Coupled Data Assimilation for Climate Estimation and Predictions at GFDL: Present Status and Future Directions

Workshop on predictability of climate in the North Atlantic Sector,
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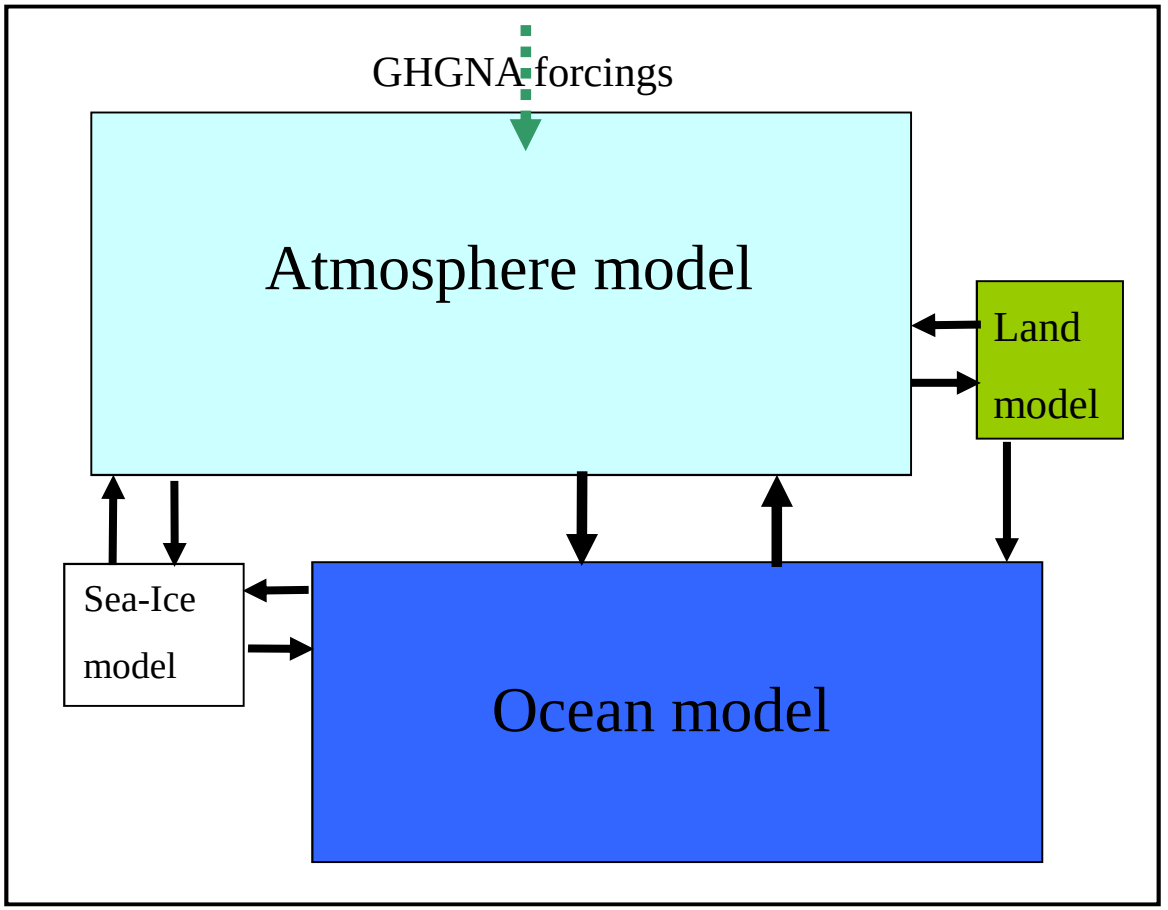
Limitation of Model Simulation in Climate Studies

Do a good job:

- ✓Simulate the interactions of multi-scale components
- ✓Assessment of global changes due to the changes of GHG-NA

But:

- ✓Different climate features
- ✓Different climate variability



Coupled Data Assimilation (CDA) for Climate Studies

Goal

Understanding climate variability to better estimate and predict climate on seasonal-interannual to decadal scales

Challenges

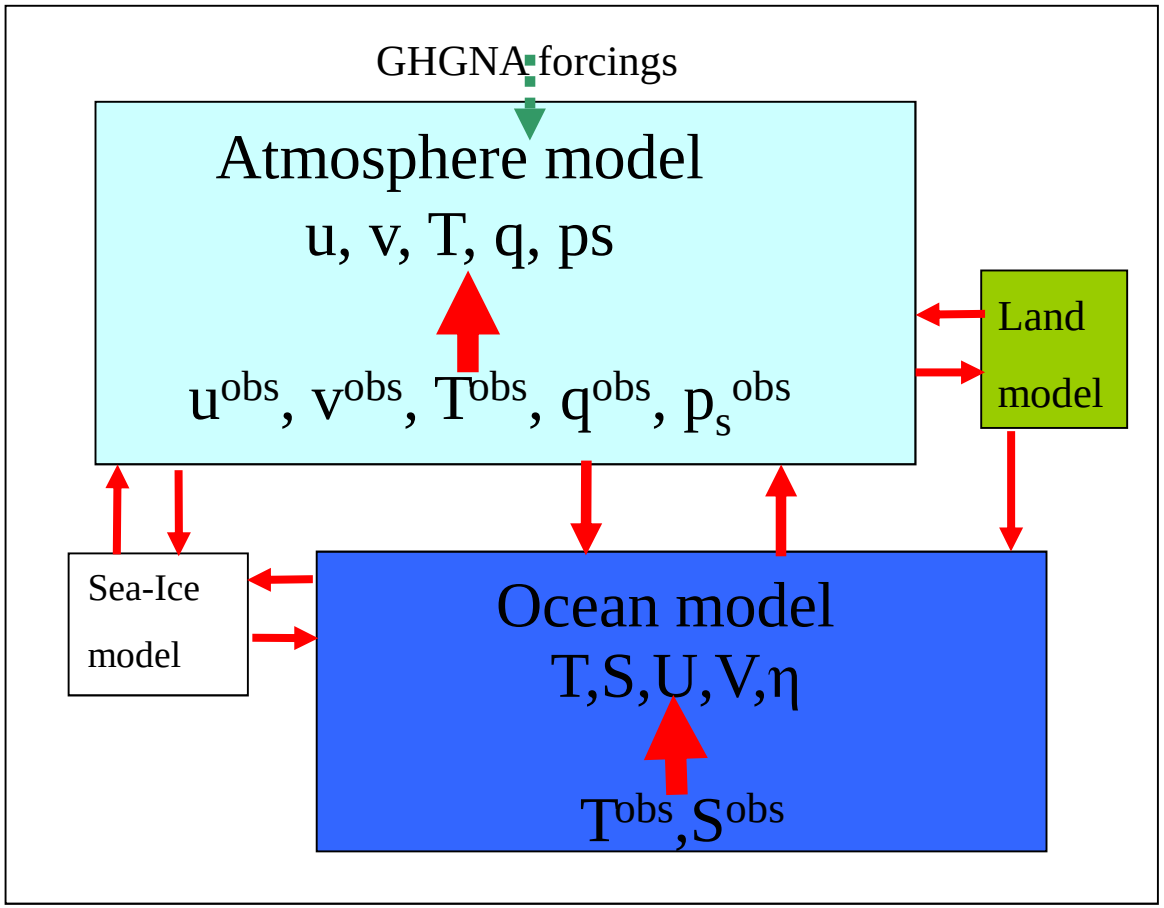
- Model always produce different climate features and variability from the real world due to modeling errors and uncertainties
- Observations always have sampling and representation errors

Methodology

Combining observed data with a climate model by a **GOOD** way, called Coupled Data Assimilation

How CDA Enhances Climate Modeling?

CDA is GOOD for climate studies – All coupled components adjusted by observed data through instantaneously-exchanged fluxes

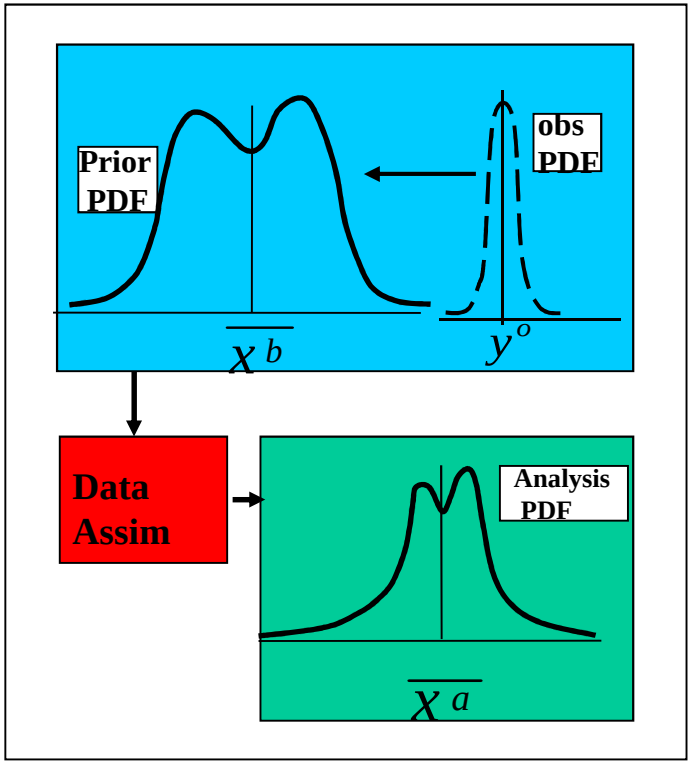


(2003 CDA Workshop, Portland)

Ensemble CDA (ECDA)

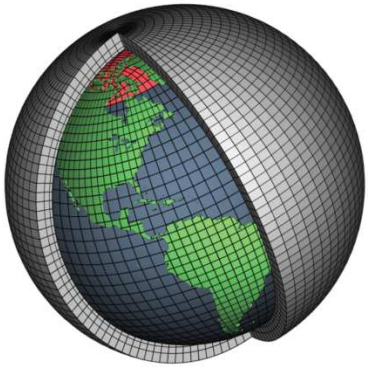
ECDA is OPTIMAL for climate studies – An ensemble of model integrations establishing the background error statistics to extract the observational information, addressing the probabilistic nature of climate evolution.

- ✓ Ensemble statistics provides multivariate relationships, such as temperature-salinity relationship and geostrophic balance.
- ✓ A set of self-balanced and coherent initial coupled states generates optimal ensemble initialization of coupled model with minimum initial shocks.
- ✓ Ensemble-based CDA is naturally and easily to extend as the model becomes more comprehensive.

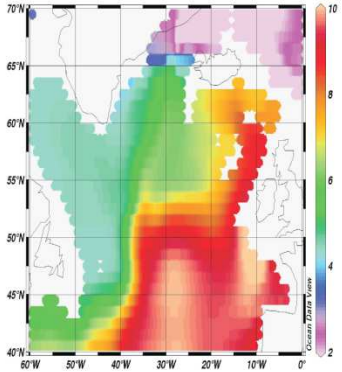


ECDA Structure Summary

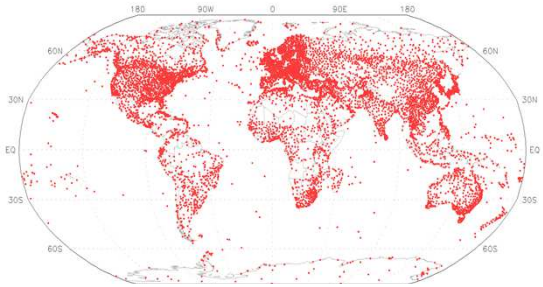
Earth System Model



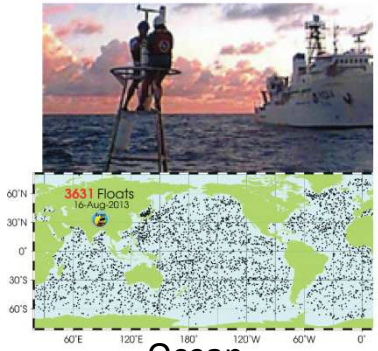
Model Temperature at 1000m



Earth Observing System

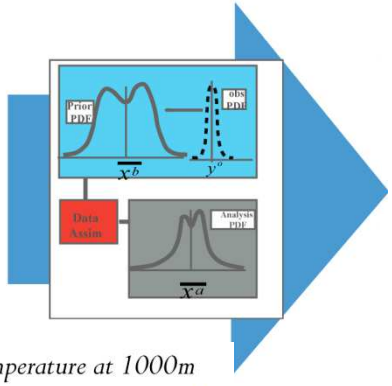


Atmosphere

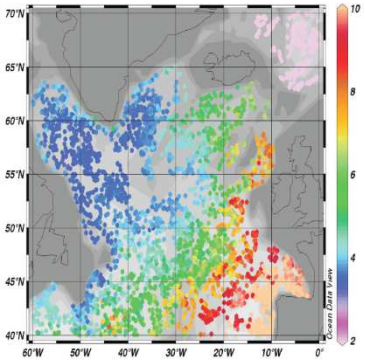


Ocean

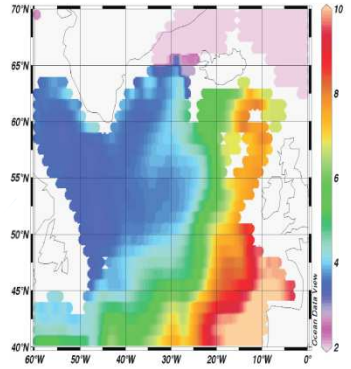
Assimilation



Observed Temperature at 1000m



Assimilation Temperature at 1000m



OUTLINE

1. **CDA – Coherent and self-balanced coupled state estimation**
2. CDA for ENSO (SI scale) prediction
3. CDA for decadal prediction
4. CDA for coupled model parameter estimation to enhance predictability
5. Additional CDA component – physically-consistent sea ice data assimilation to improve climate predictions – simple model studies
6. High-resolution CDA – A background adjustment scheme to retrieve tropical storm statistics
7. Summary, discussions and future directions

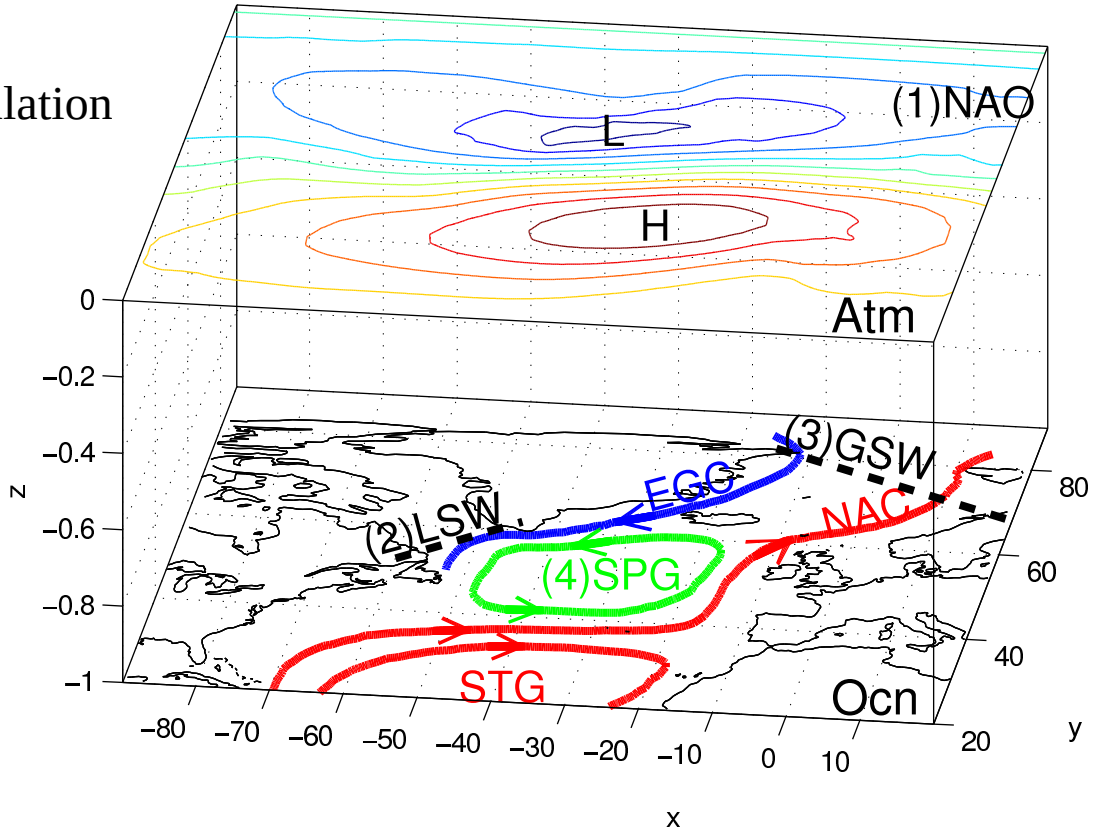
CDA for Climate Observing System Validation
XBT/Argo monitoring of AMOC & North Atlantic oscillations

1) **NAO**: North Atlantic Oscillation

2) **LSW**: Labrador Sea Water
(deep convection)

3) **GSW**: GIN Sea Water
(deep convection)

4) **NAG**: NA gyre system

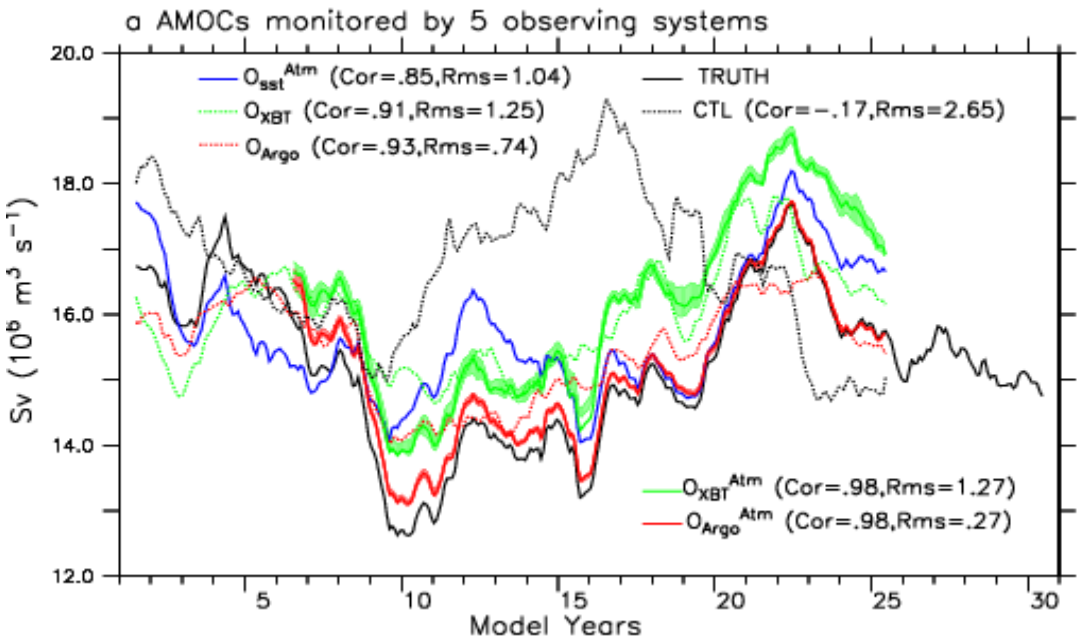


(Zhang et al. JC2010)

CDA for Climate Observing System Validation
Skill of XBT/Argo in monitoring AMOC & NA Oscillations

- ✓ Perfect twin experiment
- ✓ A simulation creates "obs" that sample "truth."
- ✓ The other simulation assimilates "obs" to recover the truth.
- ✓Ocn takes XBT/Argo profile structures.
- ✓Atm takes "reanalysis" wind & temperatures.

Time series of the reconstructed AMOC

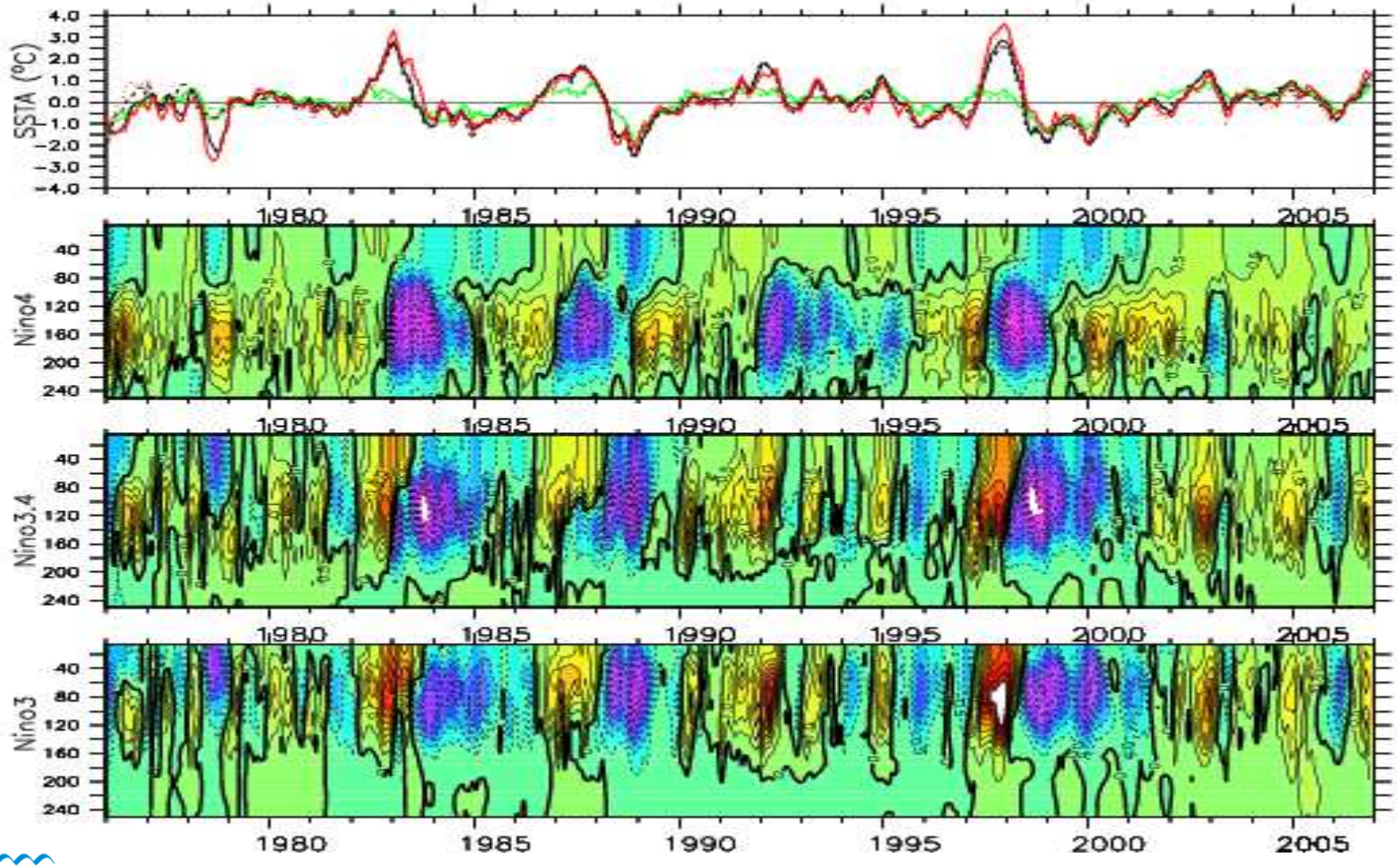


(Zhang et al. JC2010)

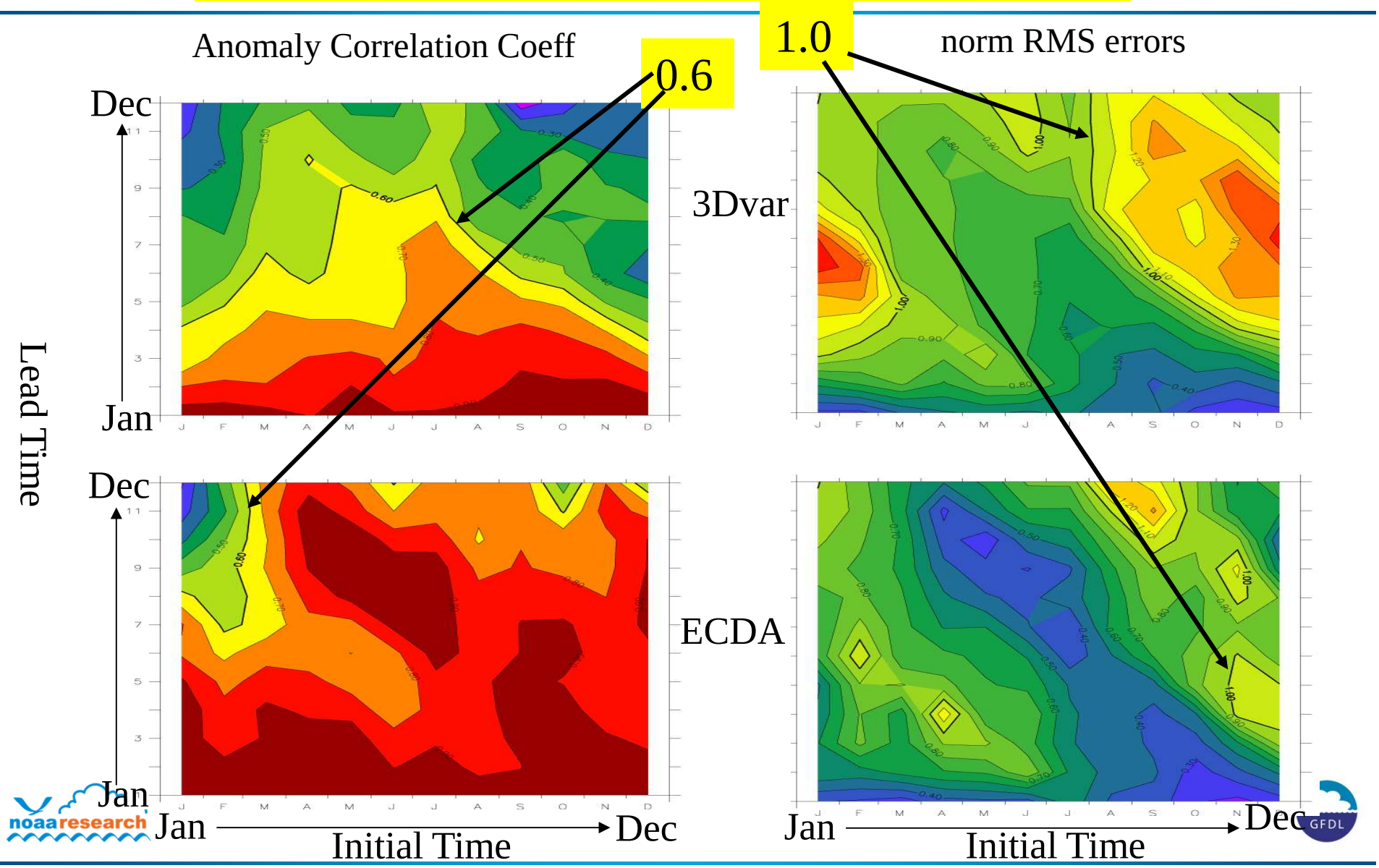
CDA for ENSO Variability Estimation

N4 SSTA Obs N3.4 SSTA Obs N3 SSTA Obs

N4 SSTA CDA N3.4 SSTA CDA N3 SSTA CDA



CDA for ENSO Prediction
Forecast skill of NINO3 SSTA

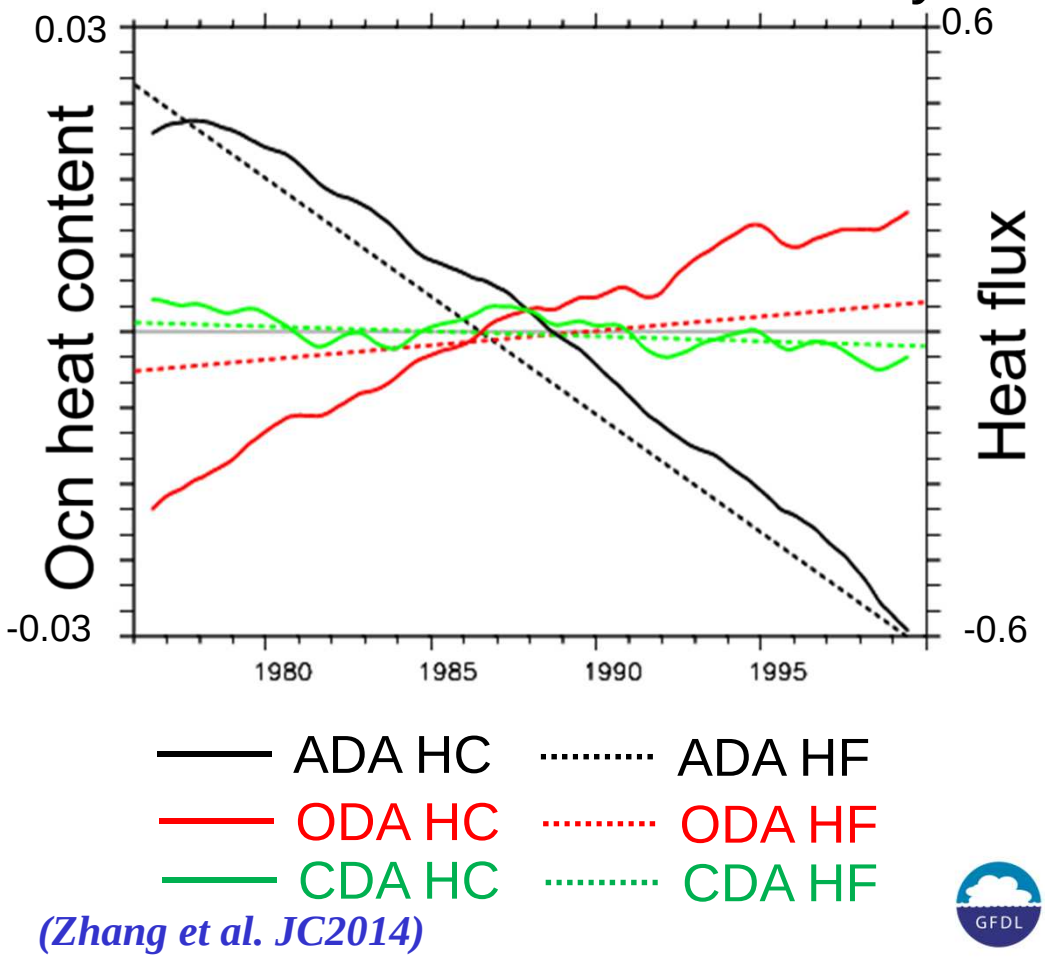


CDA for Steady and Balanced Climate Estimation
Are atmospheric/oceanic data only sufficient?

- ✓ Two IPCC-AR4 models at GFDL (CM2.0, CM2.1) to simulate the problem
- ✓ Biased twin experiments:
  Observational model – CM2.0
  Assimilation model – CM2.1
- ✓ Oceanic observing system – Argo
- ✓ Atmospheric observing system – "reanalysis" temperature and wind

ADA – only assimilating Atm obs
ODA – only assimilating Ocn obs
CDA – assimilating both A&O obs

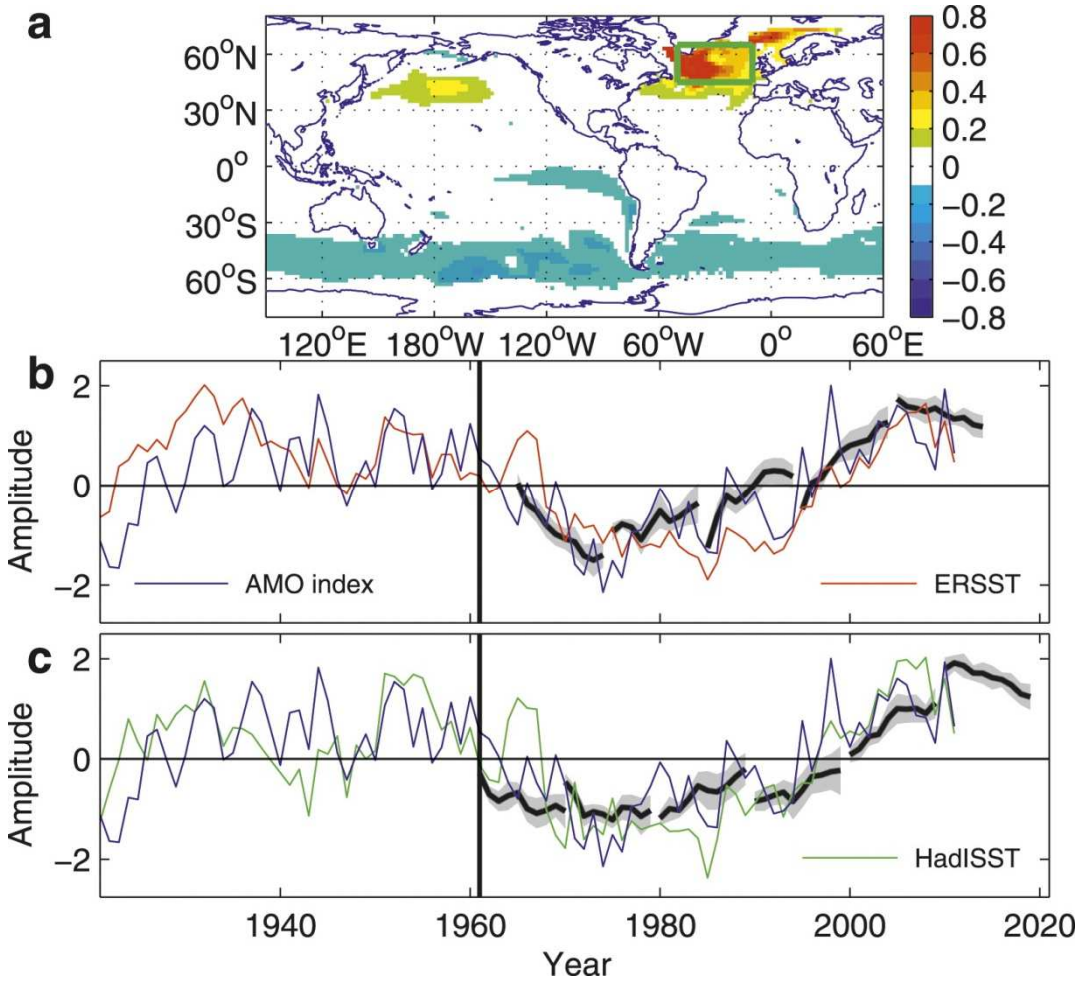
Ocn heat content anomaly
& atm-Ocn heat flux anomaly



(Zhang et al. JC2014)

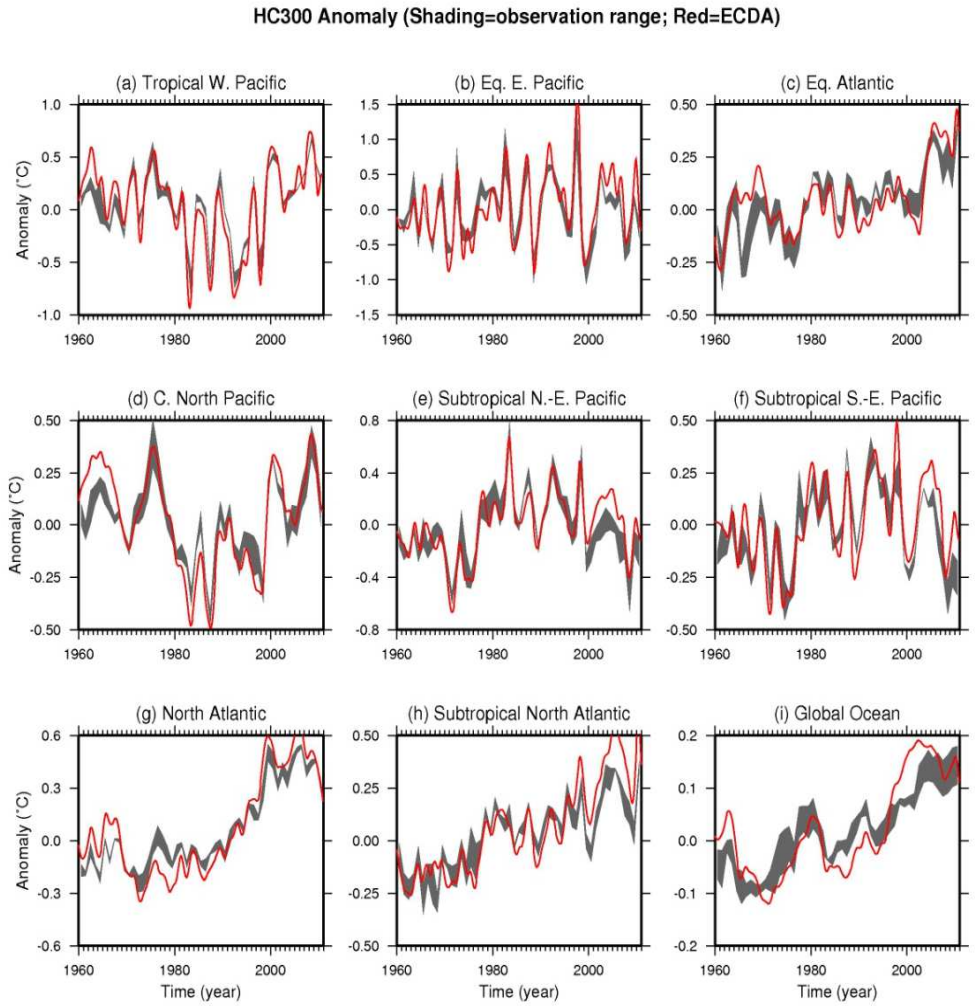
CDA for Decadal Prediction
A predictable AMO-like SST pattern

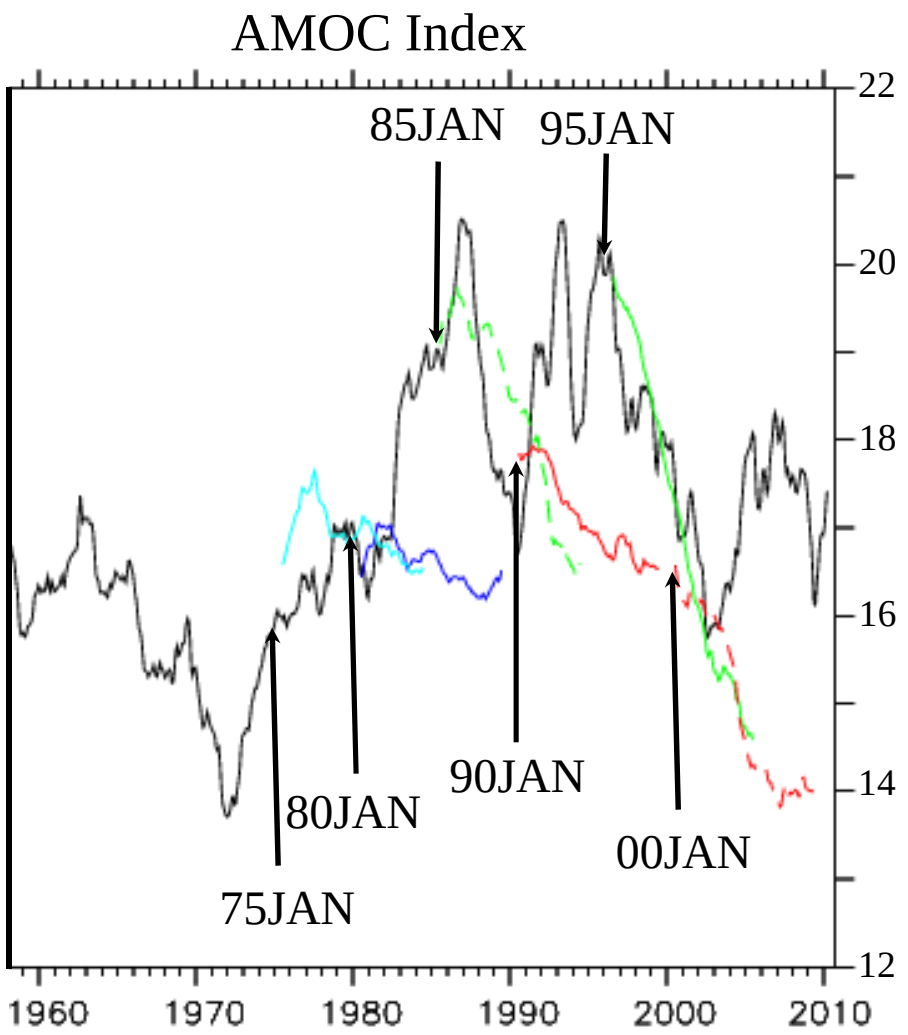
- ✓ CDA starting from 1950 with NCEP RE1/RE2 and oceanic profiles
- ✓ 10-yr forecasts initialized from the CDA states every 5 yrs starting from 1960 (totally 11 forecast cases)
- ✓ An Averaged Predictability Timescale APT analysis (similar to EOF1) to identify the most Internal Multidecadal Predictable (IMP) pattern in SSTs shown in (a)
- ✓ The APT-projected time series of SSTs shown in (b)



(Yang et al. JC2013)

Model Bias Causing Climate Drift in Climate Predictions



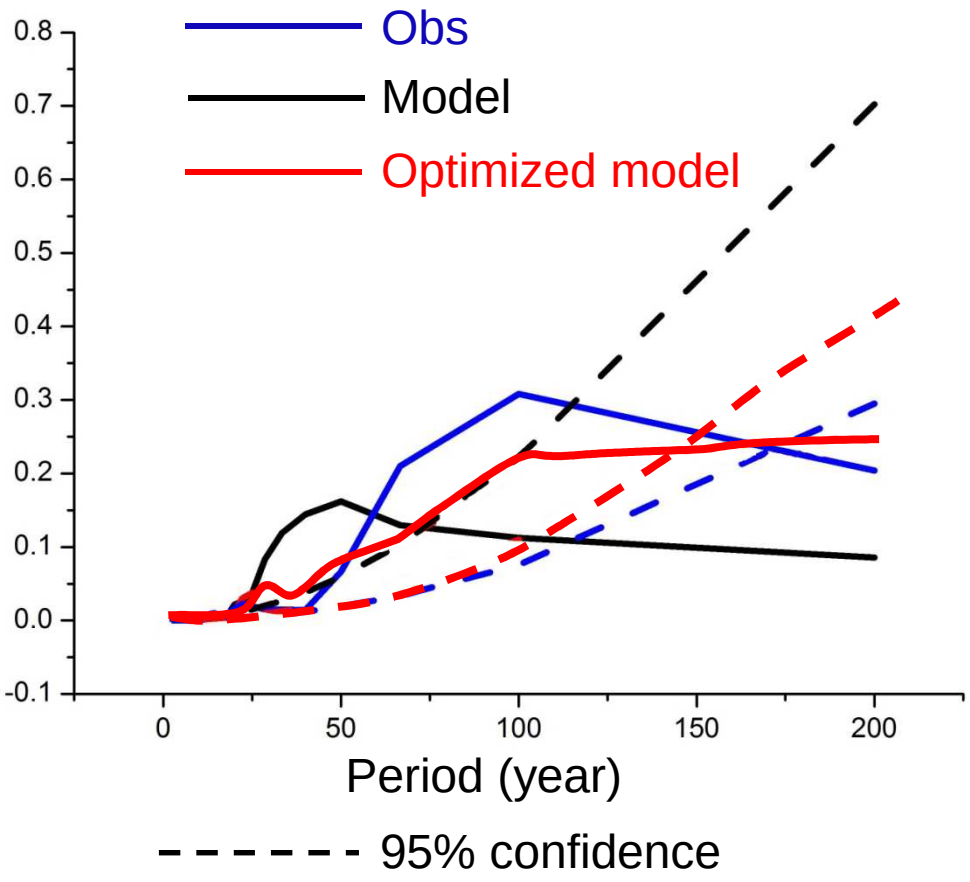


(Chang et al. CD2012)

Enhance Model Predictability by Parameter Estimation
Improved model simulation

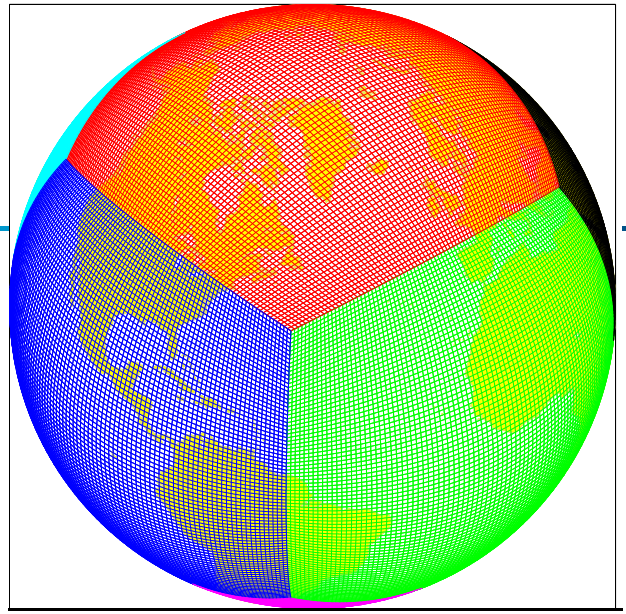
- ✓ Two different long-wave radiation parameterization schemes in a coupled model simulate a biased climate problem caused by biased physics
- ✓ Scheme-I: Obs
- ✓ Scheme-II: **Model**
- ✓ Optimized model: parameters are optimized using Ensemble Coupled Data Assimilation

power spectrum of ocean temp variability



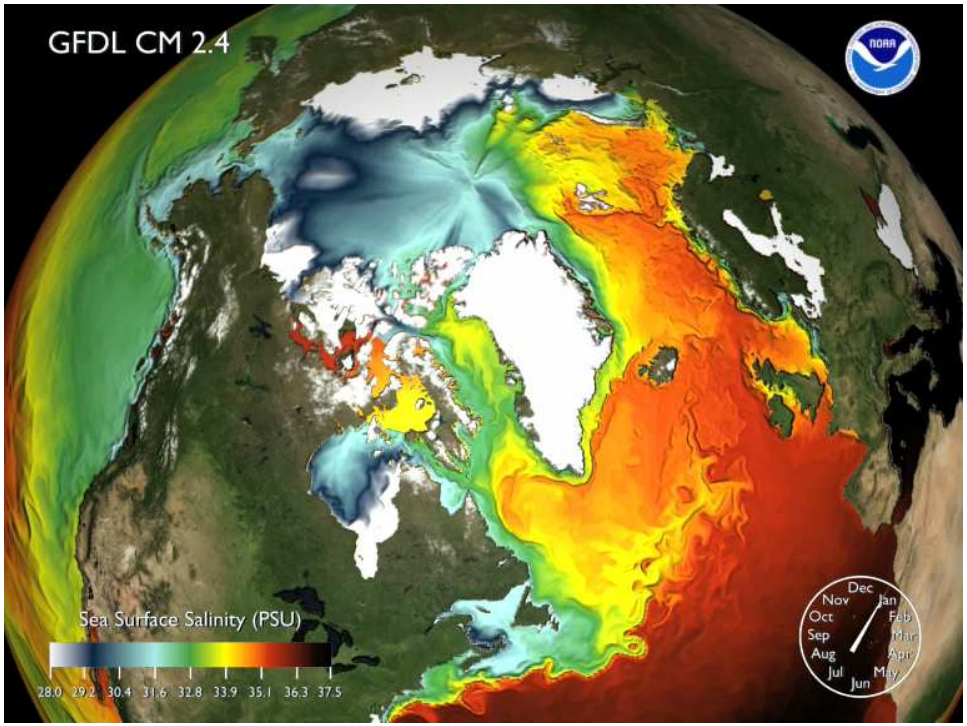
(Thanks to XZhang, GVecchi & IHeld)

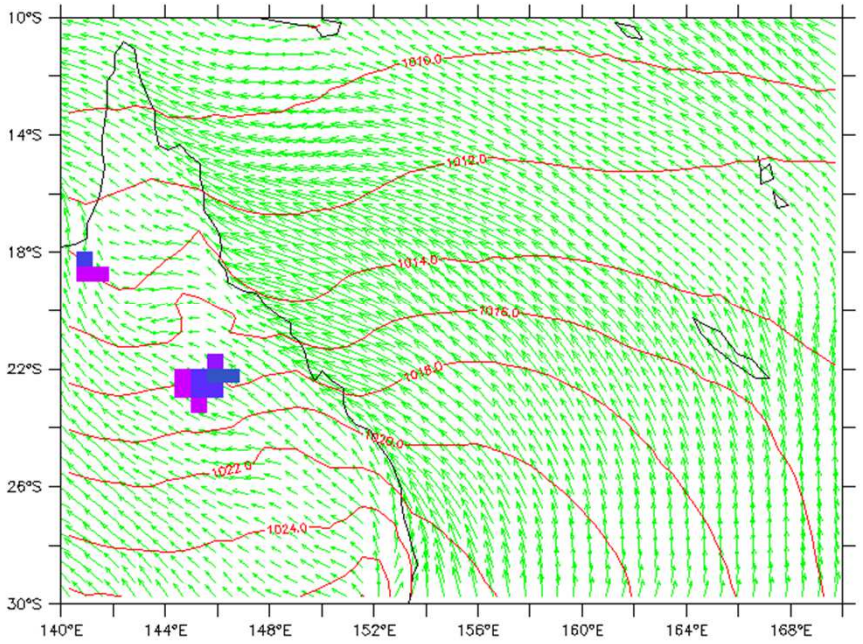
A High-Resolution Coupled Model at GFDL – CM2.5



Ocn:
1) MOM4P1
2) 1440x1070 (1/4^{o}x1/6^o)
3) 60m time-step

Atm:
1) Cubic sphere & FV
2) tile:180x180 (50x50km)
3) 20m time-step





noaaresearch

An Outstanding Issue in HR Model Data Assimilation

Tropical storms can be wiped out by data assimilation

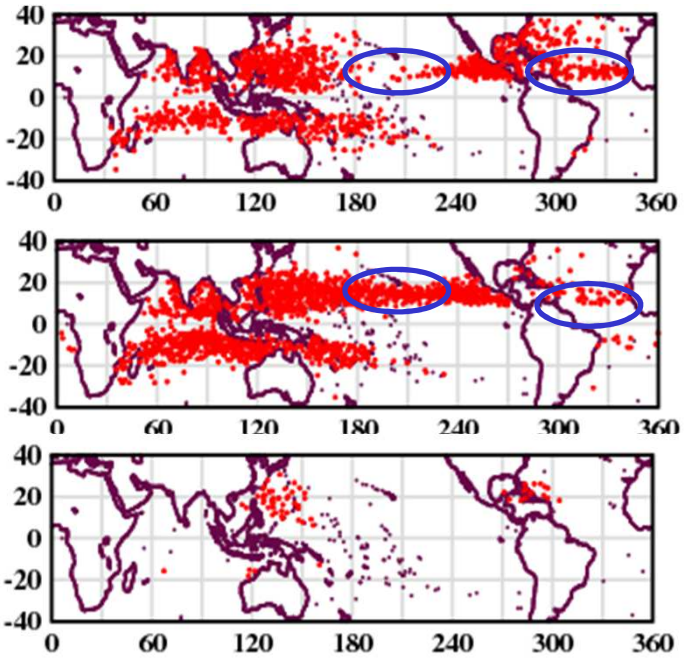
A high-resolution coupled model at GFDL: CM2.5 (½º x ½ º Atm & ¼º x ¼ º Ocn)

Total TCs (99-11)

Obs

Free model

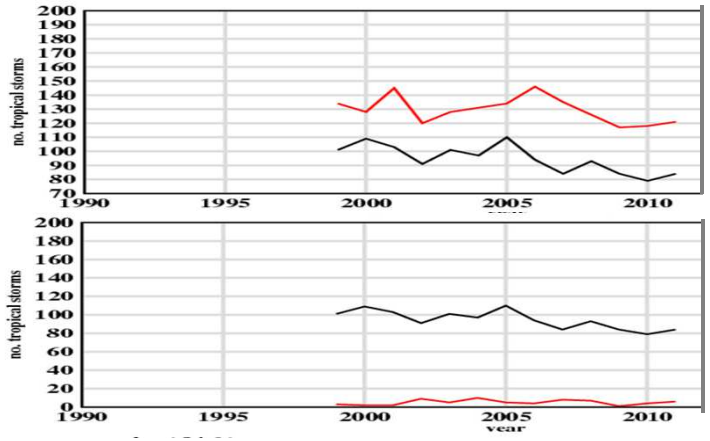
Traditional scheme



Time Series of global TCs

Obs

Model/Assim



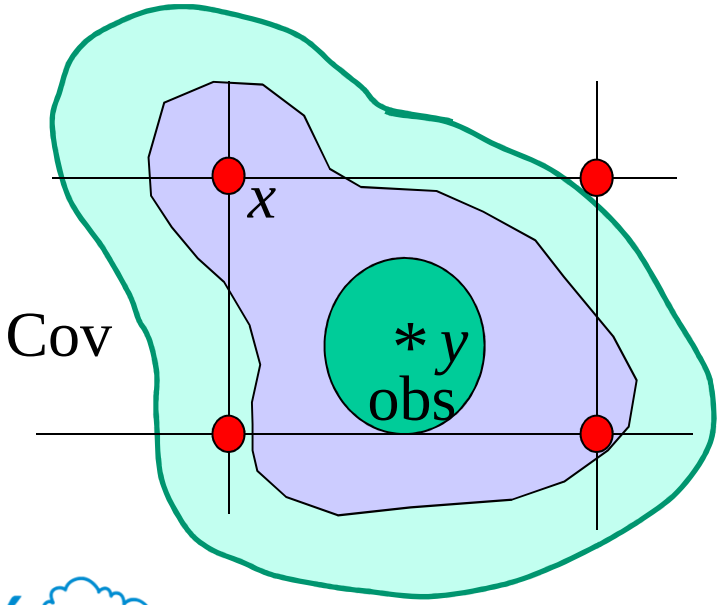
noaaresearch

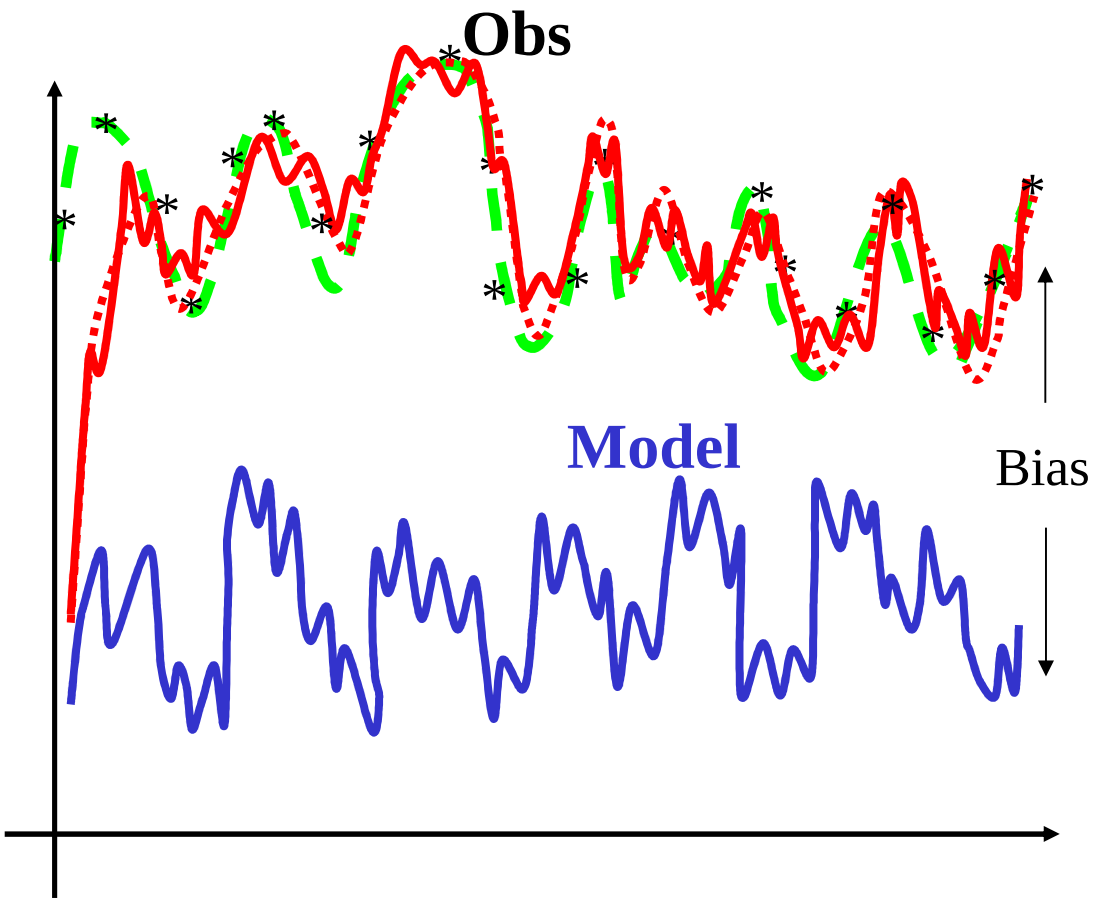
(Thanks to MZhao & S-J Lin)

GFDL

Challenges in High Resolution Coupled Model Data Assimilation

- ✓ Low-resolution obs and the smoothing nature of data assimilation wipe out tropical storms and small scale eddies in ocean.
- ✓ Model bias worsens the problem.





A Background Adjustment (BGA) Scheme

Reconstruct tropical storm distribution and variability

A high-resolution coupled model at GFDL: CM2.5 (½º x ½ º Atm & ¼º x ¼ º Ocn)

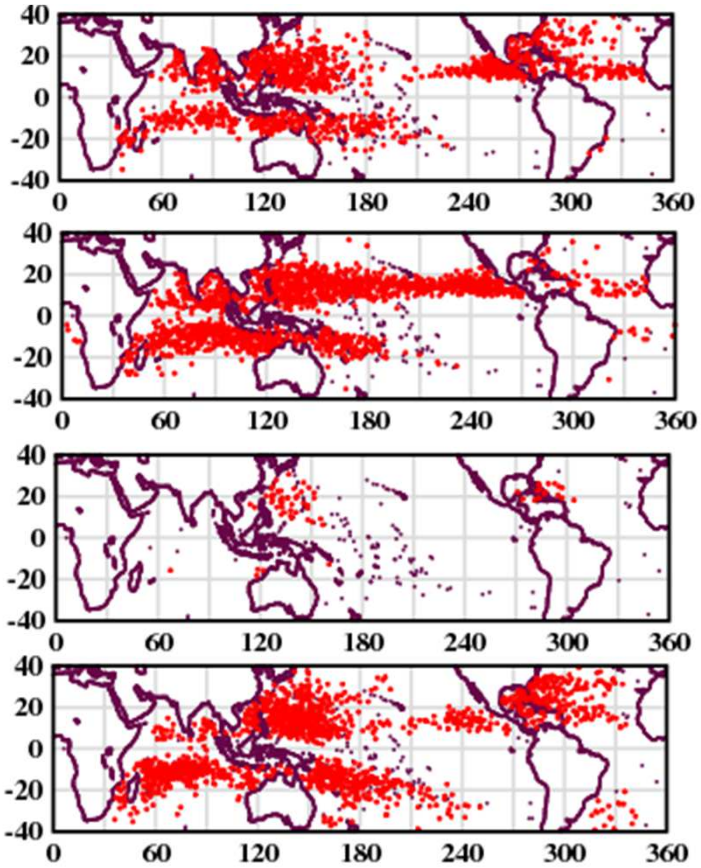
Total number of TCs (99-11)

Obs

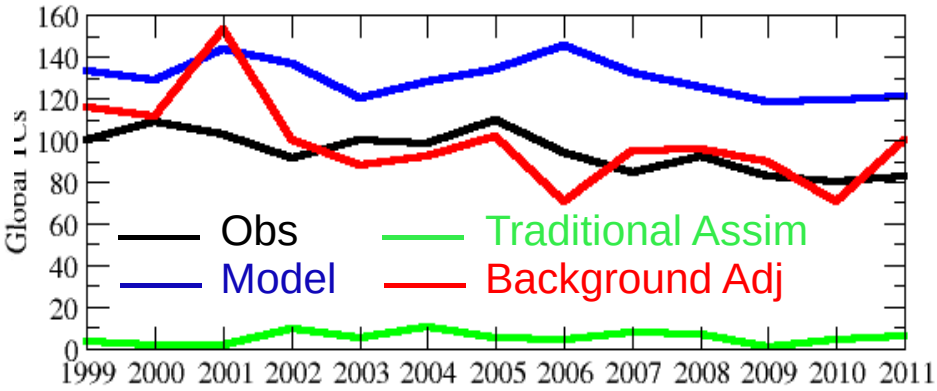
Free model

Traditional scheme

BGA scheme



Time Series of global TCs



- ✓ Background adjustment can reconstructs TC statistics by correcting large scale background & retaining small-scale perturbations
- ✓ Minimizing errors in model forecasts allowing interactions of TCs & LGS

(Zhang et al. GRL2014)

Summary

1. Based on instantaneous model error statistics, ensemble coupled data assimilation (ECDA) produces self-balanced and coherent climate estimates, providing optimal ensemble initialization for probabilistic climate forecasts.
2. Performing multiple media data constraints within a coupled system, ECDA maintains energy balances among coupled media, providing a mechanism for skillful decadal scale predictions.
3. Maintaining simultaneously-exchanged fluxes among coupled media, ECDA is an optimal way to integrate pieces of observational information in the earth observing system, particularly providing constraints on non-observable media.
4. Coupled model parameter estimation can mitigate model bias and constrain model drifts in climate predictions, thus enhancing model predictability, which shall be applied to the next generation ECDA.

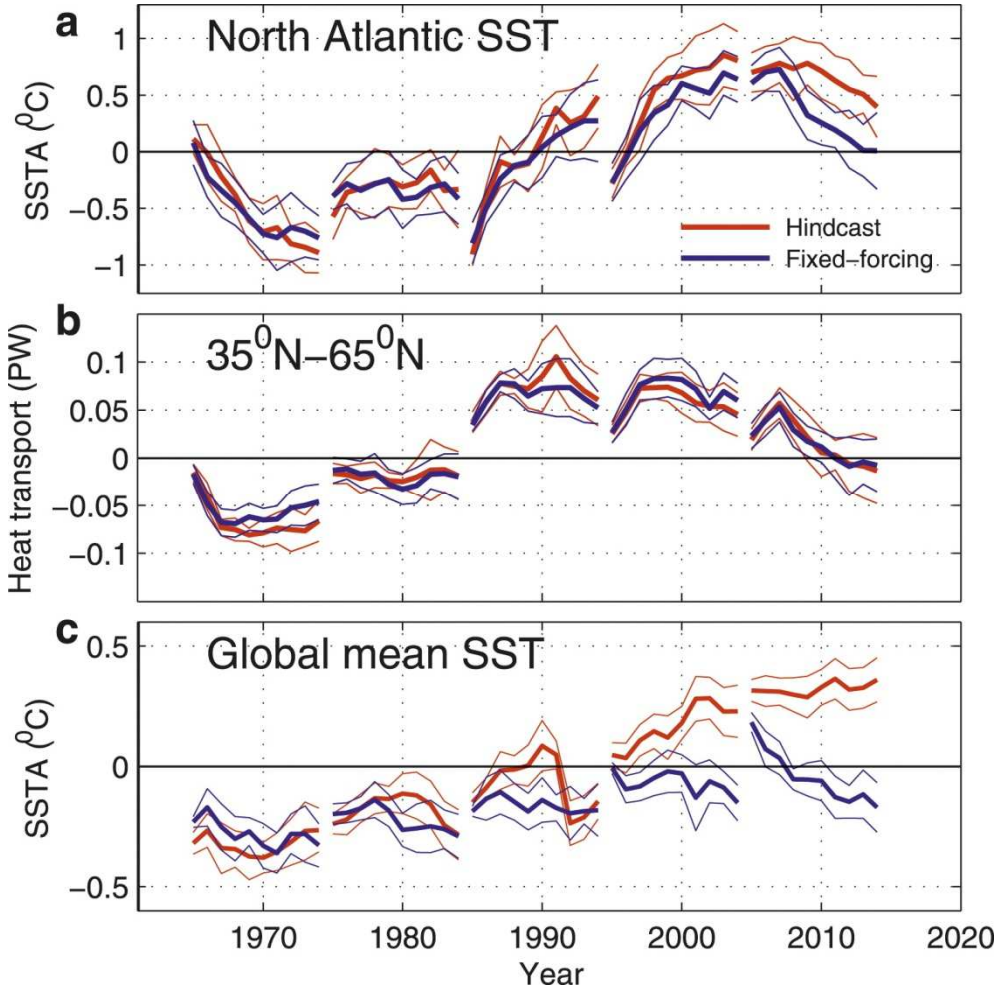
5 Separately processing the large-scale background and small-scale perturbations, the background adjustment scheme can correct tropical cyclone statistics in high-resolution ECDA. This idea shall be refined to advance high-resolution coupled model initialization, pursuing seamless numerical weather-climate studies.

Outstanding Issues for ECDA Directions

- ✓ When model resolution is higher and higher, how to optimize the representation of observing system combining with a high-resolution coupled model?
- ✓ Are the surface pressure observations sufficient to constrain the climate system – how important are 3D radiosonde data?
- ✓ How to maintain the high latitude stratification when sufficient subsurface data are lack so that a realistic AMOC (for example) can be reconstructed?
- ✓ How to mitigate model bias to enhance coupled reanalysis and climate prediction quality? – How much can coupled model parameter estimation help?
- ✓ What is the impact of sea ice data assimilation on coupled reanalysis and climate prediction?
- ✓ Extend ECDA to include land, ECO-system component?

CDA for Decadal Prediction
Initialization vs. external forcings

- ✓ CDA starting from 1950 with NCEP RE1/RE2 and oceanic profiles
- ✓ 10-yr forecasts initialized from the CDA states every 10 yrs starting from 1965
- ✓ 2 sets of forecast experiments in parallel using historical forcings (red) or 1960-fixed forcings (blue)



(Yang et al. JC2013)

CDA for Decadal Prediction of TC-count
Initialization vs. external forcings

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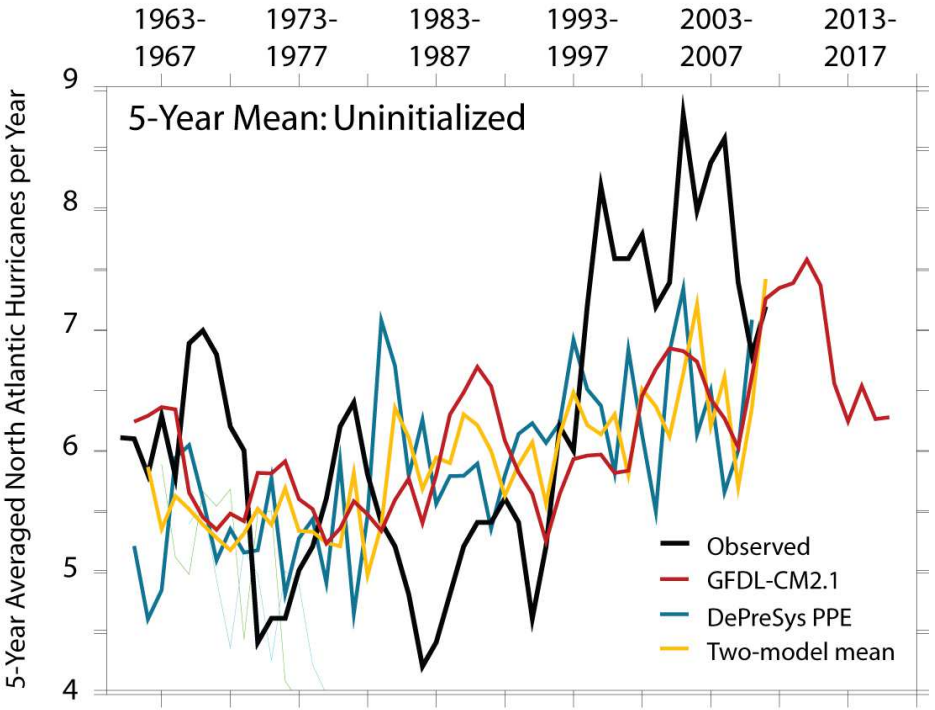
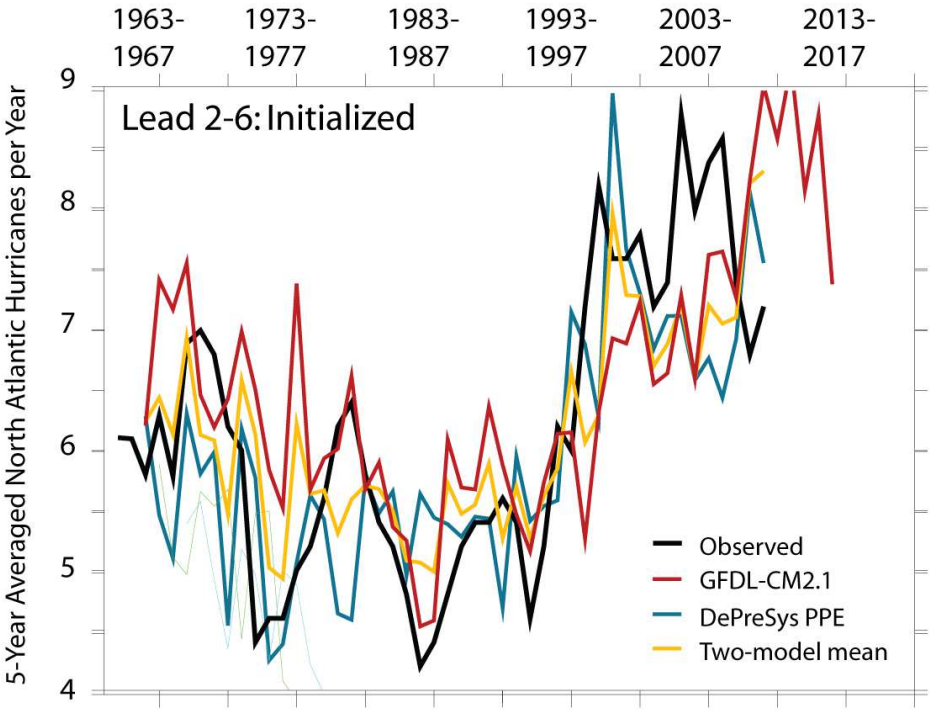


FORCED & INTIALIZED



- Retrospective predictions encouraging
- However, small sample size limits confidence
- Skill arises more from recognizing 1994-1995 shift than actually predicting it.
- This is for basinwide North Atlantic Hurricane frequency only.

Vecchi et al. (2013 and 2014), Msadek et al. (2014)

EXPERIMENTAL: NOT OFFICIAL FORECAST

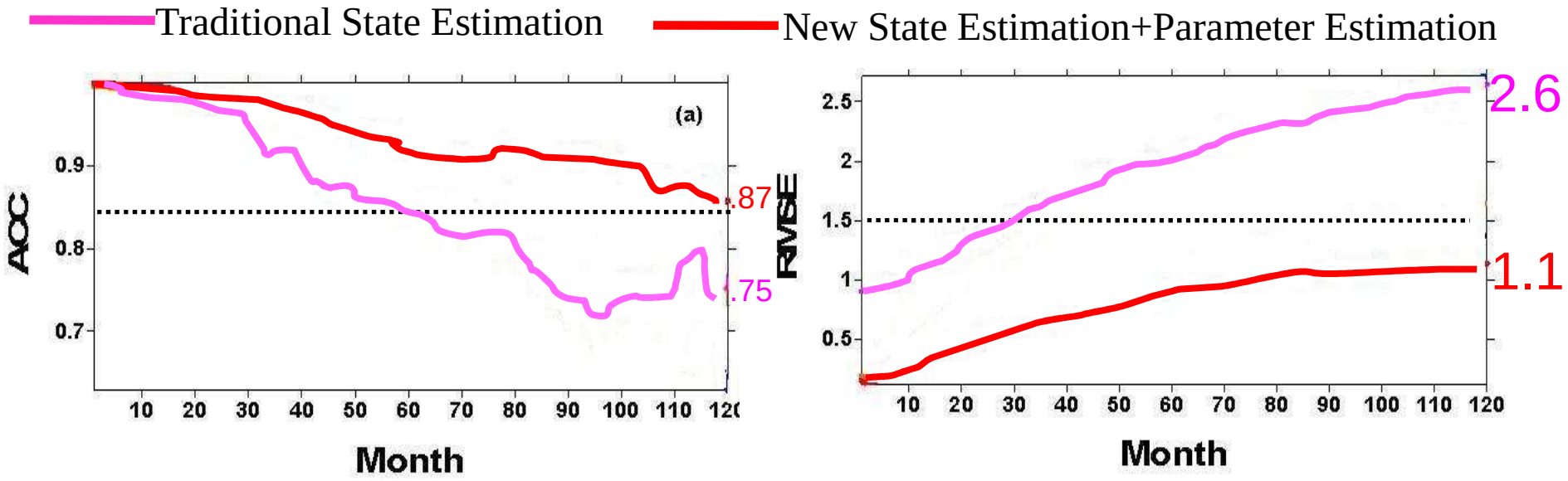
noaaresearch

Figure Courtesy Vecchi et al. 2013 & 2014; Msadek et al. 2014)

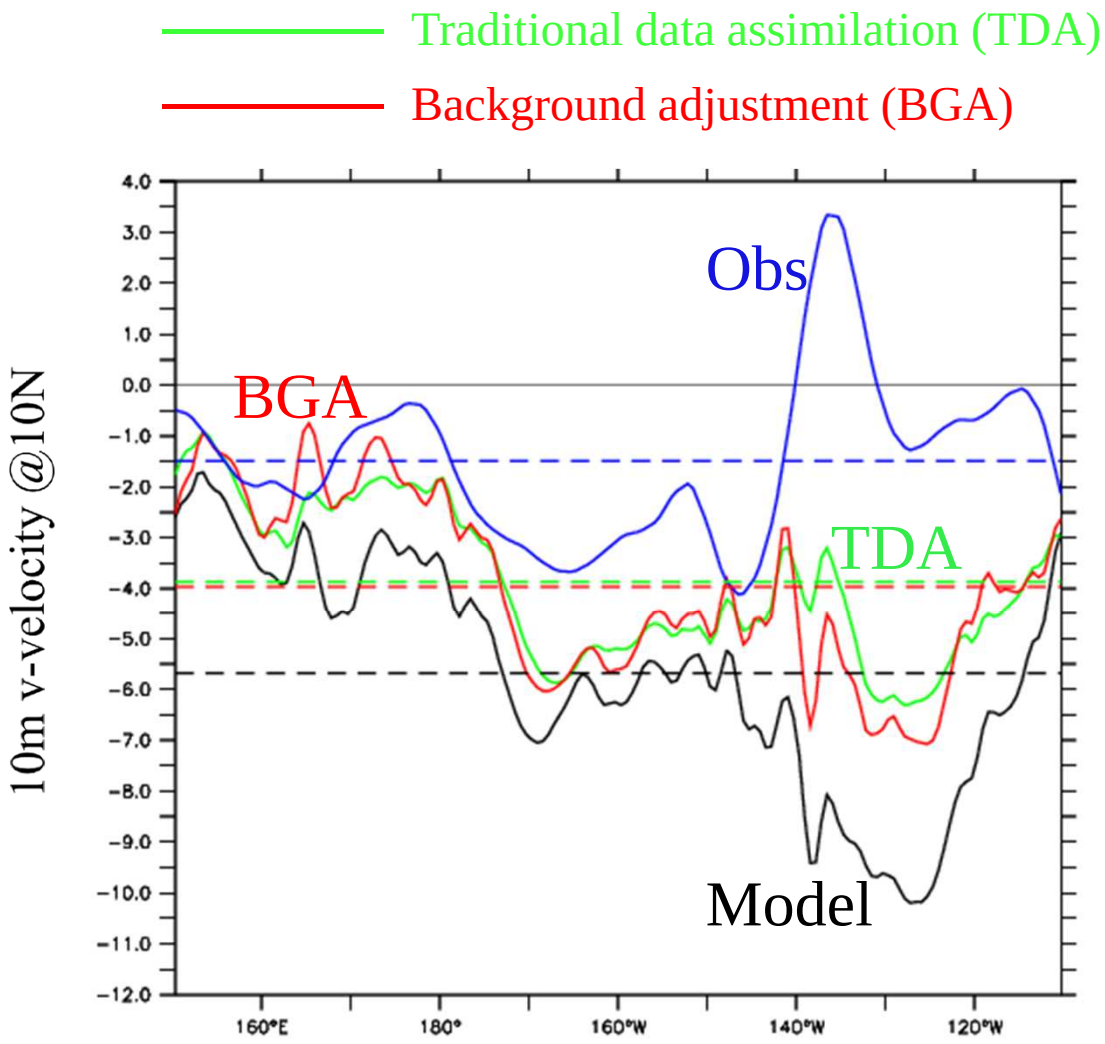
GFDL

Enhance Model Predictability by Parameter Estimation
Improved forecast skills

Ocean temperature forecast skill



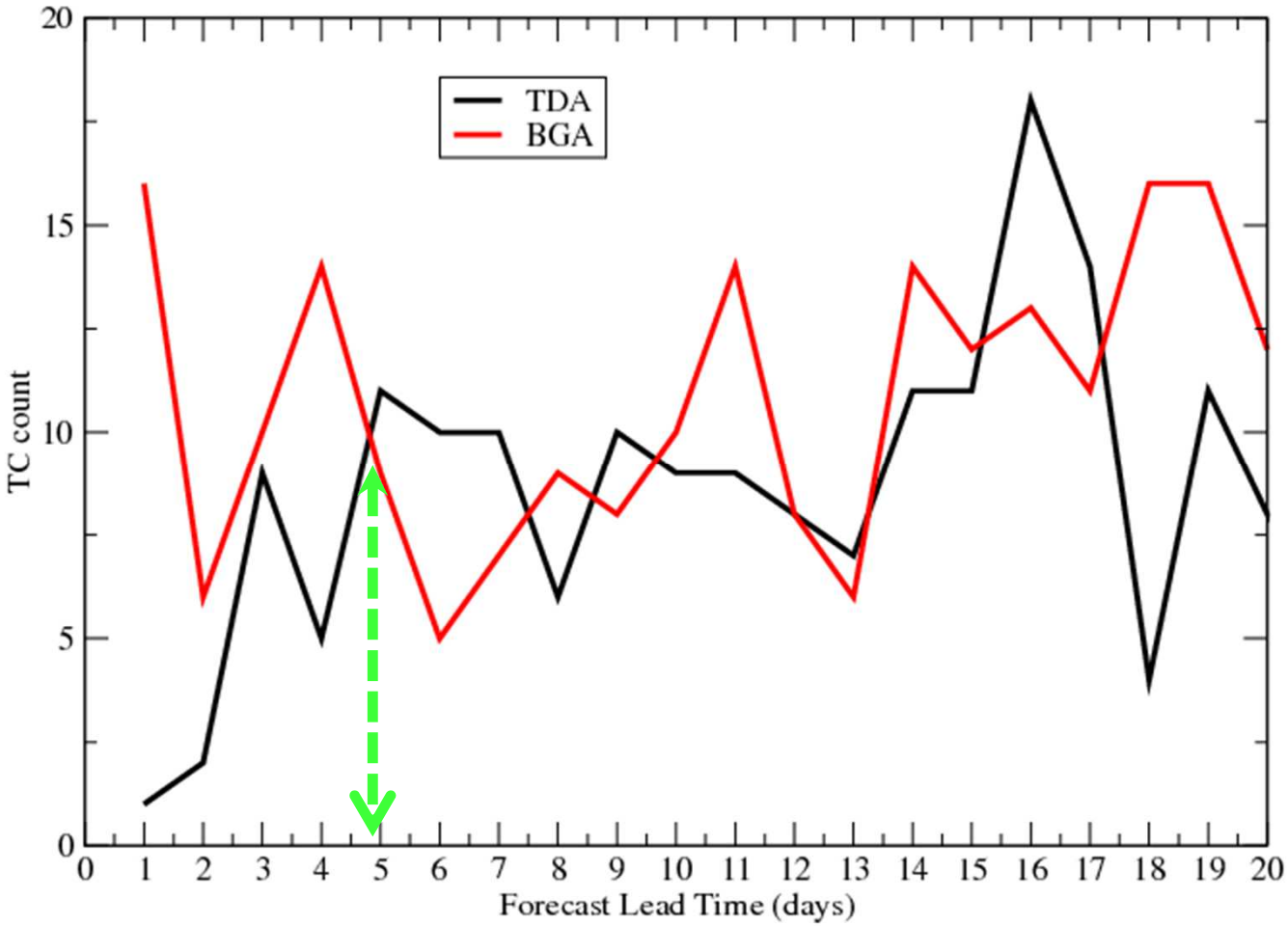
A Background Adjustment (BGA) Scheme
Retain small scale perturbations in atmosphere



Impact of Initialized TC Statistics on TC count

How long the model TCs can be spun up?

- ✓ 28-day ICs from TDA and BGA (2005 Sept)
- ✓ 180-day model Forecast for each IC



Impact of Initialized TC Statistics on SST forecasts

ACC of SSTA