Simulating the Actual Climate of the 20th Century with a Coupled GCM

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Abstract

A method has been developed which can be used to retrospectively simulate and understand the evolution of surface temperature using reanalysis surface fluxes and a coupled GCM. The method has two parts: 1) weather noise surface fluxes are extracted from the reanalysis surface fluxes by removing the ensemble mean response of an AGCM ensemble to the observed surface temperature evolution; 2) an interactive ensemble (IE) CGCM (an ensemble of atmospheric models coupled to a single OGCM) is then forced by this noise. The IE CGCM will reproduce the observed surface temperature evolution up to errors in the model, the reanalysis surface fluxes, and the ocean initial state given certain conditions. These conditions are that there is no internal ocean "weather noise" or coupled instabilities. External forcing must also be taken into account properly.

The method is illustrated in the perfect model/perfect data context of the Barsugli and Battisti (2000) simple model and with synthetic observations from a CGCM simulation. It is then illustrated using forcing data from the NCEP reanalysis 1951-2000.

Introduction

- The simplest theory of internal climate variability is the Hasselmann (1976) analogy to Brownian motion.
  - White noise (weather noise) forces an integrator (ocean) to produce red noise (e.g. in SST)
- Barsugli and Battisti (1998) explored the implications of this theory in the context of a simple coupled model (slab atmosphere forced by noise+ slab atmosphere)
- Using some new tools and procedures we can now examine how this theory relates to CGCMs and the real climate system

Plan of Talk

- Describe technique/procedures
- Present applications
  - Simple model, reanalysis data
  - CGCM perfect model/perfect data
  - CGCM, reanalysis data

For Additional Details

- Schneider, E. K., 2006: Stochastic forcing of surface climate. COLA Technical Report 224, 34 pp. ftp://grads.iges.org/pub/ctr/ctr_224.pdf

- Schneider, E. K. and M. Fan, 2007: Weather noise forcing of surface climate variability. *J. Atmos. Sci.*, in press. ftp://grads.iges.org/pub/schneider/Noise%20forced%20IE%20paper/Schneider%20JAS%202244%202nd%20revision.doc

A New Way to Diagnose Climate Variability

- Simulate observed past climate evolution event-by-event using a CGCM-class model with full coupled feedbacks.
- Carry out additional experiments with this model to understand the mechanisms of the low frequency climate variability and to attribute cause and effect to each event.

What Hasn't This Been Done?

- CGCMs are sensitive to initial conditions
  - Two CGCM simulations started from slightly different initial conditions will diverge and give different evolutions of climate events.
  - Results are not reproducible from model to model, computer to computer, etc.
- A primary reason for the sensitivity is the chaotic, unpredictable, irreproducible nature of weather noise.
  - To reproduce past climate with a CGCM requires the weather noise to be controlled. This is impossible with a realistic atmospheric model.

Simlation of Climate Variability with a CGCM

- Assuming perfectly known external forcing, a CGCM can simulate certain climate statistics, but not the actual event-by-event climate evolution, because of intrinsically chaotic components of the climate system:

1. Atmospheric weather
2. Oceanic internal variability ("oceanic weather noise")
3. Coupled low frequency atmosphere-ocean variability
4. Other?

A Short History of Climate Modelling (1998-present)

- Much can be learned about both models and the real climate system from ensembles of AGCM+land simulations forced by observed SST boundary conditions (AMIP or C20C simulations), because the results of these simulations can be compared event by event with what actually happened.
  - Ensemble means are interpreted as the atmospheric response to the SST forcing.
  - Response is deterministic.
  - Weather noise is filtered out.

Another Interpretation of AMIP/C20C

- The AGCM ensemble provides an algorithmic parameterization of the eddy fluxes in the equations of motion.
  - As in closed form parameterizations (Green, Stone, …)
  - However, no closure assumptions, potentially exact for infinite ensemble size
  - Potentially infinitely more expensive than closed form
- Deterministic, noise free nonlinear mapping of the SST evolution to the atmospheric state and fluxes

New Tool: Interactive Ensemble CGCM (IE CGCM; B. Kirtman)

- Couple an OGCM to a parameterized atmospheric model, as in an ICM (Intermediate Coupled Model)
  - The parameterized atmosphere is an AGCM ensemble,
    - The ocean sees the AGCM ensemble mean surface fluxes.
    - Each AGCM ensemble member sees the OGCM SST.

Properties of IE CGCM

1. Atmospheric weather noise filtered out
2. Internal variability is due to only ocean weather noise, coupled instability
   – Potentially much reduced low frequency variability
3. Response to external/applied forcing will be deterministic (except for [2] and finite AGCM ensemble size)
4. Includes full coupled feedbacks calculated from state-of-the-art parameterizations

Procedure to Reproduce Observed Surface Temperature Variability

- Force the IE CGCM with the weather noise in the observed surface fluxes.
  - Heat
  - Momentum
  - Moisture
- Since the IE CGCM response to forcing is deterministic, the solution will not be sensitive initial state (with provisos).
- If the weather noise is suitably defined, the observed surface temperature variability will be recovered (for ocean, land, sea ice).

Weather Noise

- It can be thought of as chaotic, random, unpredictable, etc. and parameterized as a noise process.
- In terms of diagnosis of prior climate evolution, the weather noise is part of what has already happened and is fixed (think of a single realization of a noise process).

Determining Weather Noise Surface Fluxes

$$Total = Noise + Feedback$$

- Consistent with Barsugli and Battisti model, Bretherton and Battisti (2000) interpretation of AMIP simulations
- ***Total*** surface fluxes are observed or can be inferred from observations (e.g. reanalysis)
- ***Feedback*** surface fluxes are the response of an AGCM ensemble mean to the observed surface boundary condition evolution
  - Extended AMIP ensemble with *all* surface boundary conditions specified as observed: ocean, land, sea ice, not just SST
- ***Noise*** can then be calculated as a residual

Theoretical Justification

- It can be proved that this procedure will exactly reproduce the surface climate variability forced by a specific realization of noise in the BB model
- The theory can be extended to give the conditions under which a CGCM implementation will reproduce the observed climate variability

Summary of Procedure

1. **Input data**: evolution of surface boundary state, surface fluxes
2. Determine atmospheric feedback to observed boundary state evolution using an **atmospheric model**
   - Specified observed SST
   - Specified observed land and sea ice state (*)
   - Large ensemble starting from different ICs
3. Calculate **weather noise** surface fluxes as residual
4. Force interactive ensemble **coupled model** with weather noise surface fluxes

Implementation

- Data dependent
- Model dependent
  - Procedure can be done with coupled climate models of any complexity (box model, intermediate model, CGCM) or with combinations of models
- In order to interpret the results correctly, need to understand the sources of error in the data and the models

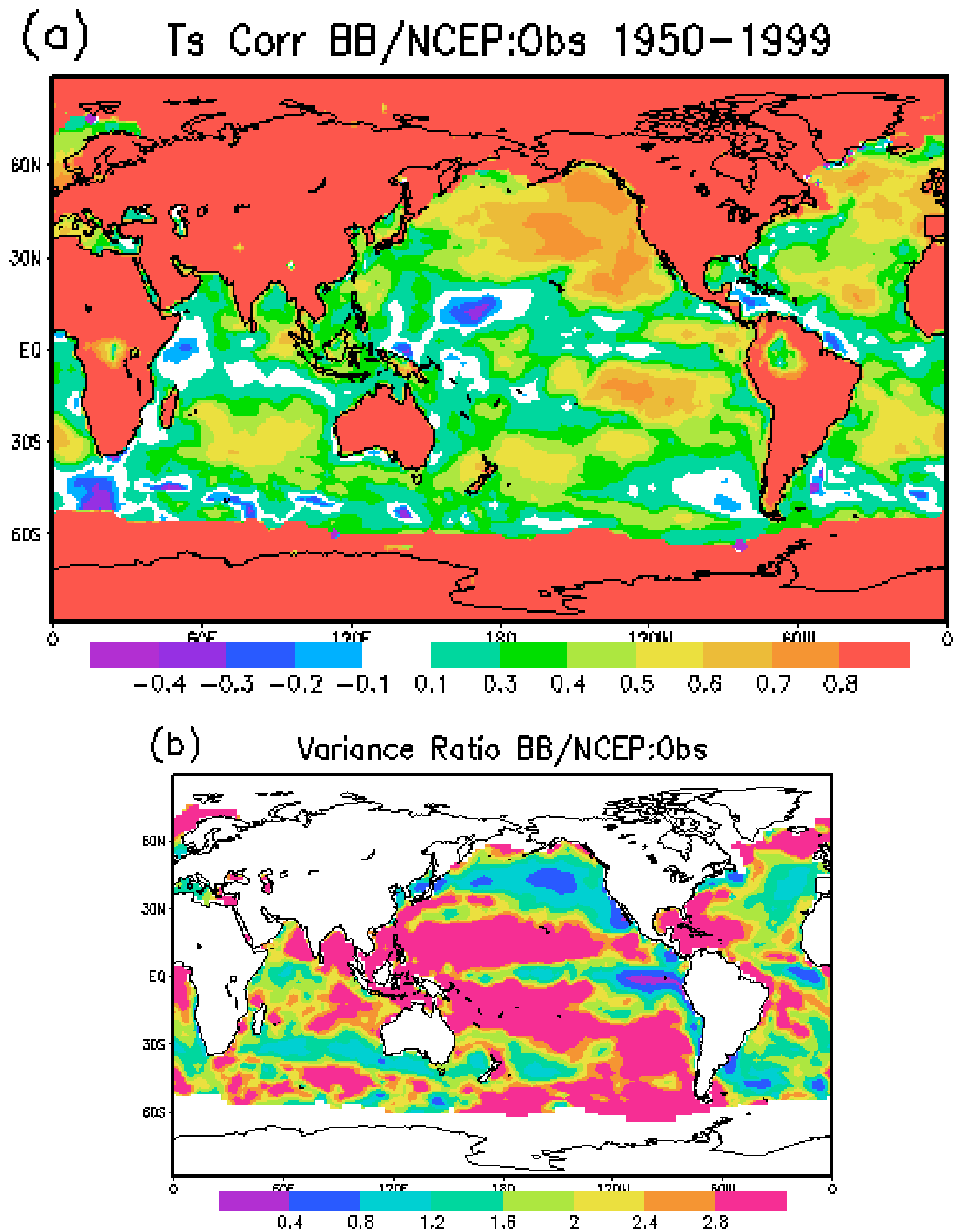
Example 1

- Barsugli and Battisti (1998) 0-D model
  - Apply point by point globally
  - 50m Slab ocean
  - 0m slab land
  - Couple to slab atmosphere
  - Total heat flux forcing from NCEP reanalysis 1951-2000

Barsugli-Battisti (Schopf?) Model

$$dT_a / dt = -aT_a + bT_o + N(t)$$

$$\beta \, dT_o / dt = cT_a - hT_o$$

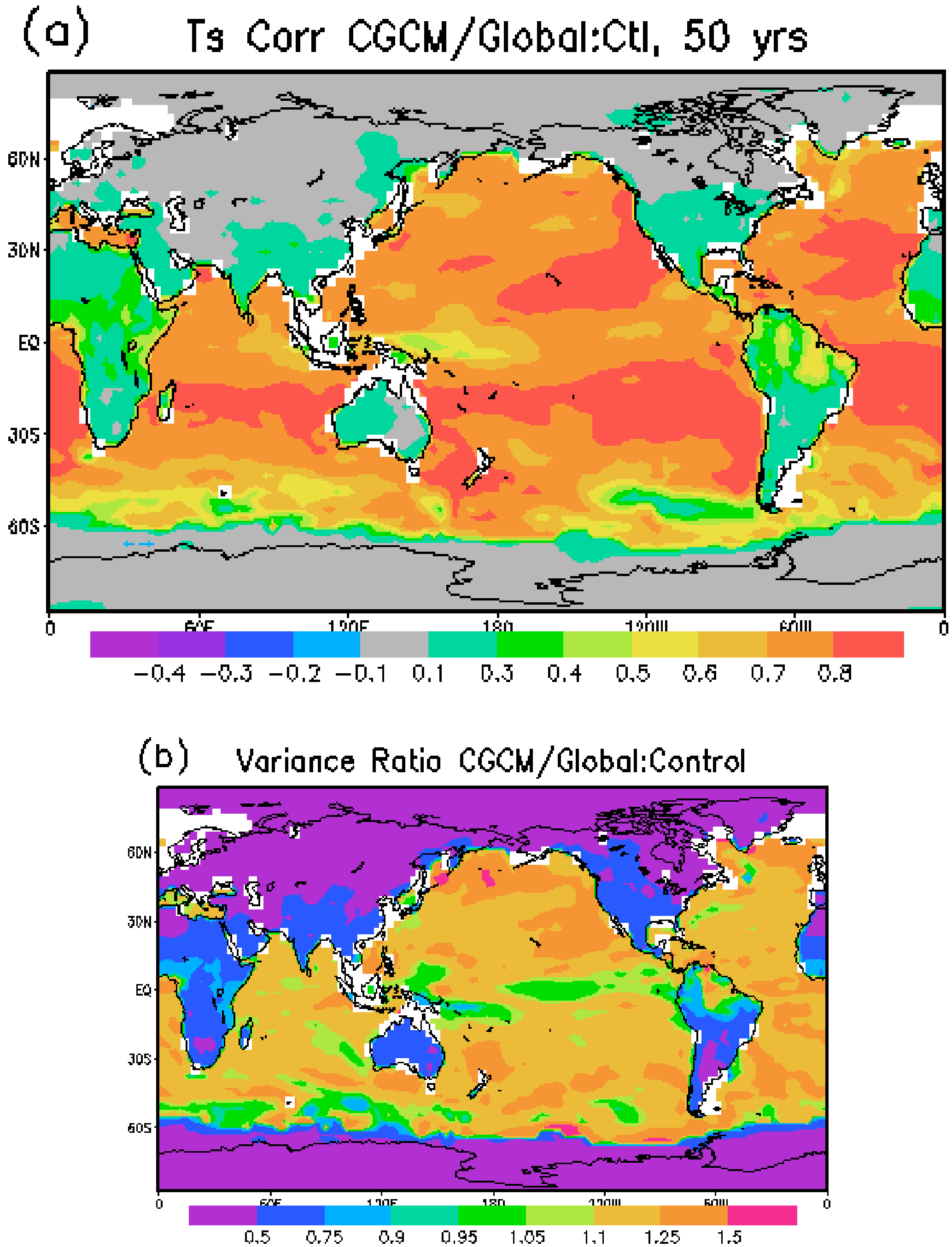

(a)
Ts Corr BB/NCEP:Obs 1950-1999
60N
30N
EQ
30S
60S
0
180
0
-0.4
-0.3
-0.2
-0.1
0.1
0.3
0.4
0.5
0.6
0.7
0.8
(b)
Variance Ratio BB/NCEP:Obs
60N
30N
EQ
30S
60S
0
180
0
0.4
0.8
1.2
1.6
2
2.4
2.8

Interpretation

- Could be errors in reanalysis fluxes
  - Inferred over ocean, not measured
  - Land surface temperature is a predicted quantity in reanalysis, so reproducing it is only a consistency check
  - No external forcing (GHG, etc.) in NCEP
- Poor diagnostic models
  - Atmospheric scale of influence is zero
  - No atmospheric teleconnections
  - No ocean dynamics
- Initial state of the ocean poor
- Despite all of this, reanalysis surface heat fluxes appear to contain some predictive information

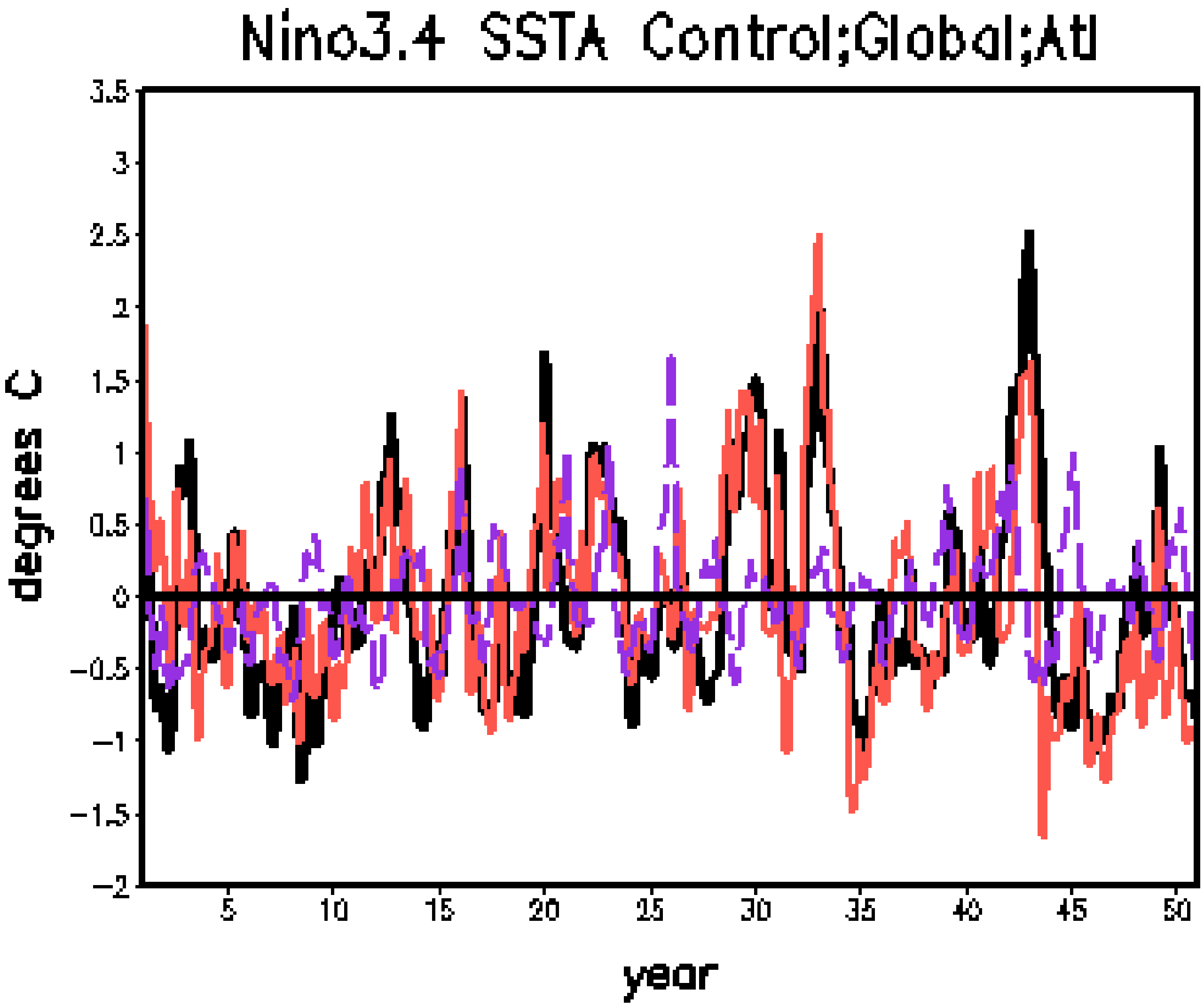
Example 2

- CGCM Perfect Model/Perfect Data
  - "Observations" are a 50 year control run of CGCM (COLA V2 AGCM coupled to MOM3 OGCM)
  - Feedback from 10 member ensemble of COLA V2 AGCM forced by 50 year evolution of "observed" SST (land free to vary)
  - Surface flux noise from observations minus feedback
  - Diagnostic simulation interactive ensemble version of CGCM (6 AGCMs coupled to 1 OGCM) forced by surface flux noise, "observed" ocean initial state

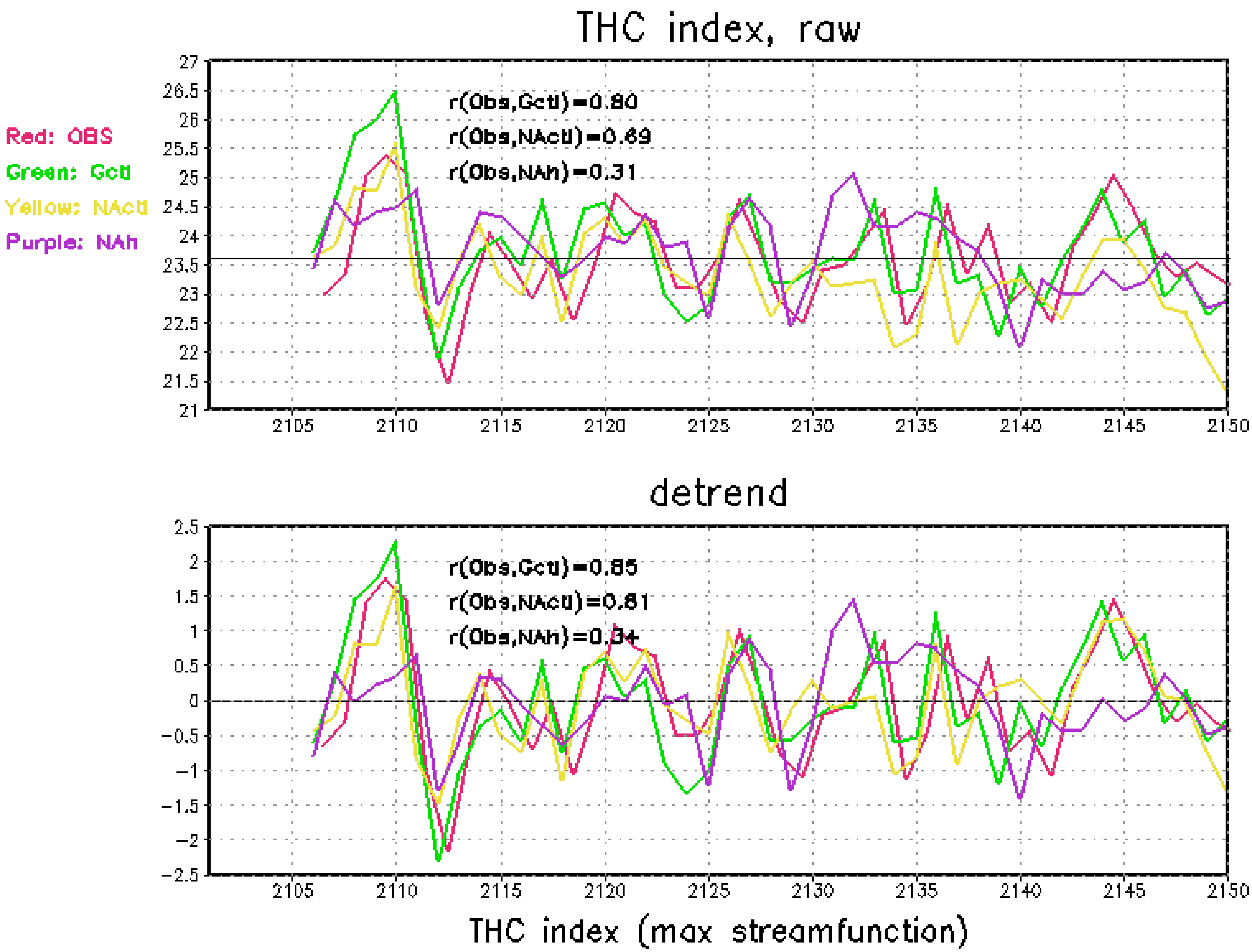

(a)
Ts Corr CGCM/Global:Ctl, 50 yrs
60N
30N
EQ
30S
60S
0
60E
120E
180
120W
60W
0
−0.4 −0.3 −0.2 −0.1 0.1 0.3 0.4 0.5 0.6 0.7 0.8
(b)
Variance Ratio CGCM/Global:Control
60N
30N
EQ
30S
60S
0
60E
120E
180
120W
60W
0
0.5 0.75 0.9 0.95 1.05 1.1 1.25 1.5

ENSO: NINO3.4 SSTA

Control, Global, and NAtl



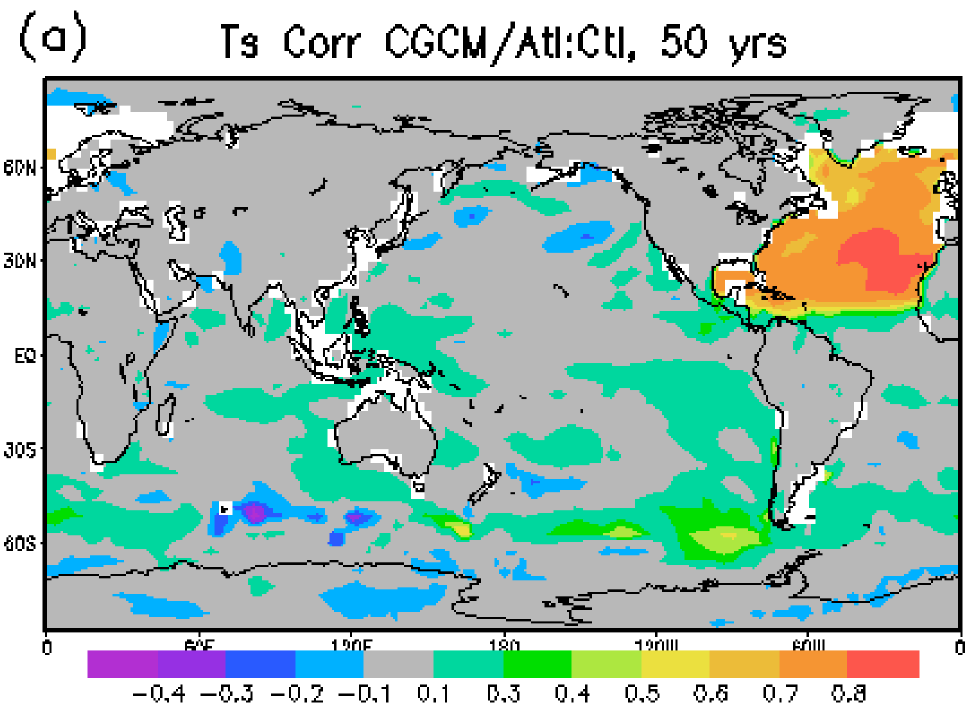
NA Thermohaline Circulation Index

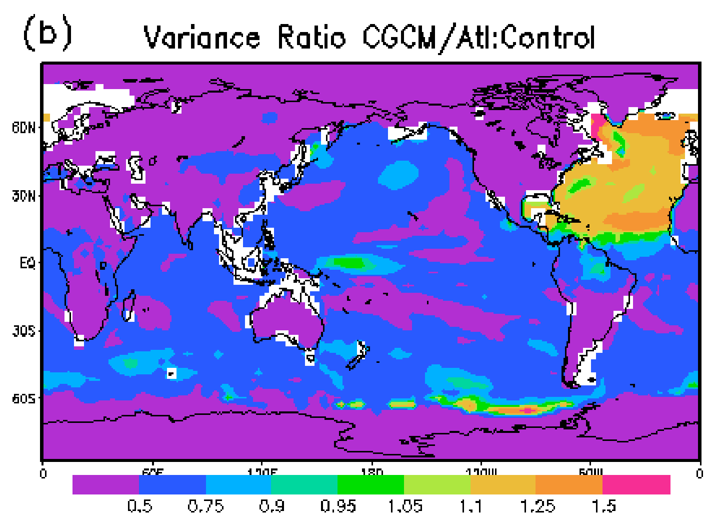


Why Regions of Lower/Higher Correlation?

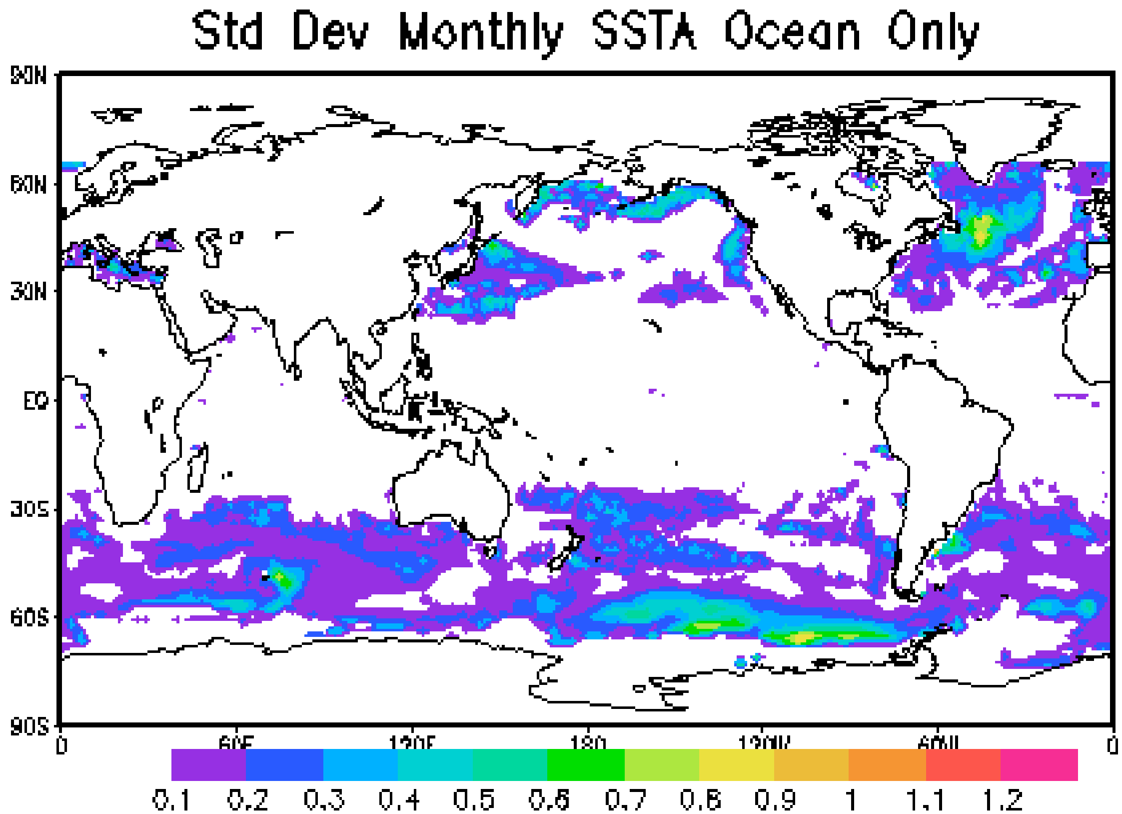
- In order to understand this, simulations are carried out with noise forcing restricted regionally or by process, and with simplified models
- Reasons for discrepancies
  - Intrinsic coupled variability in the W. Pacific
  - Ocean weather noise in higher latitudes
  - Land feedbacks not included correctly in calculation of noise
  - Other?

Noise Forcing in North Atlantic (15°-60°) Only

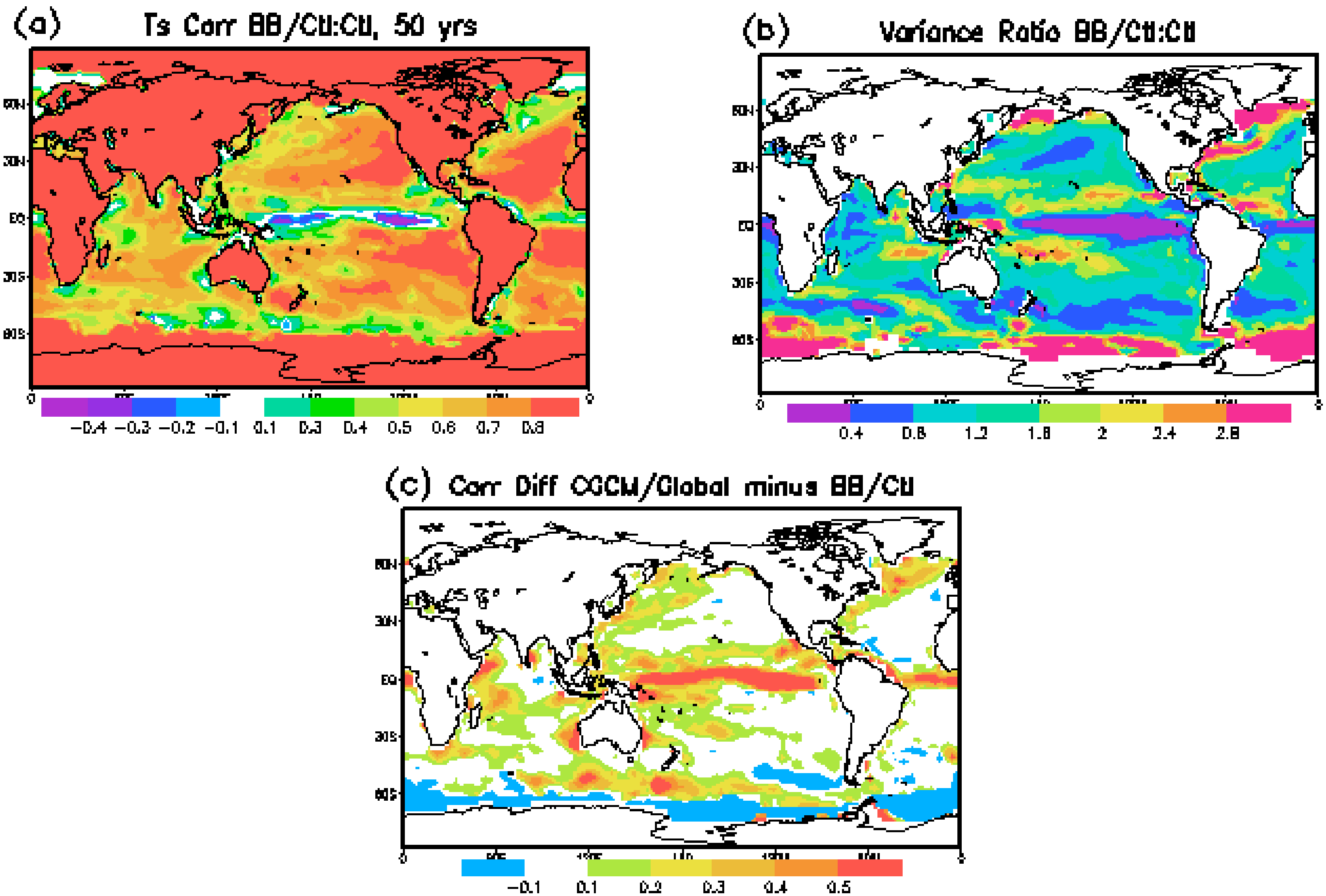




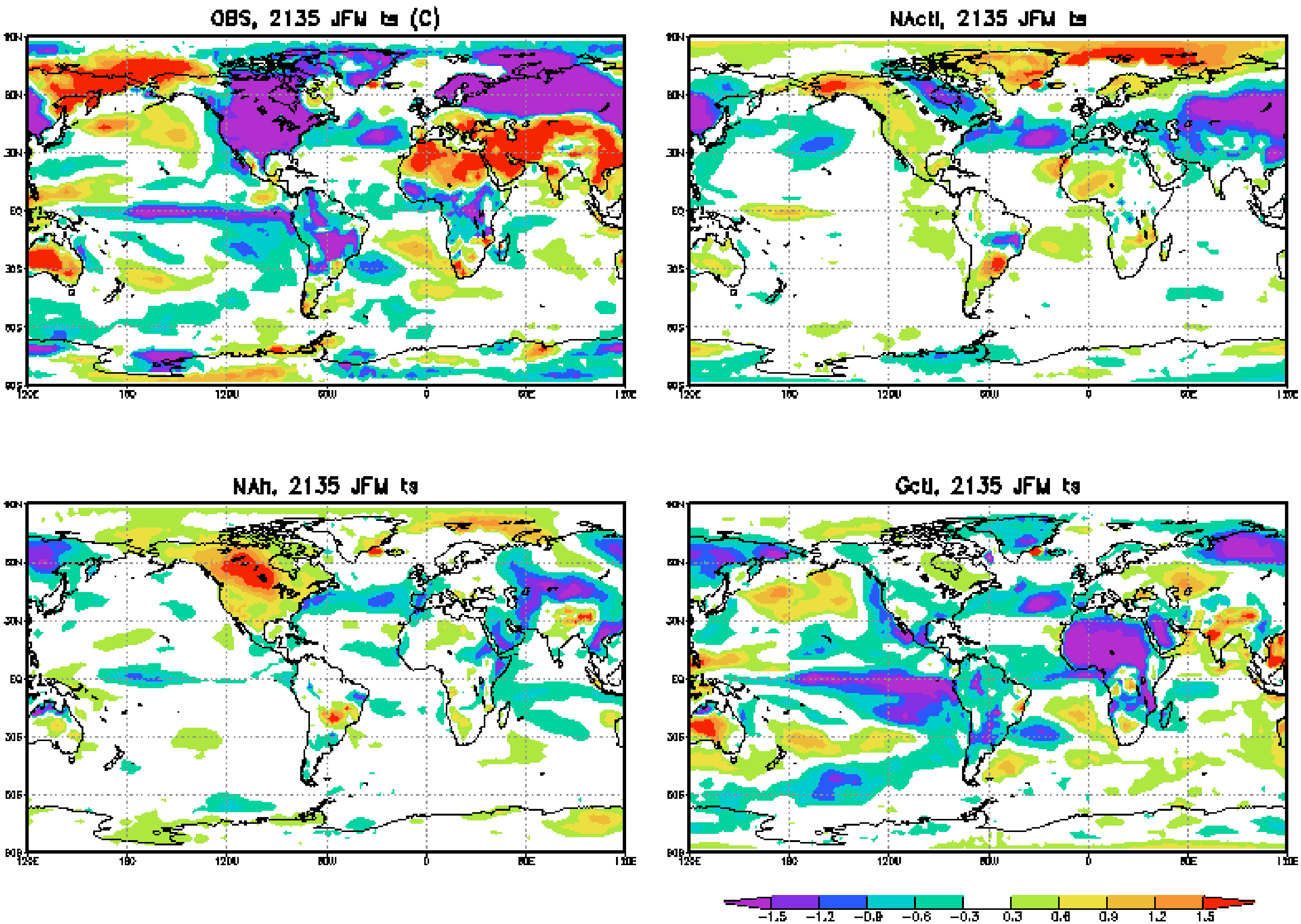
Ocean weather noise (OGCM with climatological forcing) forces SST variability in higher latitudes



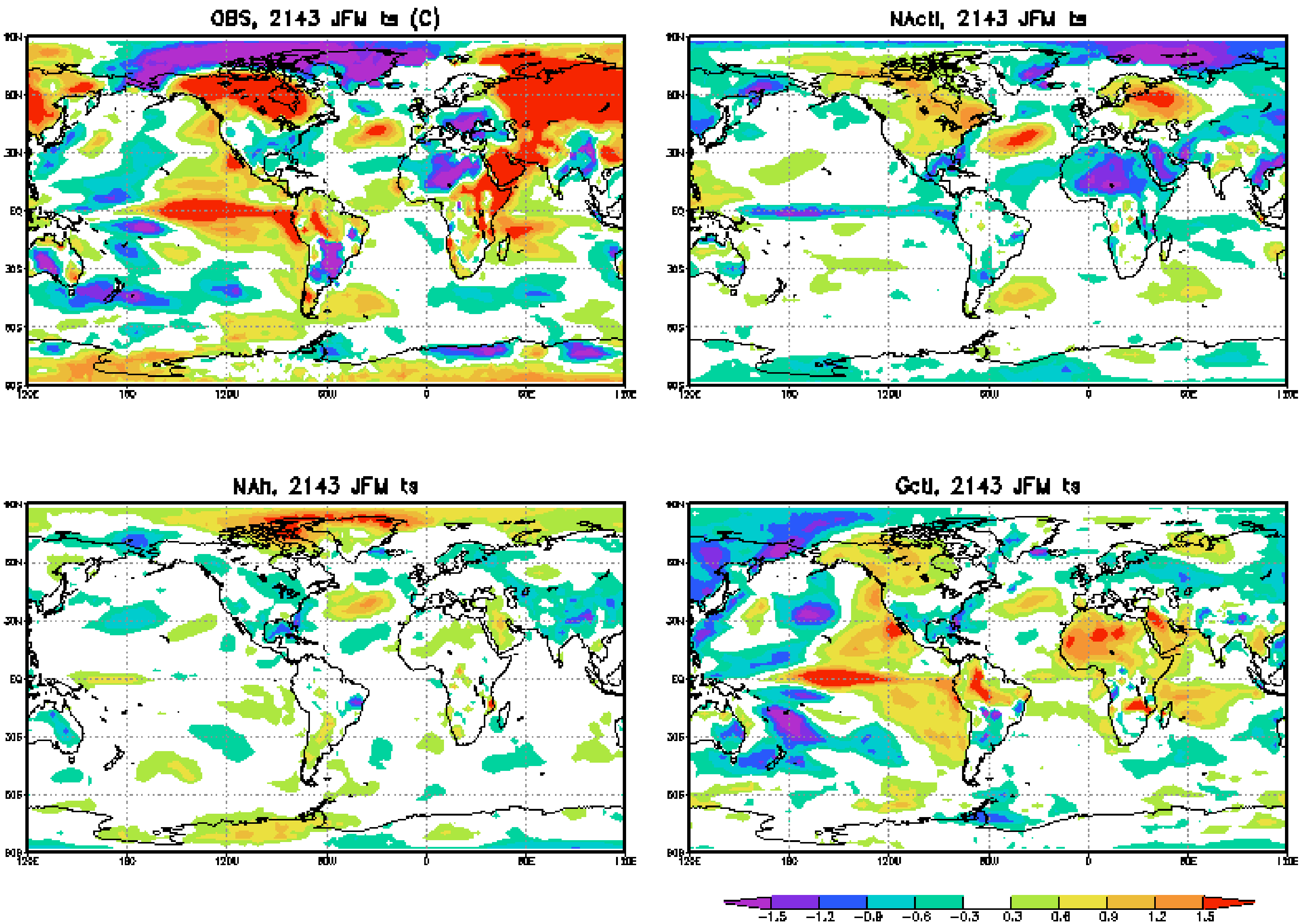
Diagnosis of CGCM Simulation Using BB Model



-NAO


OBS, 2135 JFM ts (C)
NActl, 2135 JFM ts
NAh, 2135 JFM ts
Gctl, 2135 JFM ts
90N
60N
30N
EQ
30S
60S
90S
120E
180
120W
60W
0
60E
120E
-1.5
-1.2
-0.9
-0.6
-0.3
0.3
0.6
0.9
1.2
1.5

+NAO


OBS, 2143 JFM ts (C)
NActl, 2143 JFM ts
NAh, 2143 JFM ts
Gctl, 2143 JFM ts
-1.5 -1.2 -0.9 -0.6 -0.3 0.3 0.6 0.9 1.2 1.5

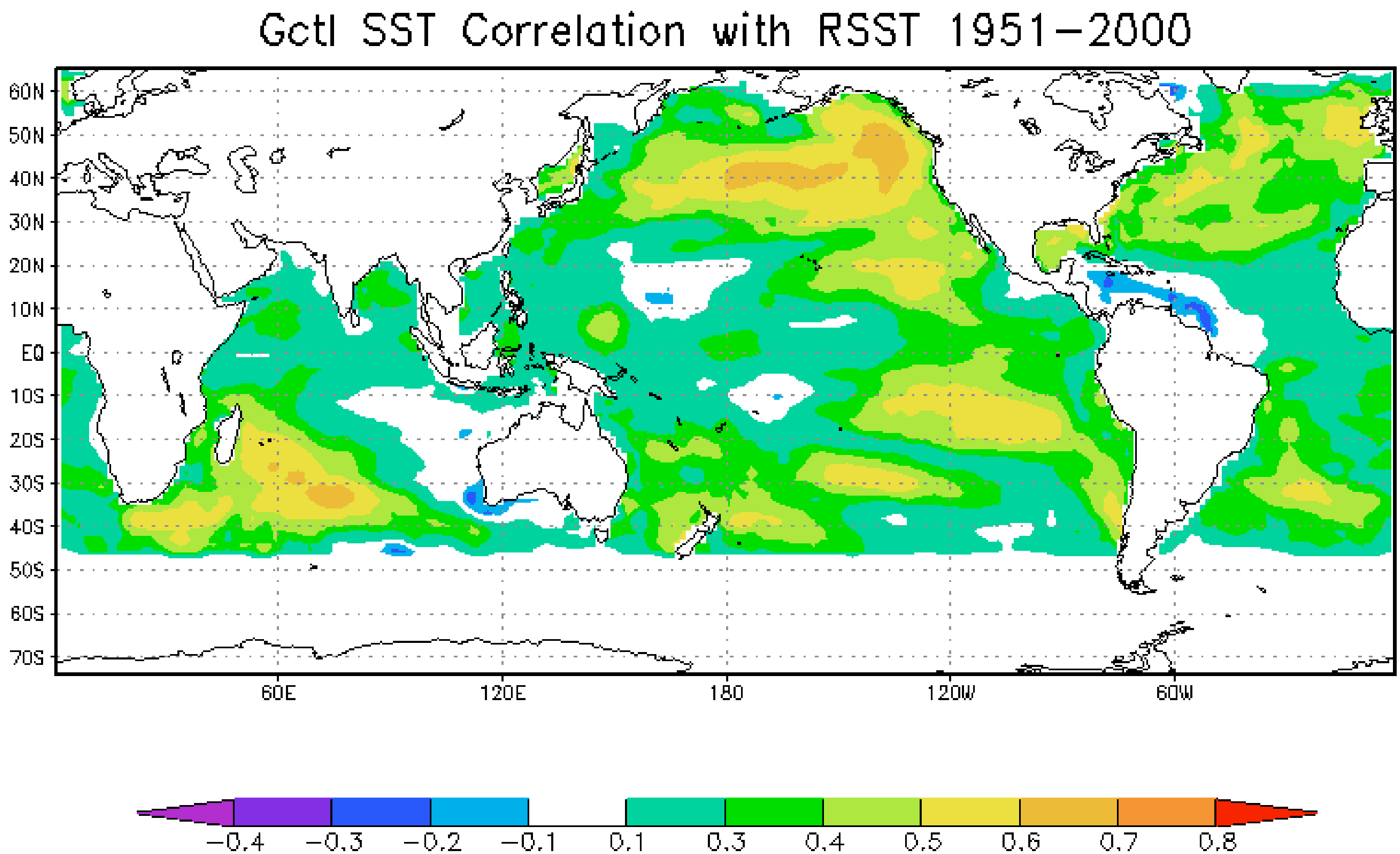
Interpretation

- Internal variability of SST in the COLA CGCM is primarily forced by atmospheric weather noise a la Hasselmann
- ENSO is marginally stable, but ENSO variability is forced by weather noise momentum flux
  - What does this imply about ENSO predictability?
- Ocean weather noise makes a significant contribution in certain regions

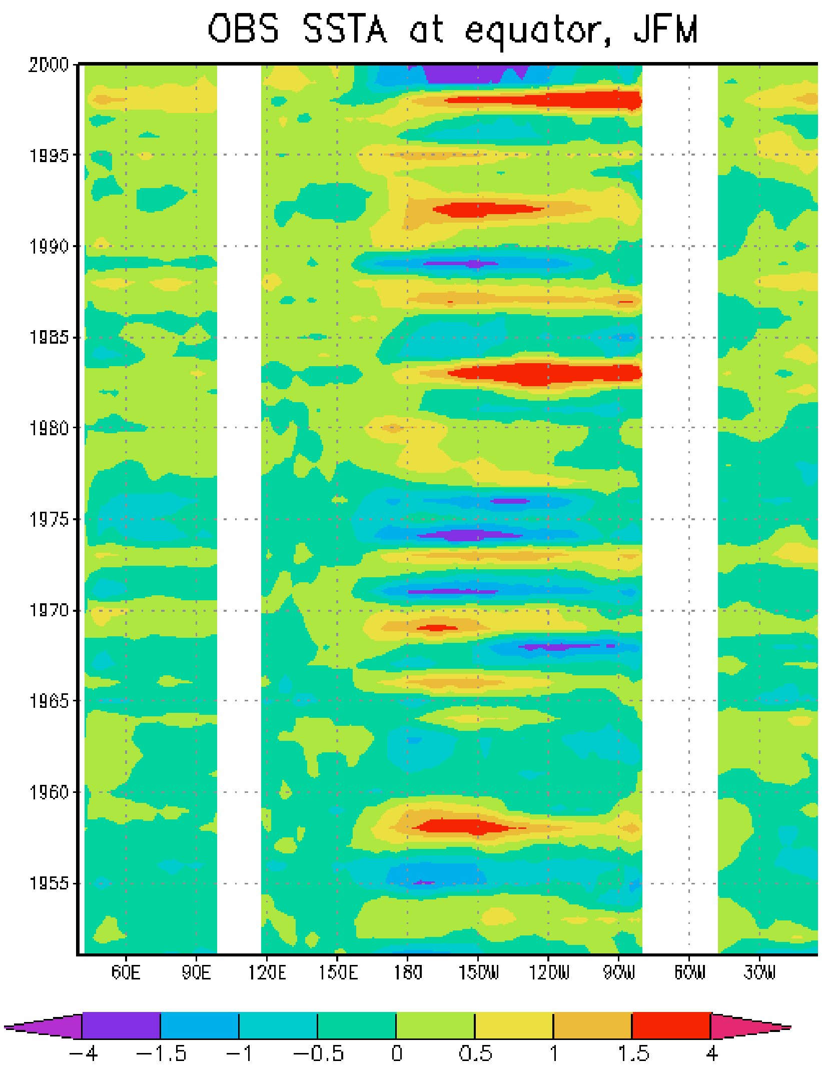
Example 3

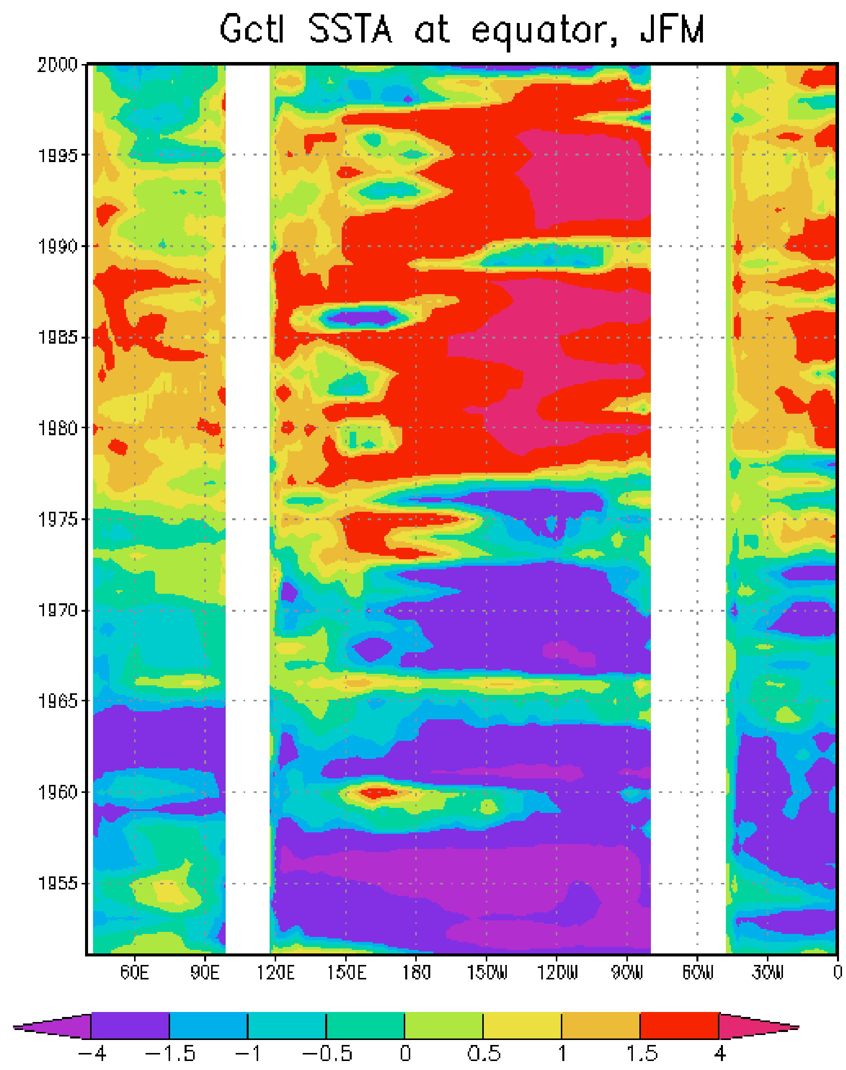
- NCEP reanalysis surface fluxes 1951-2000
- COLA AGCM and IE CGCM

Correlations Lower Than BB Model??



SSTA at Equator





Interpretation

- There is a huge jump in ~1976 in the simulated SST, but not in the observed
- This is degrading diagnostic results everywhere
- Possible sources of problem
  - Addition of satellite observations (data discontinuity)
  - NCEP reanalysis model does not include external forcing (e.g. GHG)
  - COLA AGCM does not include external forcing

Summary

- A new method to simulate and diagnose observed climate variability has been developed.
- It is the natural extension of previous techniques such as AMIP simulations, pacemaker experiments.
- It points the way to a complete understanding of observed climate variability, but requires at a minimum data that is sufficiently accurate and models that are sufficiently realistic.
- A pilot study has been done showing that the method, although computationally expensive, can produce interesting results.
- The results are telling us something interesting about the NCEP reanalysis, but we’re not sure what yet.