Understanding and Predicting Atlantic Decadal SST Variability Using a Hierarchy of Models

Edwin K. Schneider

George Mason University and COLA

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Collaborators

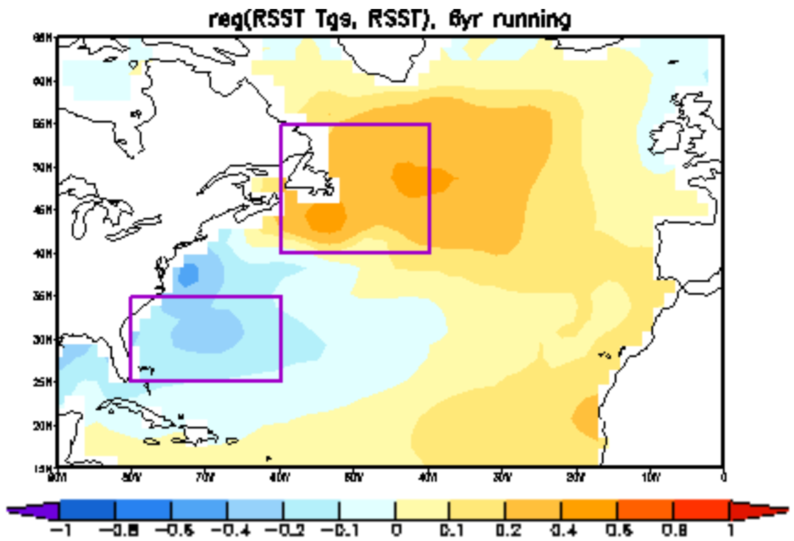
- Meizhu Fan - many of the results come from her PhD thesis.
- Ben Kirtman - developer of the “Interactive Ensemble”
- Hua Chen, Ioana Colfescu GMU graduate students

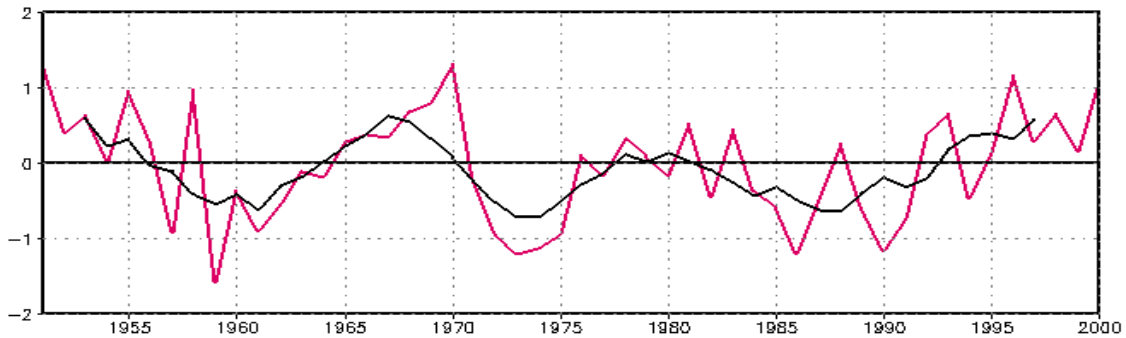
Physical Problem

- Diagnose and understand the mechanisms of observed low frequency observed (1951-2000) North Atlantic SST variability.
- In particular, what were the roles of weather noise forcing, coupled feedbacks, and ocean dynamics?
- What are the implications for decadal predictability?

Tripole

Index: area average SST difference. Northern box minus Southern. (Czaja and Marshall 2001, QJRMS)





1951 → 2000

Tripole Mechanism Issues

- External forcing or internal variability?
- Remote or local origin?
- Why decadal time scale?
- Connections to other modes of variability (e.g. NAO, AO, AMO, TAV, PDO, AMOC)?
- Implications of understanding of mechanisms for predictability?

A Menagerie of Models

- Hasselmann model (conceptual/motivational)
- Barsugli/Battisti model (conceptual/motivational)
- CGCM or reanalysis (data to interpret)
- AGCM ensemble (determine weather noise)
- Intermediate Coupled Model (parameterized atmospheric transients, controlled experiments)
- Czaja/Marshall model (conceptual/diagnostic)

The Four Mechanisms of Low Frequency Climate Variability (SST) (Sarachik et al., 1996)

1. Forced by atmospheric weather noise (Hasselmann 1976)

2. Forced by oceanic “weather noise”

3. Intrinsic coupled variability (e.g. coupled ocean-atmosphere) that is not forced by weather noise

4. Externally forced

Hasselmann’s Model (Damped Brownian Motion)

- 0-dimensional (1 point) model.
- Slab mixed layer ocean forced by stochastic heat fluxes, feedbacks damp SST anomalies.
- Stochastic heat flux forcing (white spectrum) represents random atmospheric weather noise.

- What properties of the low frequency climate variability can this minimal model explain?

$$\rho c H \frac{dT}{dt} = N - \lambda T$$

$N \text{ is "weather noise"}$

$\text{let } N = N_\omega e^{i\omega t}$

$\text{look for solutions } T = T_\omega e^{i\omega t}$

$$T_\omega = \frac{N_\omega}{\lambda + i\omega\rho c H}$$

and for white noise $\left|N_\omega\right| = const.$

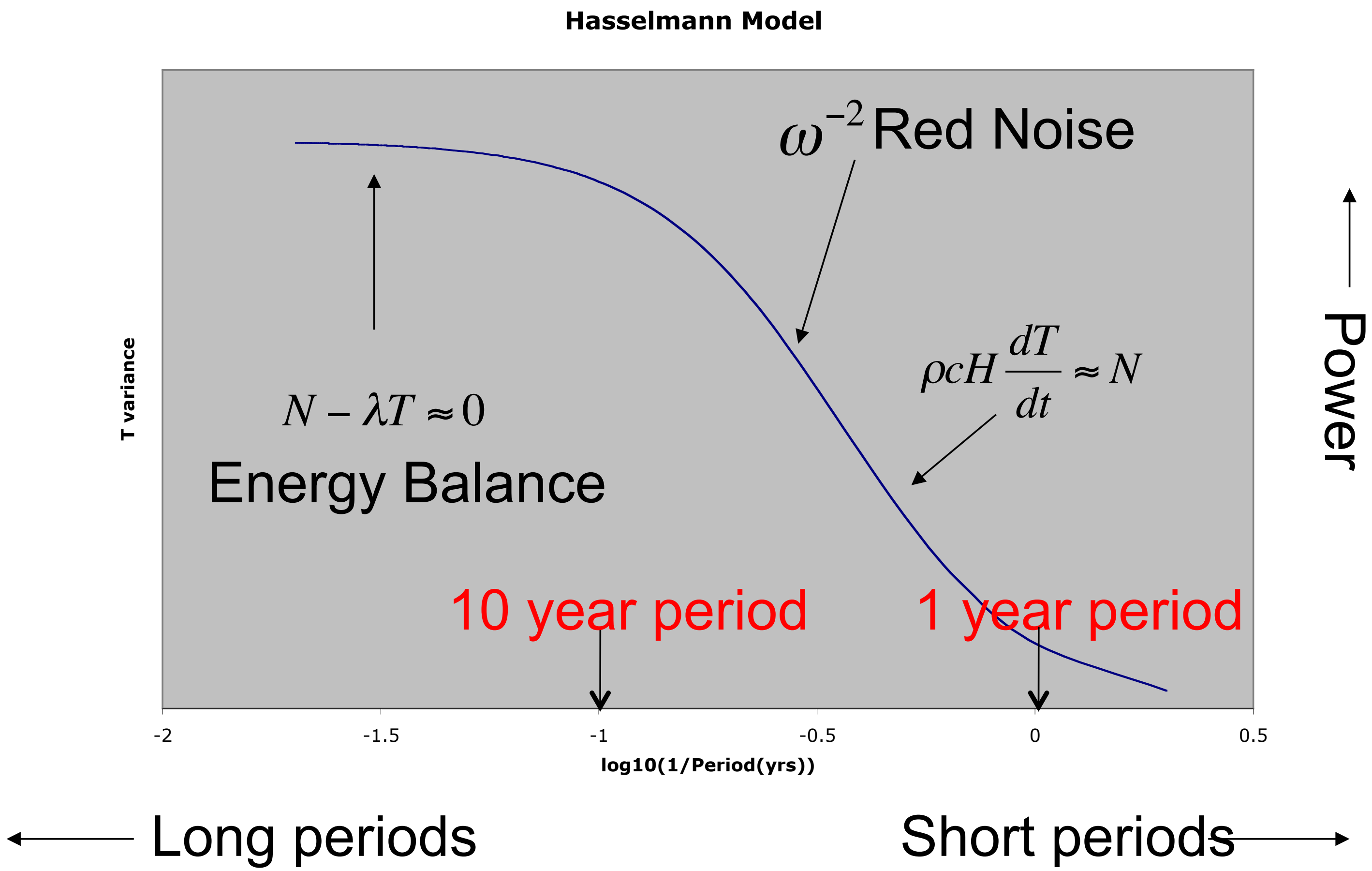
So for high frequencies $\omega\rho c H >> \lambda$

$$\left|T_\omega^2\right| \sim k_1 / \omega^2$$

while for low frequencies

$$\left|T_\omega^2\right| \sim k_2$$

Response to white noise forcing for 50m slab mixed layer, damping 15 W m^{-2} K^{-1}



Properties of Hasselmann's Model

- No SST variability without weather noise forcing.
- Appears to explain redness of climate spectra (but not the peaks).
- Suggests a testable null hypothesis for climate variability: all low frequency variability is the response to forcing by random weather noise.

The Plan

- Scale up Hasselmann's model to a CGCM class model.
- Force the ocean with *specified* weather noise surface fluxes.
- Main issues
  - What sense does it make to force a CGCM with weather noise? The CGCM produces its own chaotic weather variability that can't be predicted or controlled.
  - How to choose *N* ?

Barsugli and Battisti (BB) Model

- 0-dimensional (1 point model)
- Slab atmosphere coupled to slab ocean
- Atmosphere forced by radiation, ocean (surface fluxes), and weather noise
- Ocean forced by atmosphere (surface fluxes)
- Makes contact with CGCM architecture
- Hasselmann model is a special case (energy balance limit).

Barsugli and Battisti Model

- Atmosphere T_a, ocean T_o, weather noise N
- Atmosphere (T_a): $$dT_a/dt = -aT_a + bT_o + N$$
- Ocean (T_o): $$\beta\, dT_o/dt = cT_a - hT_o$$
- Reduces to Hasselmann model for slave atmosphere ($dT_a/dt \cong 0$).

Equivalent BB Model

- Atmosphere: $$dT_a/dt = -aT_a + bT_o$$
- Ocean: $$\beta\, dT_o/dt = cT_a - hT_o + N_f$$
- Forcing: $$if \quad \frac{1}{c}\frac{dN_f}{dt} + \frac{N_f}{a} = N$$

  (but remember we don't know *N*)

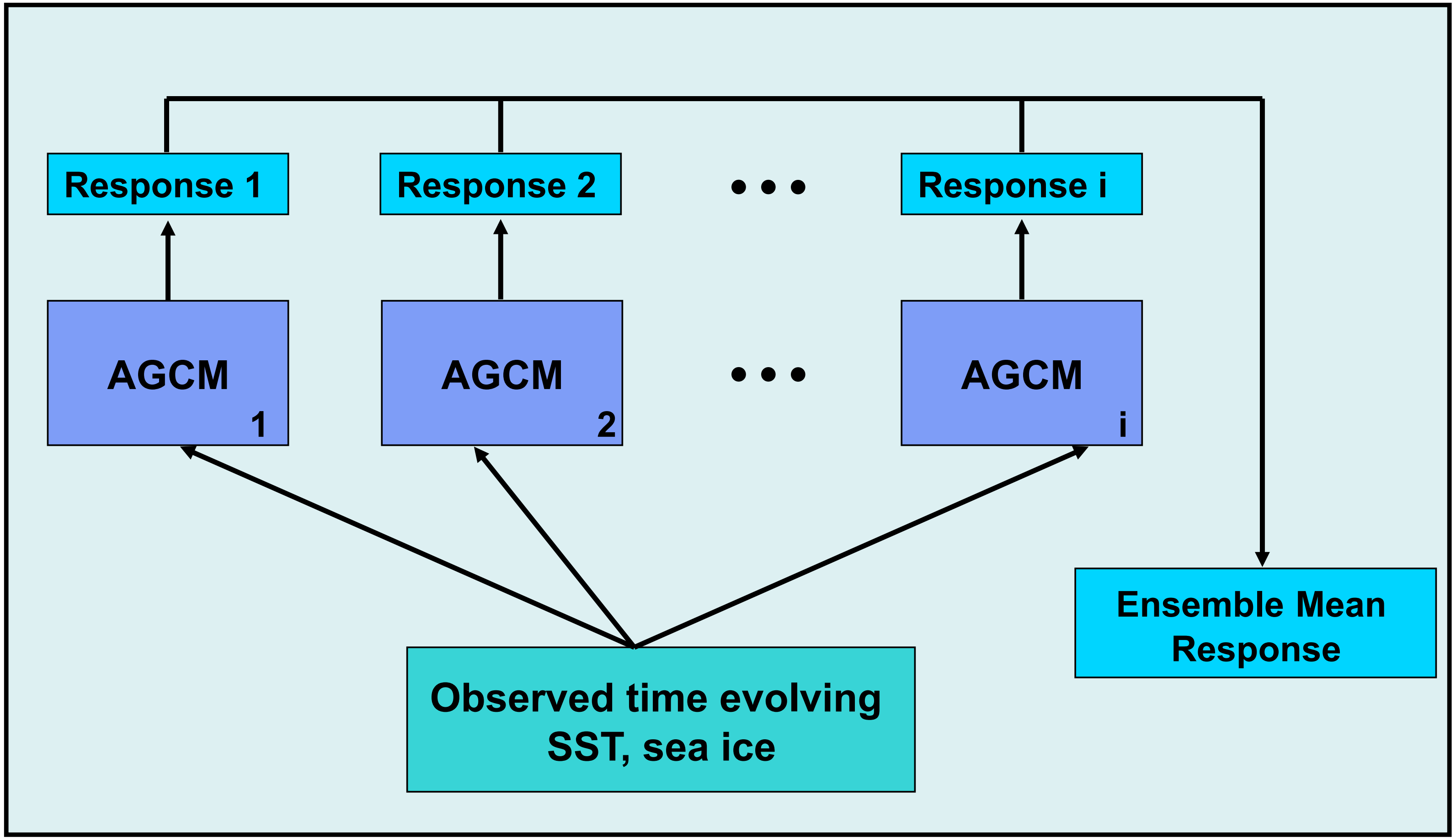
- Noise free atmosphere, ocean forced by "weather noise" surface fluxes.
- Diagnostic only – the weather noise has to be determined from the output of the original model.

"AMIP Ensemble"

- Force an ensemble of AGCMs with the same SST and external forcing evolution.

- Each ensemble member has a different initial condition.

- Gates et al. 1999.



Response of $AGCM_i$ = SST forced signal + $Noise_i$

$Noise_i$ is distinct for each $AGCM_i$

AMIP/GOGA Ensemble

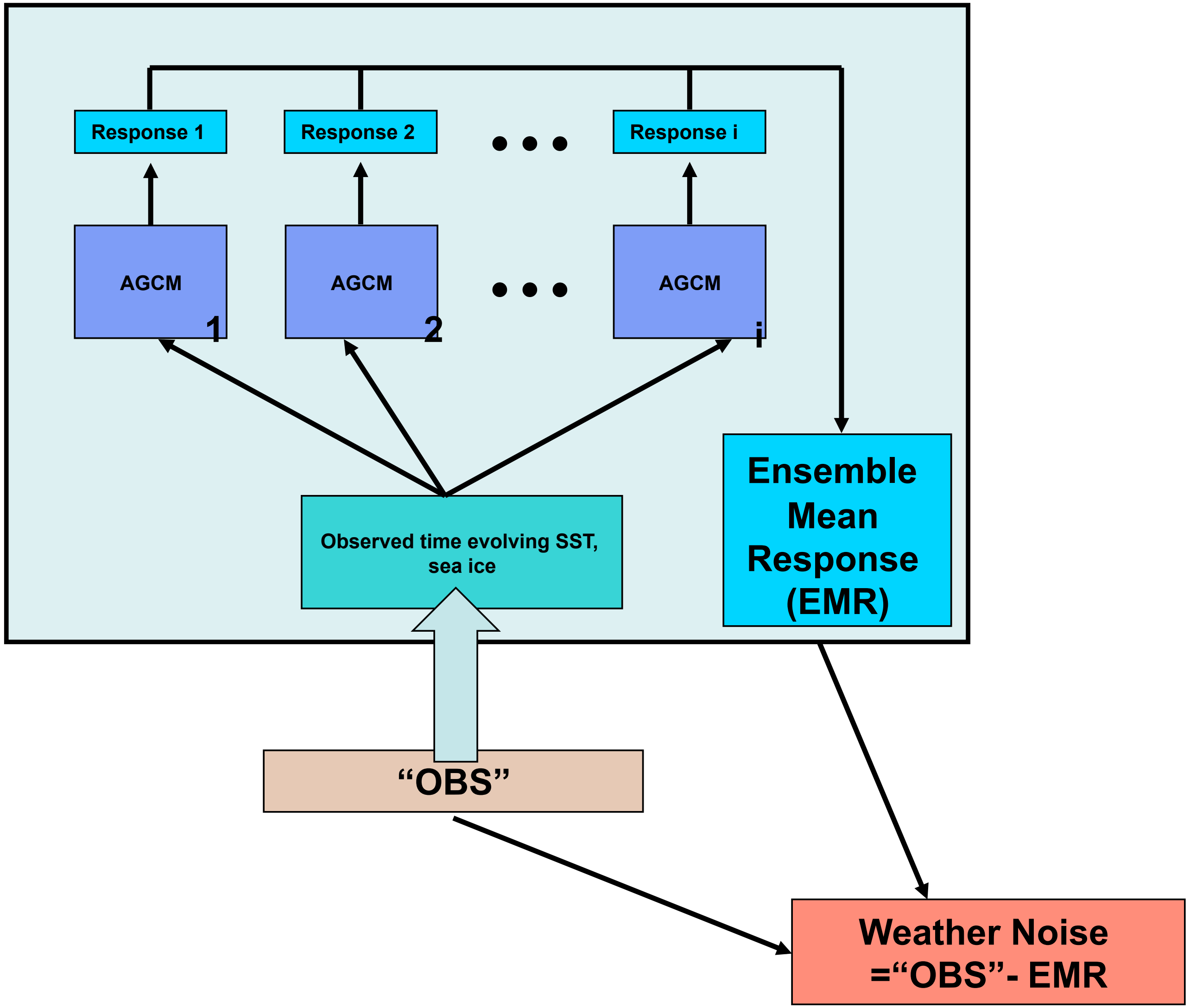
AMIP Ensemble Properties

- The AMIP ensemble mean is the SST forced “signal.” It is independent of the choice of initial atmospheric states.
- Then the solution for each ensemble member is:
  (the SST/externally forced ensemble mean) + (the residual)
- The residuals are uncorrelated between ensemble members.
- The ensemble mean can be thought of as an atmospheric model with
  - parameterized transient eddy fluxes
  - No weather noise
- The residuals are the “weather noise” the non-parameterizeable and unpredictable part of the atmospheric evolution.

Diagnosis of the Weather Noise

- To find the weather noise in data produced by an AGCM simulation (or in observations), remove the ensemble mean of the AMIP ensemble forced by the same SST and external forcing.

Weather Noise = (observed) – (SST forced)



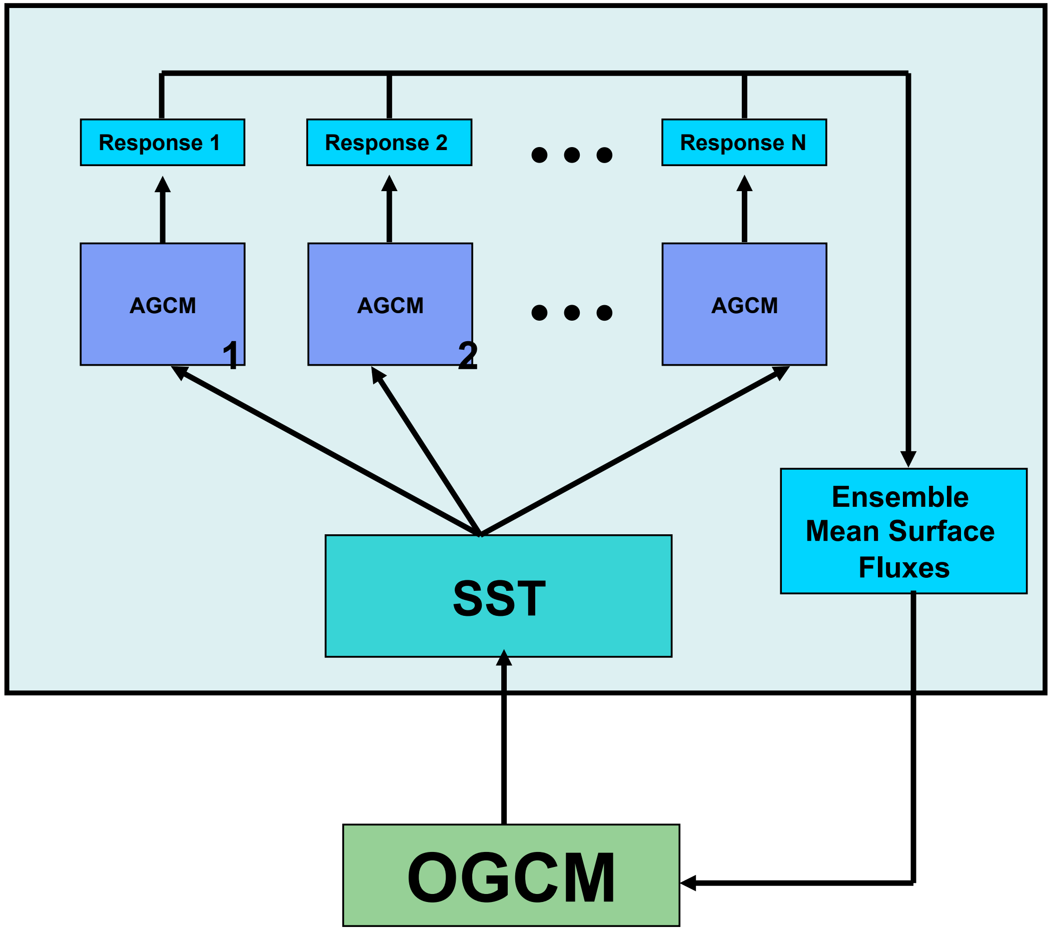
Determination of the Weather Noise

Other Ingredient: Coupled Model With a Noise Free Atmosphere (Intermediate Coupled Model)

- Couple AGCM AMIP ensemble to OGCM.
  - Each AGCM ensemble member sees the same OGCM SST
  - OGCM sees ensemble mean surface fluxes from the atmospheres (no weather noise)
  - The AGCM ensemble and the OGCM interact just as the AGCM and OGCM do in a CGCM

- "Interactive Ensemble CGCM" or IE-CGCM
  - Kirtman and Shukla
  - CGCM class feedbacks, parameterizations

Interactive Ensemble CGCM



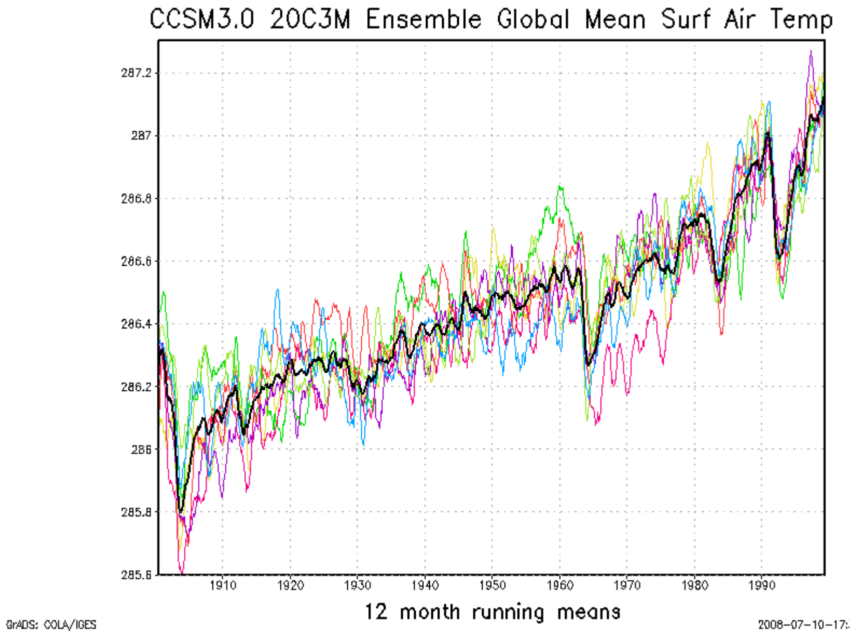
Properties of IE-CGCM

- Much reduced internal SST variability on *all time scales* compared to CGCM when no external forcing.
  - No intrinsic AMOC variability, as in other ICMs.
  - ***Proves*** that internally generated SST variability in the CGCM is forced primarily by atmospheric weather noise.
- Exceptions
  - ENSO-related SST variability in the equatorial Western Pacific
  - Internal ocean variability associated with strong currents (ocean "weather noise").

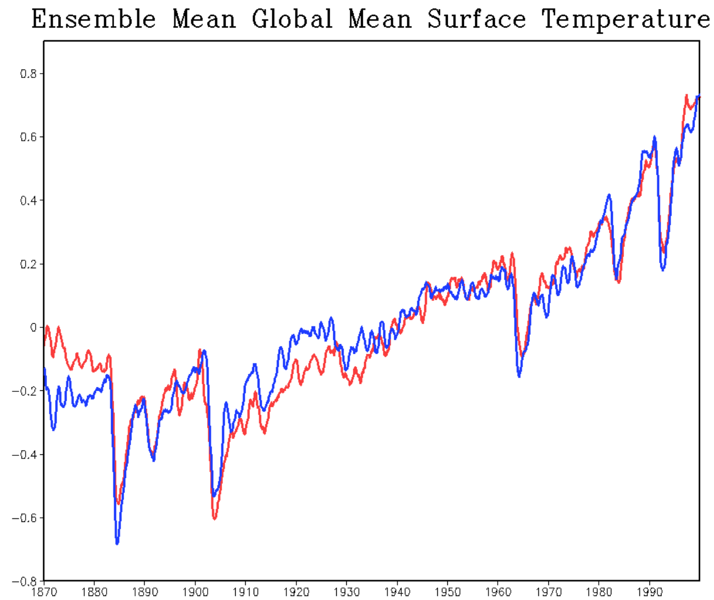
Response to Observed External Forcing 1870-2000 (20C3M)

CCSM3 CMIP4

Colors = ensemble members
Black= ensemble mean



Red = CCSM3 ensemble mean
Blue = CCSM3 IE



Noise Forced IE-CGCM

- Specified weather noise surface flux forcing is added to the surface fluxes seen by ocean
  - Heat, momentum, fresh water

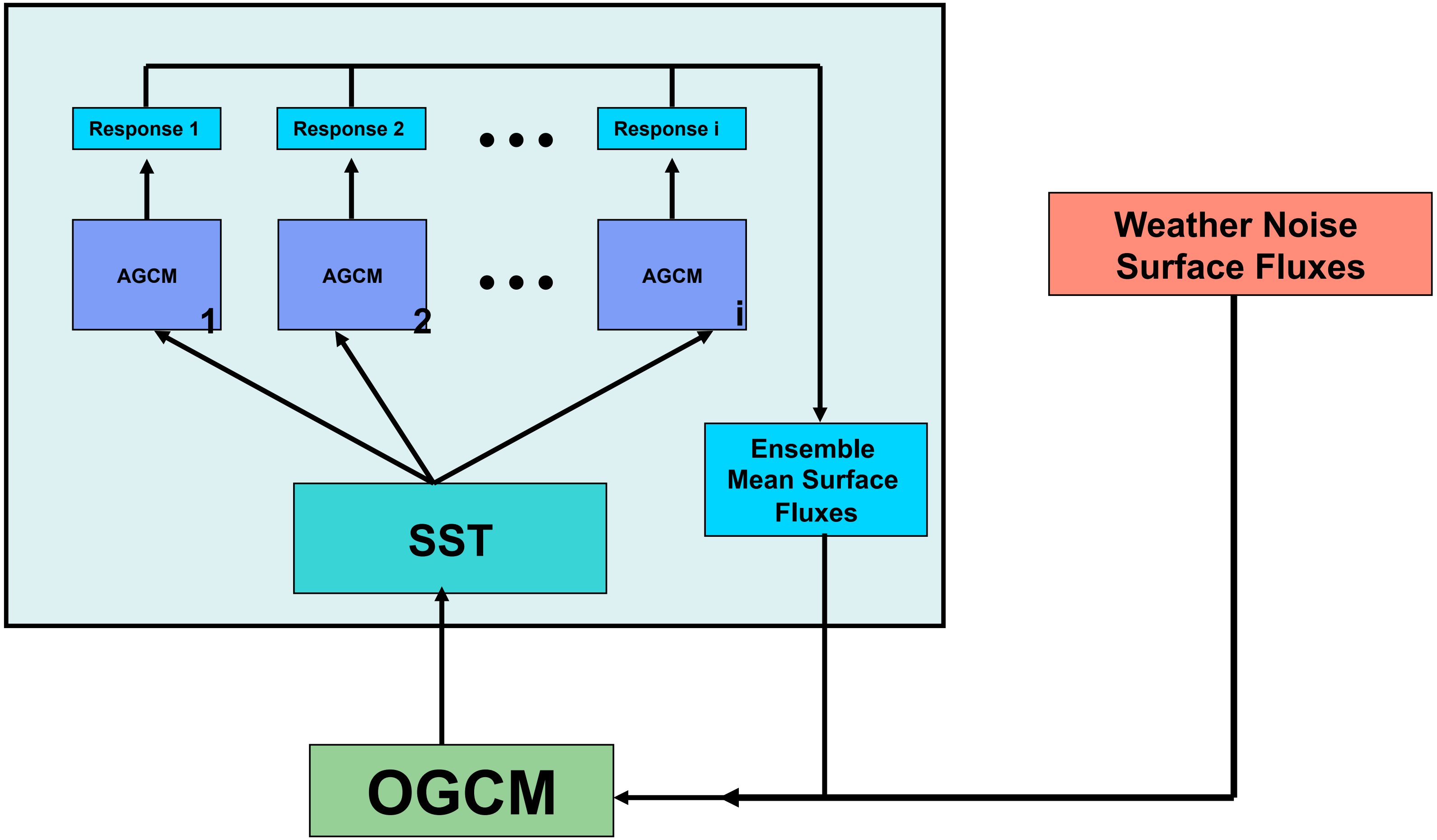
- Weather noise is calculated from observations (or CGCM output) and the SST forced AMIP ensemble

- The model is an ICM with deterministic solutions to the weather noise forcing.

- **It is many times more "complex" and more expensive that the underlying CGCM (➔∞).**

- Applied to the BB model, this procedure yields the "equivalent BB model," a diagnostic coupled model.

Noise Forced Interactive Ensemble



Other Ways to Think About Weather Noise Forced IE CGCM:

- It is like an **OGCM simulation** forced by observed fluxes but with feedbacks correctly taken into account.
  - "OGCM" simulations typically include atmospheric feedbacks (e.g. damping) as well as specified observed fluxes. This is inconsistent.
- It is a type of **Coupled Data Assimilation**
  - CGCM-like model constrained by data

Tripole Problem

- Simulate the observed 1951-2000 tripole index using a CGCM-class model forced by observed weather noise.
- Try to understand the results in the framework of the simple model of Frankignoul and Hasselmann (1976) as extended by Marshall et al. (2001), Czaja and Marshall (2001):
  - Weather noise
  - Atmospheric feedback to SSTA
  - Gyre circulation
  - AMOC

Earlier Work

- Kushnir 1994; Deser and Blackmon 1993
  - Observational
- Seager et al 2000
  - Force ocean with reanalysis surface fluxes. Heat flux forcing dominates, ocean dynamics secondary for SST
- Marshall et al. 2001; Czaja and Marshall 2001
  - Observational diagnosis. Simple model of tripole variability
- Eden and Willibrand 2001
  - Force OGCM in NA with NCEP reanalysis surface fluxes
- Eden and Greatbatch 2003
  - Force OGCM in NA with simple stochastic atmosphere
- Visbeck et al. 2003
  - Role for ocean dynamics at longer time scales
- Bellucchi et al. 2008
  - Analysis of tripole simulated in SINTEX-G CGCM

Data and Models

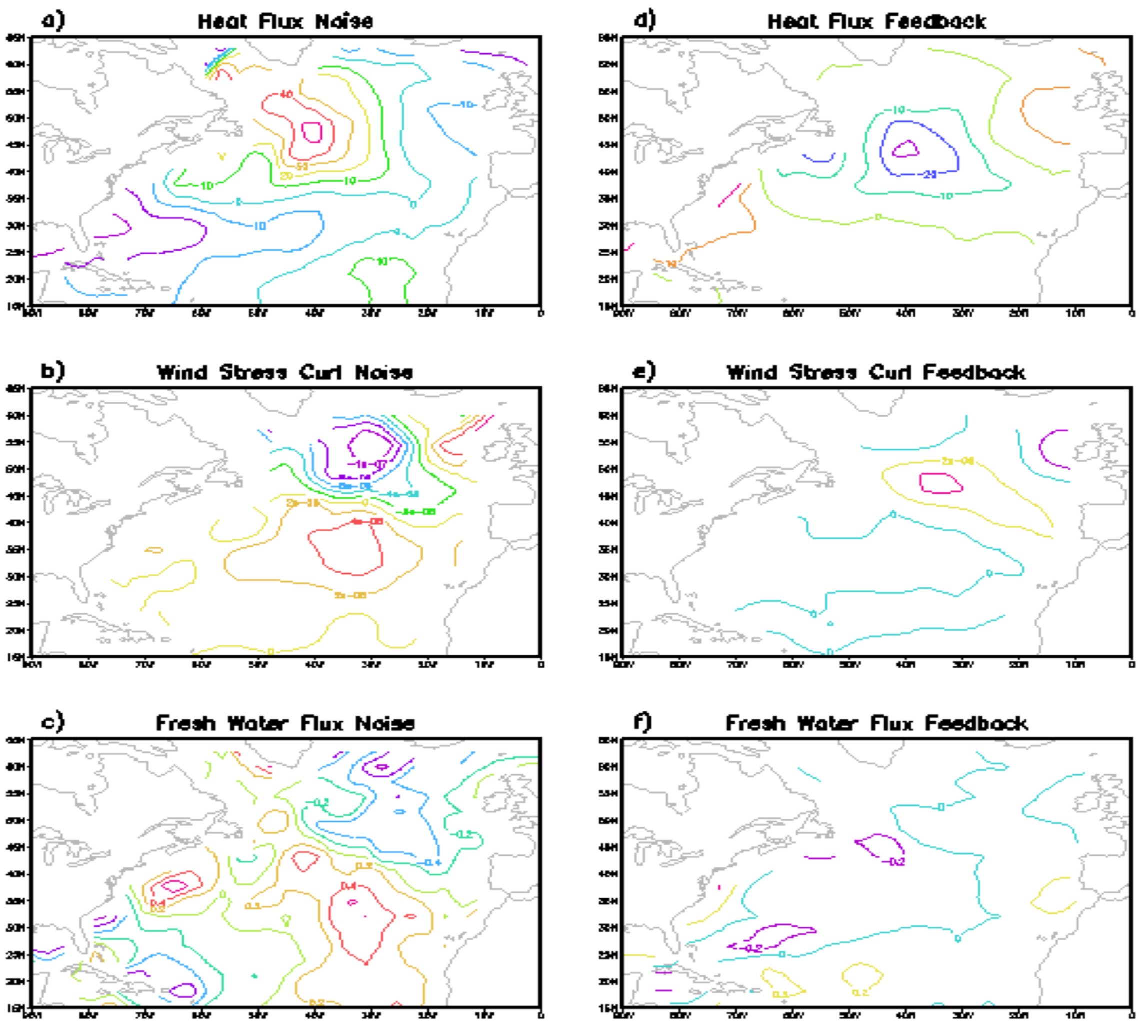
- NCEP reanalysis 1951-2000, monthly means
- COLA CGCM and IE-CGCM
  - COLA V2 AGCM (T42, L18)
  - MOM3 OGCM (1.5º, finer meridional near equator) non-polar domain
  - Anomaly coupled

Elements of Tripole SST Variability

- Weather noise (NAO variability)
- Feedback of SST ➔ NAO
  - In terms of heat flux is this positive? negative?
- Ocean dynamics heat flux
  - Gyre circulations
    - Modulations of mean gyre
    - Intergyre gyre
  - AMOC

Weather Noise and Feedbacks

regression 7 year running mean onto tripole



Experiments

- Force Interactive Ensemble (IE) CGCM with weather noise surface fluxes for 1951-2000.

- If the SST variability was the response to the weather noise, it will be reproduced.
  - Further experiments will then isolate the role of various processes in the SST variability (e.g. ocean dynamics, location and type of weather noise forcing, …)

- Diagnostic only ("additive noise").

Need to Understand Model's Own Internal Variability

- The model matters. Different models may produce different results due to different biases

- Perfect model, perfect data application
  - The COLA CGCM NAO and tripole patterns are shifted eastward ~25° from the observed locations
  - The tripole is forced by weather noise heat fluxes

Experiments to Diagnose Observed Variability

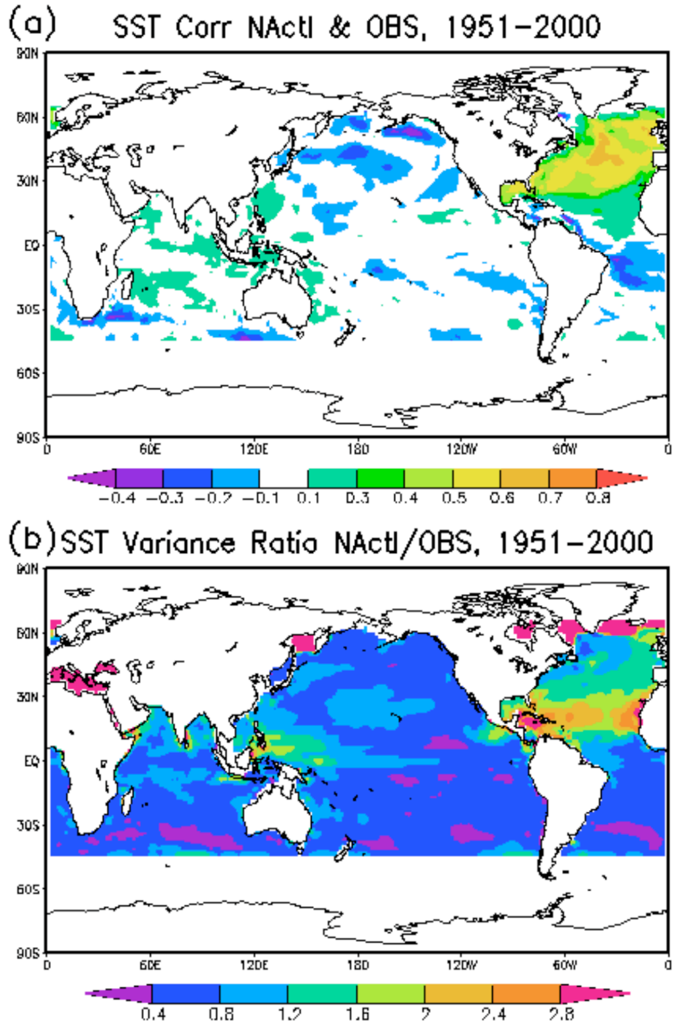
- Forcing Data: 1951-2000 NCEP reanalysis monthly surface fluxes and SST

Experiment	Forcing Noise	Forcing Region
Gctl	all	Global ocean
NActl	all	North Atlantic 15^0N~65^0 N
NAh	heat	…
NAm	momentum	…

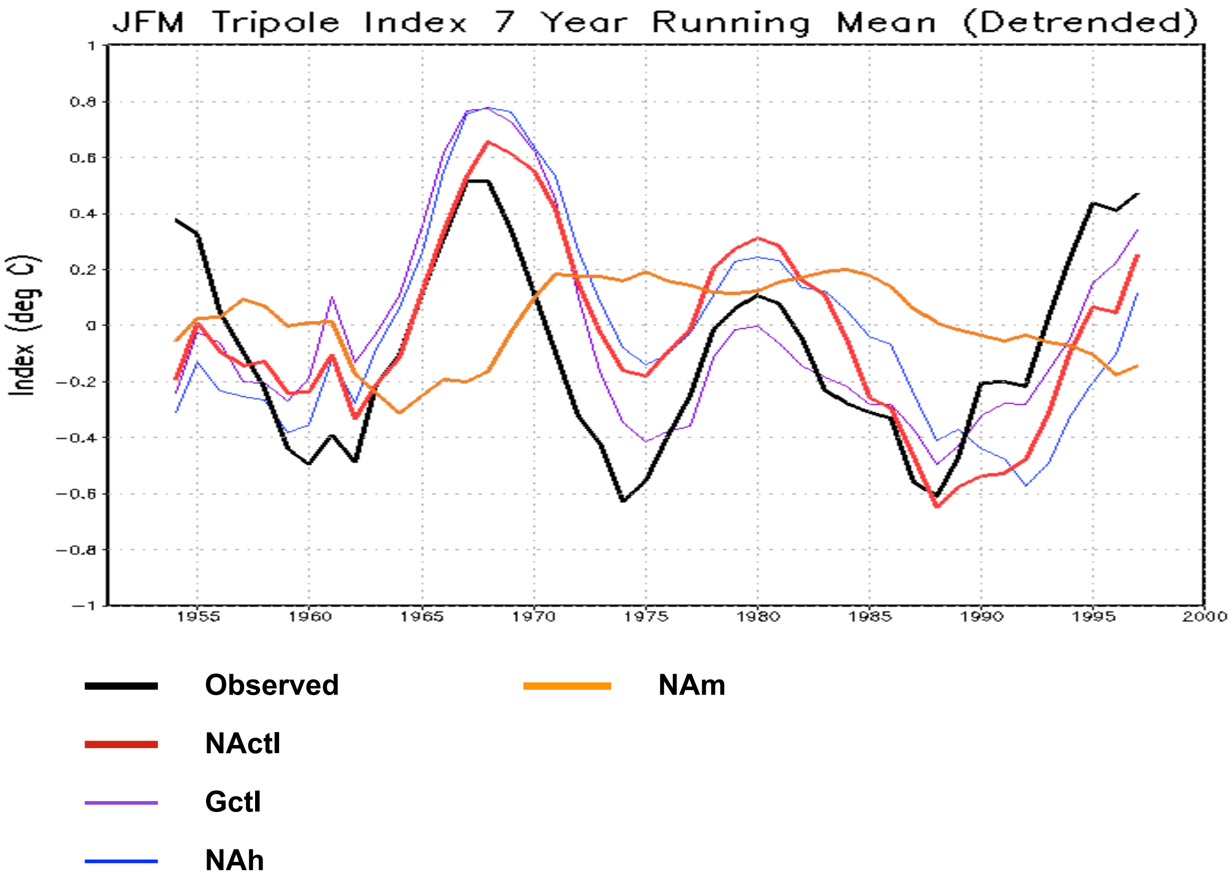
Note: "all" ~ freshwater, heat, and momentum

- *N.B.: biased model, inaccurate data, no external forcing in model or analysis*

NActl Reconstruction of Monthly SSTA



Tripole Index (Detrended)

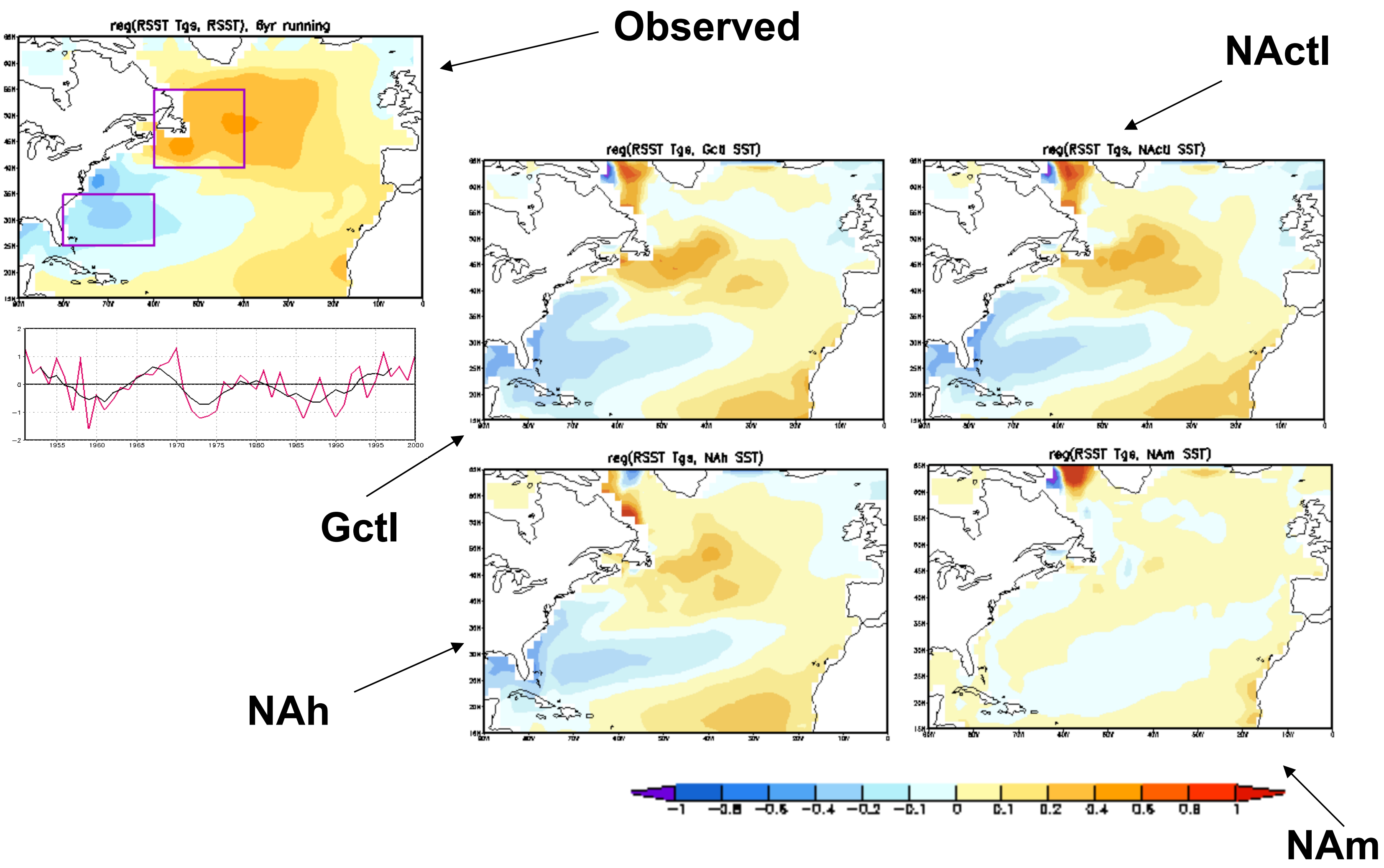


Summary of Results

- The tripole index is locally forced by the weather noise heat flux (Gctl, NActl, NAh).

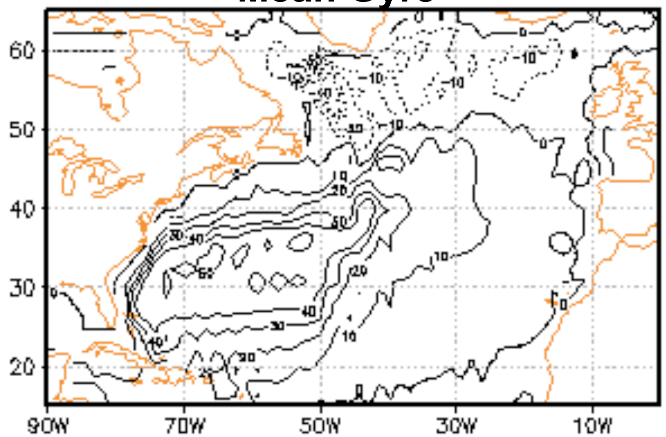
- Wind stress weather noise forces a tripole response that damps the full response.

Extract Model Patterns by Regression of Simulation Results Against Observed Tripole Index

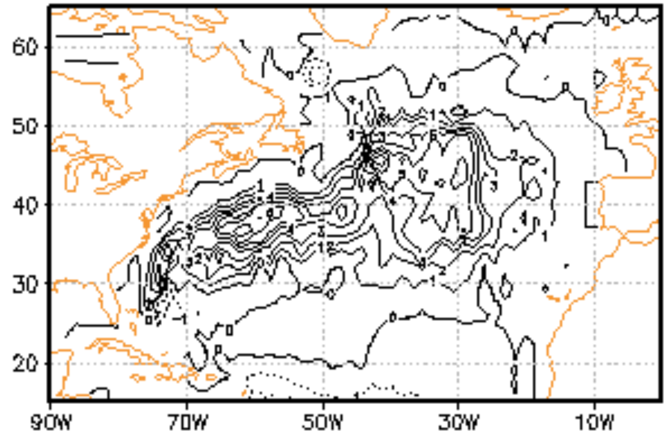


Gyre Circulation and Variability in NActl

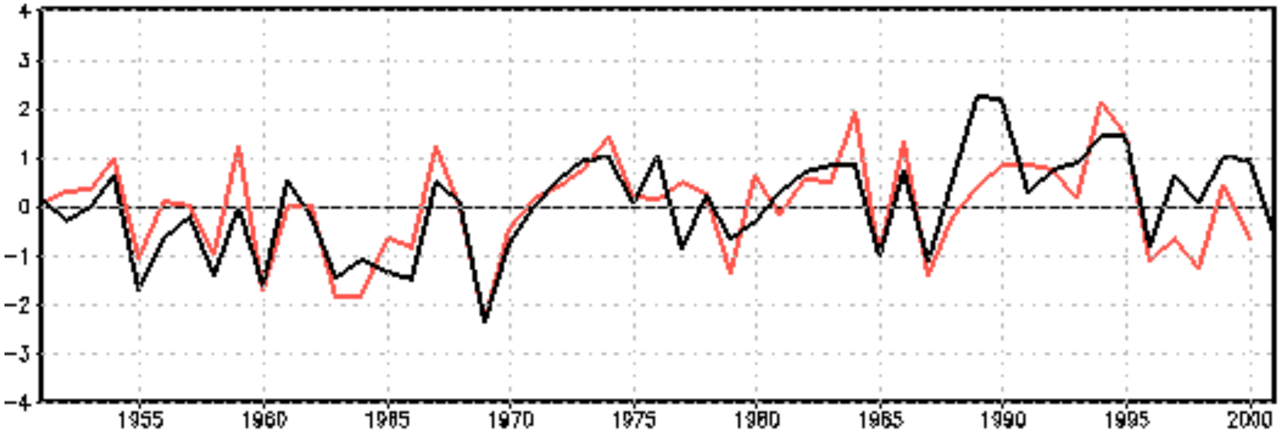
Mean Gyre



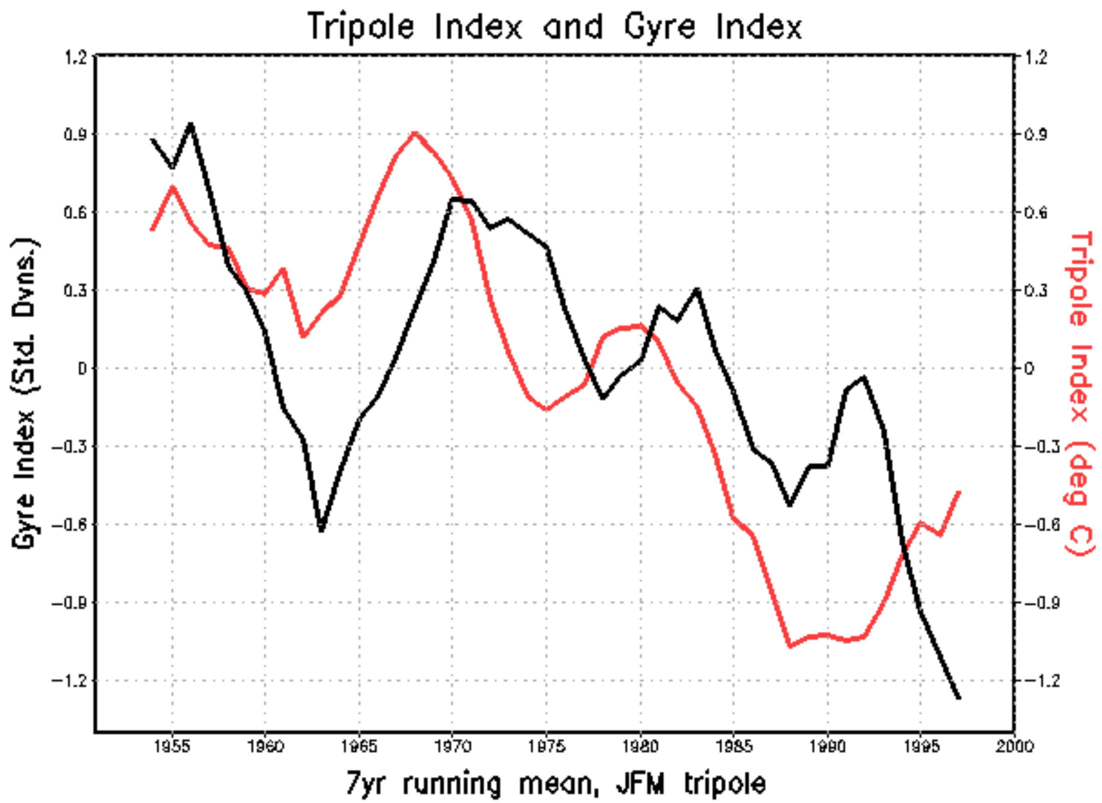
EOF 1 (31%) (“Intergyre Gyre”)



PC1 of EOF1 (gyre index); NAO Index (observed)

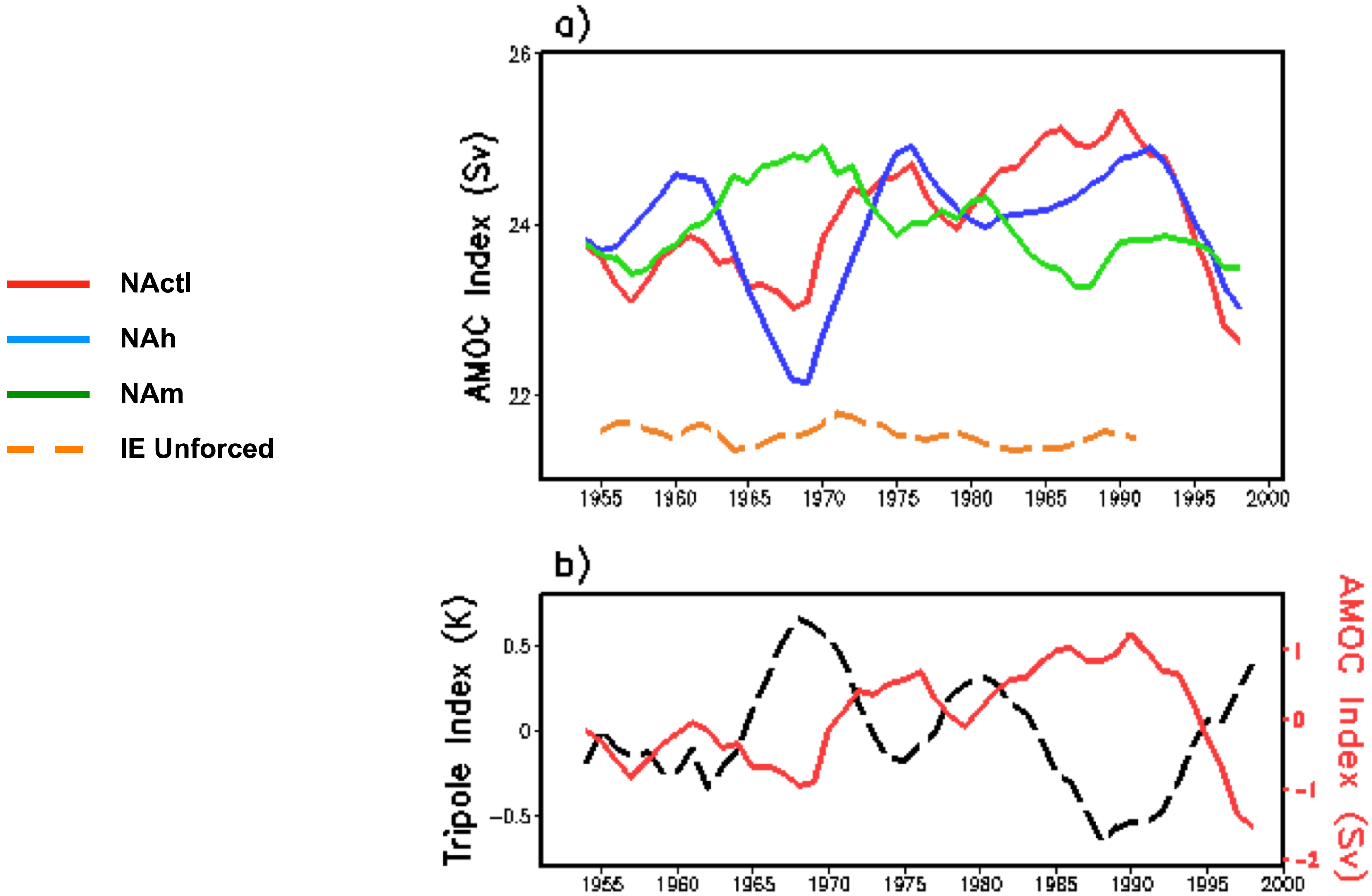


Tripole and Intergyre Intergyre Gyre Indices NActl



Gyre index: area avg. streamfn., 60°W-40°W, 35°-45°N

AMOC


NActl
NAh
NAm
IE Unforced
a)
26
24
22
AMOC Index (Sv)
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
b)
0.5
0
−0.5
Tripole Index (K)
AMOC Index (Sv)
1
0
−1
−2
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000

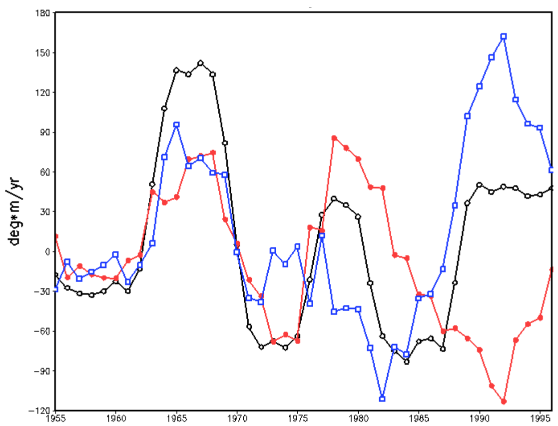
Heat Budget Analysis

- Vertical integral over full depth of the ocean
  - Heat storage tendency = dynamics tendency + surface heat flux
    - Surface heat flux is total (noise + feedback)
    - Heat storage tendency calculated from monthly mean output
    - Dynamics tendency obtained as residual

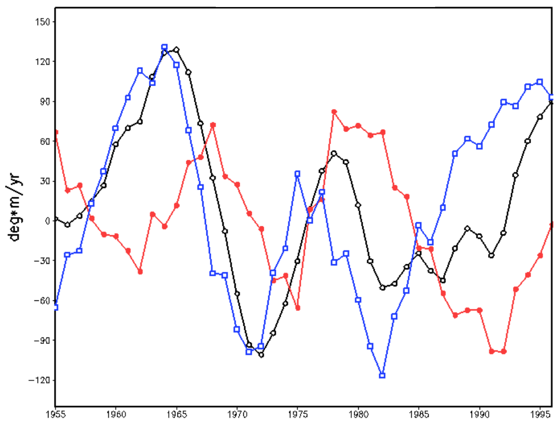
Heat Budget Tendencies

7 year running annual means

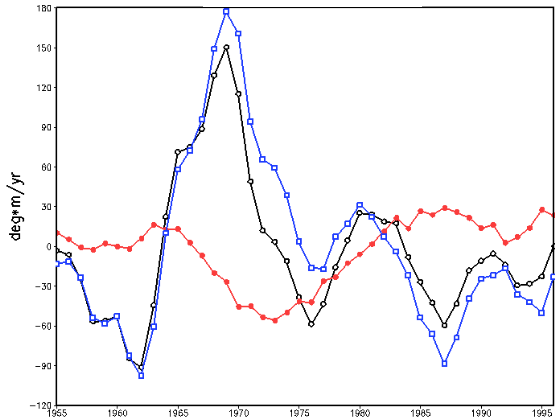
NActl



NAh



NAm



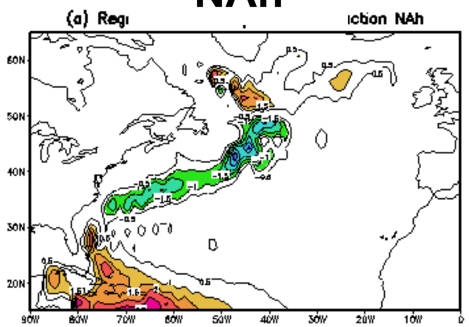
Heat storage tendency

Net surface heat flux

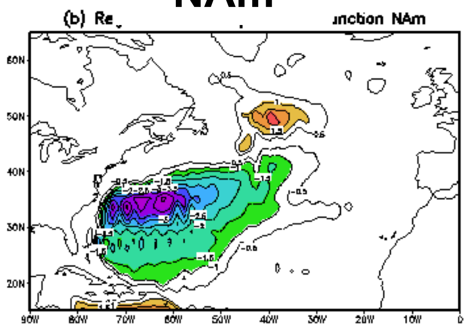
Ocean Dynamics tendency

Regression of Barotropic Streamfunction Against Ocean Dynamics Tendencies

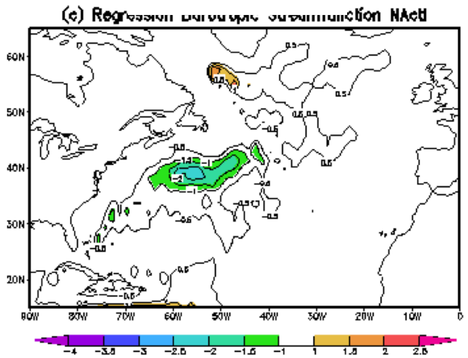
NAh



NAm



NActl



“Intergyre gyre”

Counterclockwise increases tripole Δ heat (!)

Modulation of mean gyres:

Reduction increases Δ heat

Simple Model
Czaja and Marshall 2001

Interpretation: Parameterized ocean heat budget. Heat storage parameterized as proportional to ΔT

$$\frac{d\Delta T}{dt} = -\lambda \Delta T + \alpha N + g\psi_g \quad \textbf{(1)}$$

ΔT Tripole temperature difference, north minus south

ψ_g Intergyre gyre strength (IGG, positive clockwise)

N Tripole surface heat flux noise difference, north minus south

λ Damping parameter

g IGG heat storage tendency parameter (CM01 assume >0)

α $=1/(\rho c H)$ with heat budget interpretation, effective depth *H*

$$\frac{d\Delta T}{dt} = -\lambda \Delta T + \alpha N + g\psi_g$$

Hasselmann model + Ocean dynamics

Simple Model II

$$\tau = \gamma N - f' \Delta T$$

τ Tripole wind stress difference, north minus south

γ Relates tripole wind stress to surface heat flux (<0)

f' Feedback factor for tripole on wind stress, >0 when the feedback heat flux is >0.

$$\psi_g = a \int_{t-t_d}^{t} \tau dt \approx -f \Delta T (t - \frac{t_d}{2})$$

t_d Delay time for wind stress to set up the IGG, related to Rossby wave propagation

Simple Model III

$$\frac{d\Delta T}{dt} = -\lambda \Delta T - fg\Delta T(t - \frac{t_d}{2}) + \alpha N \quad \textbf{(2)}$$

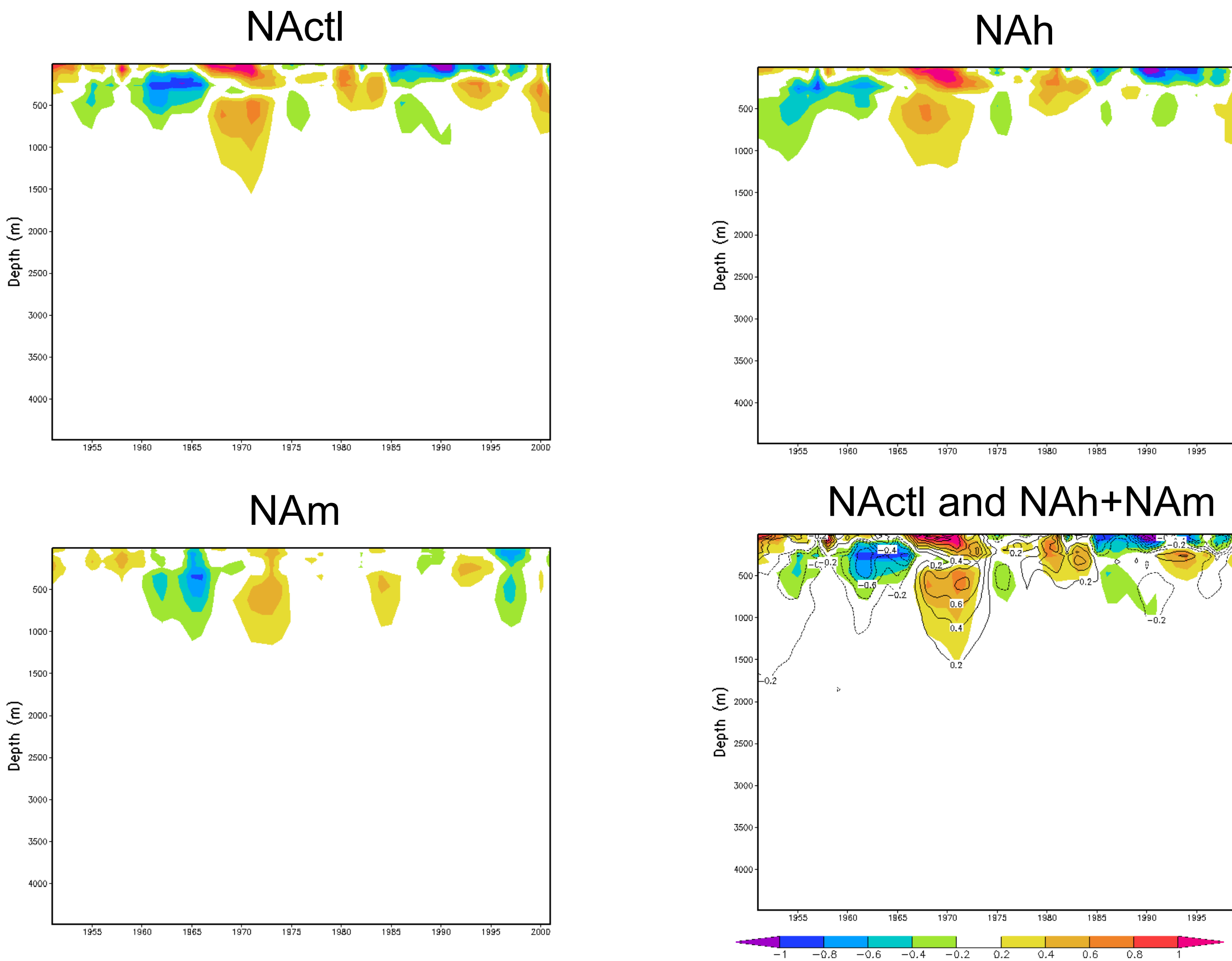
- Stochastically forced delayed oscillator equation.
  - If N=0, properties governed by the parameter ***R = fg/λ***
    - $R < 0$ solutions are damped, non-oscillatory
    - R > 0 solutions are oscillatory
      - ○ $R < R_0$ decaying ($1<R_0<\pi$)
      - ○ $R > R_0$ growing

Simple Model Parameter Estimation and Results

- With the heat budget interpretation, we can now determine the parameters λ, f, g, H, t_d from the properties of the numerical simulations.

- Use the simple model to estimate the predictability of the tripole.
  - ❖ Annual mean data averaged over the calendar year.

Vertical Structure of Annual Mean Tripole T: *H* ≈ *500 m*



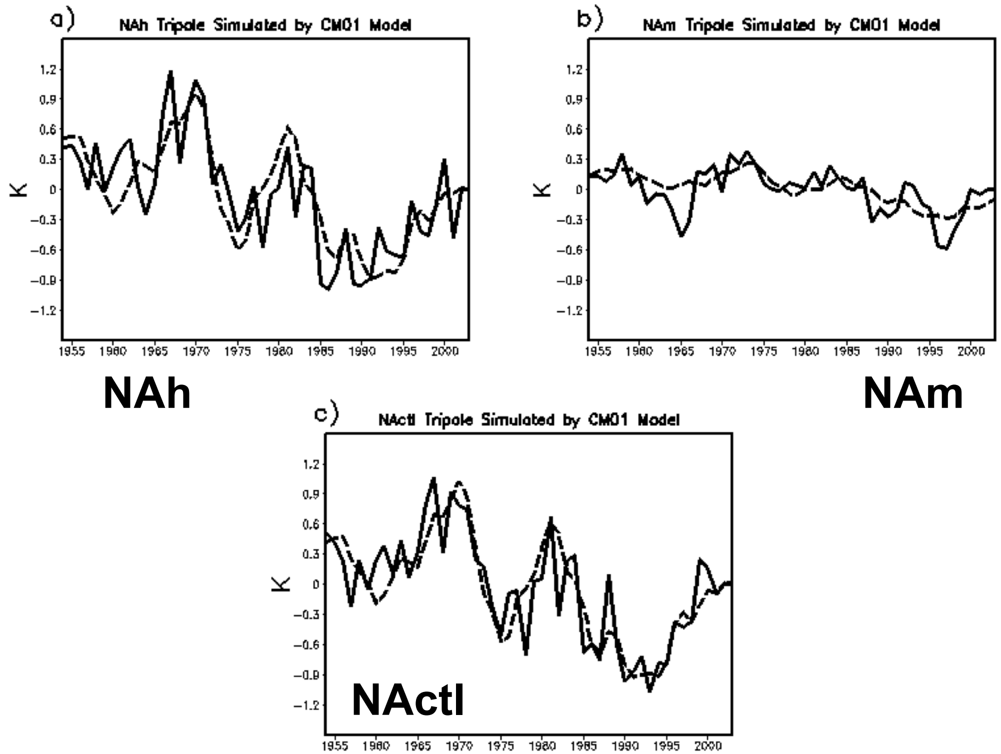
Fit Parameters

- Define gyre index for IGG
  - Use the barotropic stream function from NAh (noise heat flux forcing only), averaged over a box between the two tripole boxes.
- Do lag regression of ΔT against gyre index.
  - $t_d/2$ = 3-4 years
  - f = -3 K Sv^{-1}
    - Implies negative heat flux feedback on tripole SSTA

- ***R = 0.48***
  - *0<R<1* implies the unforced solutions are damped oscillatory
- ***g = -0.054 K Sv*** $^{-1}$***yr*** $^{-1}$
  - So *g<0,* while CM01 assert g>0 is a given
  - Therefore counter-clockwise IGG increases tripole ΔT

Simple Model (eq. 3) Verification

- Force with observed heat flux noise
- Use initial conditions 1950-1953, observed noise

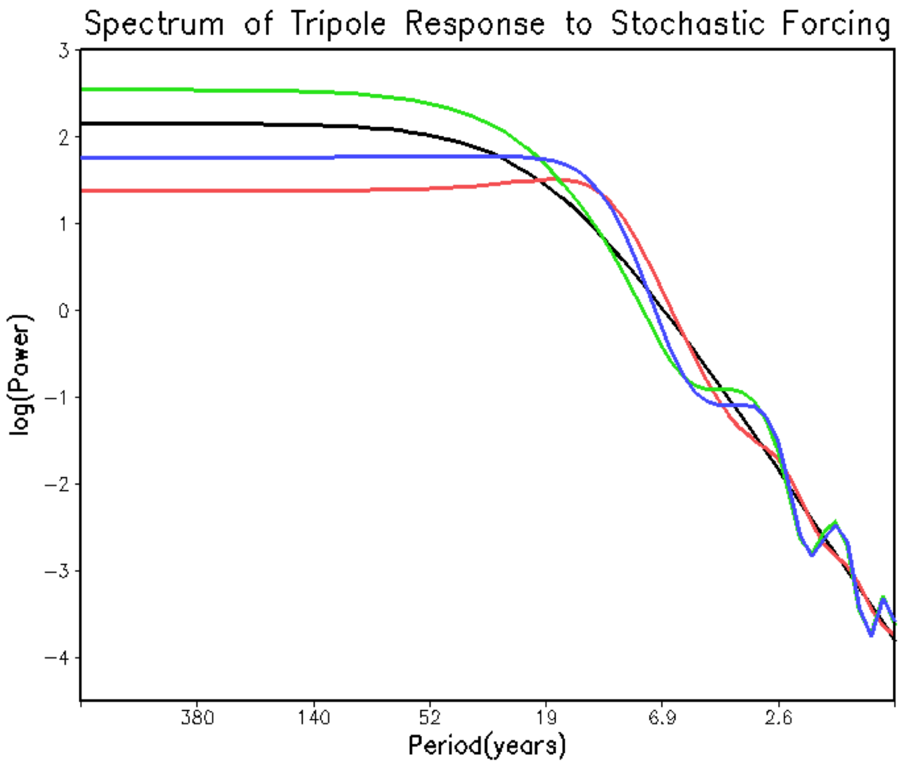


Simulation

Simple model solution

Power Spectrum of Response to Stochastic Forcing

- **Black: Hasselmann**
- **Blue: full model**
- **Red: feedback wind stress only**
- **Green: noise wind stress only**



Implications for Predictability

- Tripole is weather noise forced, but the weather noise can't be predicted.
  - Therefore weather noise destroys predictability.
  - Predictability arises from accuracy of the initial state, realism of the model feedbacks.
  - Hypothesis: the best model to make predictions is the interactive ensemble with weather noise forcing = 0, best ocean initial state.

Example: Retrospective Predictions with Simple Model (Hindcasts)

$$\frac{d\Delta T}{dt} = -\lambda \Delta T - fg\Delta T(t - \frac{t_d}{2}) + \alpha N$$

- Set heat flux noise to zero

- NAh initial conditions
  - Need ΔT for 3, 2, and 1 years before initial time
  - Initial growth possible, but turns out not to play an important role

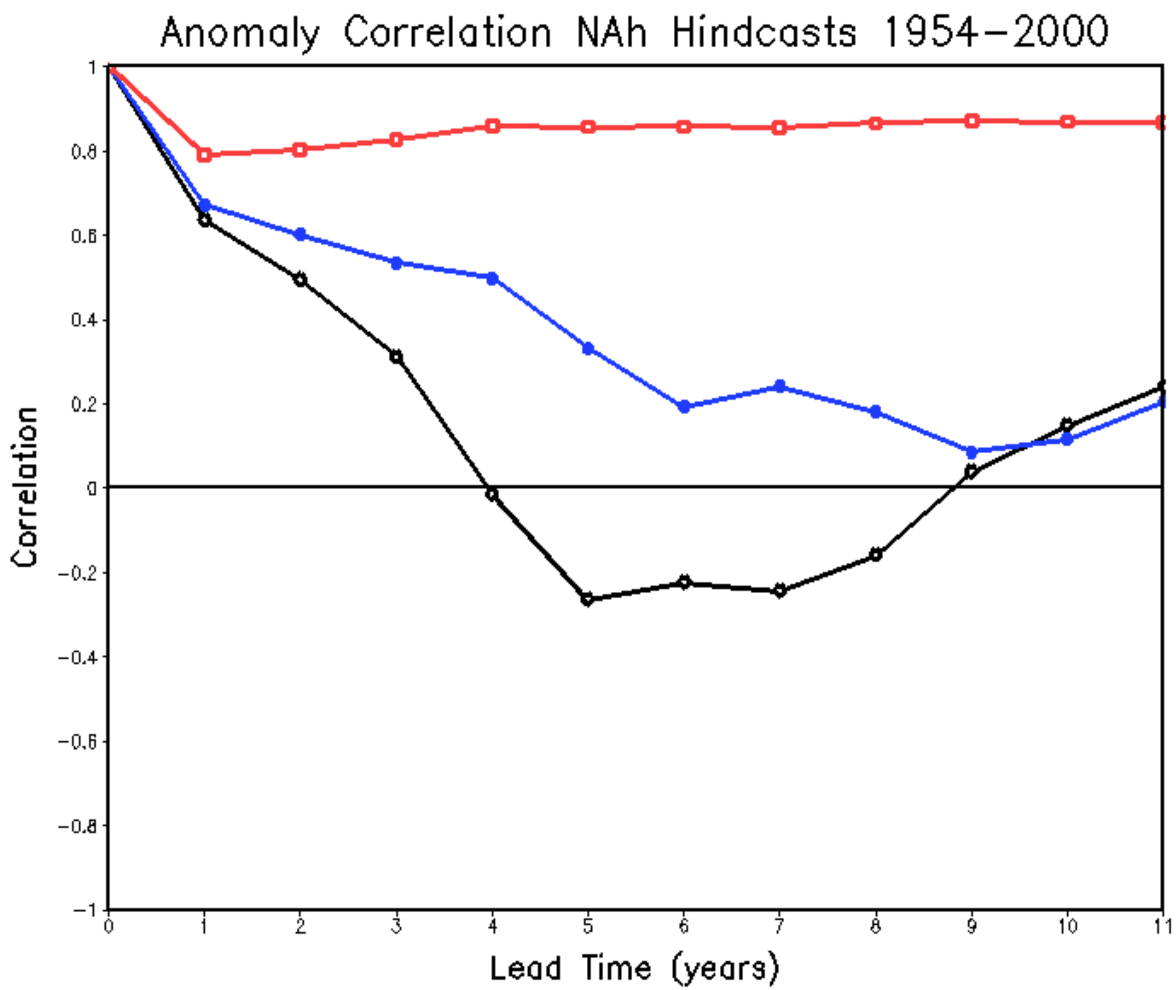
- 12 year predictions starting each year 1954-1999
- Verified against NAh ΔT

Hindcast Verification Simple Model

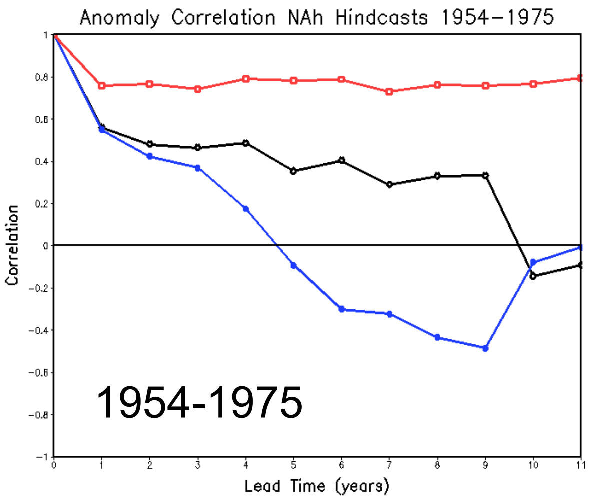
Hindcasts

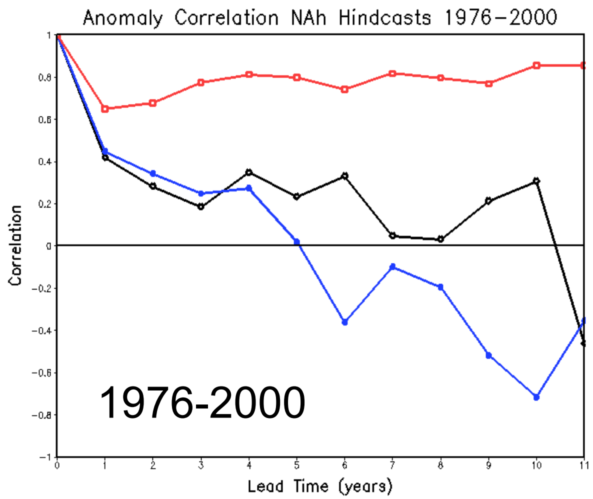
Persistence

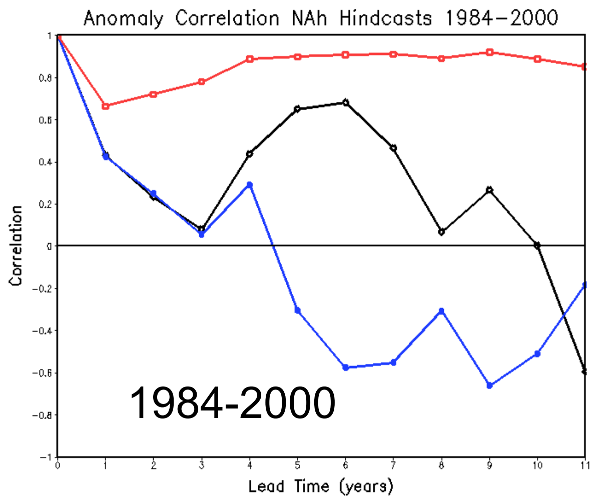
Simulation



Subperiods





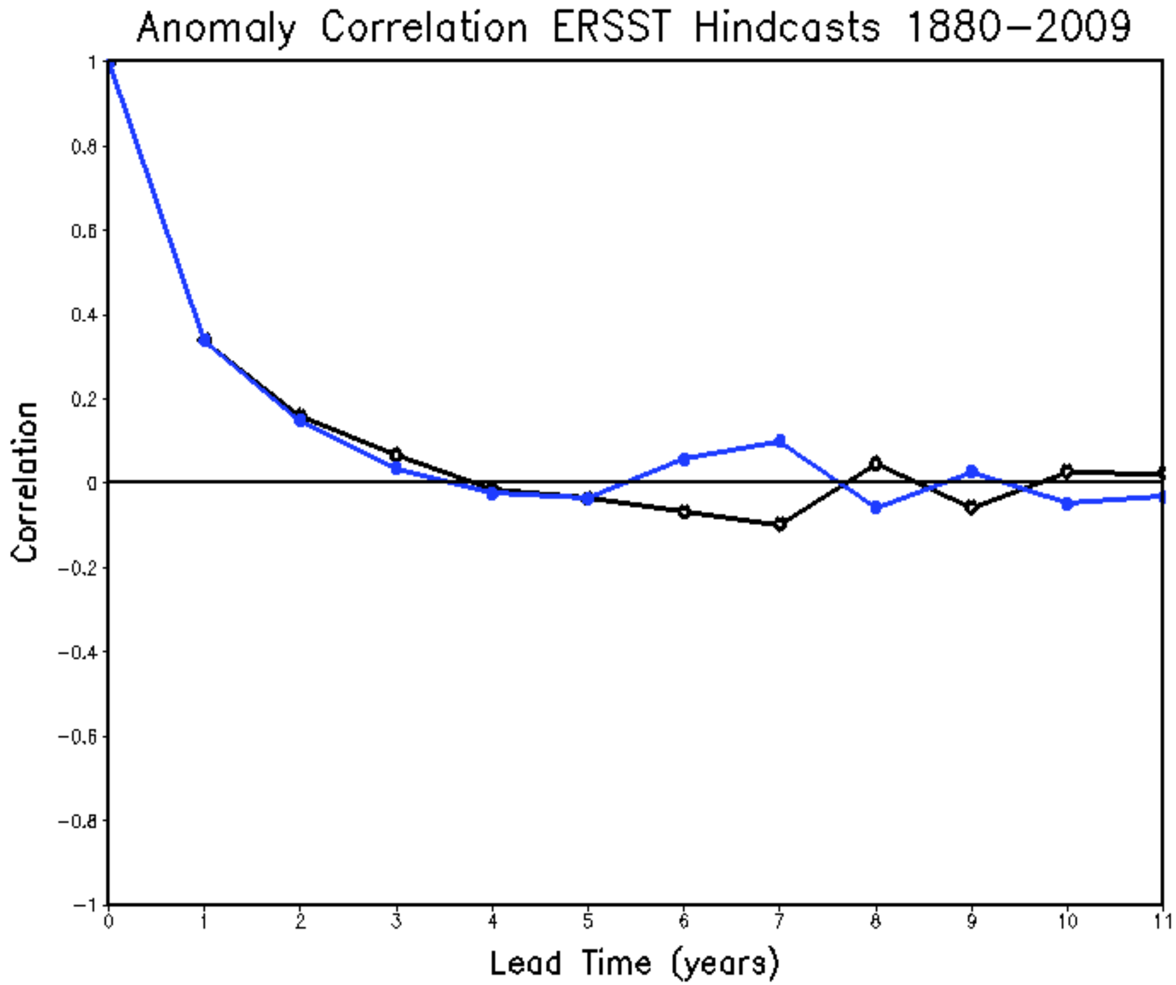


Hindcasts

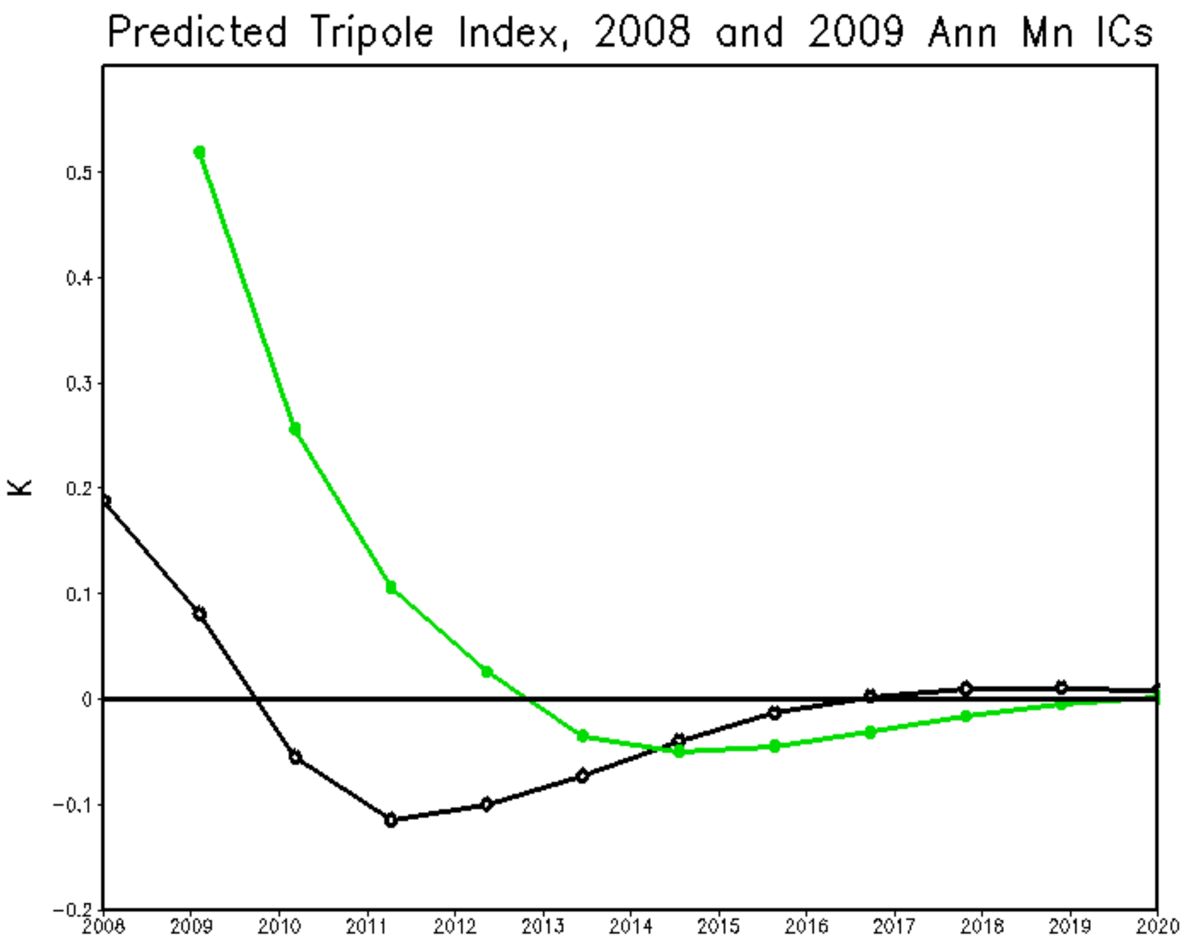
Persistence

Simulation

Hindcasts from 1880-2009 ERSST Initial Conditions



Tripole *ΔT* Predictions from 2008 and 2009 ICs

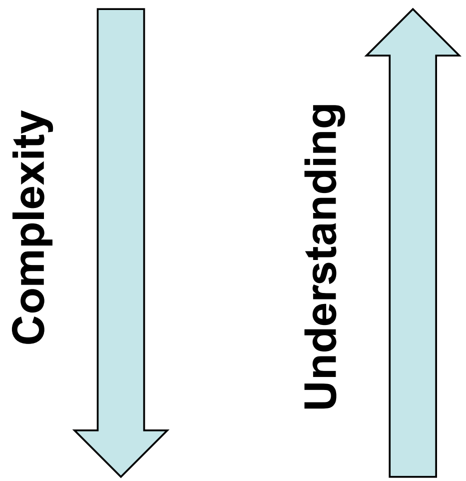


COLA Model Diagnosis of the Observed North Atlantic SST Variability

- The reconstructed later 20th century North Atlantic tripole SST variability is predominantly forced by the local weather noise.
- In the context of the simple model of Czaja and Marshall (2001), the tripole is in a damped oscillatory regime, even though the atmospheric heat flux feedback to the tripole is negative, because the intergyre gyre carries heat in the opposite direction from that found/assumed in other studies.
- A decadal peak in the spectrum should result from the simple model with $R>0$ forced by white noise (Czaja and Marshall 2001).
- The simple model indicates no decadal predictability of the tripole variability.

Hierarchy of Models

- CGCM or reanalysis
- Intermediate Coupled model
- AGCM ensemble
- Czaja/Marshall model
- Barsugli Battisti model
- Hasselmann model



For Additional Details

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