Multiscale Interactions and Hierarchical Modeling of Climate Variability

R. Saravanan

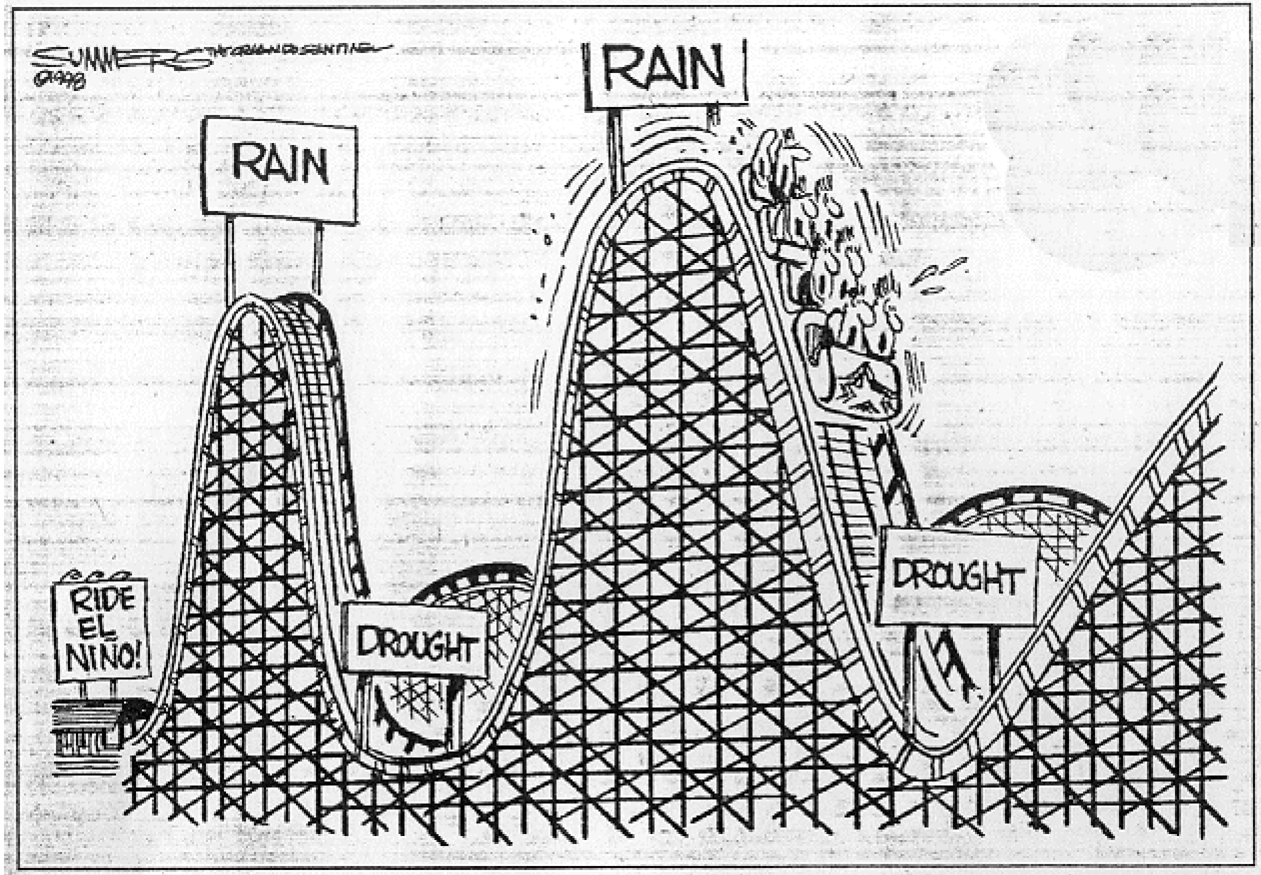
Texas A&M University

Questions

- **What role do multi-scale interactions play in climate variability?**
- **How can we study (and predict) climate variability using a hierarchy of models?**

- ***Strawman*****:** ***Are simple (and intermediate) models better than complex General Circulations Models?***
  - ***OR, When it is appropriate to use simple models?***

El Niño-Southern Oscillation



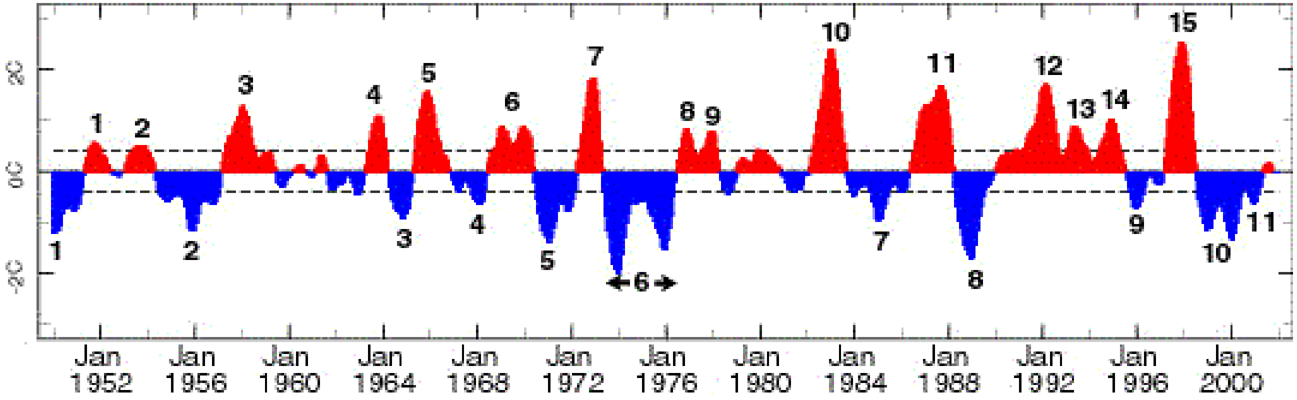
By Dana Summers, The Orlando (Fla.) Sentinel, Tribune Media Services

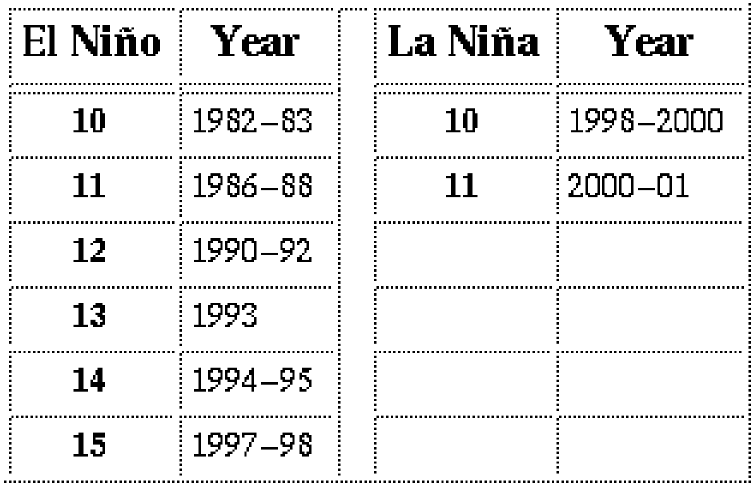
www.coaps.fsu.edu/lib/climatoons

COAPS

NINO 3.4 index

(Kaplan SST data set; base period 1951-1980)

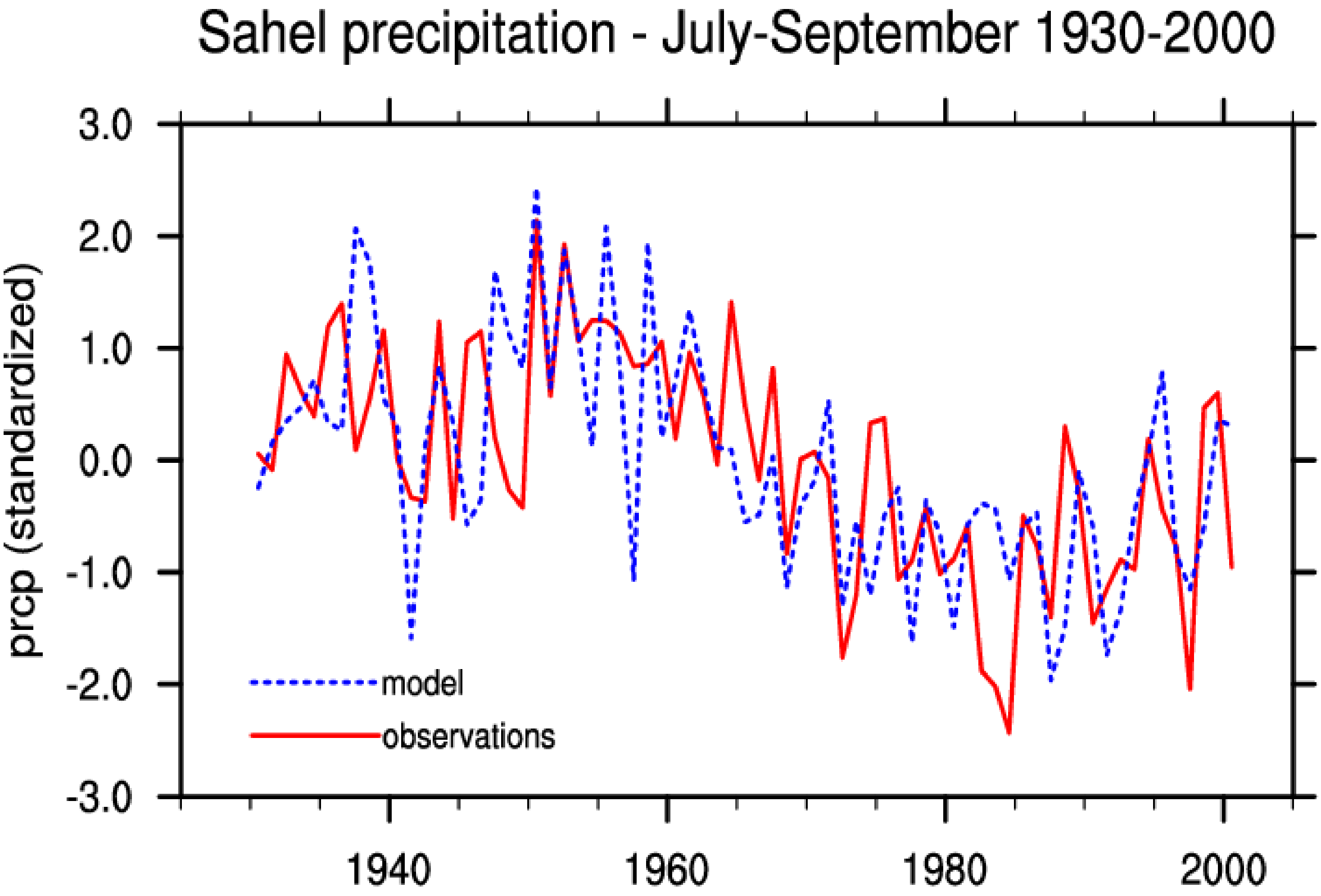




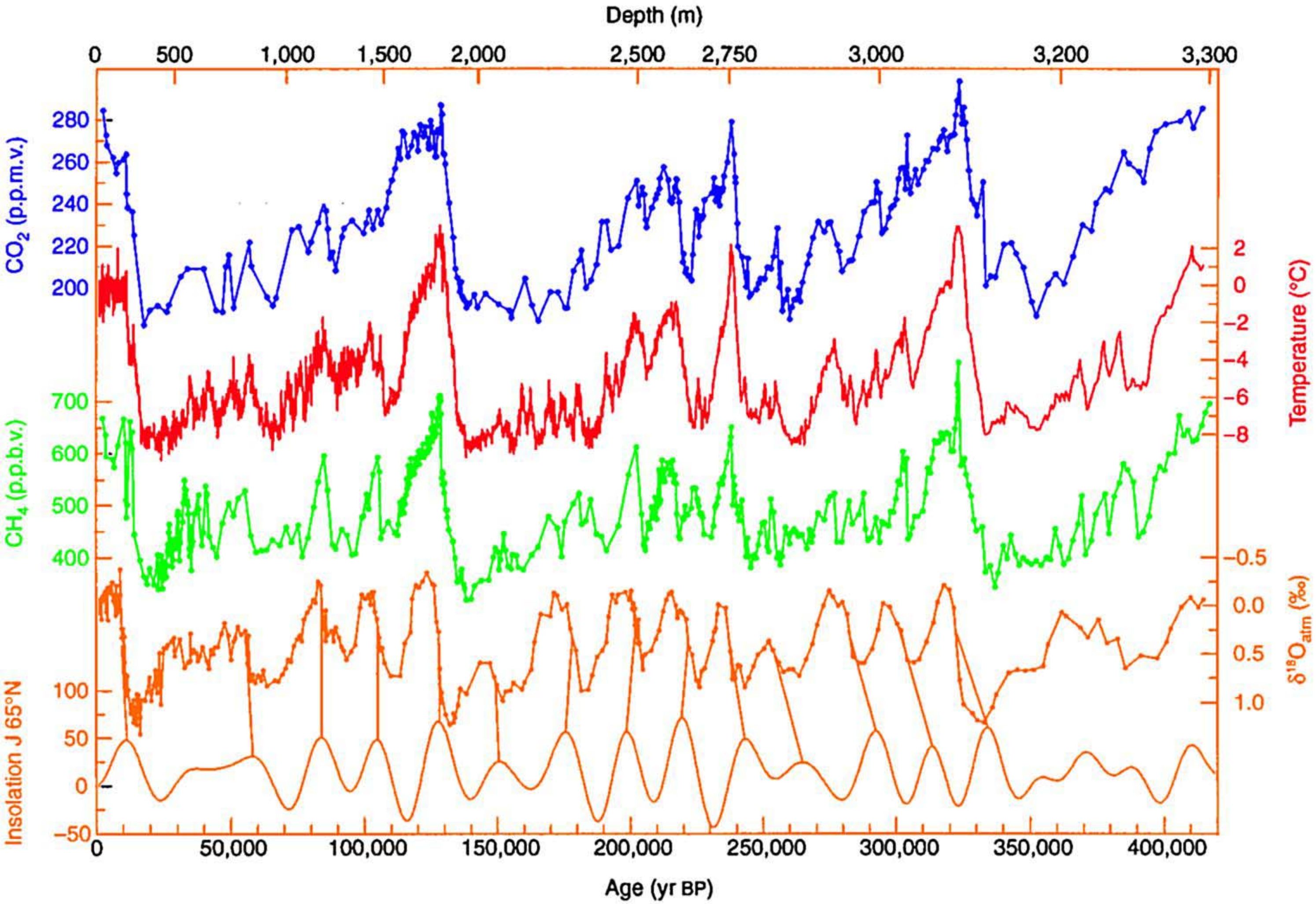
El Niño	Year	La Niña	Year
10	1982–83	10	1998–2000
11	1986–88	11	2000–01
12	1990–92		
13	1993		
14	1994–95		
15	1997–98		

Low frequency variability of Sahel Rainfall

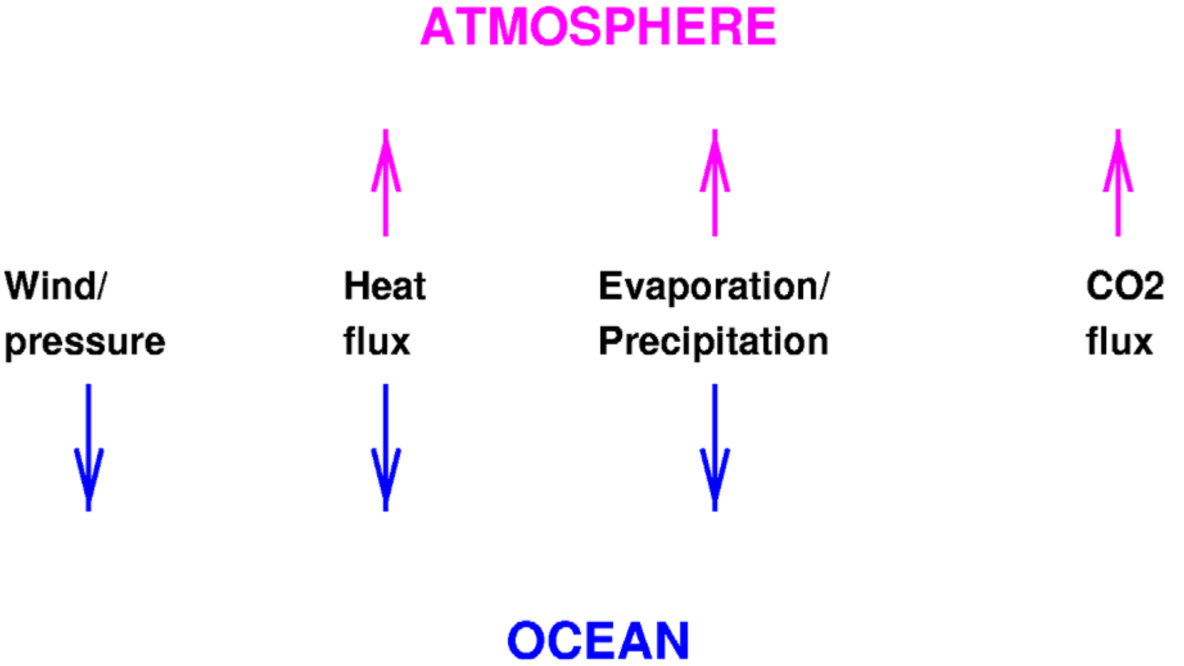
Giannini, Saravanan, and Chang (2003)



Vostok core


Depth (m)
0
500
1,000
1,500
2,000
2,500
2,750
3,000
3,200
3,300
CO$_2$ (p.p.m.v.)
280
260
240
220
200
Temperature (°C)
2
0
−2
−4
−6
−8
CH$_4$ (p.p.b.v.)
700
600
500
400
δ^{18}O$_{atm}$ (‰)
−0.5
0.0
0.5
1.0
Insolation J 65°N
100
50
0
−50
0
50,000
100,000
150,000
200,000
250,000
300,000
350,000
400,000
Age (yr BP)

Ocean-Atmosphere Interaction



ATMOSPHERE

Wind/
pressure

Heat
flux

Evaporation/
Precipitation

CO2
flux

OCEAN

Days Months Years Decades Centuries Millennia

ENSO

*Decadal
variability*

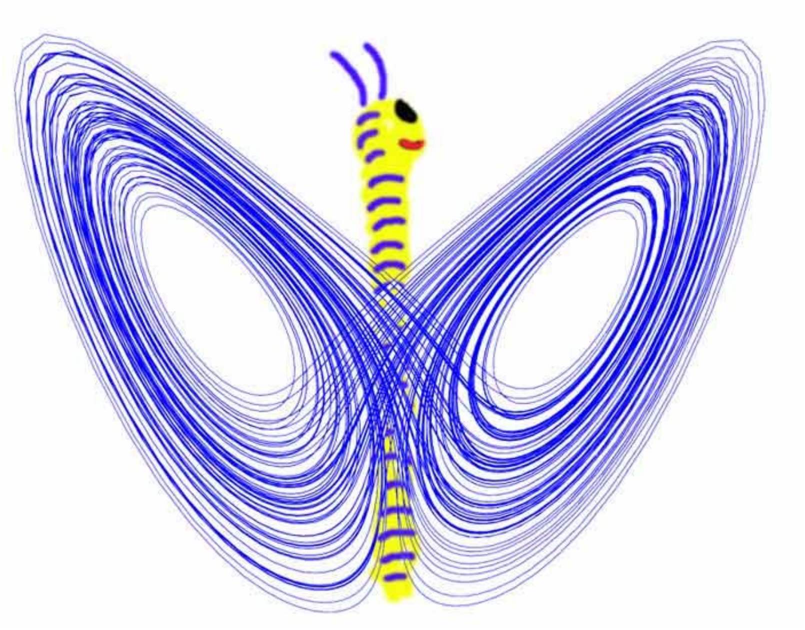
*"Climate
change"*

Multi-scale Interactions

- **Often there is no clear separation of scales, i.e., no "spectral gap"**
- **Interaction of time scales (*global domains*)**
  - **Flux closures**
  - **Energy Balance Models**
  - **Earth Models of Intermediate Complexity (EMICs)**
- **Interaction of spatial scales (*regional domains*)**
  - **"Superparameterizations"**
  - **Two-way nested models**

Deterministic Nonperiodic Flow ("Chaos")

Lorenz (1963)



Does the flap of a butterfly's wings in Brazil set off a tornado in Texas? ***Lorenz (1972)***

Superrotation in an Earth-like model

Almost intransitive behaviour

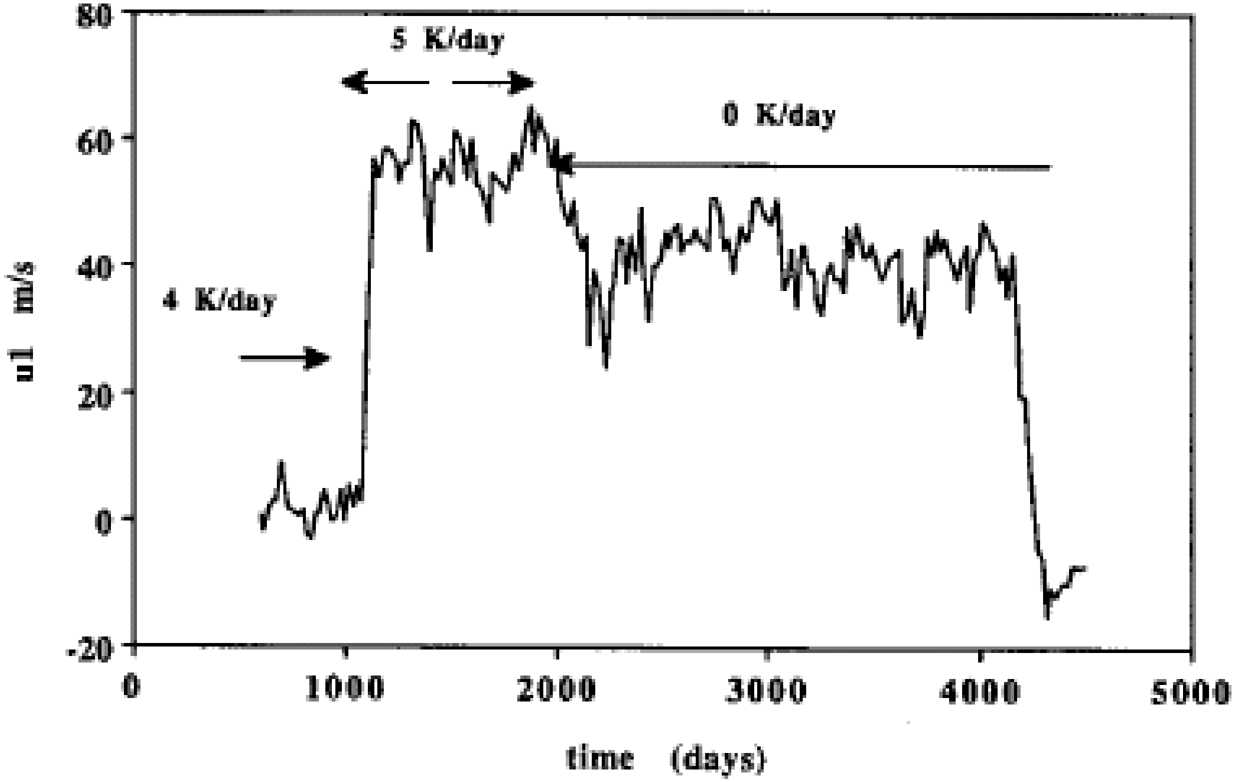


FIG. 3. Time evolution of equatorial $[u_1]$ during a 4500-day integration of the T21 model for varying values of tropical eddy heating rate A_T. The $[u_1]$ values were sampled once every 20 days.

Climatic Predictability

Lorenz (1975)

- **Predictability of the First Kind (*weather prediction*)**
  - **Effect of uncertainty in initial conditions**
- **Predictability of the Second Kind (*climate prediction*)**
  - **Response of climate system to boundary conditions**
    - ***Solar radiation***
    - ***Sea surface temperature***
    - ***Soil wetness***
    - ***Sea ice distribution***
    - ***Carbon dioxide concentration***

Stochastic climate modelling

- Parameterizing “weather” for climate models
  - Separation in timescales, rather than spatial scales
- Linear models are not very good at weather prediction
  - Timescales of 1-5 days
  - Strong nonlinearity
  - Non-normal PDFs
- Linear models can be quite good at climate prediction
  - Seasonal-to-decadal timescales
  - Weak nonlinearity (the AR(1) model)
  - Approximately normal PDFs

Stochastic coupled models

(forward models, not inverse models)

- Stochastic models of atmospheric variability
  - Leith (1975), Branstator (1995), …
- 0-d stochastic models of oceanic response
  - Hasselmann (1977), …
- Coupled 0-d models of the atmosphere-ocean system
  - Barsugli & Battisti (1998), …
- 1-d stochastic models of atmosphere-ocean coupling
  - Saravanan & McWilliams (1998), Chang, Ji, and Saravanan (2001)
  - "Spatial Resonance" (Antarctic Circumpolar Wave, Tropical Atlantic)

0-d climate model (Hasselmann, 1977)

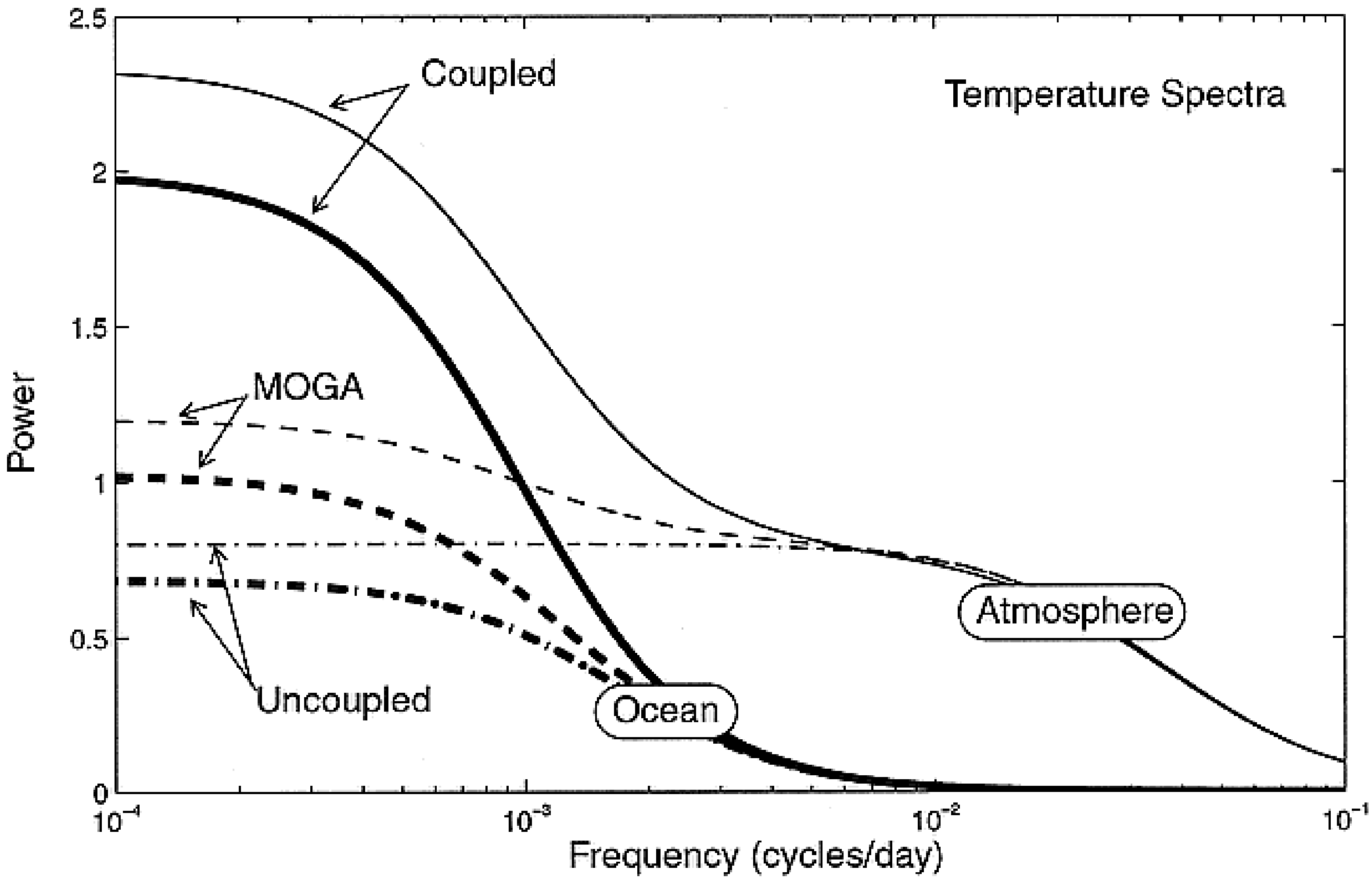
$$\frac{dT_o}{dt} = -\alpha T_o + \varepsilon_a(t)$$

Oceanic Response

Atmospheric forcing

0-D Coupled Ocean-Atmosphere Model

Barsugli & Battisti (1998)



0-d coupled oscillator

Chang, Saravanan, DelSole, and Wang (2002)

$$\frac{du}{dt} = +fv - \alpha u$$

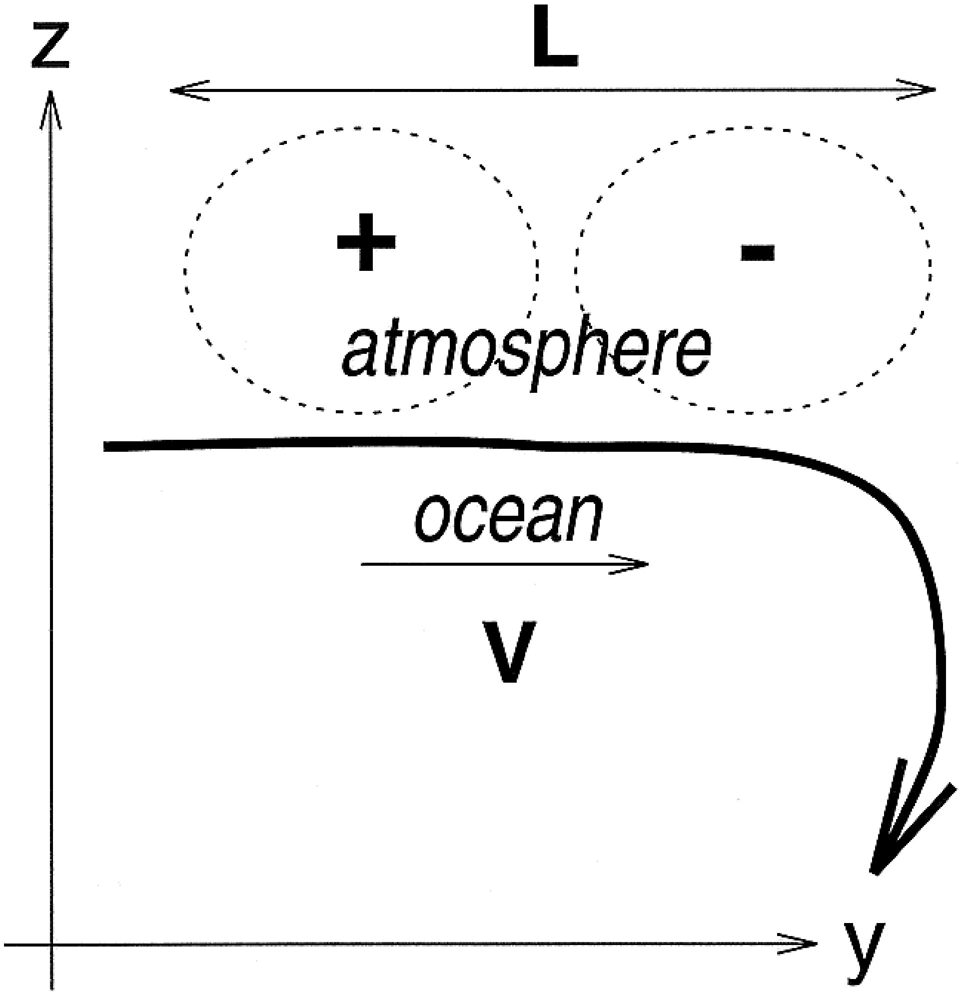
Differential damping

$$\frac{dv}{dt} = -fu - \gamma u$$

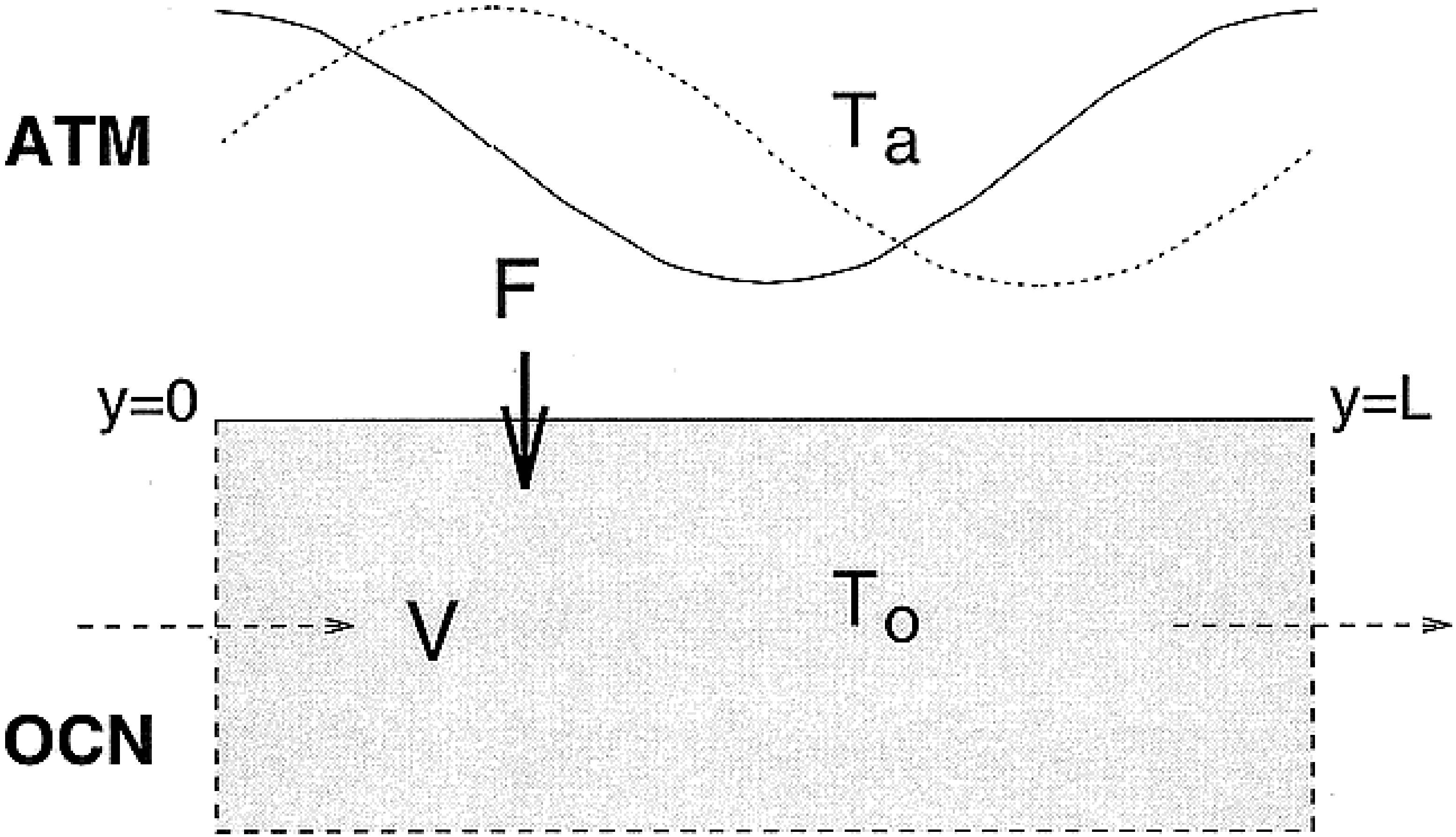
Eigenvalues $\lambda_{\pm} = -(\alpha + \gamma) \pm iF$

$$F = \sqrt{f^2 - (\alpha - \gamma)^2}$$

1-d atmosphere-ocean coupling



1-d atmosphere-ocean coupling



1-d advective coupled model

$$\partial_t T_a = -\alpha T_a - \frac{F}{C_a} + \varepsilon_a(y,t),$$

$$\partial_t T_o = -V \partial_y T_o + \frac{F}{C_o},$$

$$F = \kappa(T_a - T_o),$$

$$\frac{\varepsilon_a}{\alpha} = W(t)\sin(2\pi\frac{y}{L}).$$

Boundary condition $T_o(0,t) \equiv 0$

Fourier transform in t . . .

$$\left[1+\Gamma\left(i\nu+\frac{1}{2\pi}\partial_y\right)\right]\hat{T}_o=\hat{W}(\nu)\sin(2\pi y)$$

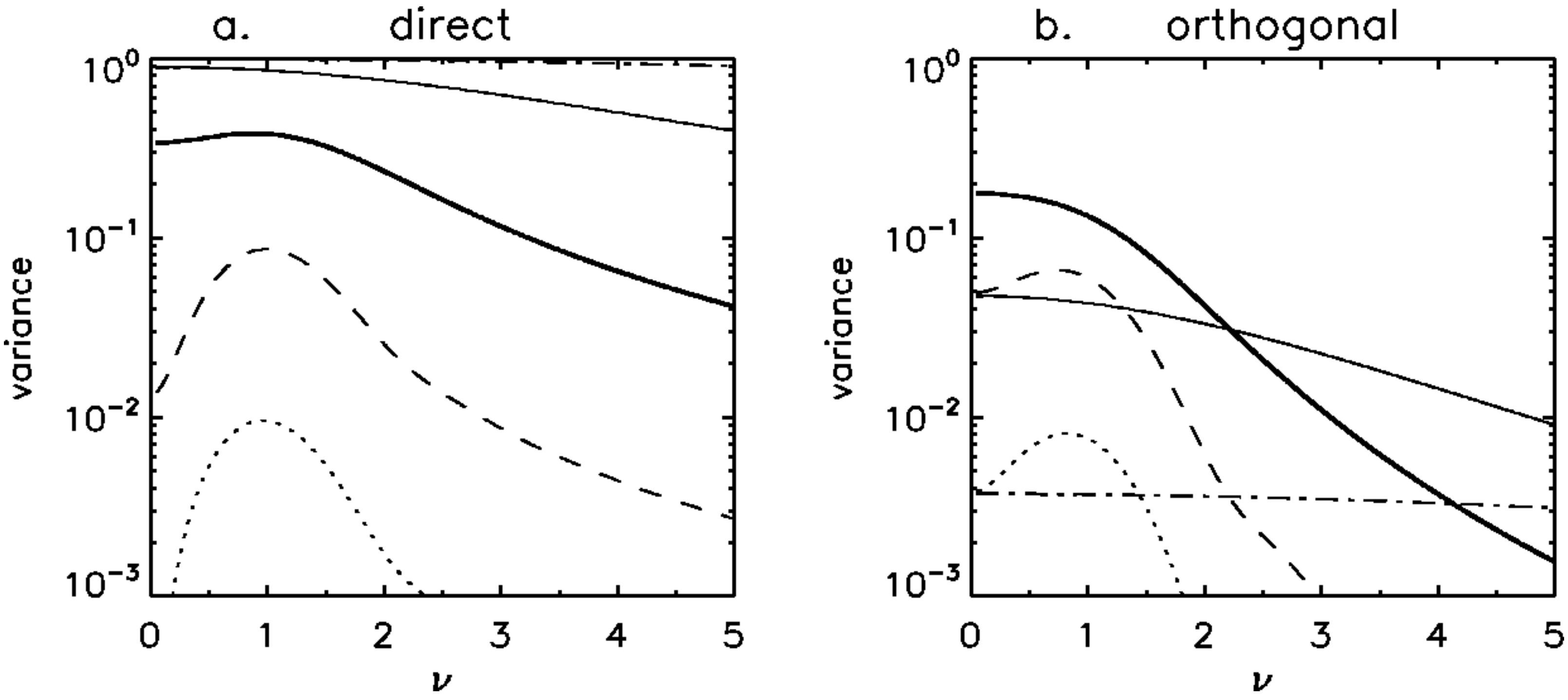
$$\Gamma \;\equiv\; 2\pi\frac{\lambda_{\rm eff}^{-1}}{L/V} \qquad \propto \qquad \frac{\text{damping time-scale}}{\text{advection time-scale}}$$

Laplace transform in y and invert . . .

$$\hat{T}_o(y,\nu)=\frac{\hat{W}}{\Gamma(1+\xi^2)}\left[\xi\sin 2\pi y-\cos 2\pi y+e^{-\xi 2\pi y}\right],$$

$$\xi\equiv\frac{1}{\Gamma}+i\nu.$$

Saravanan & McWilliams (1998)



Sine mode

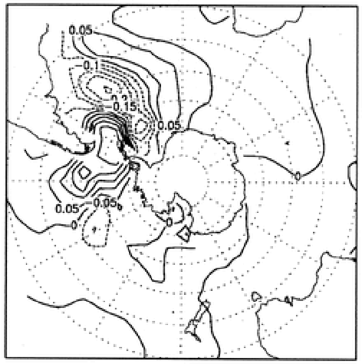
Cosine mode

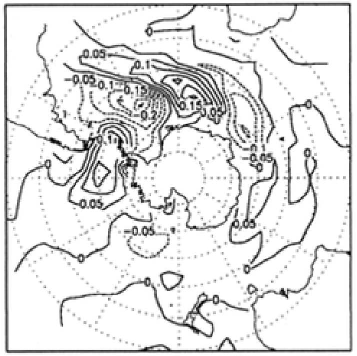
Oceanic response for Γ = 1/16, ¼, 1, 4, 16

Haarsma, Selten, and Opsteegh (2000)

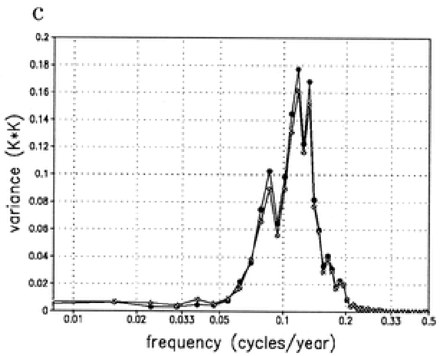
Antarctic Circumpolar Wave in the ECBILT Model

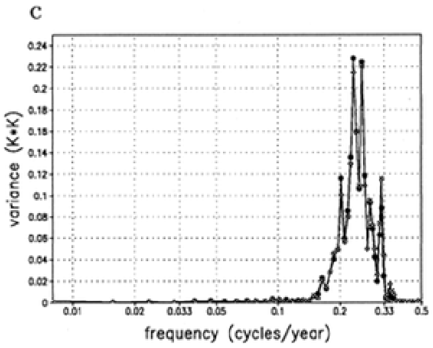
Ocean T
(80m-300m)





Power





frequency

Normal ACC

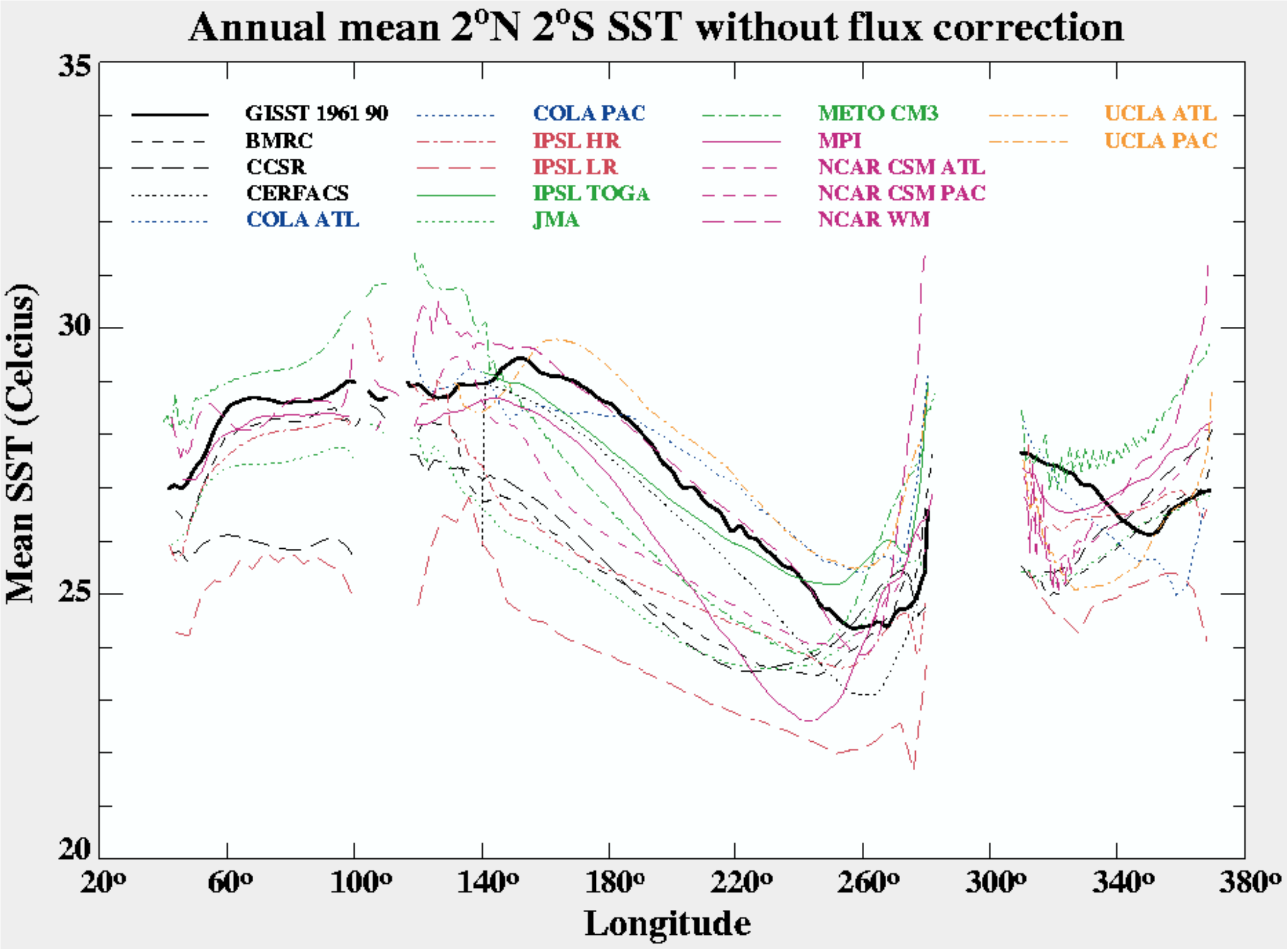
Fast ACC

When GCMs have O(1) errors …

- **Simple models can be used to study, and even predict phenomena**
- **El Niño-Southern Oscillation, Tropical Atlantic Variability**
  - **GCMs have systematic errors in simulating the mean state and the annual cycle in the Tropical Pacific & Atlantic**

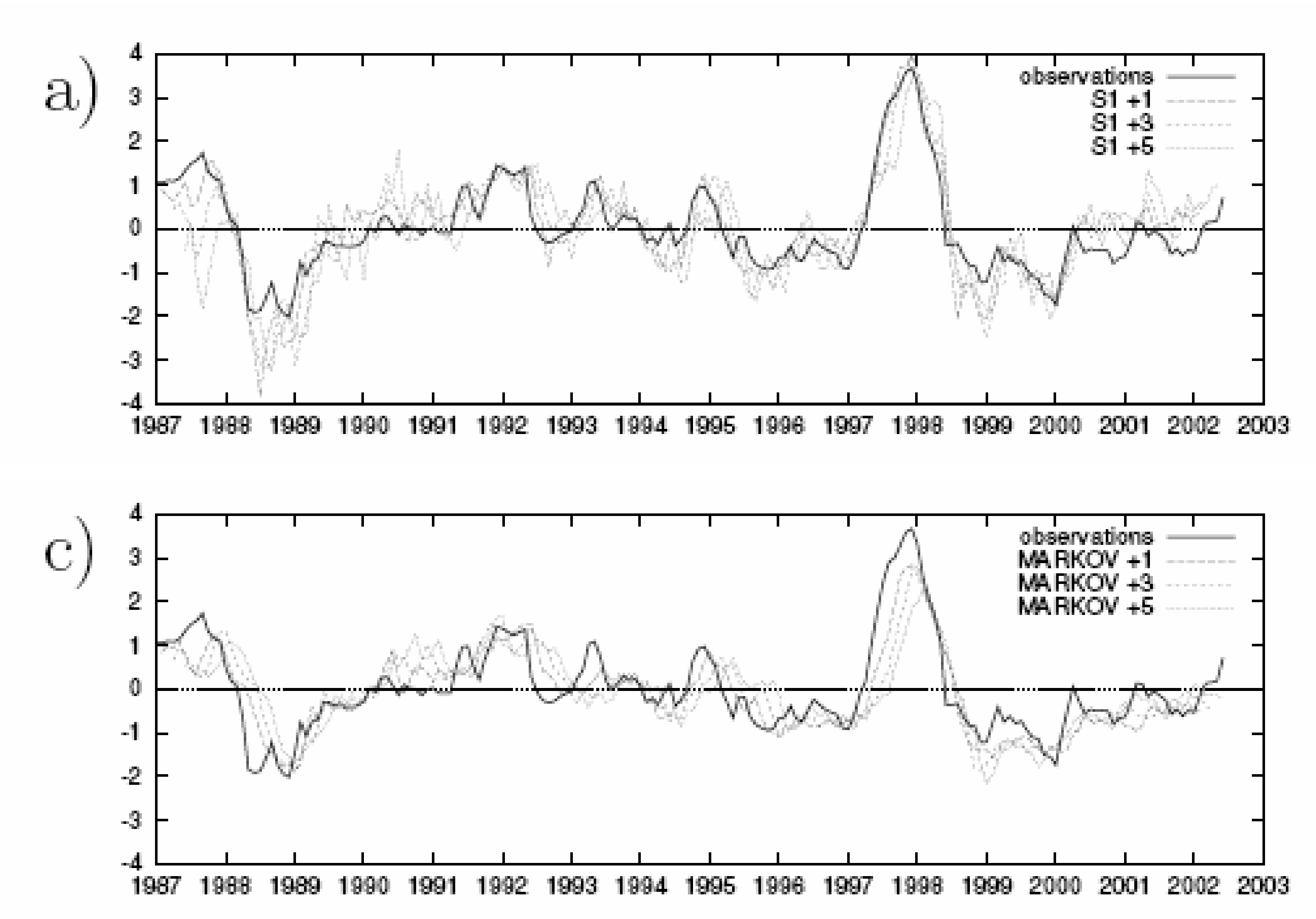
Intercomparison of Simulated Equatorial SST

(STOIC: Davey et al., 2002)

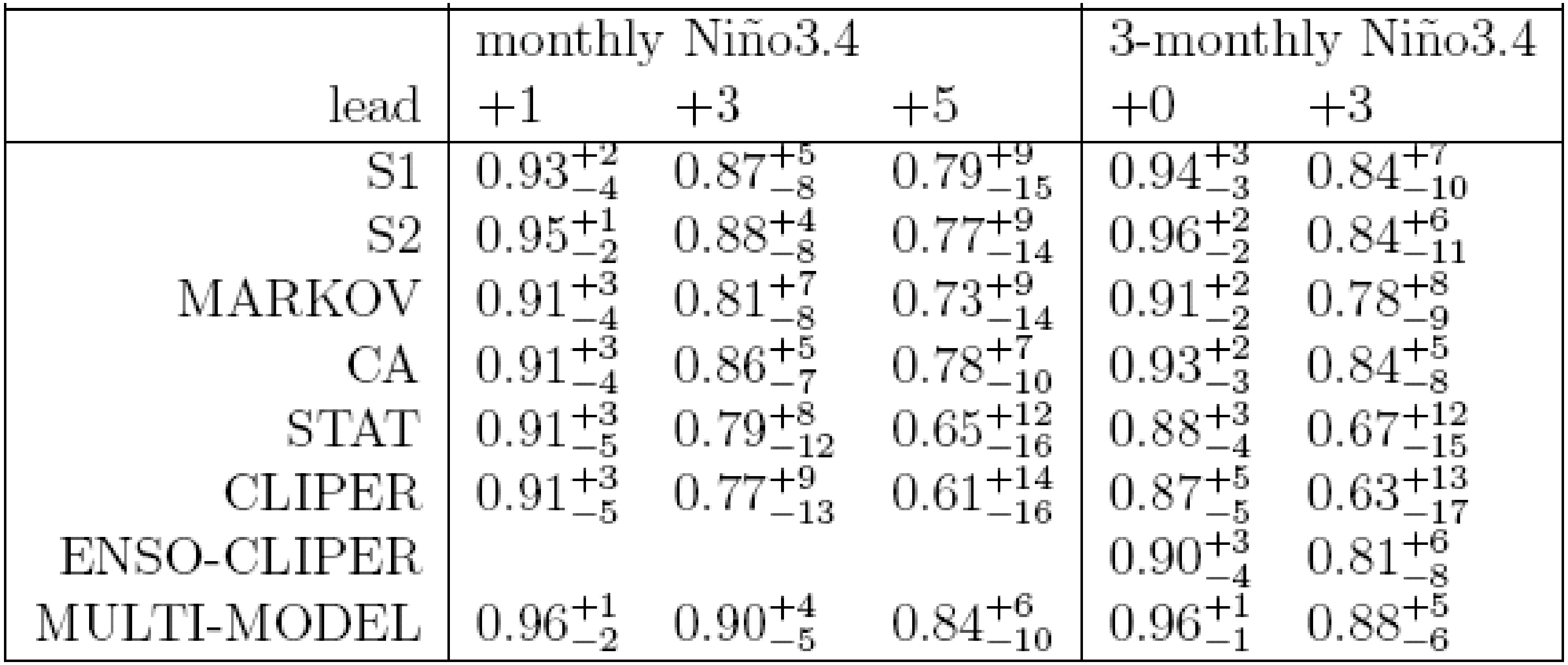


Did the ECMWF seasonal forecast model outperform statistical ENSO forecast models over the last 15 years?

(van Oldenborgh et al., 2006)



van Oldenborgh et al., 2006

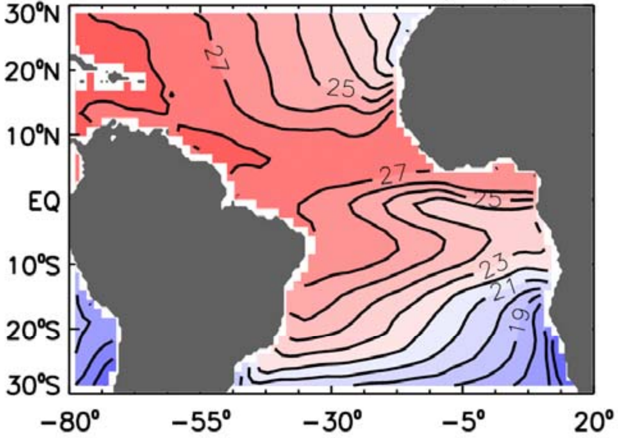


	monthly Niño3.4			3-monthly Niño3.4	
lead	+1	+3	+5	+0	+3
S1	0.93^{+2}_{-4}	0.87^{+5}_{-8}	0.79^{+9}_{-15}	0.94^{+3}_{-3}	0.84^{+7}_{-10}
S2	0.95^{+1}_{-2}	0.88^{+4}_{-8}	0.77^{+9}_{-14}	0.96^{+2}_{-2}	0.84^{+6}_{-11}
MARKOV	0.91^{+3}_{-4}	0.81^{+7}_{-8}	0.73^{+9}_{-14}	0.91^{+2}_{-2}	0.78^{+8}_{-9}
CA	0.91^{+3}_{-4}	0.86^{+5}_{-7}	0.78^{+7}_{-10}	0.93^{+2}_{-3}	0.84^{+5}_{-8}
STAT	0.91^{+3}_{-5}	0.79^{+8}_{-12}	0.65^{+12}_{-16}	0.88^{+3}_{-4}	0.67^{+12}_{-15}
CLIPER	0.91^{+3}_{-5}	0.77^{+9}_{-13}	0.61^{+14}_{-16}	0.87^{+5}_{-5}	0.63^{+13}_{-17}
ENSO-CLIPER				0.90^{+3}_{-4}	0.81^{+6}_{-8}
MULTI-MODEL	0.96^{+1}_{-2}	0.90^{+4}_{-5}	0.84^{+6}_{-10}	0.96^{+1}_{-1}	0.88^{+5}_{-6}

June-July-August mean SST

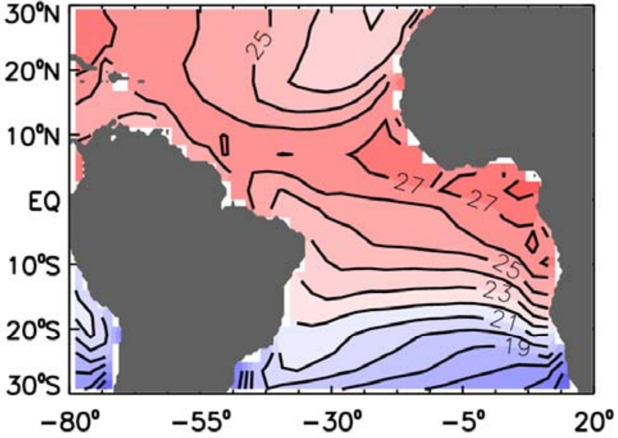
OBS

a. OBS: TS mean (JJA)



(14.99 to 28.91 by 1) degC

b. CCSM1: TS mean (JJA)

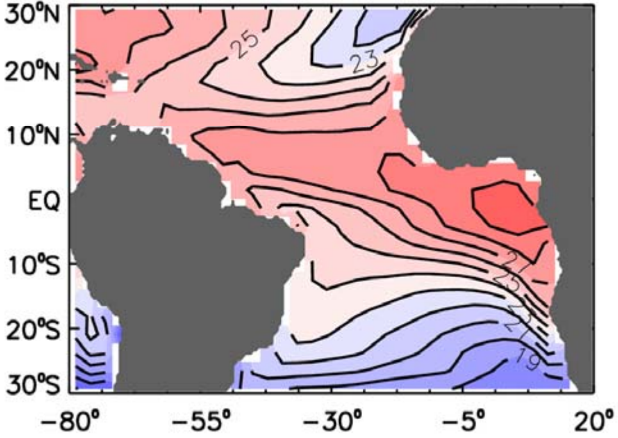


(14.97 to 28.37 by 1) degC

CCSM1

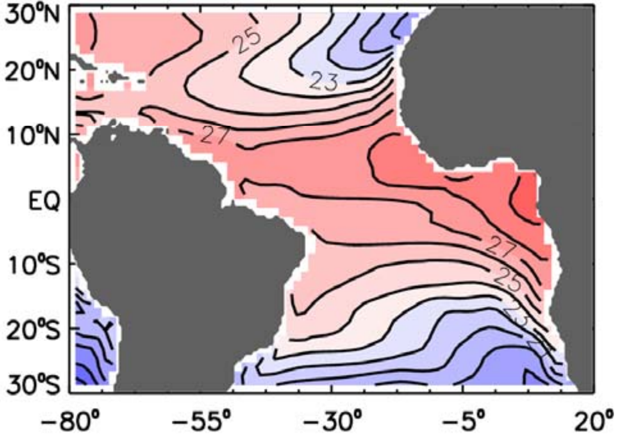
CCSM2

c. CCSM2: TS mean (JJA)



(16.93 to 29.51 by 1) degC

d. CCSM3: TS mean (JJA)



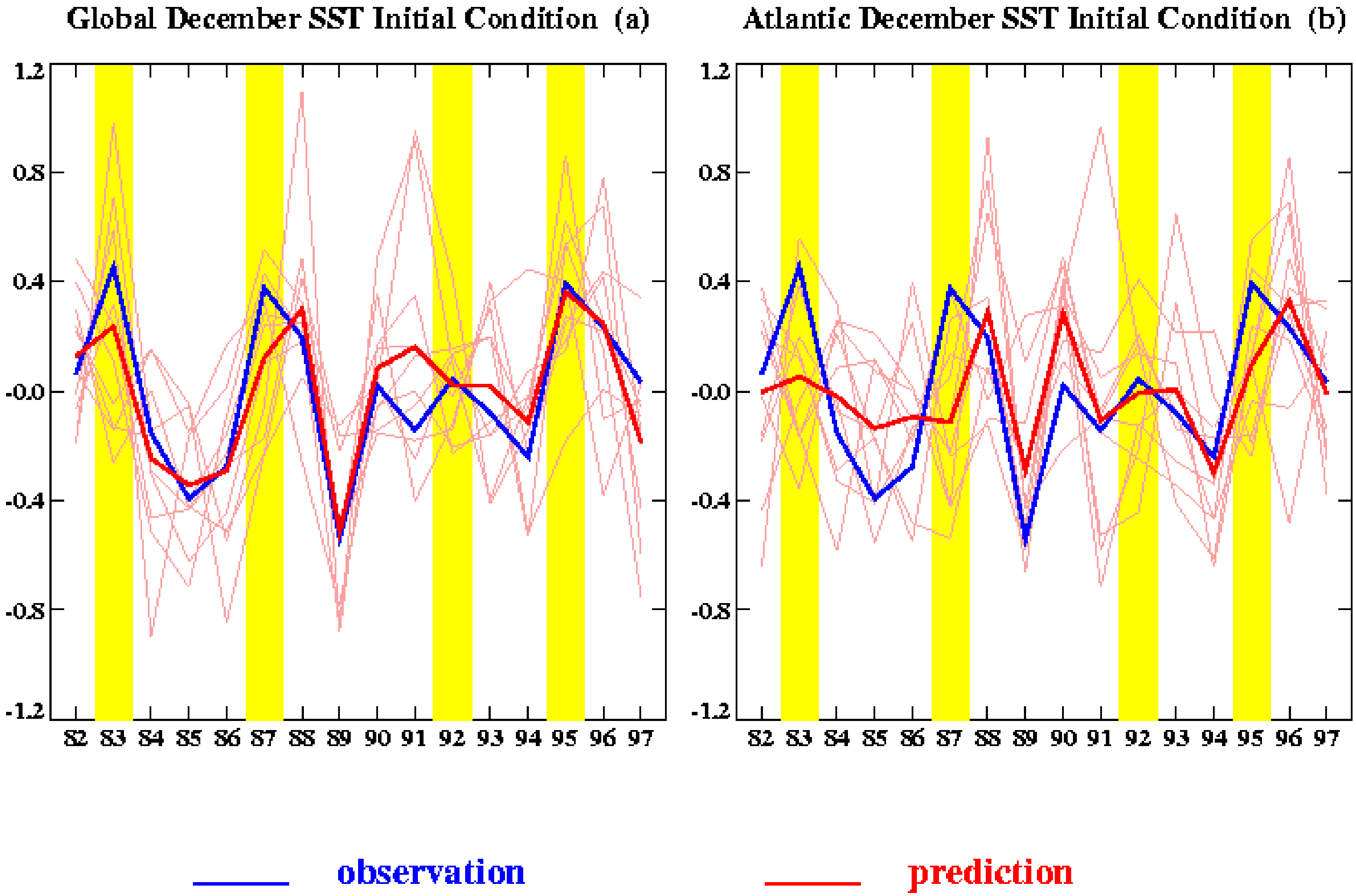
(16.53 to 29.77 by 1) degC

CCSM3

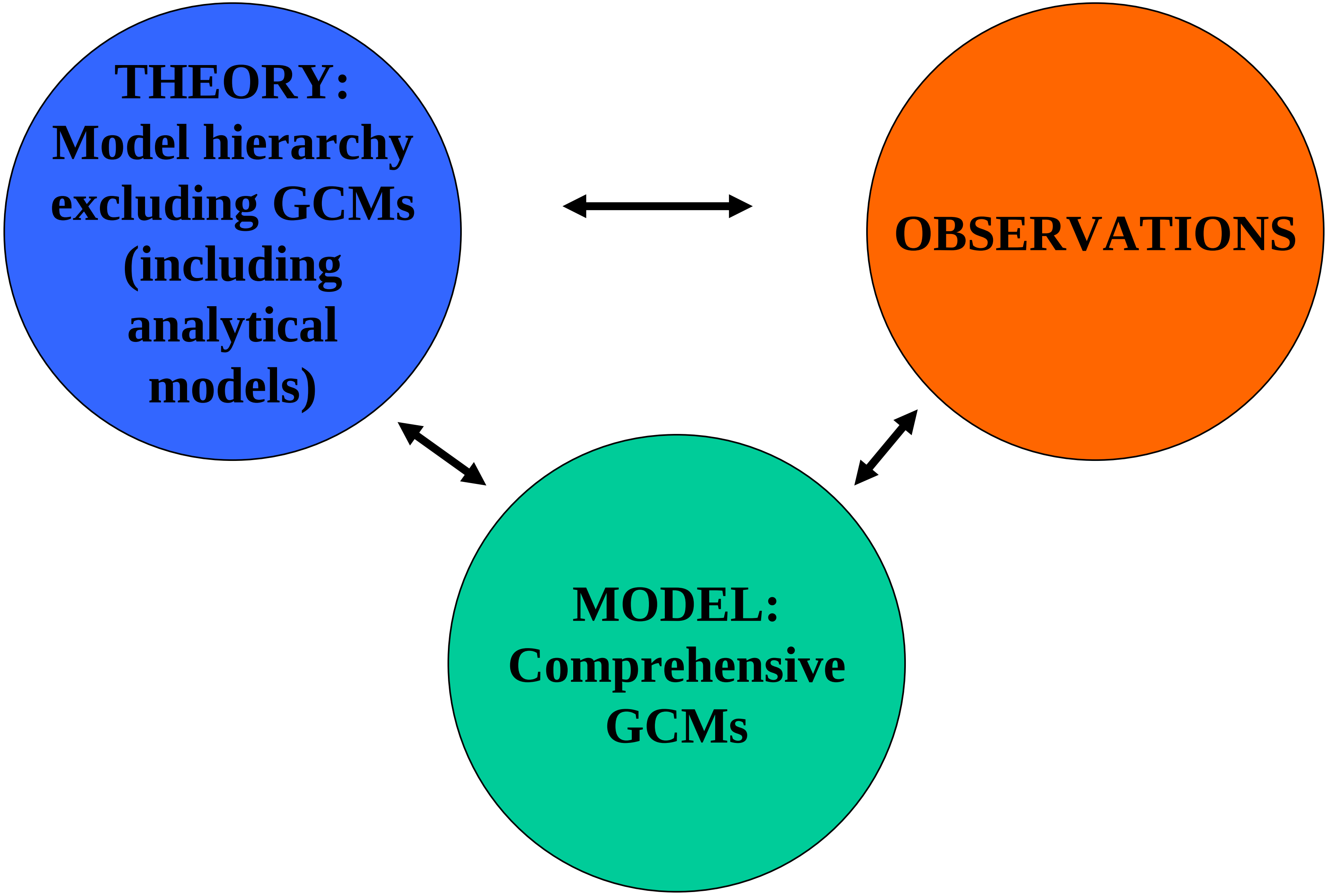
CCM3-ML integrations

- *Control* integration
  - CCM3.6.6 + Slab Ocean, with annual-mean mixed layer depth
  - 100 years
- Forecasts with *Global* SST Initial Condition
  - 16 cases (1981-1996), 9 month forecast, 10 member ensemble
  - Observed December monthly-mean initial condition for SST
  - Observed December 15 initial condition for atmosphere
- Forecasts with *Atlantic* SST Initial Conditions
  - Observed SST in Atlantic only (30S – 60N)

CCM3-ML “Caribbean” predictions (4 month lead time)



Theory vs. Model vs. Observations



THEORY:
Model hierarchy excluding GCMs (including analytical models)

OBSERVATIONS

MODEL:
Comprehensive GCMs

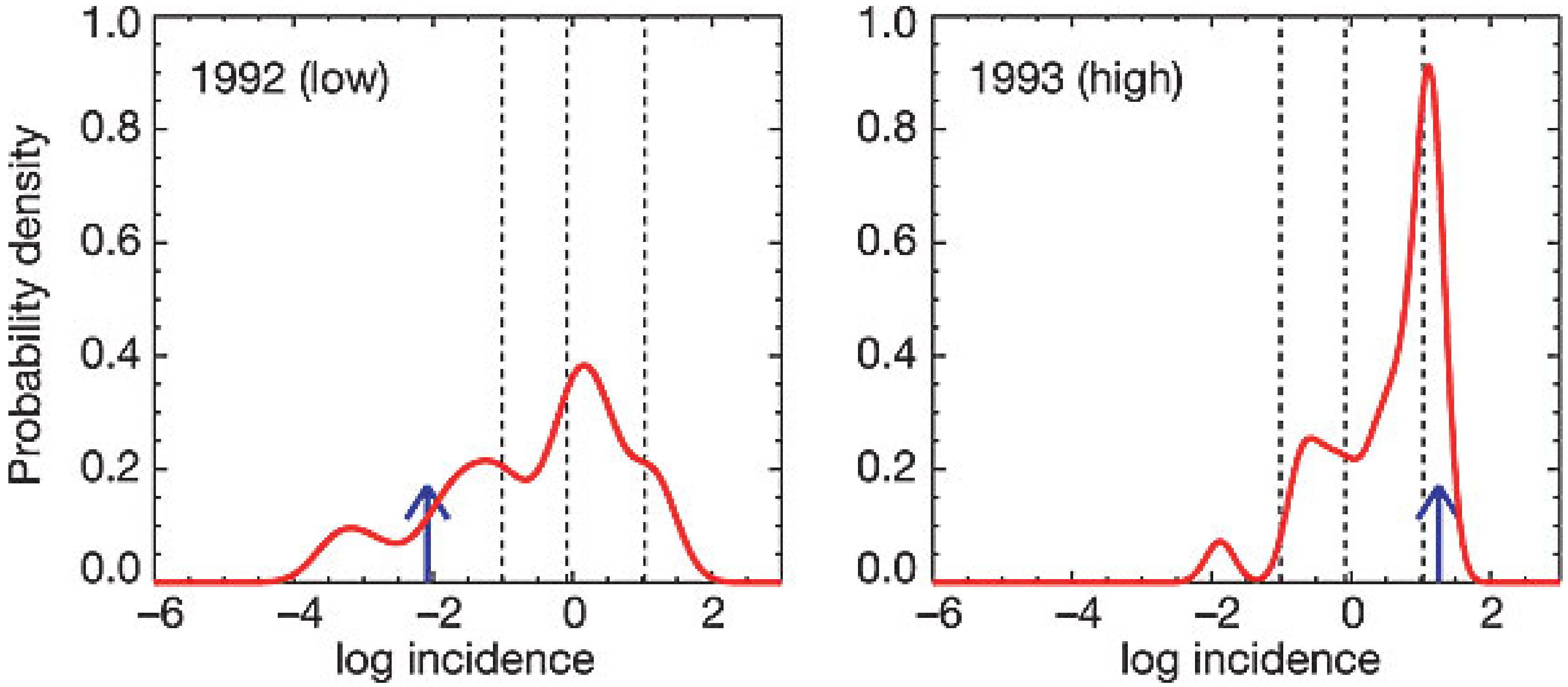
Conclusions

- **Utility of model hierarchy**
  - **“Cheaply” identify mechanisms to test against observations and GCMs**
  - **Provide the context for GCM behaviour (in climate parameter space)**
  - **Serve as “scouts” in the frontiers of research**
  - **Useful for predictions when GCMs have O(1) errors**
- **It is always possible to construct a GCM that is a superset of the simpler model**
  - **If a simple model and its corresponding superset GCM disagree, the simple model is more likely to be wrong (as it makes more approximations)**

- **Parameterizing “weather noise” as a stochastic process can provides some remarkable insights into the nature of climatic variability**
  - **Red-noise character of climate variability**
  - **Resonant interactions involving spatial structures**
- **Is the coupled atmosphere-ocean system subcritical or supercritical (with regard to instability)?**
  - **In the tropics? In the middle latitudes?**
  - **Does it matter?**
- **Forward modelling vs. inverse modelling?**

Forecast probability of malaria annual incidence for Botswana

(Thomson et al., Nature, 2006)



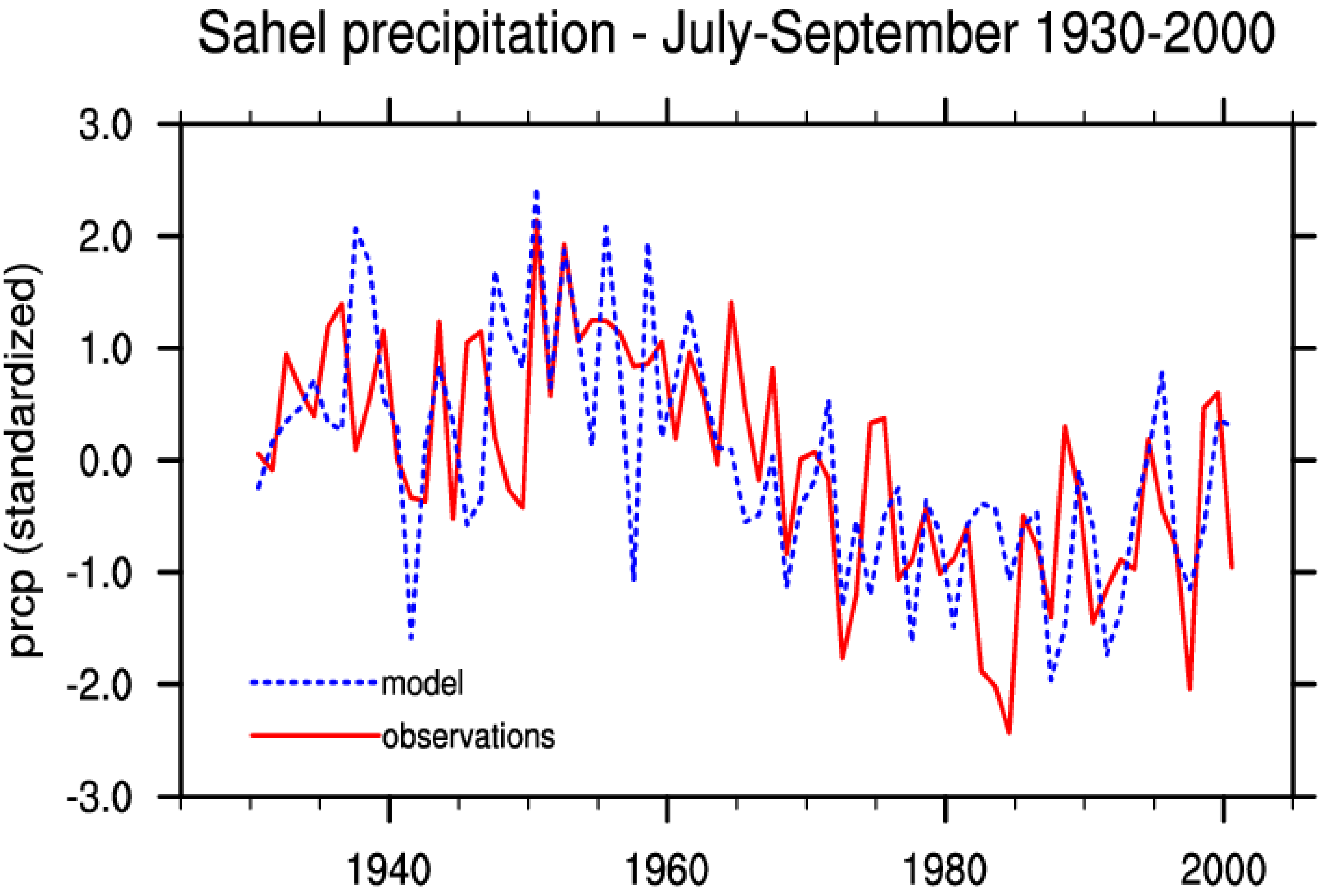
Mechanistic Modeling

- **NSIPP1: NASA Seasonal-to-Interannual Prediction Project**
  - **2x2.5 degrees, 34 vertical levels**

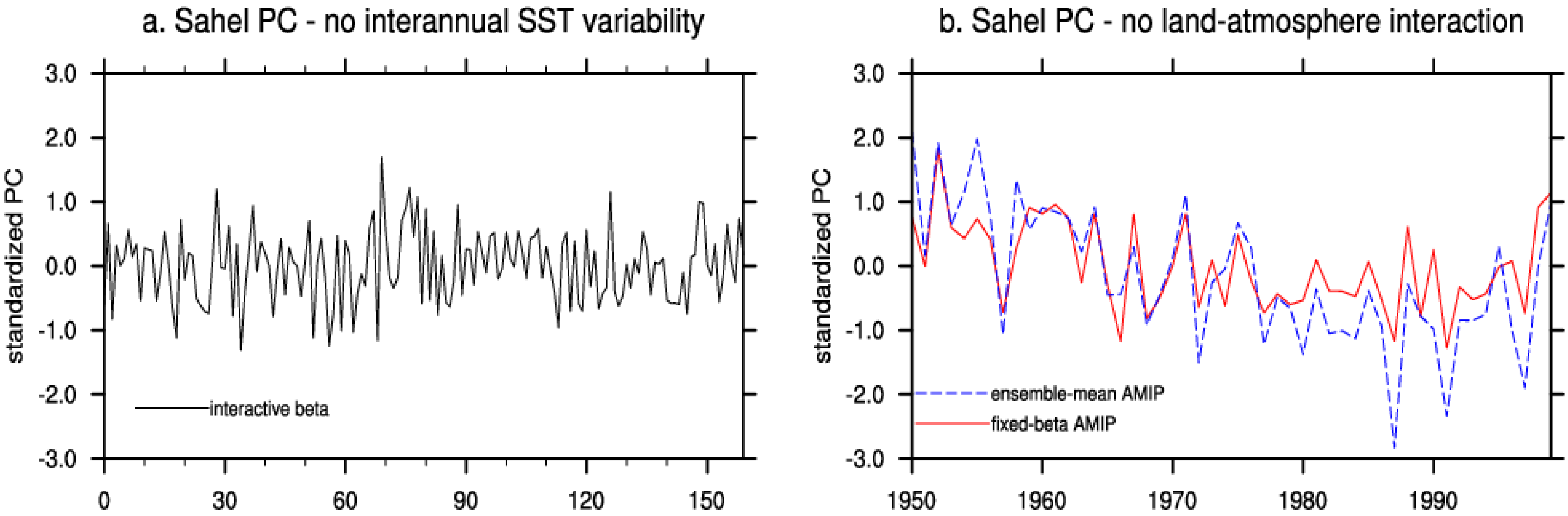
- **NSIPP1/AMIP: Observed SST forcing (1950-1999)**
- **NSIPP1/ACYC: Annual cycle of SST forcing**
- **NSIPP1/FBETA: Observed SST, but prescribed “evaporation efficiency” β (ratio of evaporation to potential evaporation)**

Low frequency variability of Sahel Rainfall

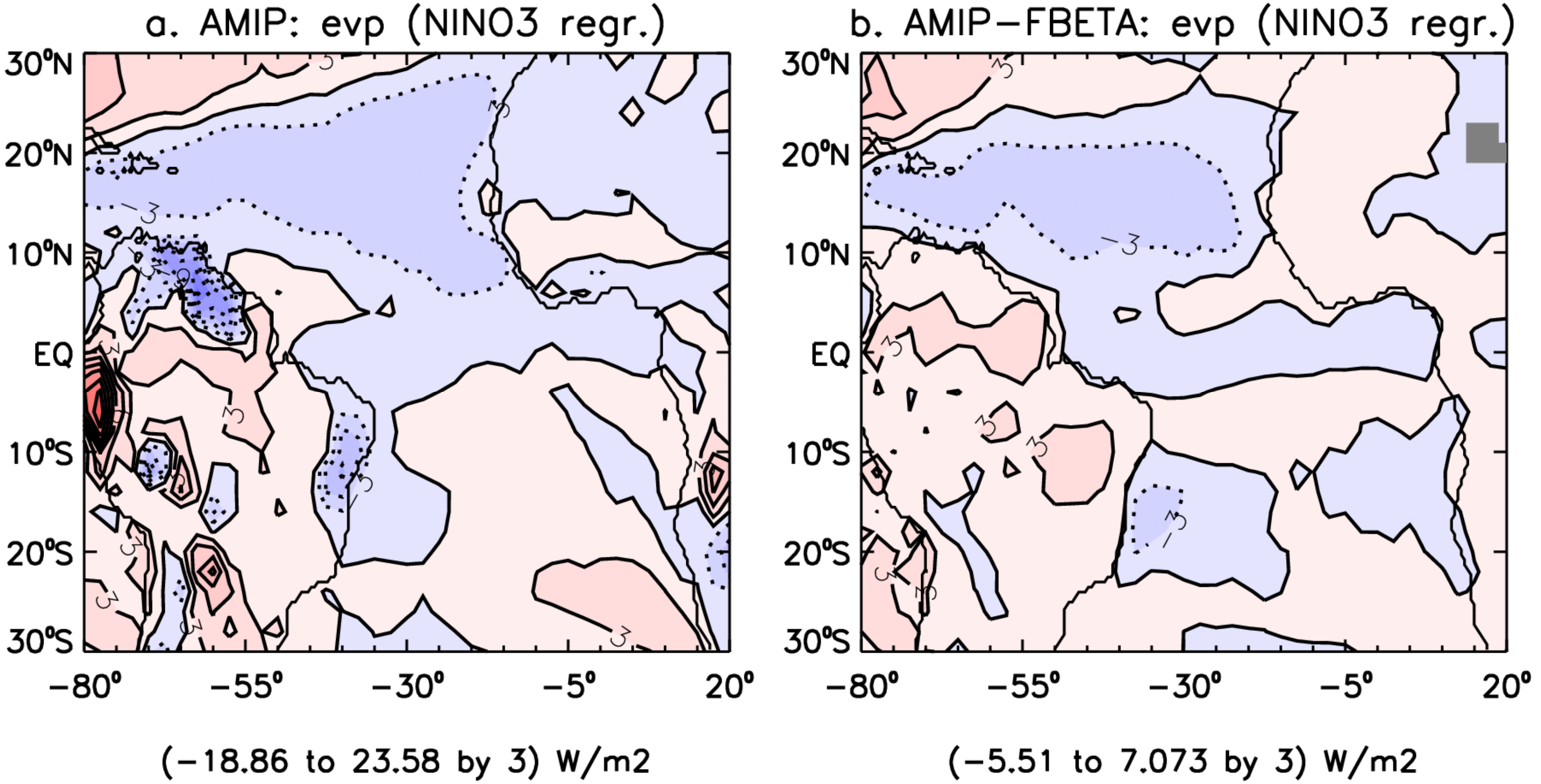
Giannini, Saravanan, and Chang (2003)



Giannini et al. (2003)



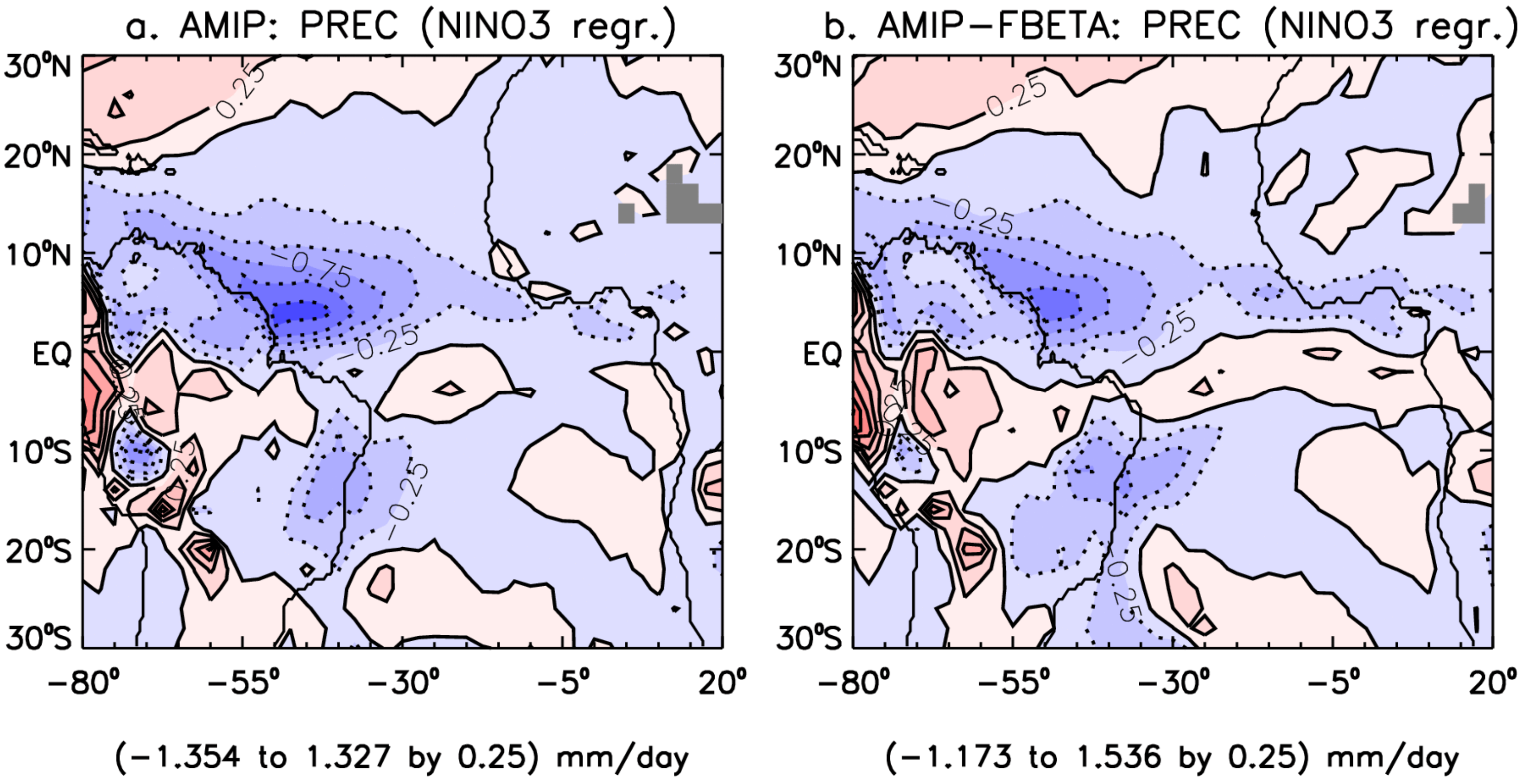
NASA/NSIPP: EVAP regression (DJF)



AMIP

AMIP/Fixed β

NASA/NSIPP: PRECIP regression (DJF)



AMIP

AMIP/Fixed β