

Decadal climate variability, predictability, and high-resolution coupled modeling

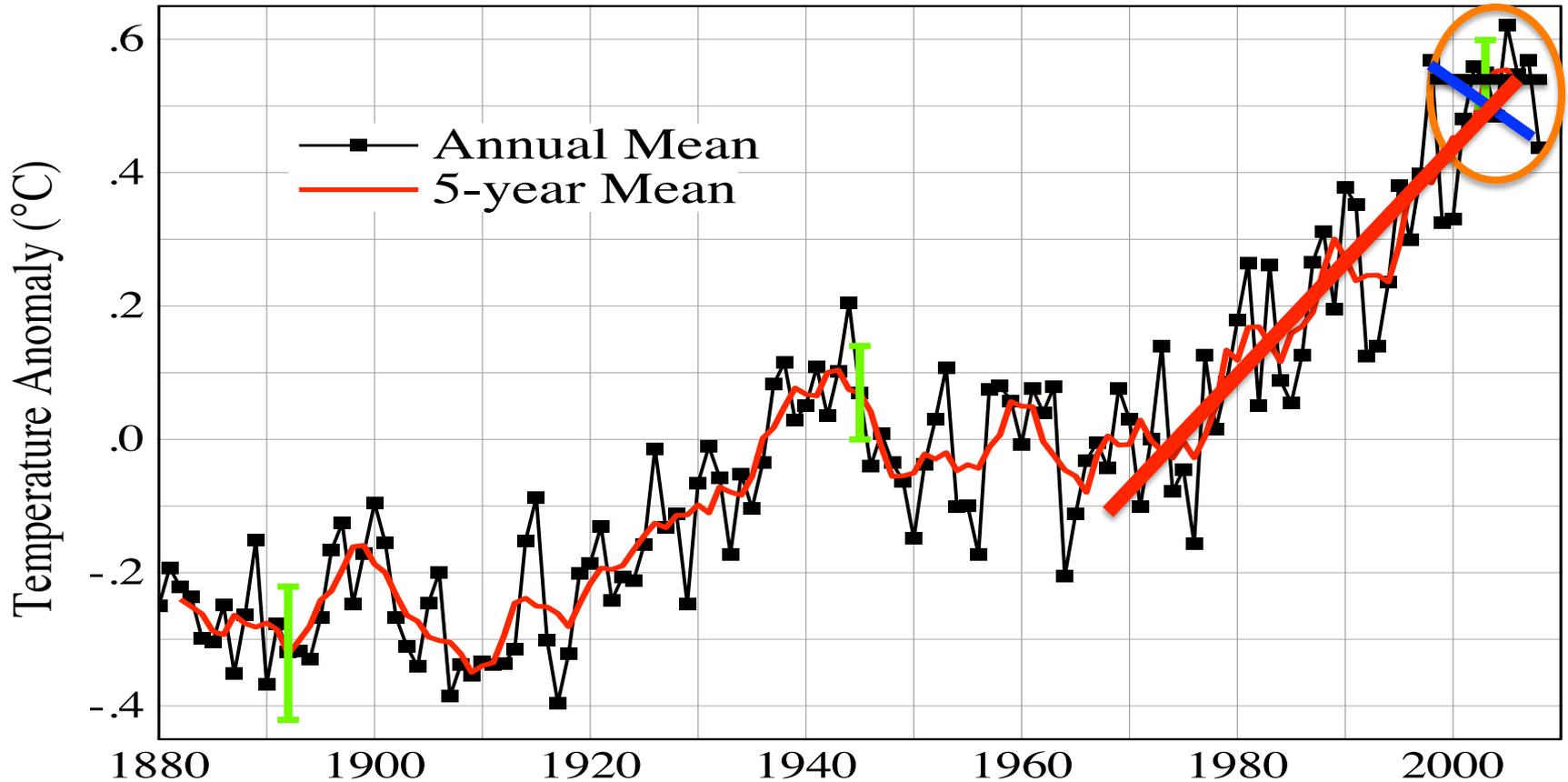
T. Delworth, R. Zhang, S. Zhang, A. Rosati, K. Dixon,
R. Msadek, F. Zeng, H.-C. Lee, W. Anderson

Presented by Tony Rosati

- 1. Background on decadal variability and predictability*
- 2. Current GFDL efforts at decadal prediction*
- 3. High resolution coupled modeling for predictions and projections*



Global Land-Ocean Temperature Index

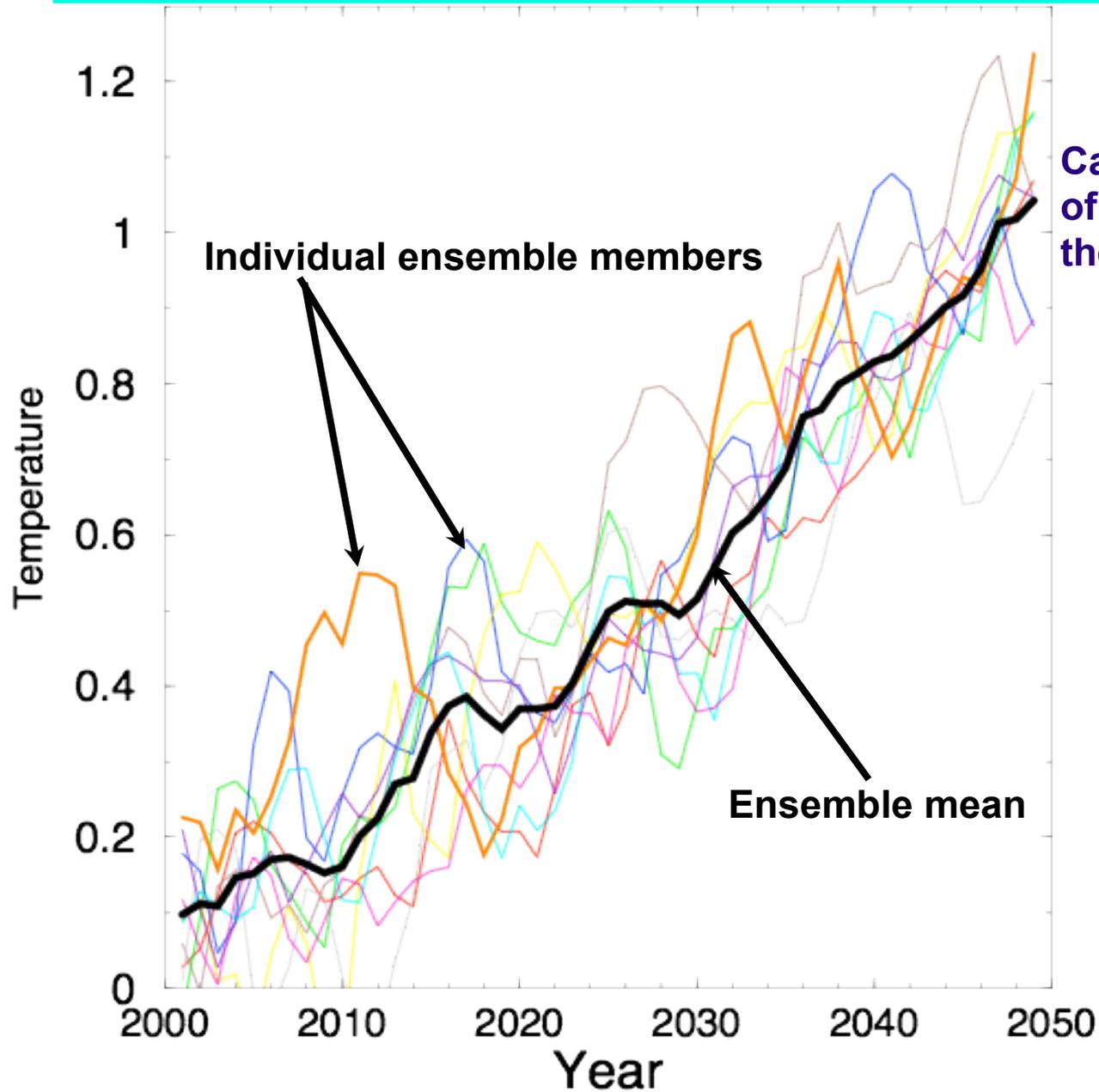


"If you're 29, there has been no global warming for your entire adult life. If you're graduating high school, there has been no global warming since you entered first grade. There has been no global warming this century. None."

Mark Steyn, National Review online, July 4, 2009, as quoted by syndicated columnist George Will on July 23, 2009 in the Washington Post

Simulated Atlantic Sea Surface Temperature

(based on GFDL CM2.1)



Individual ensemble members

Can we predict the trajectory of Atlantic temperatures over the next several decades?

Ensemble mean

Key questions:

What are the relative roles of radiative forcing and natural climate variability in these variations?

Are these variations potentially predictable?

How can we realize any potential predictability?

Would such predictions be “useful”?

To address these questions we require:

Improved understanding of decadal variability and its predictability

Development of the capability to make decadal-scale (2-20 years) projections and predictions of climate variability and change on both global and regional scales.

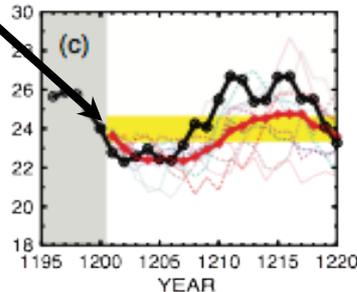
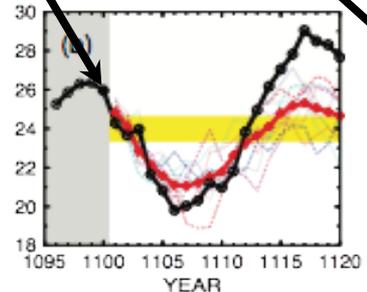
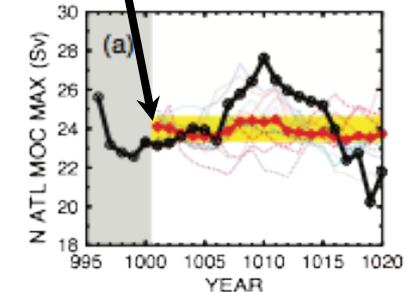
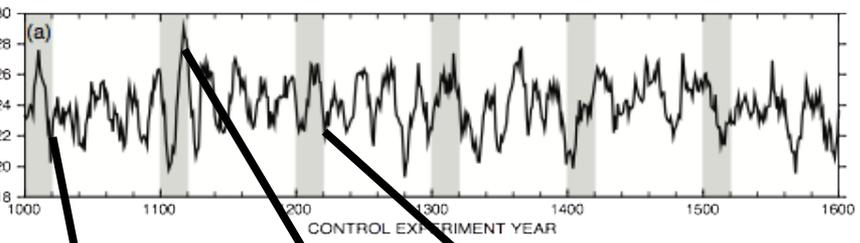
==> Includes state of the art models, as well as advanced assimilation and observing systems

Approaches:

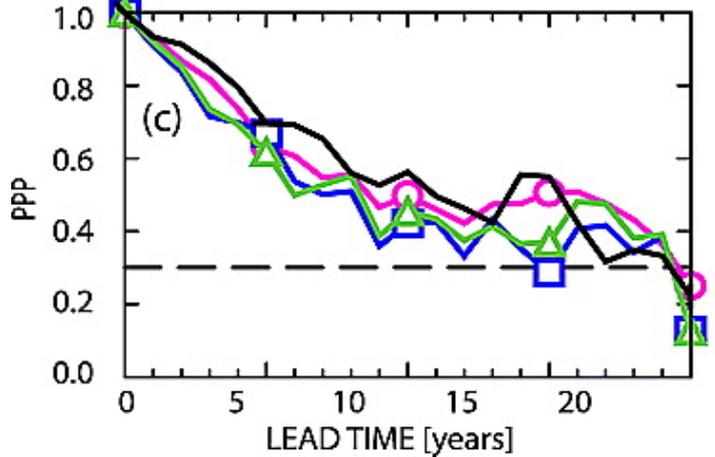
1. Use theory, observations (instrumental and paleo) to improve understanding of decadal variability and its mechanisms

Examples include:

- Collaboration between GFDL, NCAR and MIT on decadal variability across a hierarchy of models
- Collaboration between GFDL, PMEL, Univ Washington, Univ Miami on aspects of simulated and observed Atlantic



Statistical estimate of predictability
Msadek et al., 2010



These suggest oceanic fluctuations could be predictable a decade in advance

At GFDL, long history of research on prediction systems for seasonal to interannual time scales (ENSO).

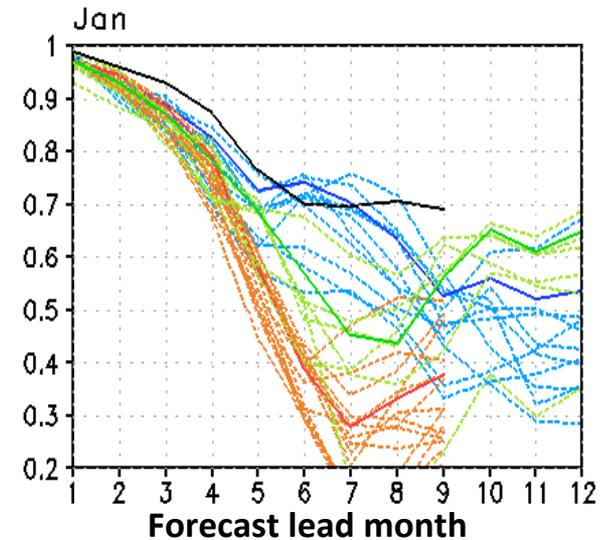
Requires:

- *adequate, sustained observing system*
- *assimilation system to initialize models*
- *models to make predictions*
- *conduct large sets of hindcasts to evaluate skill*

GFDL research has contributed to NCEP seasonal forecast systems, and is now contributing to a developing national Multi-Model Ensemble (MME).

Preliminary results on
forecast skill from MME

ACC of NINO3.4 Index (Jan IC)



NCEP ensemble mean
NCEP members
GFDL ensemble mean
GFDL members



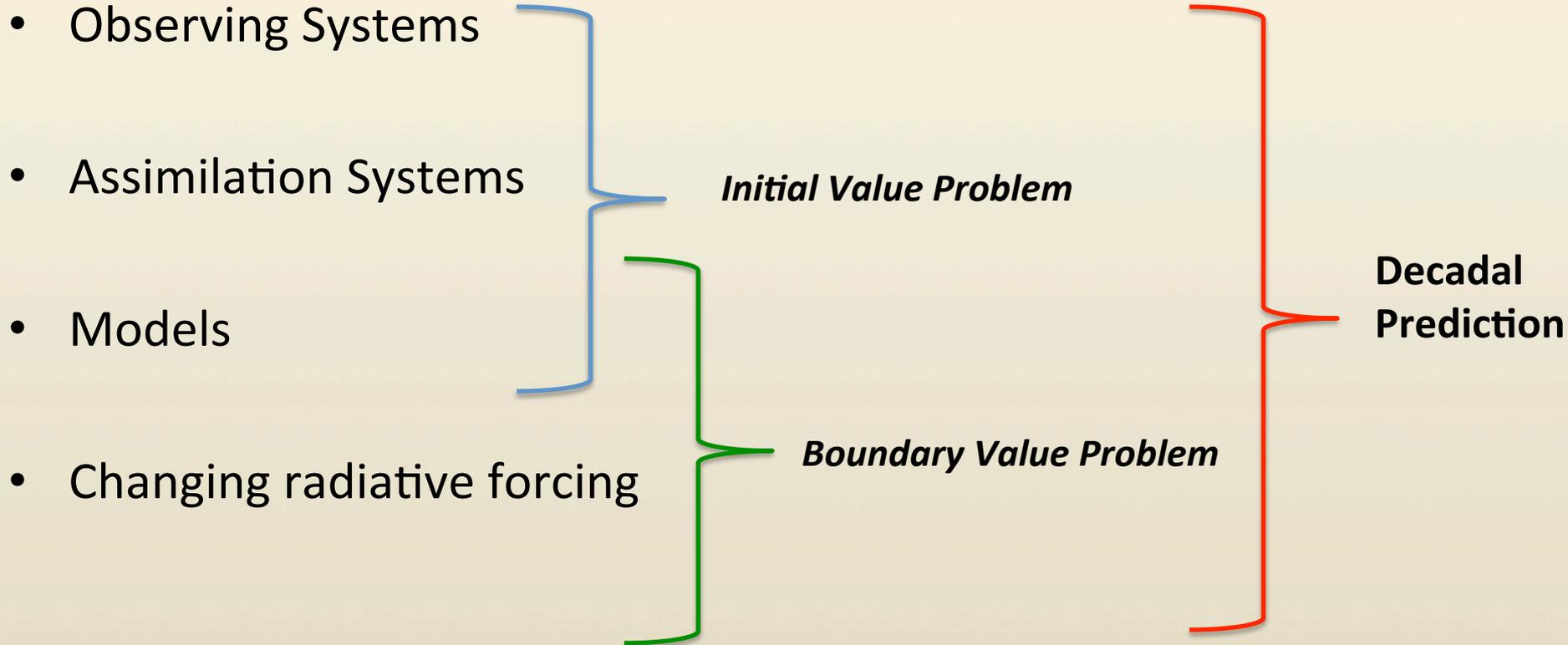
NCAR ensemble mean
NCAR members
MME (NCEP+GFDL+CCSM)



Types of Predictions and Projections

- **Seasonal predictions**
 - ✓ mainly an Initial Value Problem (ENSO is classic example)
- **Centennial scale climate projections**
 - ✓ mainly a Boundary Value Problem (changing radiative forcing)
 - ✓ Example: IPCC projections for year 2100
- **Decadal Climate Prediction**
 - ✓ combination of Initial and Boundary Value Problems

Components of Prediction Systems



Goal: Continuous predictions and projections from seasonal to decadal to centennial time scales

Decadal Prediction Key Question

- **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?**



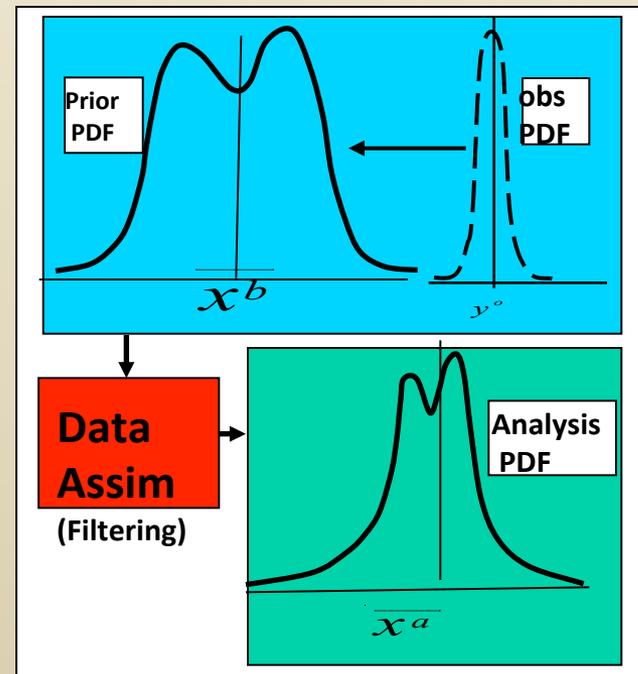
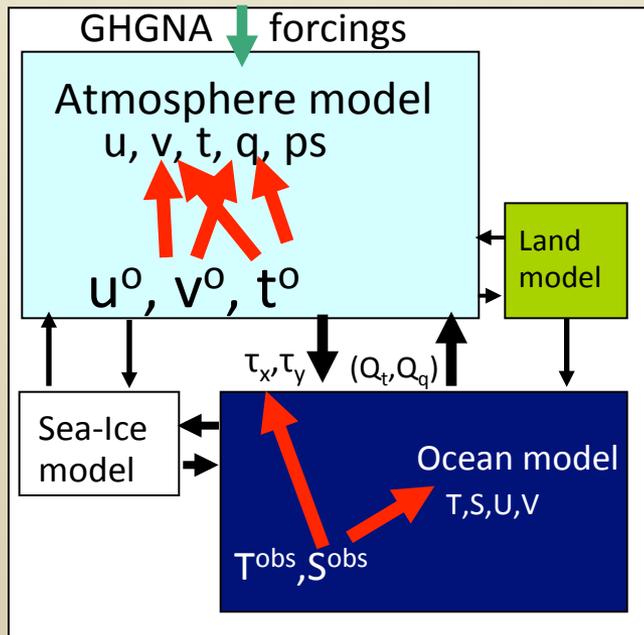
Ensemble Coupled Data Assimilation (ECDA) is at the heart of GFDL prediction efforts

- **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

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

- Multi-variate analysis maintains physical balances between state variables such as T-S relationship – primarily geostrophic balance
- Ensemble filter maintains the nonlinearity of climate evolution
- All coupled components adjusted by observed data through instantaneously-exchanged fluxes
- Optimal ensemble initialization of coupled model with minimum initialization shocks



S. Zhang, M. J. Harrison,
A. Rosati, and A.
Wittenberg
MWR 2007

ECDA research activities to 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 and pseudo Salinity**

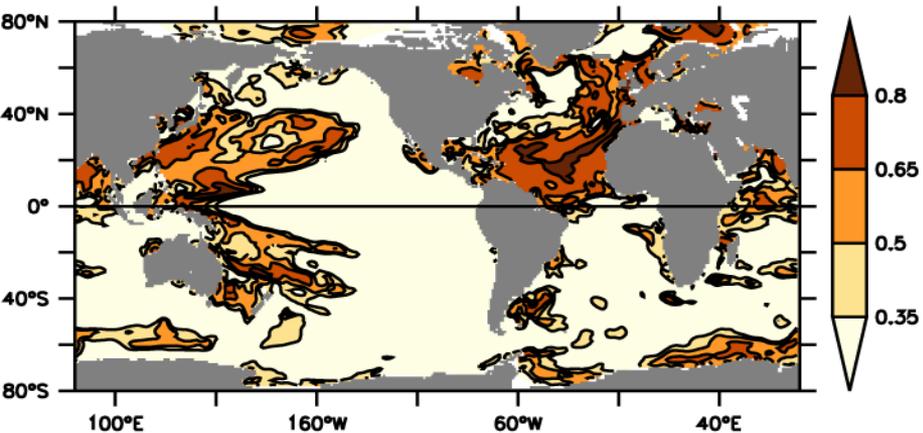
Prototype dynamical decadal prediction – initial suite

- **Use GFDL CM2.1 climate model for decadal predictions**
- **Initialize based on GFDL Ensemble Coupled Data Assimilation (ECDA) system**
- **First Suite (completed):**
 - Use “observed” radiative forcing through the year 2005, and estimated forcing from IPCC AR4 RCP 4.5 scenario after the year 2005
 - Start ensembles from 1 January of each year from 1960 to 2011
 - Each ensemble has 10 members, each member is 10 years in duration
 - Total of 5100 model simulated years in this first suite of decadal hindcasts and predictions (51 ensembles * 10 members * 10 years)
 - Companion 10-member ensemble of simulations without initialization but forced with changing radiative forcing agents (ghgs, aerosols, etc)

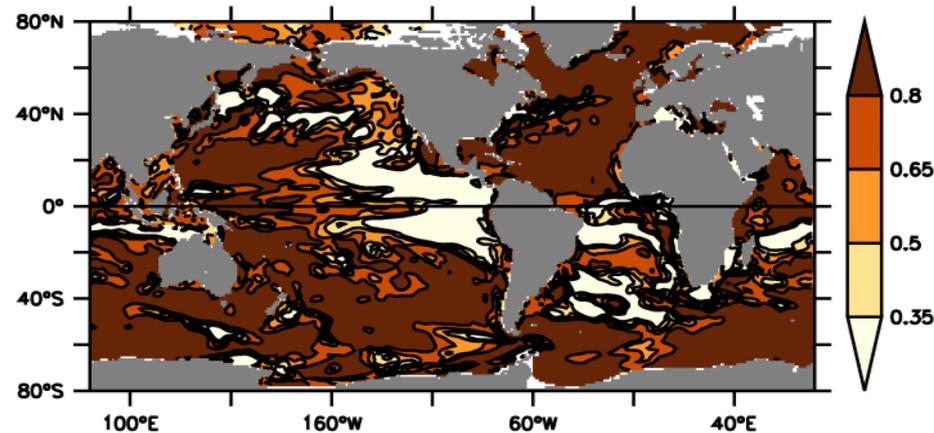
Prototype dynamical decadal prediction – additional suites

- **If resources permit, will also do the following (mainly for the ARGO period)**
 - Conduct coupled reanalysis with high resolution coupled model (GFDL CM2.5) using computer resources at Oak Ridge National Laboratory
 - Decadal predictions with high resolution coupled model
- **A prototype statistical prediction methodology** has also been developed (Mahajan et al, 2011) based on observed and simulated relationships between Atlantic temperature, SSH, and the AMOC

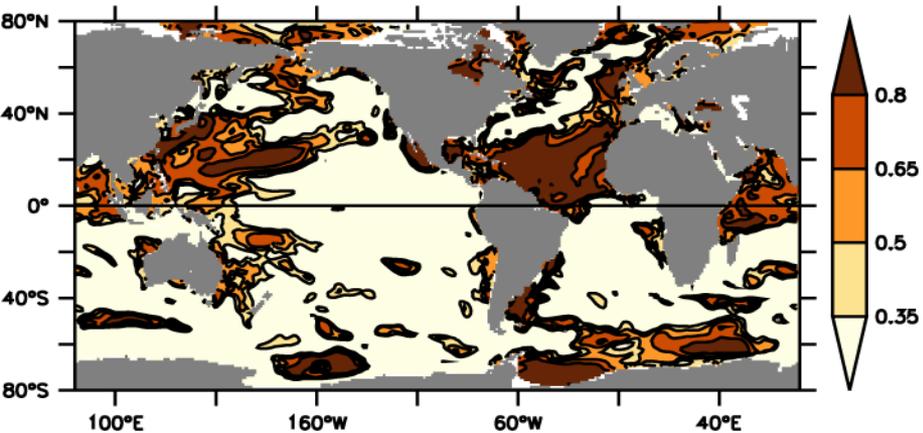
SST CORR between OBS and Hindcasts



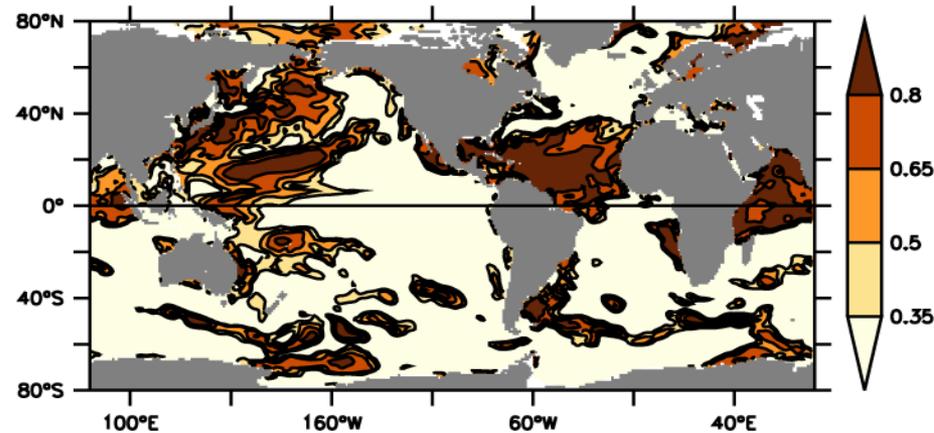
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YR1

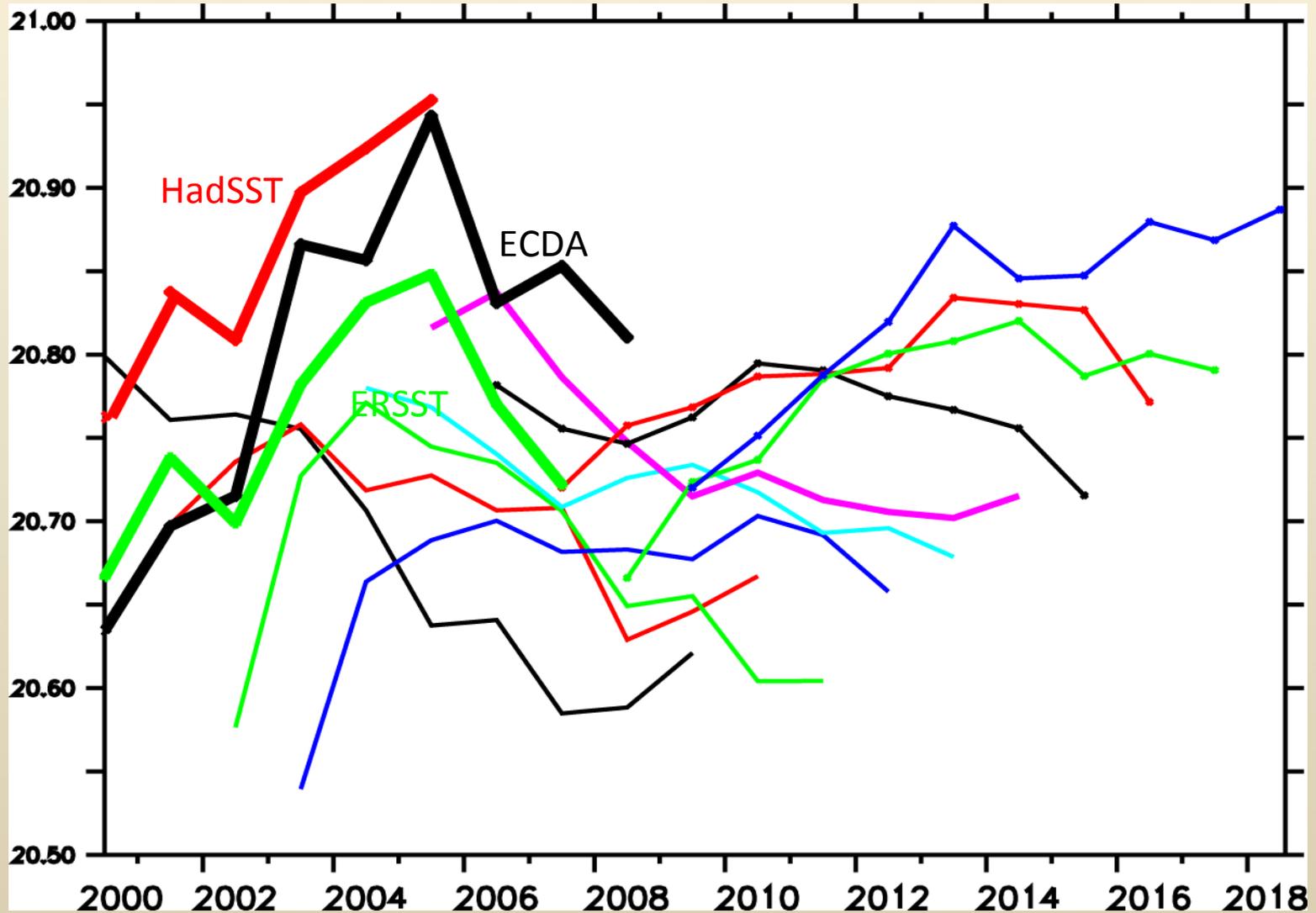


YR5



YR10

N.H. SST Predictions



Anticipated outcomes from decadal prediction efforts

- **Ongoing assessment of what climate signals are predictable on decadal time scales, and what their impacts are**
- **Development and experimental use of decadal prediction system**
 - *Predictions based on both internal variability and forced climate change*
 - *Predictions may be based on both numerical and statistical models*
- **In concert with coupled reanalysis system, research into attribution of observed decadal climate variations**

What can we say about roles of internal variability and radiative forcing in observed climate fluctuations, such as

 - *rapid Arctic change*
 - *continental droughts*
 - *changing ocean conditions and their impacts on tropical storms*

- 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 have limited predictability, it is still important to better understand them to aid in the interpretation of observed climate change.

Challenges and opportunities

- **Decadal prediction is a cutting edge research topic ... not clear what will be predictable**
 - *Predictability is likely greater for large-scale ocean features, smaller for regional scale continental climate*
- **Formidable challenges remain, including:**
 - *model fidelity*
 - *observing systems*
 - *fundamental understanding*
- **However ... the potential utility of decadal predictions and attribution is enormous.**
 - *early warning system for potentially abrupt climate change*
 - *attribution of observed multiannual to decadal climate fluctuations, such as drought and extreme events (eg, SW US drought, Arctic climate change, etc)*

What we learn from model based studies of decadal variability and predictability is *influenced by the fidelity of the model used*. Estimates of variability and predictability with relatively coarse resolution models may be substantially biased.

Therefore ... we are moving to much higher resolution models that **may** have more realistic simulations of decadal variability.

The motivation is that as more processes (such as oceanic eddies) are explicitly resolved rather than parameterized, the model's physics become more robust.

High Resolution Model Development

Scientific Goals:

- Developing improved models (higher resolution, improved physics and numerics, reduced bias) for studies of variability and predictability on intra-seasonal to decadal time scales
- Explore impact of atmosphere and ocean on climate variability and change using a high resolution coupled model
- New global coupled models: CM2.4, CM2.5, CM2.6, ...
- A constraint on the resolution we use is dictated by 3 simulated years per day



Sequence of coupled models with increasing resolution

MODEL	ATMOSPHERE	OCEAN	LAND	Comments
CM2.1	2° lon x 2.5° lat 24 levels	1° lon x 1/3-1° lat	LM2	IPCC AR4 model
CM2.1.1	2° lon x 2.5° lat 24 levels	1° lon x 1/3-1° lat	LM2	Higher order advection in ocean, and low viscosity
CM2.3	1° lon x 1.25° lat 24 levels	1° lon x 1/3-1° lat	LM2	Same ocean as CM2.1, higher resolution atmosphere
CM2.4	1° lon x 1.25° lat 24 levels	25Km in Tropics to 9 Km in polar regions Square grid.	LM2- LM3	Same atmosphere as CM2.3, higher resolution ocean
CM2.5	50 Km atmosphere, 32 levels, cubed sphere grid	Similar to CM2.4, uses z* as vertical coord.	LM3	Uses icebergs in ocean Similar ocean to CM2.4, higher resolution atmosphere
CM2.6	50 Km atmosphere, 32 levels	10 Km in Tropics to 3 Km in polar regions	LM3	Same atmosphere as CM2.5, higher resolution ocean

Plans for high resolution coupled model CM2.5

- Preliminary decadal prediction experiments
- Extended control simulation and idealized climate change
- Ensemble of 19th-21st century simulations (1860-2100)

- Coupled reanalysis with CM2.5 (large resource requirement)
- Extensive set of hindcasts with CM2.5 to evaluate seasonal to decadal predictive skill

- In addition ... exploratory simulations with even higher resolution (CM2.6 and beyond) to study critical processes in the climate system (ocean eddies, small-scale air-sea coupling and feedbacks, etc.)

CM2.5 Component Characteristics

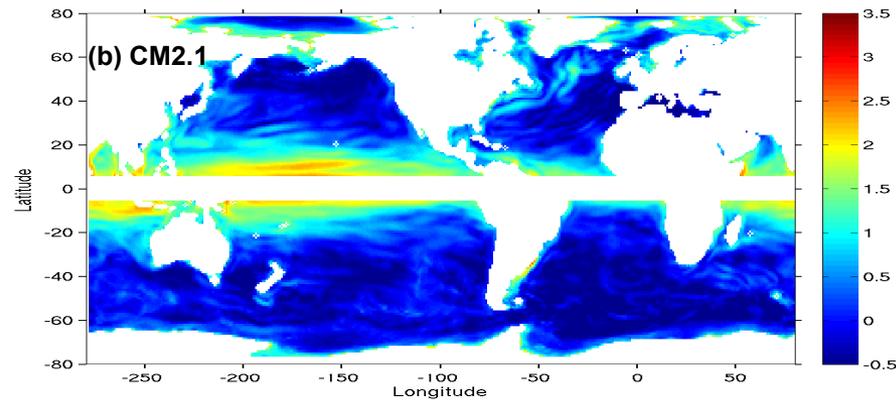
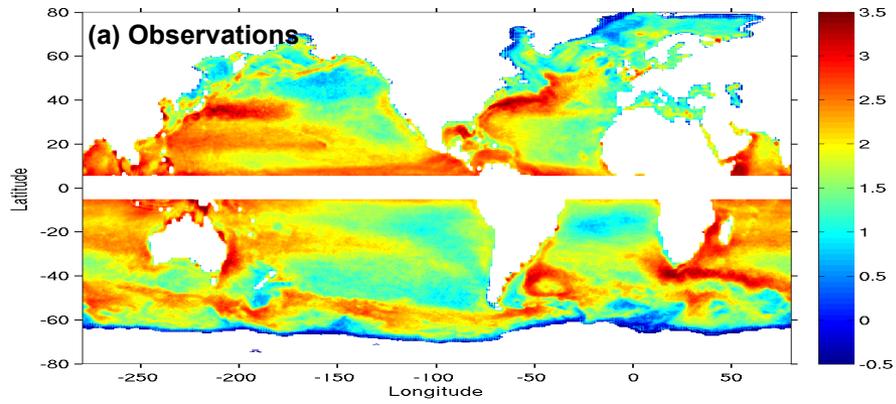
ATMOSPHERE:

- *50 Km resolution, 32 vertical levels, Cubed-sphere grid*
- *Atmospheric physics similar to AM2.1/CM2.1*
- *Incorporates LM3 land model with advanced hydrology*

OCEAN:

- *Resolution varies from 27 Km at Equator to 9 Km at high latitudes*
- *Latest MOM4p1 ocean code*
- *High order advection scheme provides extremely high accuracy, non-dissipative*
- *No explicit vertical diffusion, very low viscosity*
- *No parameterization of the effects of ocean eddies*
- *Incorporates parameterization of the effects of sub-mesoscale eddies*

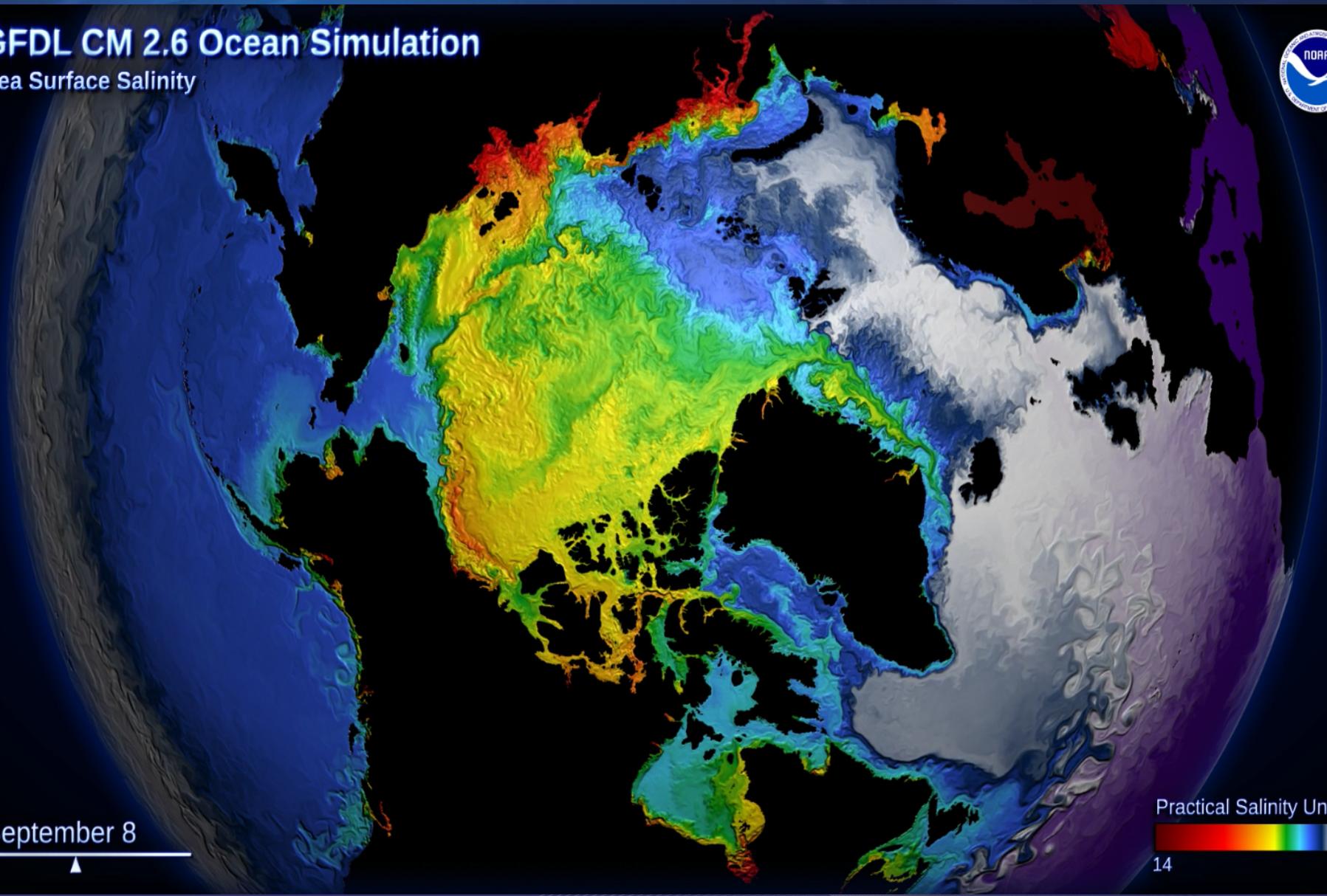
Ocean Eddy Kinetic Energy – Observed and Simulated



CM2.1: 200 Km atmosphere, 100 Km ocean

GFDL CM 2.6 Ocean Simulation

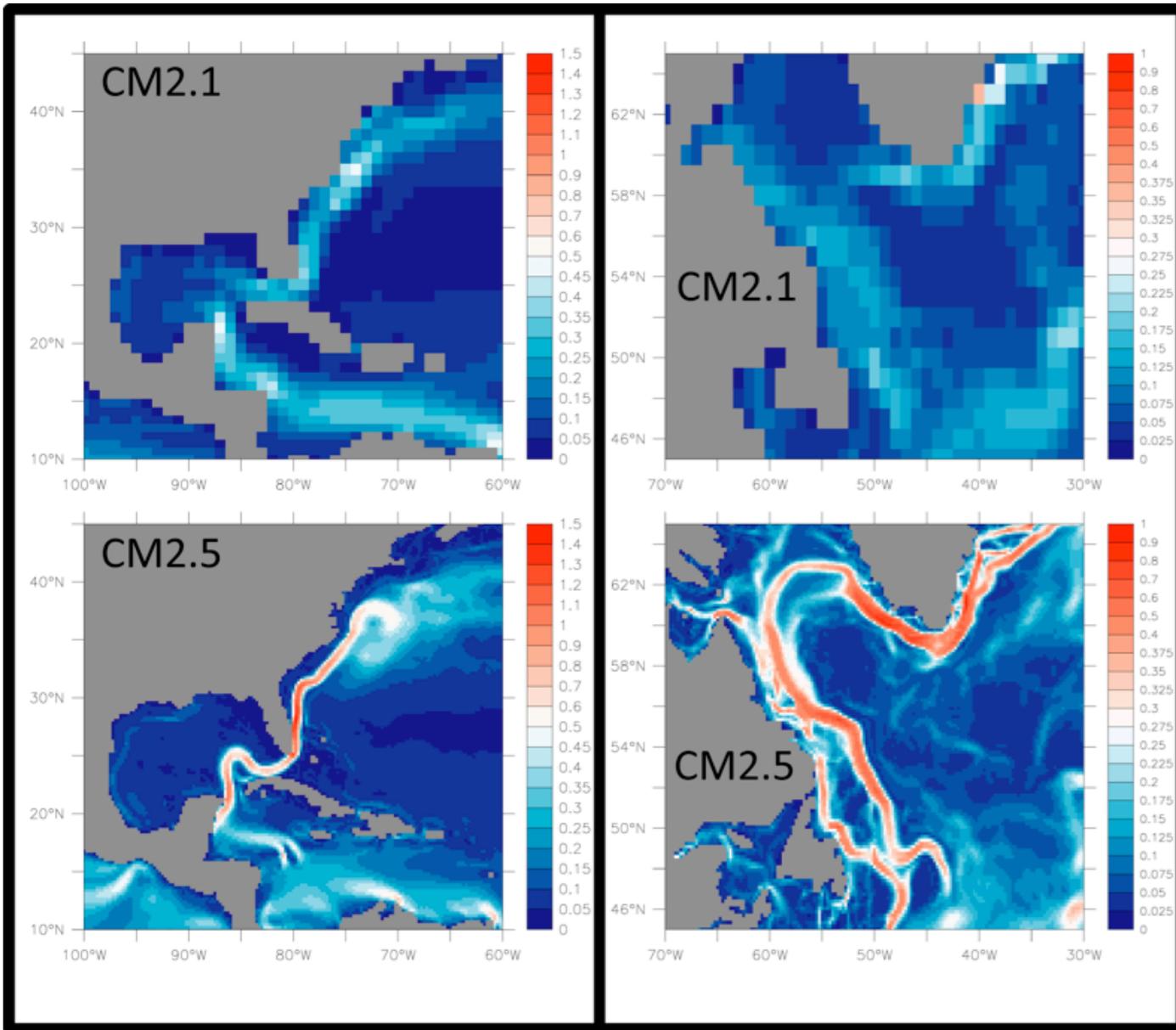
Sea Surface Salinity



September 8

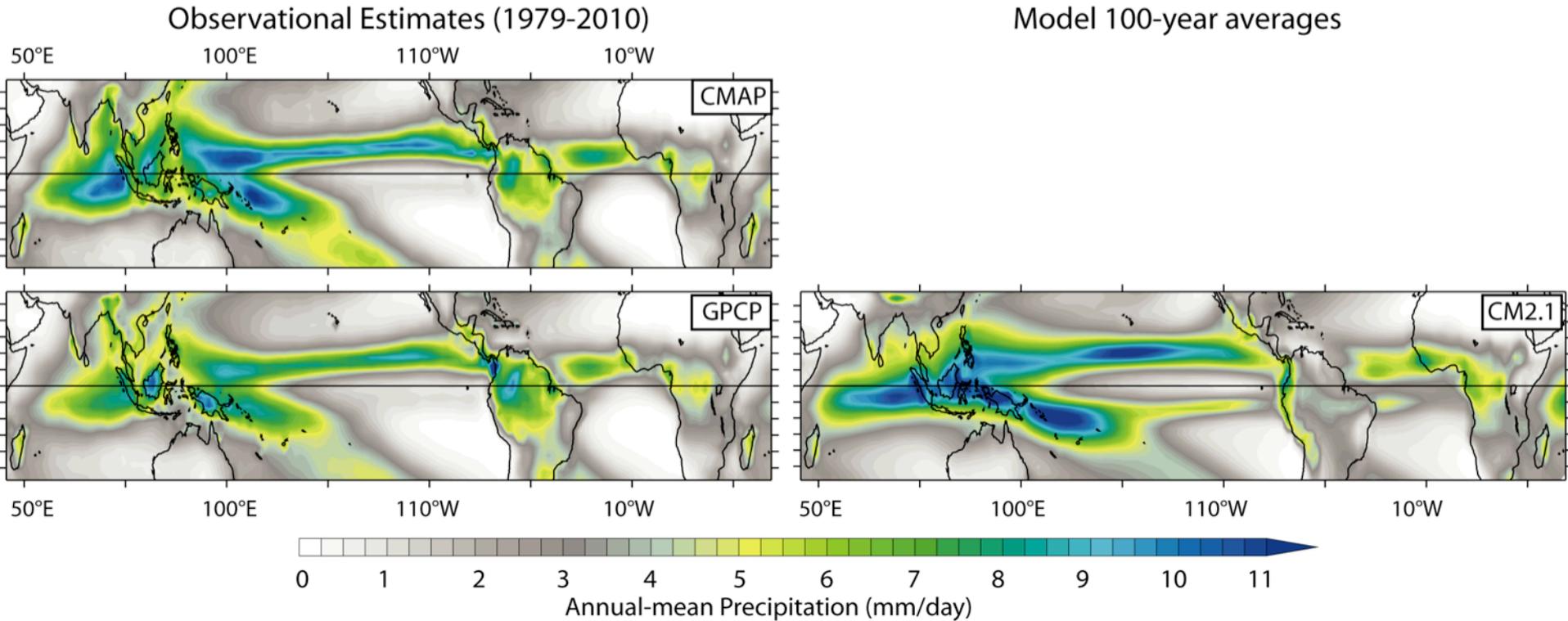


Surface currents much more energetic



Some Aspects of Tropical Climate Improve with Resolution

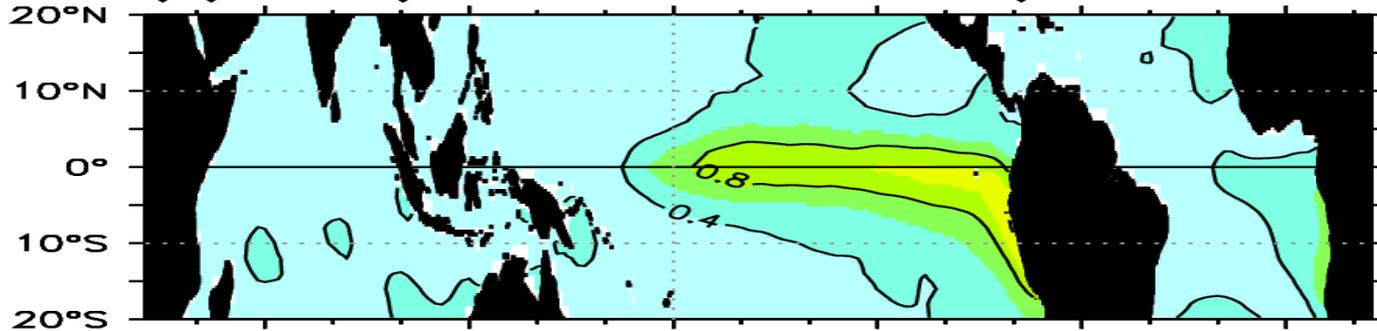
Annual Tropical Precipitation on 2.5x2.5 Grid



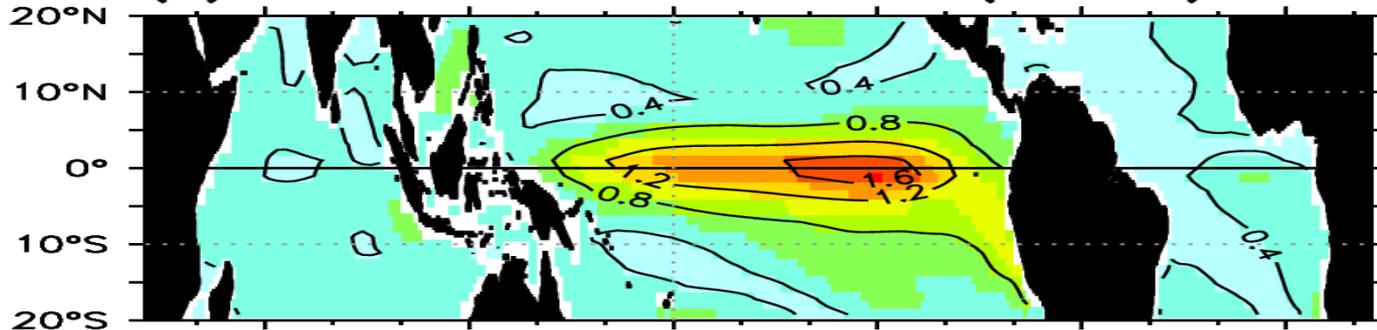
Adapted from Delworth et al (2011)

Interannual standard deviation of SST

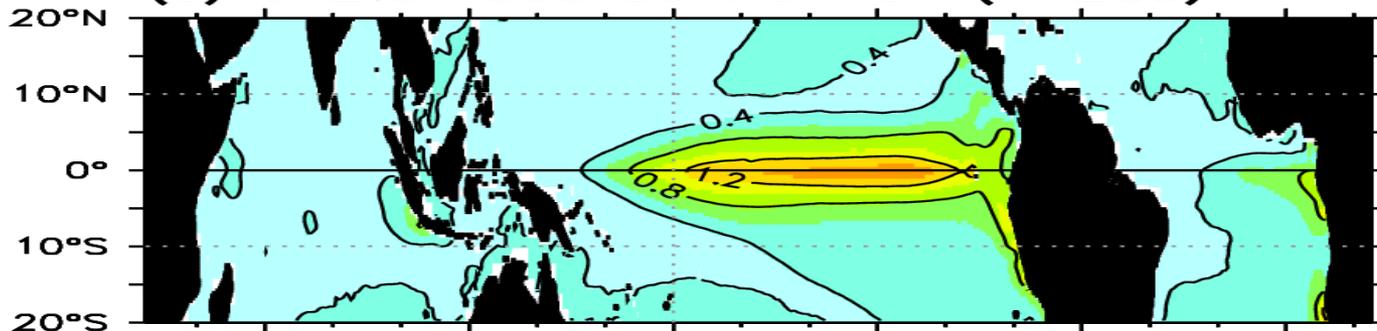
(a) Obs (ERSST.v3 1949–2008)



(b) CM2.1 1990 Control Run (1–300)

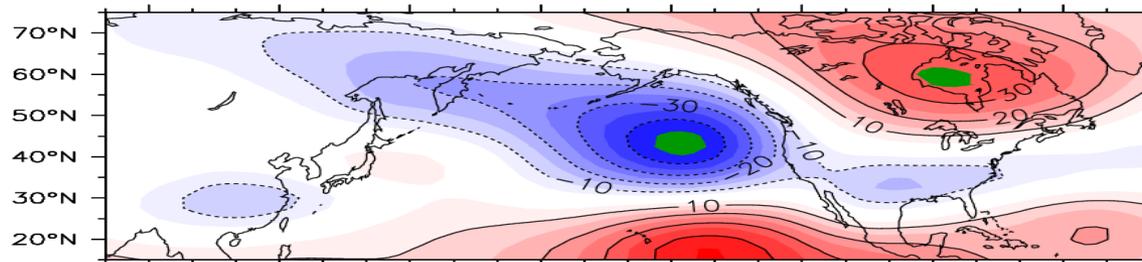


(c) CM2.5 1990 Control Run (1–280)



Detrended DJF 200 hPa height anomaly
regressed onto detrended DJF NINO3 SSTA

(a) NCEP/NCAR Reanalysis (1961–2001)



(b) CM2.1 1990 Control Run (11–290)

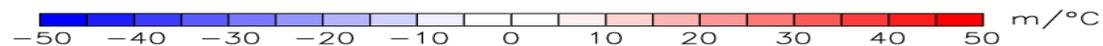
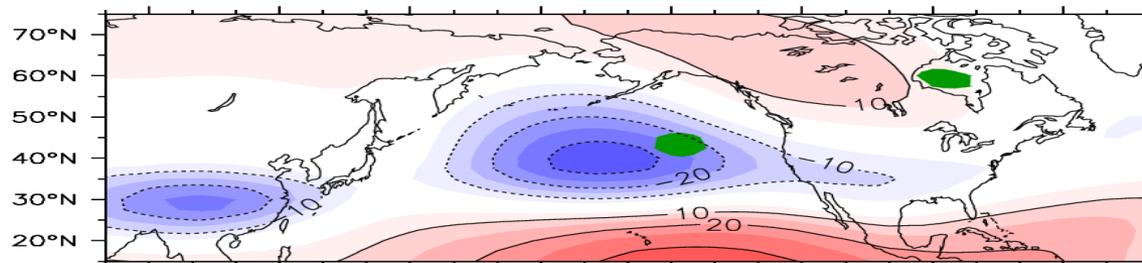
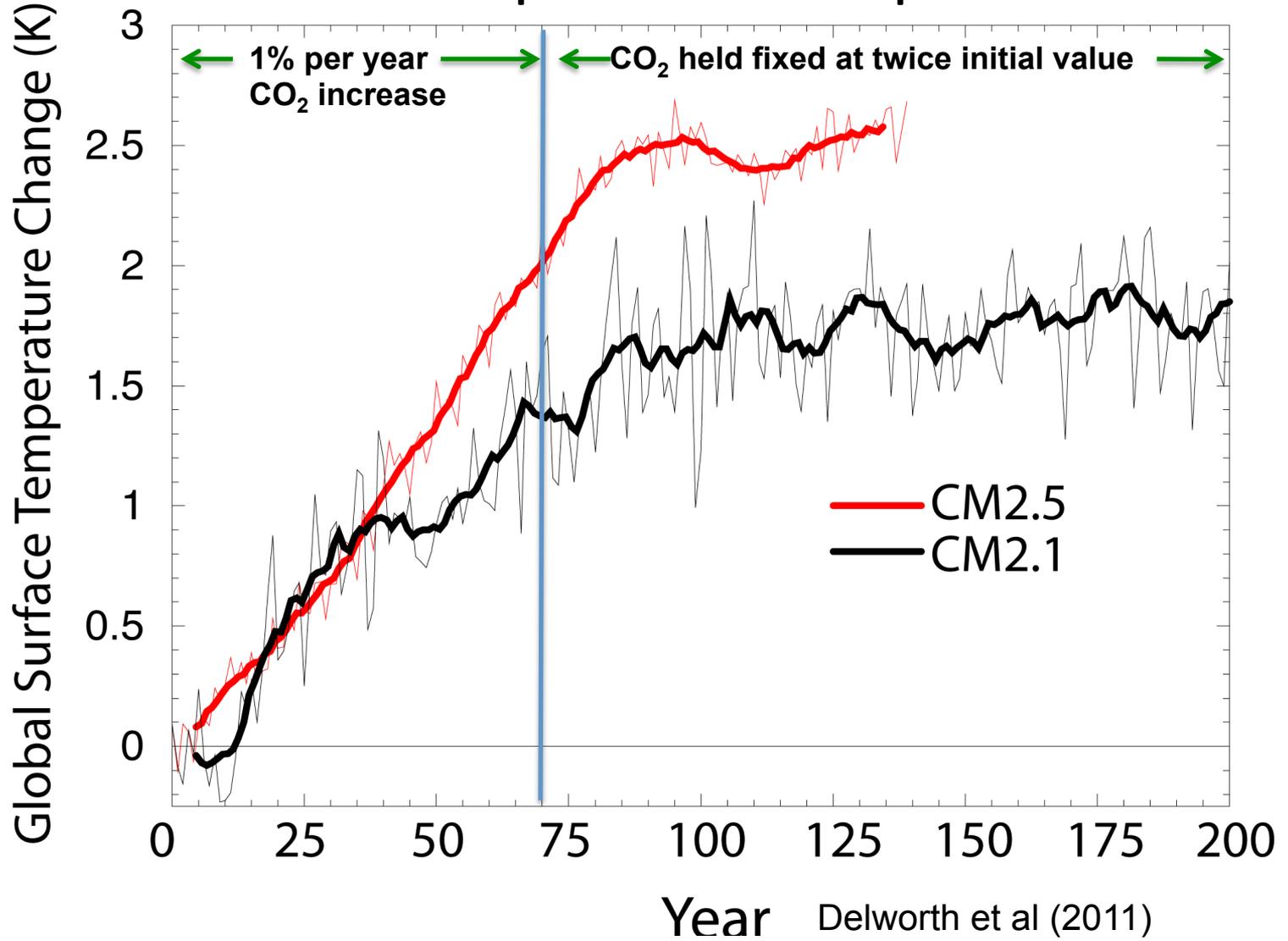
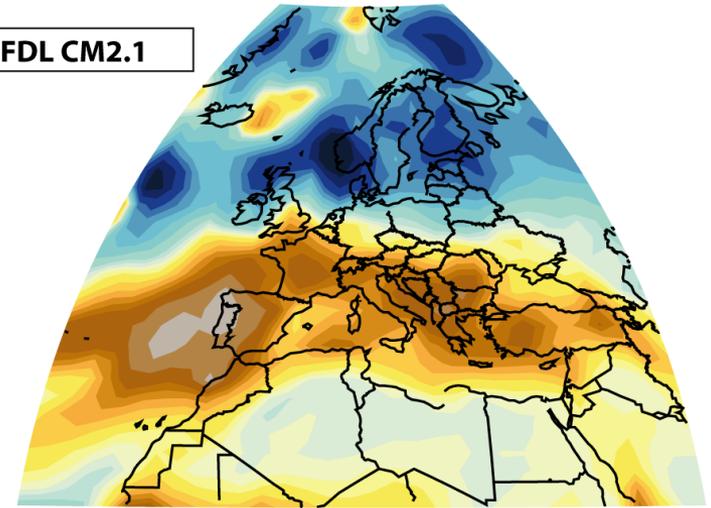


Figure 17 DJF 200-hPa geopotential height anomalies regressed onto DJF NINO3 SSTAs, computed using (a) the NCEP/NCAR Reanalysis (Kistler et al. 2001) for 1961-2001; (b) the CM2.1 1990 control run for years 11-290; (c) the CM2.5 1990 control run for years 11-0270. The zero contour is omitted. Green shading in all panels indicates the positions of the observed extrema over the North Pacific and Canada. Prior to computing the seasonal anomalies and regressions, all time series were detrended by removing a 20-yr running mean.

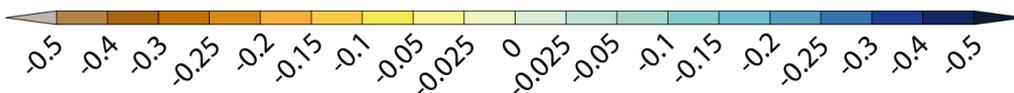
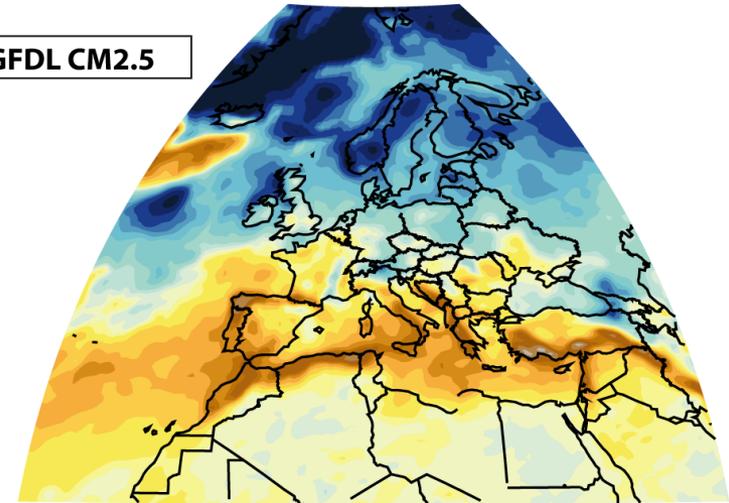
Global Surface Temperature Response to 2xCO₂



) GFDL CM2.1



) GFDL CM2.5



Annual-mean Precipitation Response to $2xCO_2$ (mm/day)

ANNUAL MEAN RAINFALL RESPONSE TO DOUBLED CO₂:

The response in Mediterranean precipitation appears different in the high-resolution model ... is that difference in regional climate response “random” or a consequence of the higher resolution?

Summary

1. Decadal and multidecadal variability is an integral part of the climate record, with significant societal relevance – especially for hydrology, and for **regional scales**.
2. Ocean processes (such as the **Atlantic Meridional Overturning Circulation**) may be crucial for decadal variability.
3. An important goal is to gain a better understanding of the **mechanisms of decadal variability**, thereby improving our ability to understand the observed climate record.
4. Can we **predict decadal scale fluctuations**? Probably to some degree. However, estimates of decadal predictability are model dependent and may evolve over time.
5. A **sustained observing system** is critical to any potential predictive skill.
6. Decadal-scale variability and predictability, in concert with regional climate change, provides part of the motivation for moving to **much higher-resolution global coupled models**.
7. We are moving to a new class of models with substantially higher resolution, more energetic ocean circulation, and substantially improved tropical climate. These will be used extensively, in concert with other models, for **seasonal to decadal to centennial scale predictions and projections**.



CM2.0, CM2.1 – state of the art physical
climate models (1° ocn; 2° atm)

Circa 2005

Circa 2010

ESM2M, ESM2G

- Carbon cycle
- Vegetation feedback
- Ocean formulation

HIRAM

- High spatial resolution (atm only)
- Time-slice experiments
- Climate extremes

CM3 (Primary Physical Model)

- Aerosols, indirect effect
- Stratosphere
- Convection, Land Model
- Atmospheric Chemistry

CM2.5

- High spatial resolution (coupled)
- Energetic ocean
- **Variability and change in coupled system at high resolution**



CM4 ?? - drawing on what is learned
from these various streams