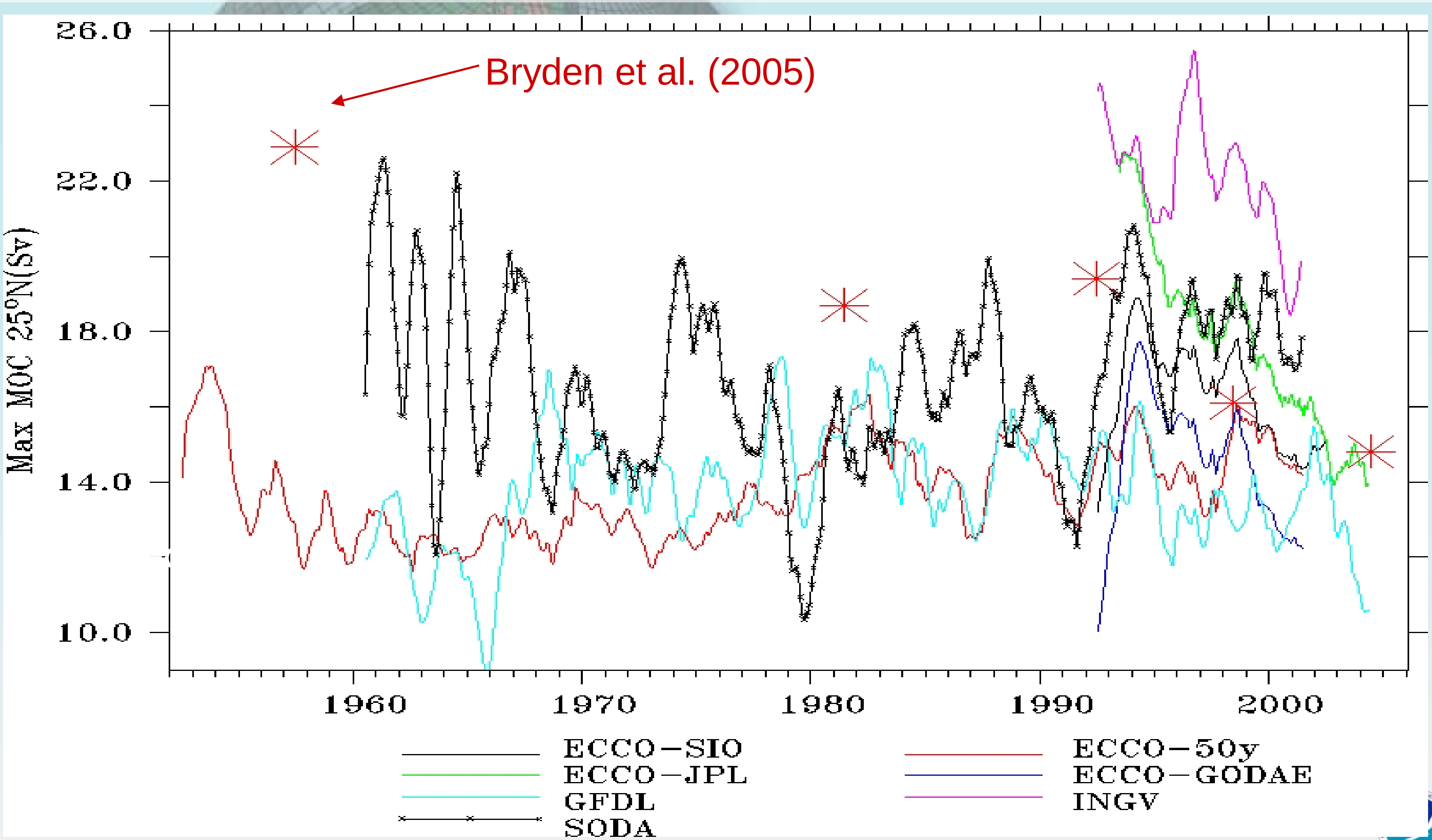
What is the best method of initialization

Need to minimize initialization shock

Requires improved models and improved assimilation methods

Challenges with Ocean Initialization

Many different global reanalysis products, and significant differences exist



More Balanced Intialization

- Coupled Data Assimilation

  "Assimilation of ocean data with a coupled model"
  - Coupled 4D-var: JAMSTEC
  - EnKF: GMAO, GFDL

- Coupled Breeding Vectors:
  - generation of the ensemble by projecting the uncertainty of the initial conditions on the fastest error-growth modes of the coupled system

- Anomaly Initialization:
  - Depresys (Met Office)
  - GECCO

Ensemble Coupled Data Assimilation (ECDA) is at the heart of prediction efforts

- Provides initial conditions for Seasonal-Decadal Prediction
- Provides validation for predictions and model development
- Ocean Analysis kept current and available on GFDL website
- Active participation in CLIVAR/GSOP intercomparisons

Pioneering development of coupled data assimilation system

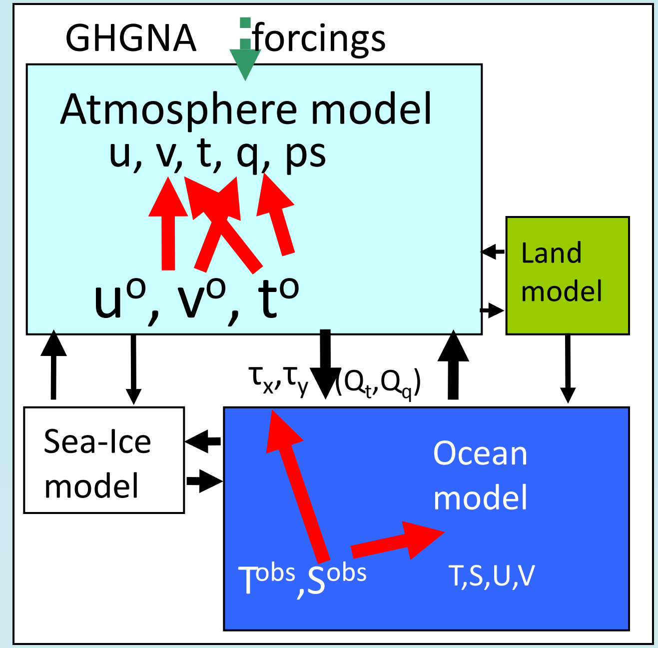
Coupled Ensemble Data Assimilation estimates the *temporally-evolving probability distribution* of climate states under observational data constraint:

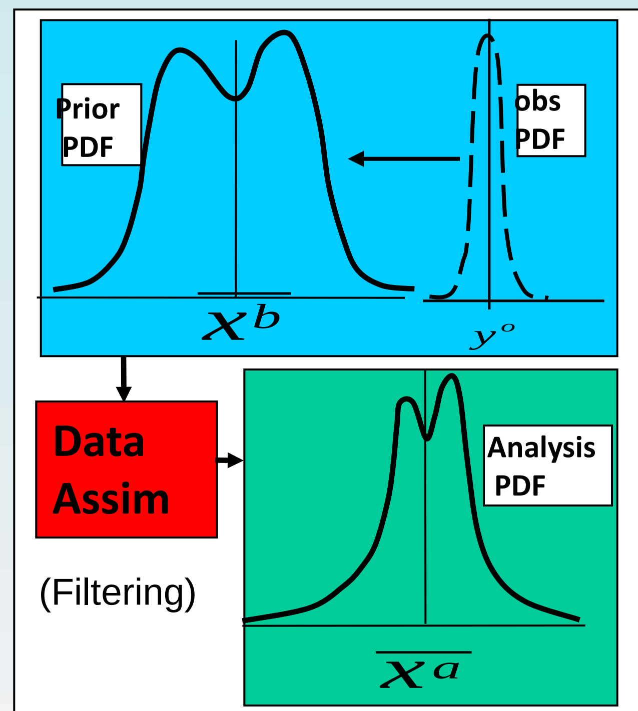
✓ Multi-variate analysis maintaining physical balances between state variables such as T-S relationship

✓ Ensemble filter maintaining the nonlinearity of climate evolution

✓ All coupled components adjusted by observed data through instantaneously-exchanged fluxes

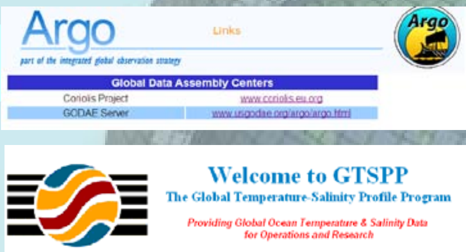
✓ Optimal ensemble initialization of coupled model with minimum initial shocks





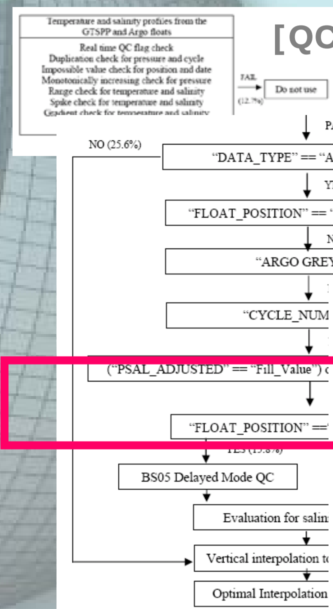
GFDL Argo DB [monthly update]

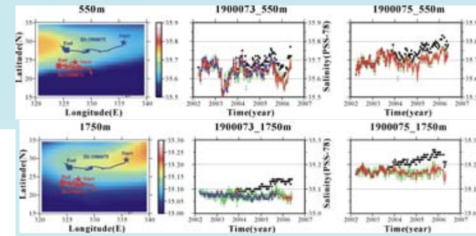
Step 1: Data Mirroring System
(Identified Argo + GTSPP)



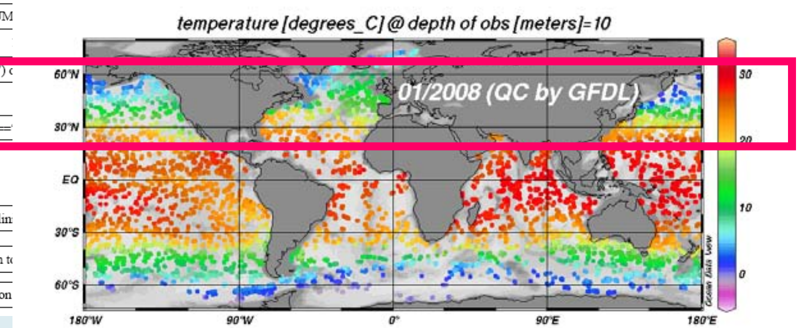
Step 2: Quality Control System
(Real Time + Delayed Mode)

[QC Process]

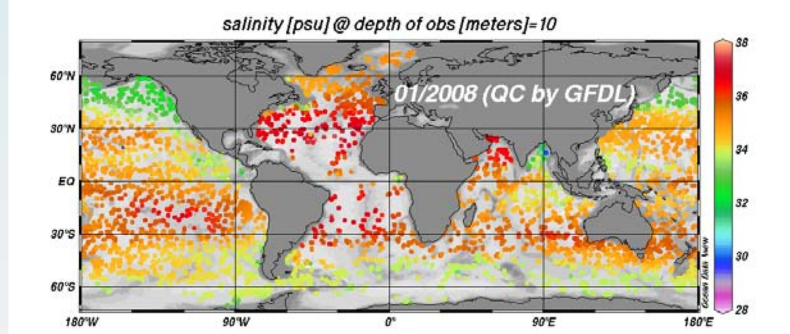




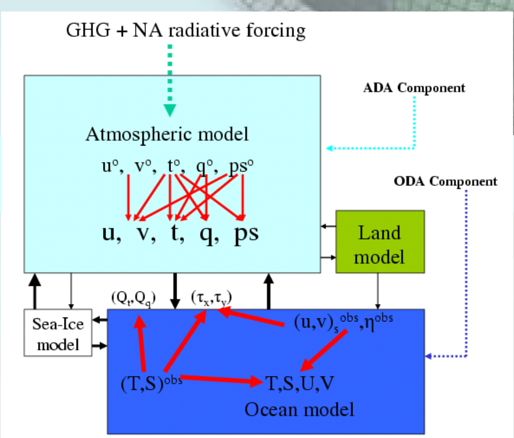
[DMQC result]



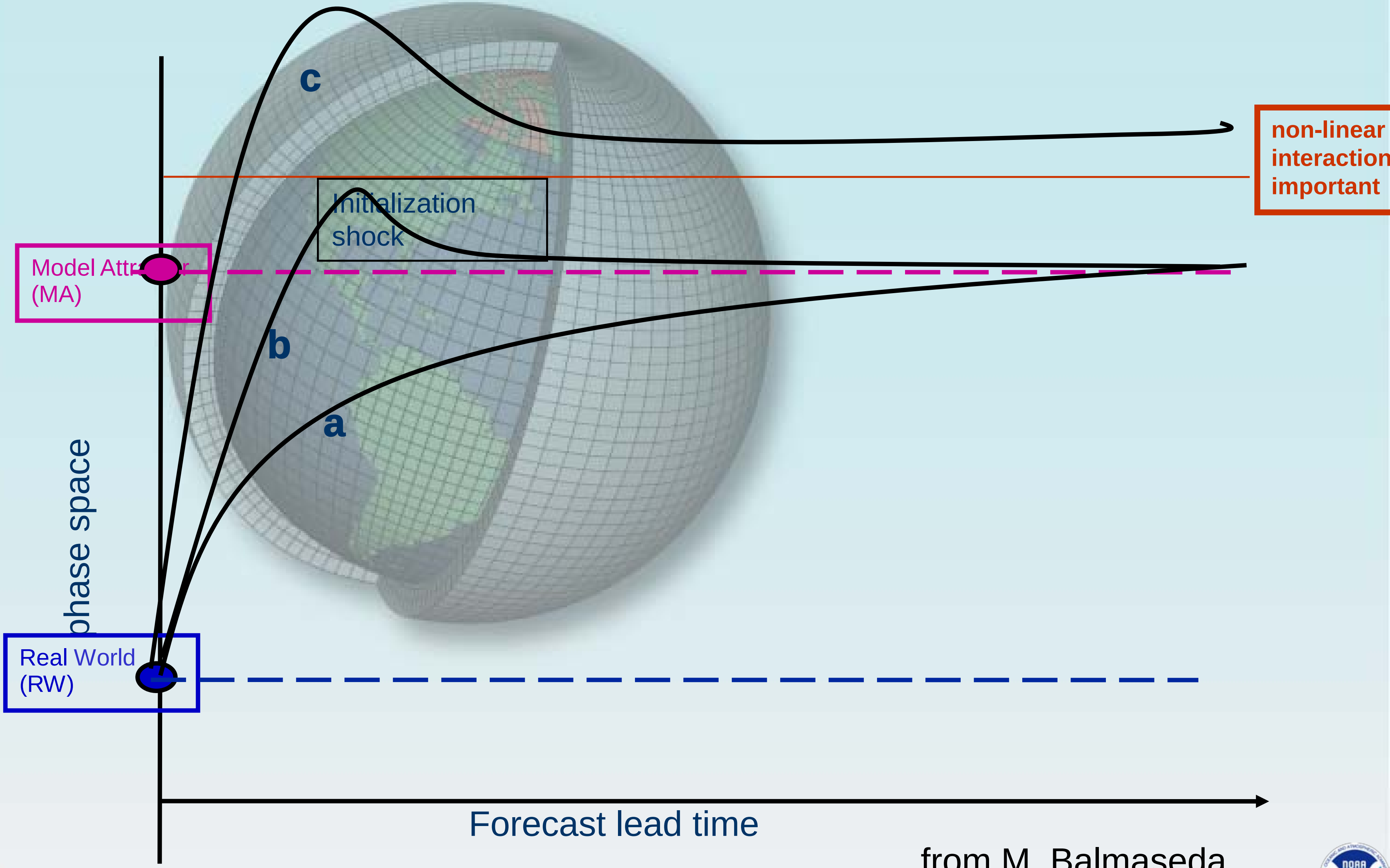
[GFDL Argo DB]



Step 3: Coupled Data Assimilation System



“Initialization shock” can be detrimental if non linearities matter.

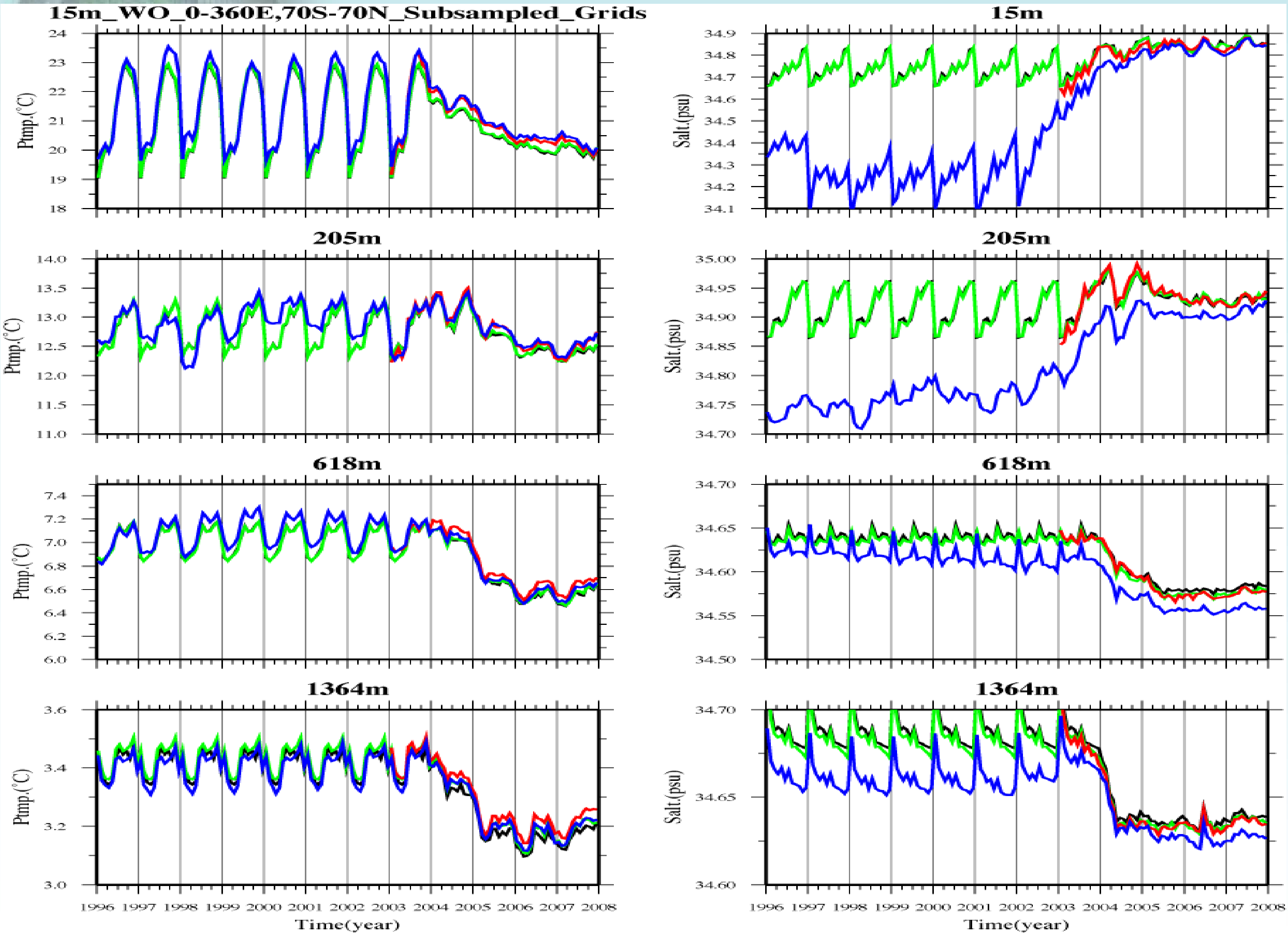


from M. Balmaseda

WOA1(black), WOA5(green), CDA(blue), ARGO(red)

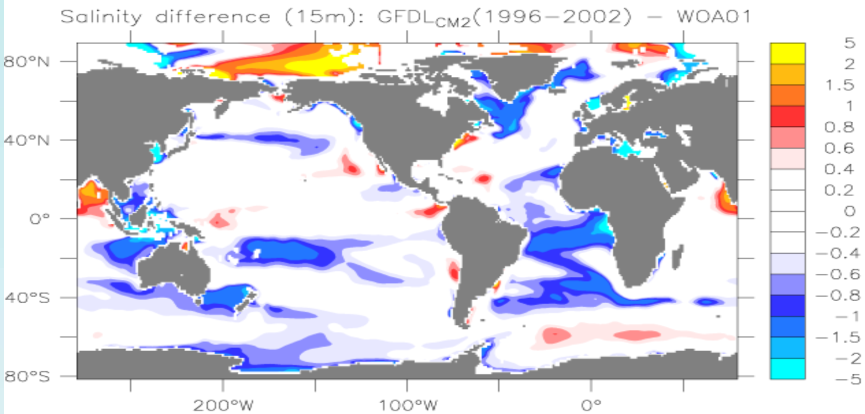
Subsampled grids indicate the matching points with monthly Argo distribution every year

Subsampled grids from ‘97-’03 used the Argo distribution of 2003

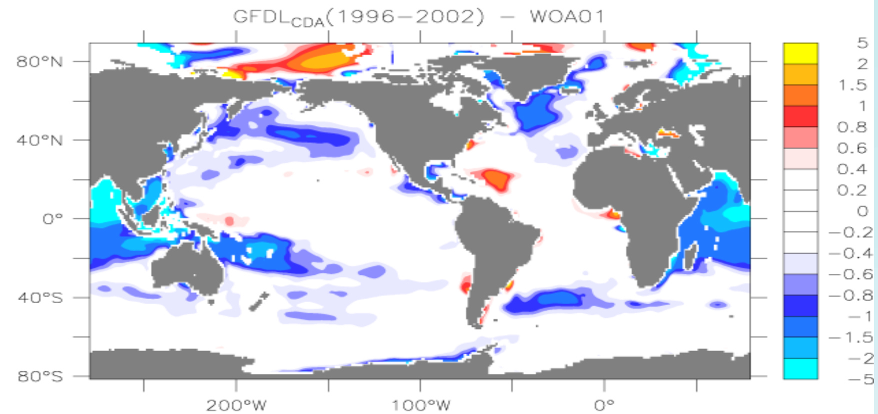


Salinity differences (15m) with WOA

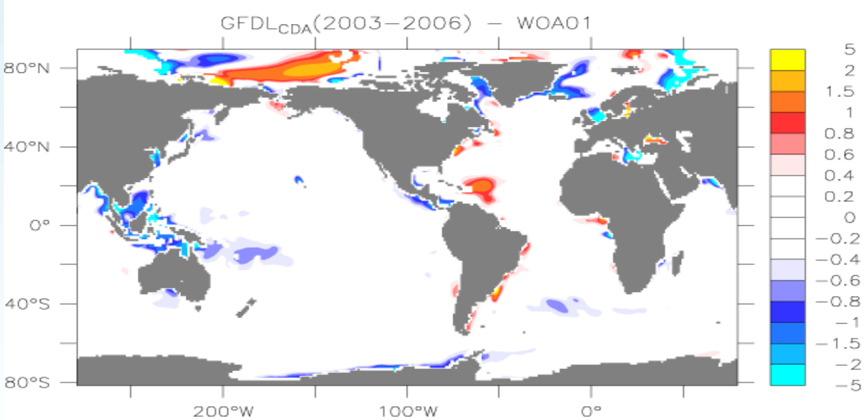
CM2



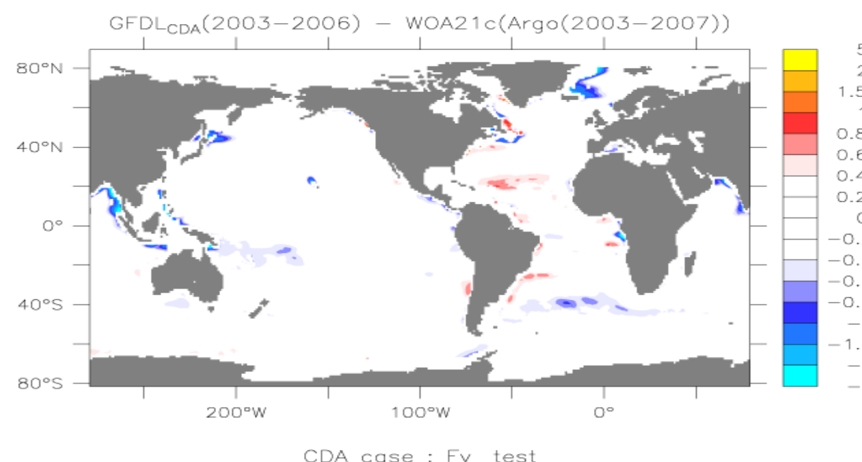
ECDA (1996-2002)



ECDA (2003-2006)



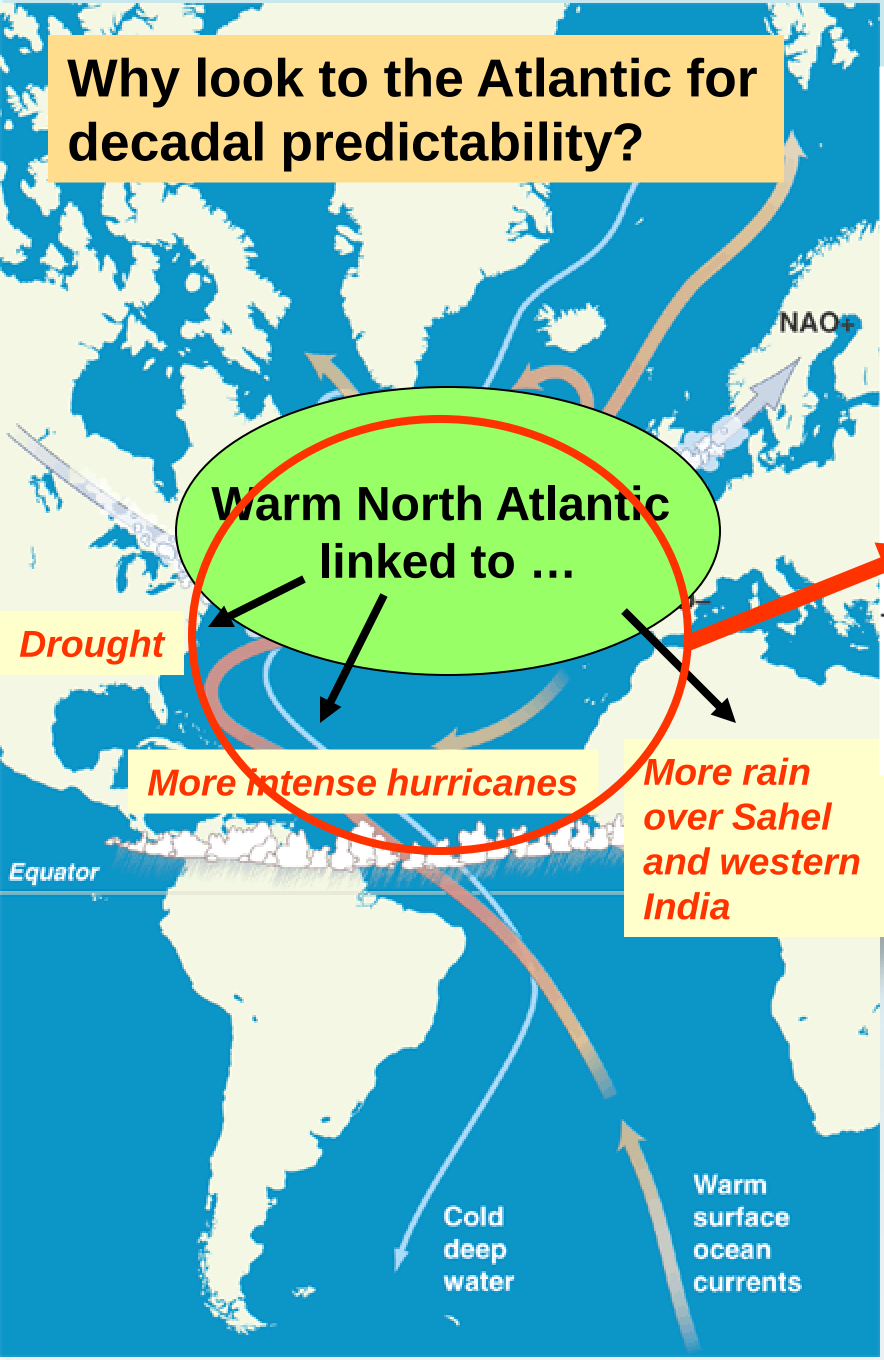
ECDA (03-06)-Argo(03-06)



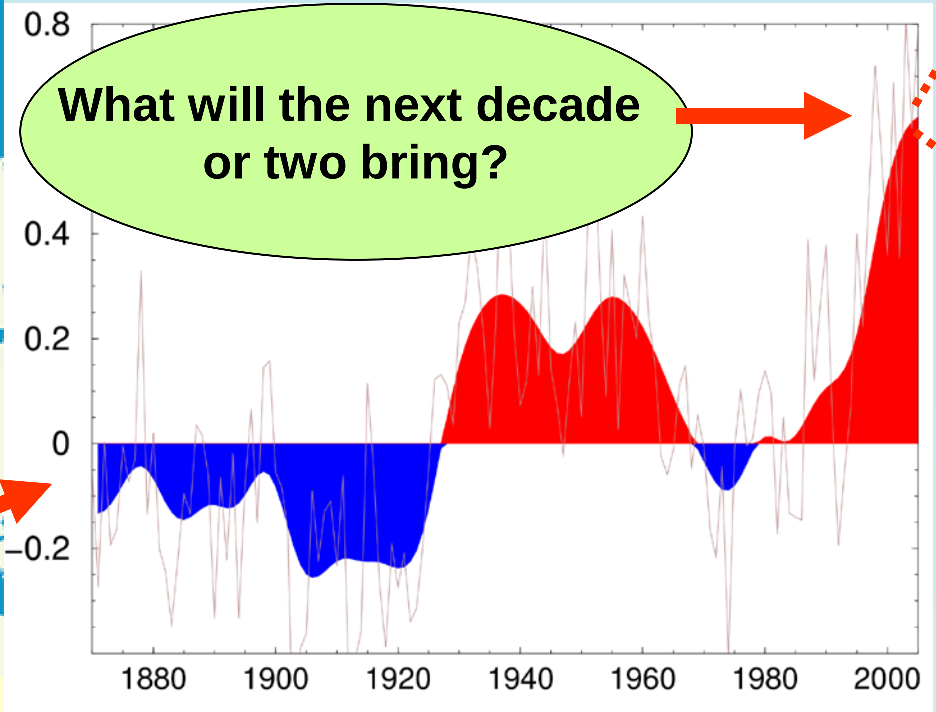
ECDA research activities improve initialization

- **Multi-model ECDA to help mitigate bias**
- **Fully coupled model parameter estimation within ECDA**
- **ECDA in high resolution CGCM**
- **Assess additional predictability from full depth ARGO profilers**

Why look to the Atlantic for decadal predictability?

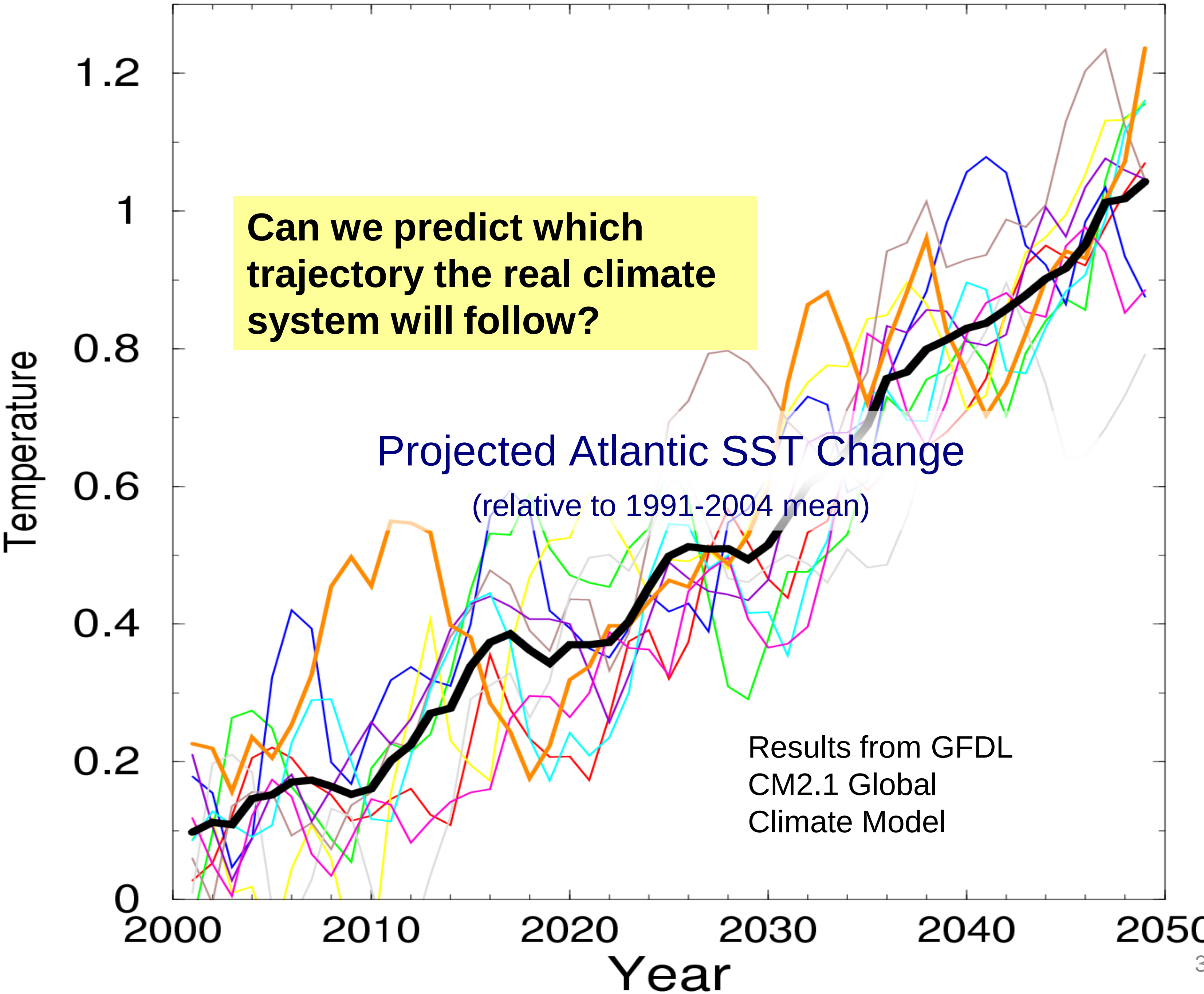


North Atlantic Temperature

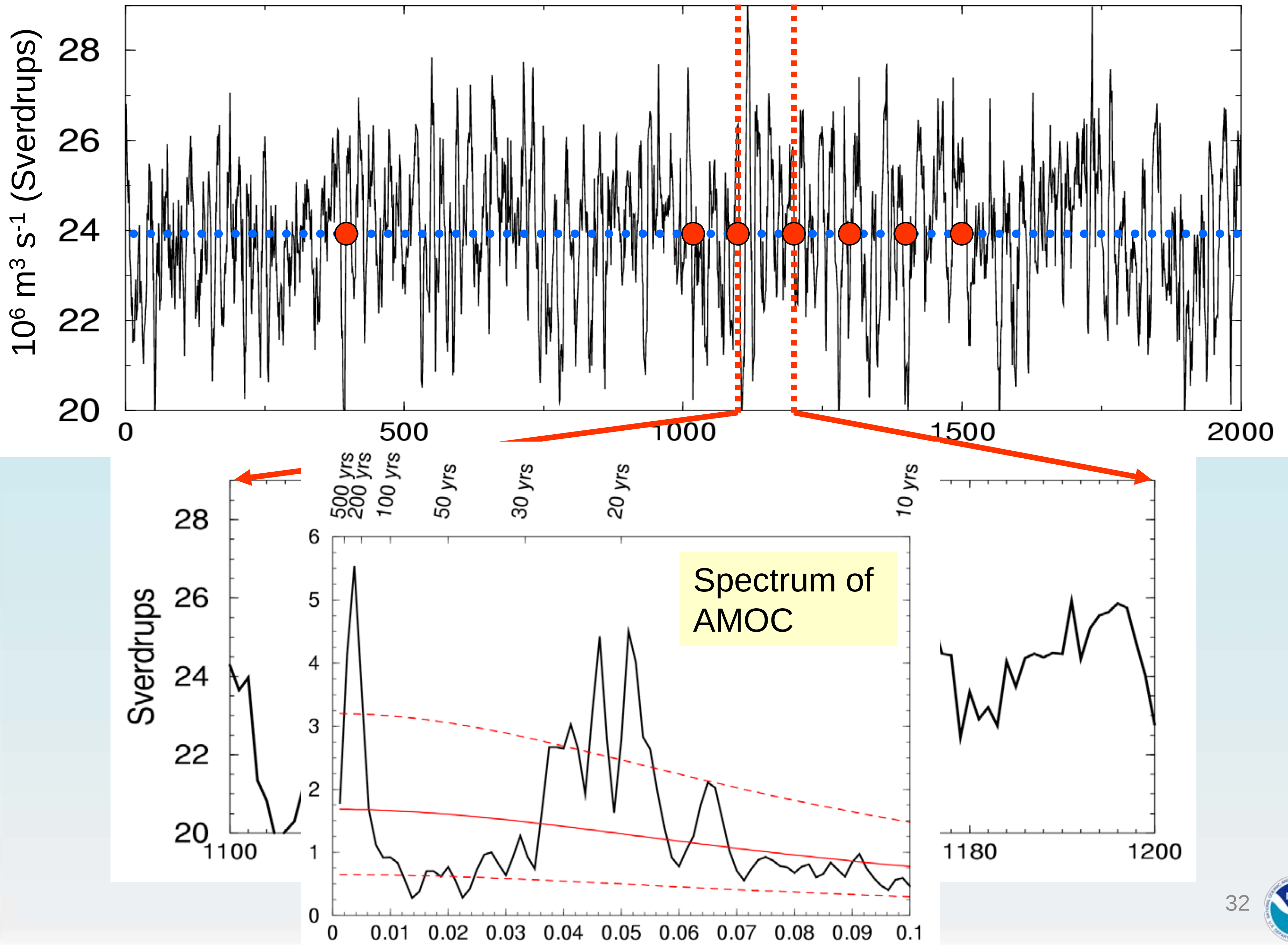


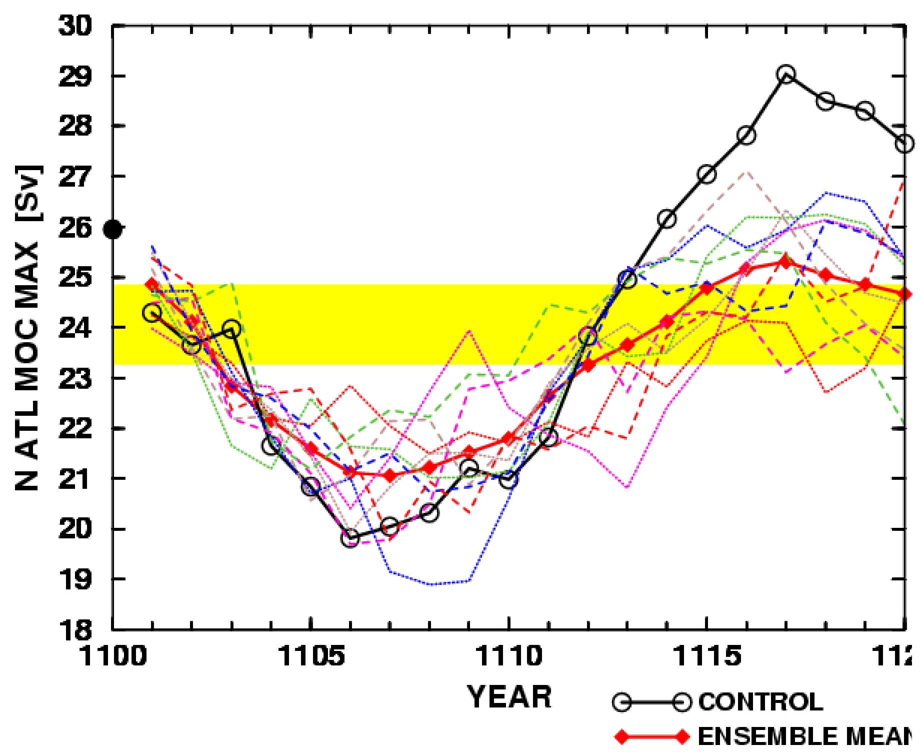
Two important aspects:

a. Decadal-multidecadal fluctuations
b. Long-term trend


Can we predict which trajectory the real climate system will follow?
Projected Atlantic SST Change
(relative to 1991-2004 mean)
Results from GFDL CM2.1 Global Climate Model
Temperature
1.2
1
0.8
0.6
0.4
0.2
0
2000
2010
2020
2030
2040
2050
Year

Atlantic Meridional Overturning Circulation (AMOC) in GFDL CM2.1 Model





Predictability of Atlantic Meridional Overturning Circulation (AMOC) in GFDL CM2.1 Climate Model

Decadal Potential Predictability with a focus on the Atlantic

- **How well does the ECDA system constrain the AMOC?**
- **Given that the ocean observing system is non-stationary, what impact does that have on the AMOC predictability?**
- **What are the sources of AMOC predictability and how dependent are they to the various observing networks ?**

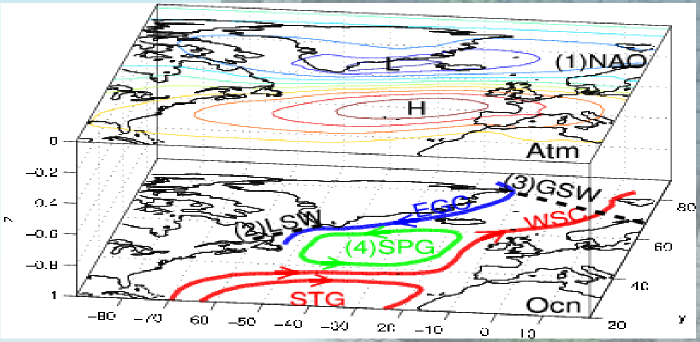
We use a “perfect model” framework to address these questions

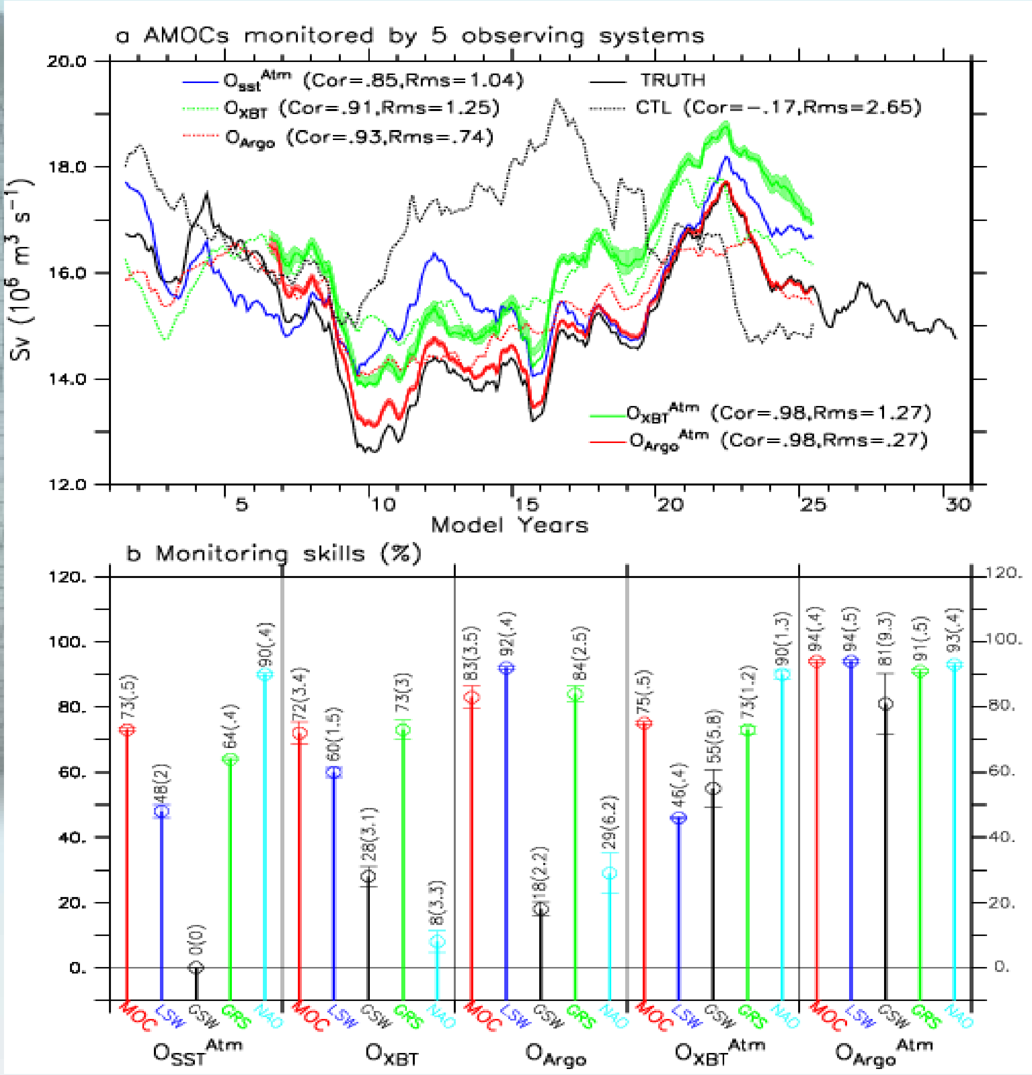
Results: The ARGO network outperforms the XBT network in both assimilation and forecast skill in idealized experiments

Assess the skill of ECDA to constrain AMOC as well as adequacy of observing systems

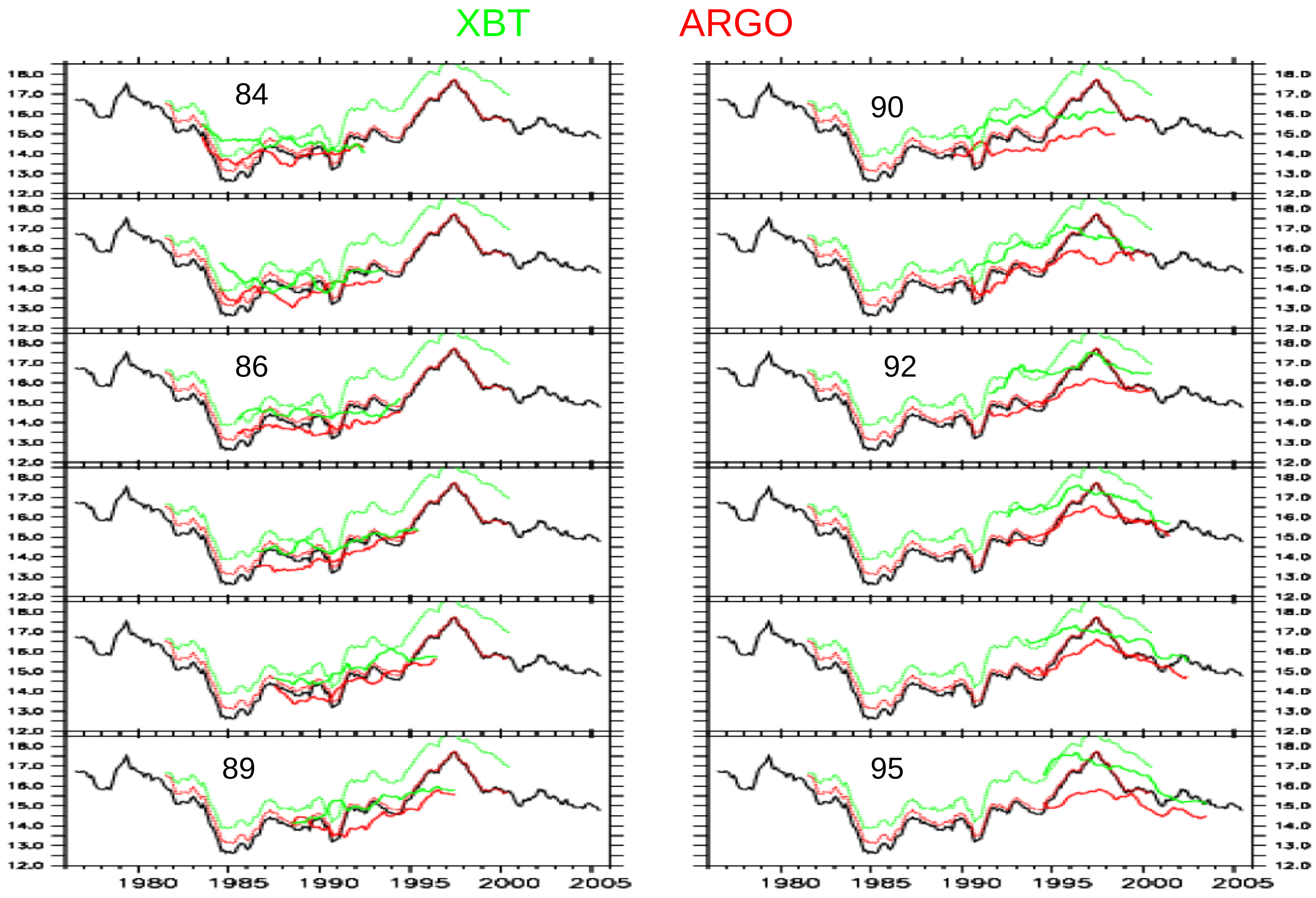
a) Time series of the reconstructed AMOC

b) The accuracy of the reconstructed AMOC, NAO, LSW, GSW,GRS





AMOC Predictability from OSSE



High resolution modeling

Scientific goals

1. Assess model sensitivity of decadal variability and predictability to model resolution and physics.

2. Explore ocean's role in climate variability and change using a high resolution coupled model.

Specific Plans

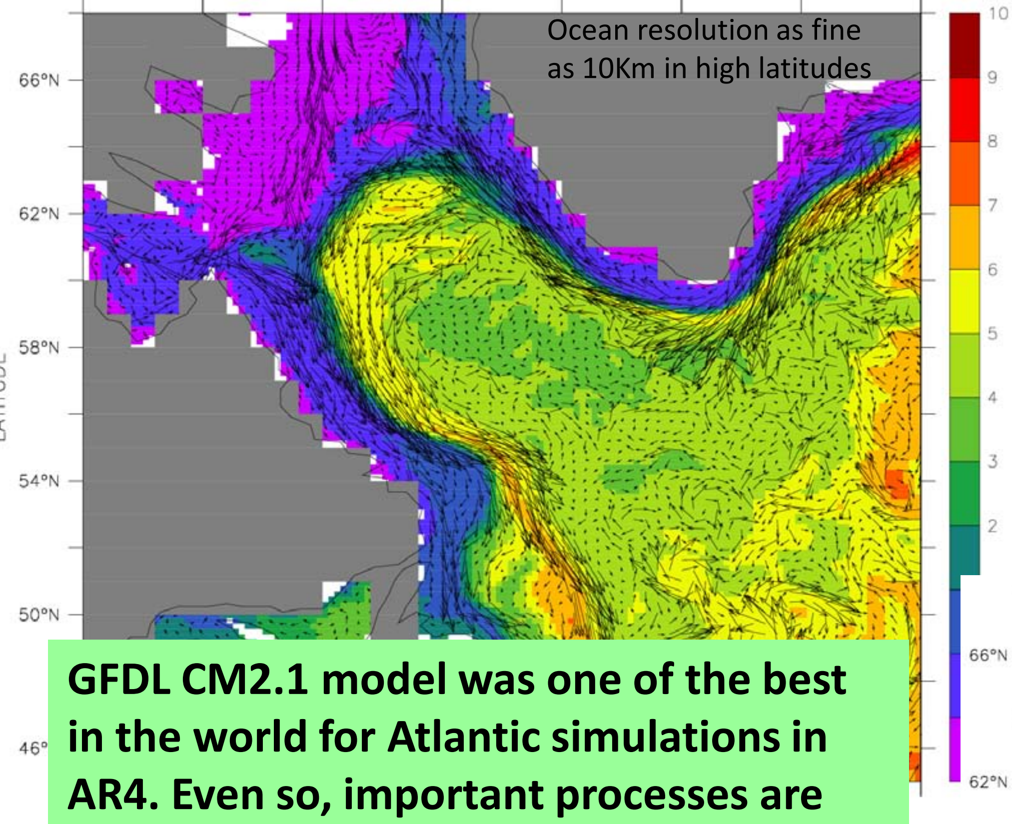
Model development

- **Simulated variability and predictability is likely a function of the model**

- **Developing improved models (higher resolution, improved physics, reduced bias) is crucial for studies of variability and predictability**

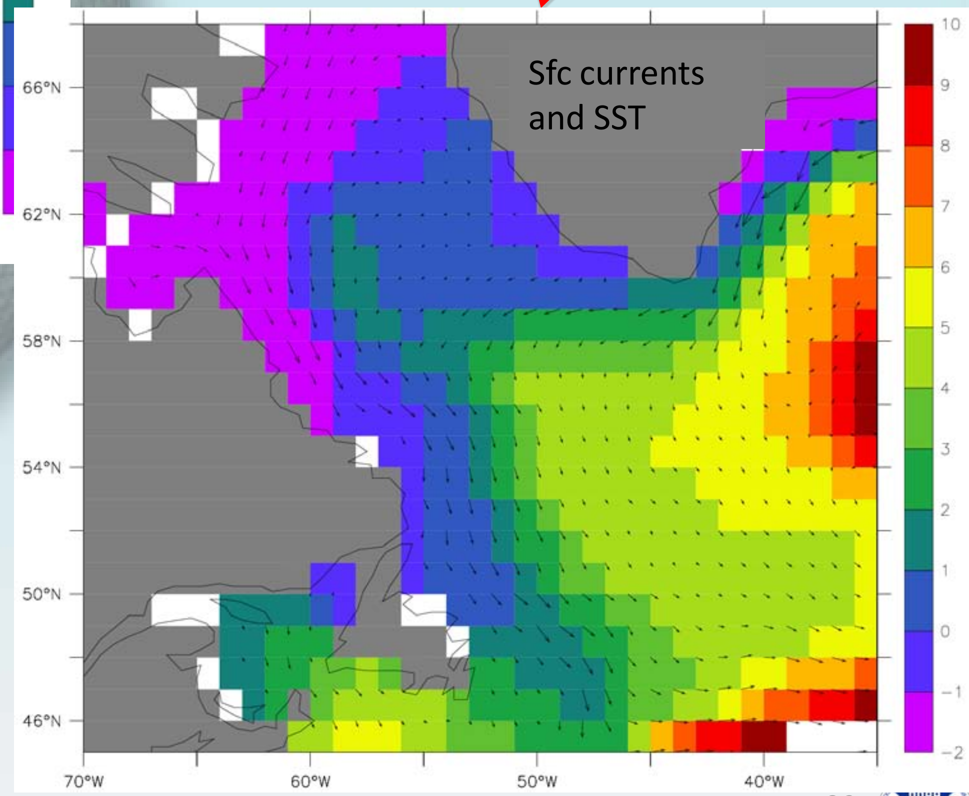
- **New global coupled models: CM2.4, CM2.5, CM2.6**

	Ocean	**Atmos**	**Computer**	**Status**
CM2.4	10-25 Km	100 Km	GFDL	Running
CM2.5	10-25 Km	50 Km	DOE	In development
CM2.6	4-10 Km	50 Km	DOE	In development



GFDL CM2.4 Global Coupled Model SST, surface currents

GFDL CM2.1 Global Coupled Model SST, surface currents

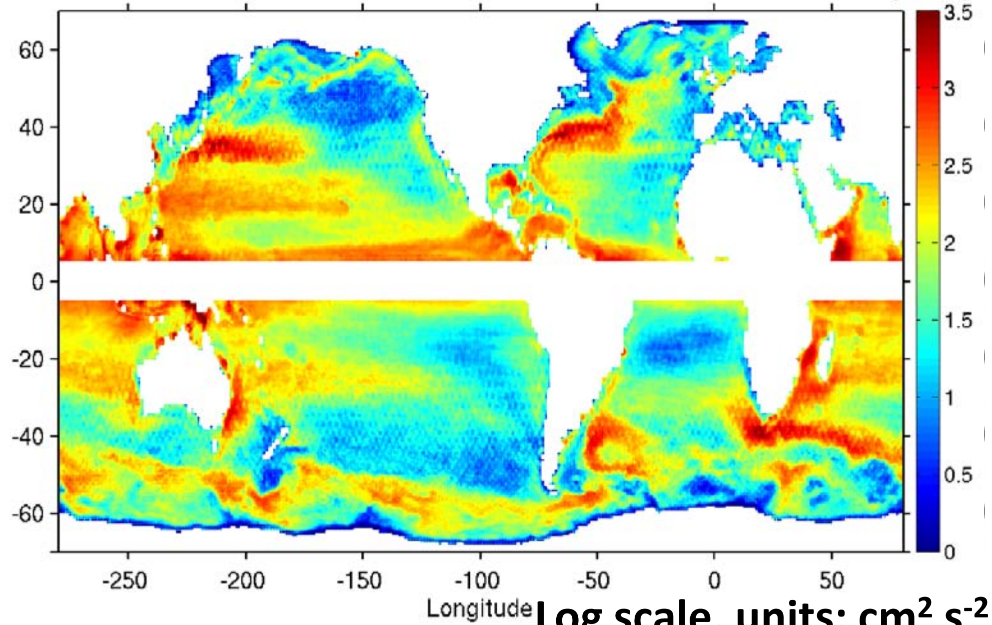


GFDL CM2.1 model was one of the best in the world for Atlantic simulations in AR4. Even so, important processes are not well resolved.

decadal variability and predictability to model resolution and physics?

Other issues:
- ocean heat uptake
- ocean circulation changes (ENSO, AMOC, Southern Ocean)

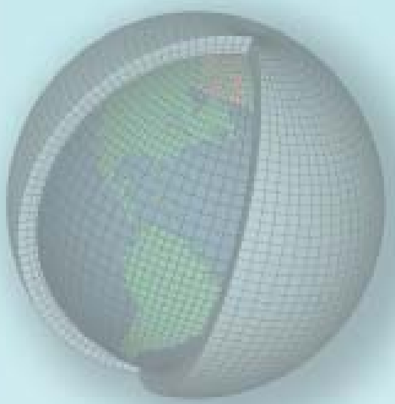
Observational estimates (satellite)



Log scale, units: cm^2 s^{-2}

Eddy Kinetic Energy from satellite records and models (using 5 day means)

Courtesy Riccardo Farneti



QuickTime™ and a
H.264 decompressor
are needed to see this picture.

Current/planned activities at GFDL

- **Ongoing studies with CM2.1 climate model to develop improved understanding of**
  - **a) Mechanisms of simulated decadal variability**
  - **b) Decadal scale predictability arising from internal variability**
  - **c) Detection and attribution of observed change**

- **Development and use of higher resolution coupled models. Use of DOE computers.**

- **Development and use of new coupled assimilation system for analysis and initialization**

- **Assessment of observation systems for decadal predictability**

- **Prototype decadal predictions planned for 2009 in concert with IPCC AR5/CMIP 5 protocols**

- **Assess predictability and predictions in collaboration with efforts at NCAR and MIT**

GFDL Decadal Prediction Research in support of IPCC AR5

Key goal: assess whether climate projections for the next several decades can be enhanced when the models are initialized from observed state of the climate system.

- **Use ECDA for initial conditions from "observed state"**
  - **Produce ocean reanalysis 1970-2009**
- **Use "workhorse" CM2.1 model from IPCC AR4 [2009]**
  - **Decadal hindcasts from 1980 onwards (10 member ensembles)**
  - **Decadal predictions starting from 2001 onwards (10 member ensembles)**
- **Use experimental high resolution model (if scientifically warranted) [2010]**
  - **Decadal predictions starting from 2001 onwards (10 member ensembles)**
- **Use CM3 model for IPCC AR5 [2010, tentative]**
  - **Decadal predictions starting from 2001 onwards (10 member ensemble)**

Discussion

- Decadal prediction/projection is a mixture of boundary forced and initial value problem
- Changing radiative forcing (esp. aerosols) will be a key ingredient
- Some basis for decadal predictability of internal variability, probably originating in ocean
- Some of predictability will arise from unrealized climate change already in the system
- Substantial challenge for models, observations, assimilation systems, and <u>theoretical understanding</u>

Cautionary Notes

- **This field (decadal predictability) is in its infancy – many fundamental challenges remain**

- **Results from AR5/CMIP5 decadal predictions should be viewed with caution in light of:**

  - *Model bias and drift and their impacts on prediction*
  - *Varying initialization strategies*
  - *Unknown level of true predictability of the system*

- **It is possible that initial decadal prediction attempts will show little or no "meaningful" predictability (from internal variability). That would lead to at least two possibilities:**

  1. *The system is not predictable on decadal time scales*
  2. *We are not yet able to realize that predictability*

Will we be able to distinguish between these two possibilities?

Concluding Remarks

- **Decadal climate variability:**
  - **Crucial piece – predictability may come from both**
    - **forced component**
    - **internal variability component**

    … and their interactions.

- **Decadal predictions will require:**
  - **Better characterization and mechanistic understanding (determines level of predictability)**
  - **Sustained, global observations**
  - **Advanced assimilation and initialization systems**
  - **Advanced models (resolution, physics)**
  - **Estimates of future changes in radiative forcing**
- **Decadal prediction is a major scientific challenge**
- **An equally large challenge is evaluating their utility**

QuickTime™ and a
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