The Abdus Salam
International Centre
for Theoretical Physics

2356-17

Targeted Training Activity: ENSO-Monsoon in the Current and Future Climate

30 July - 10 August, 2012

ENSO Predictability and Prediction

KIRTMAN Benjamin Paul

Rosenstiel School of Marine and Atmospheric Science, University of Miami
4600 Rickenbacker Causeway Miami 33149
Florida
U.S.A.

UNIVERSITY
OF MIAMI
ROSENSTIEL
SCHOOL of MARINE &
ATMOSPHERIC SCIENCE

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ENSO Predictability and Prediction

Ben Kirtman
University of Miami – Rosenstiel School

ENSO Predictability

- **What is the Source of Irregularity?**
- **What Limits ENSO Predictability?**
- **Are There Variations in Predictability?**

- **Chaos within the Non-Linear Dynamics of the Coupled System**
- **External Stochastic or Unpredictable Forcing**

Which Mechanism is Operating Has Implications for the Limit of Predictability

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ENSO Predictability

- **What is the Source of Irregularity?**
- **What Limits ENSO Predictability?**
- **Are There Variations in Predictability?**

- **Chaos: Mostly Think About Initial Condition Errors**
- **External: Space-Time Structure of External Forcing (and Initial Condition)**

Which Mechanism is Operating Has Implications for the Limit of Predictability

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Outline

- **“Defining” ENSO Predictability**
  - The Extent to Which We Can Predict
  - Contrast “Forced Response” vs. Coupled System
- **Conceptual Model for Predictability**
  - Non-Linear and Chaotic vs. Linear and Stochastically Forced (Stuff in Between)
- **Prediction**

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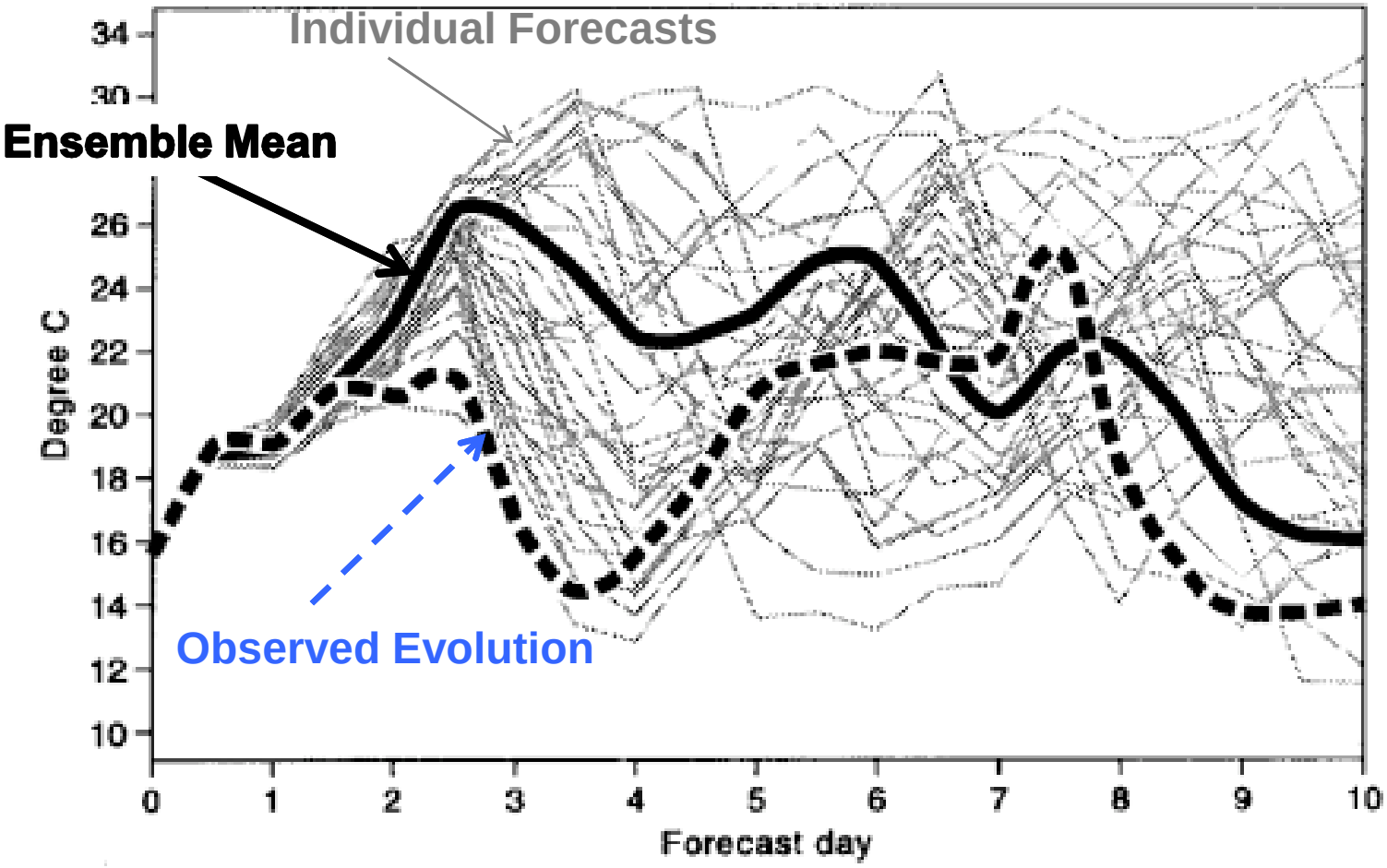
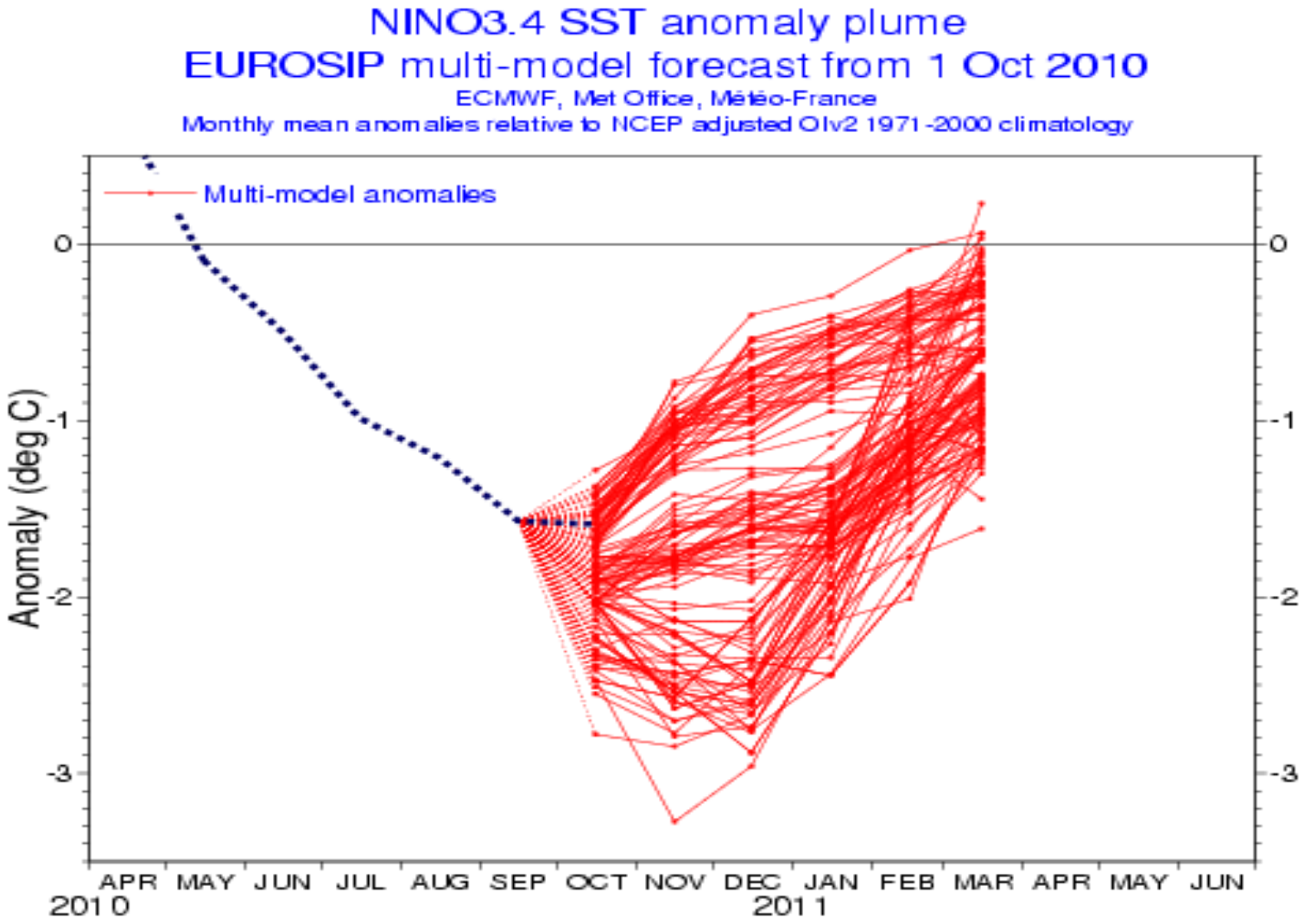
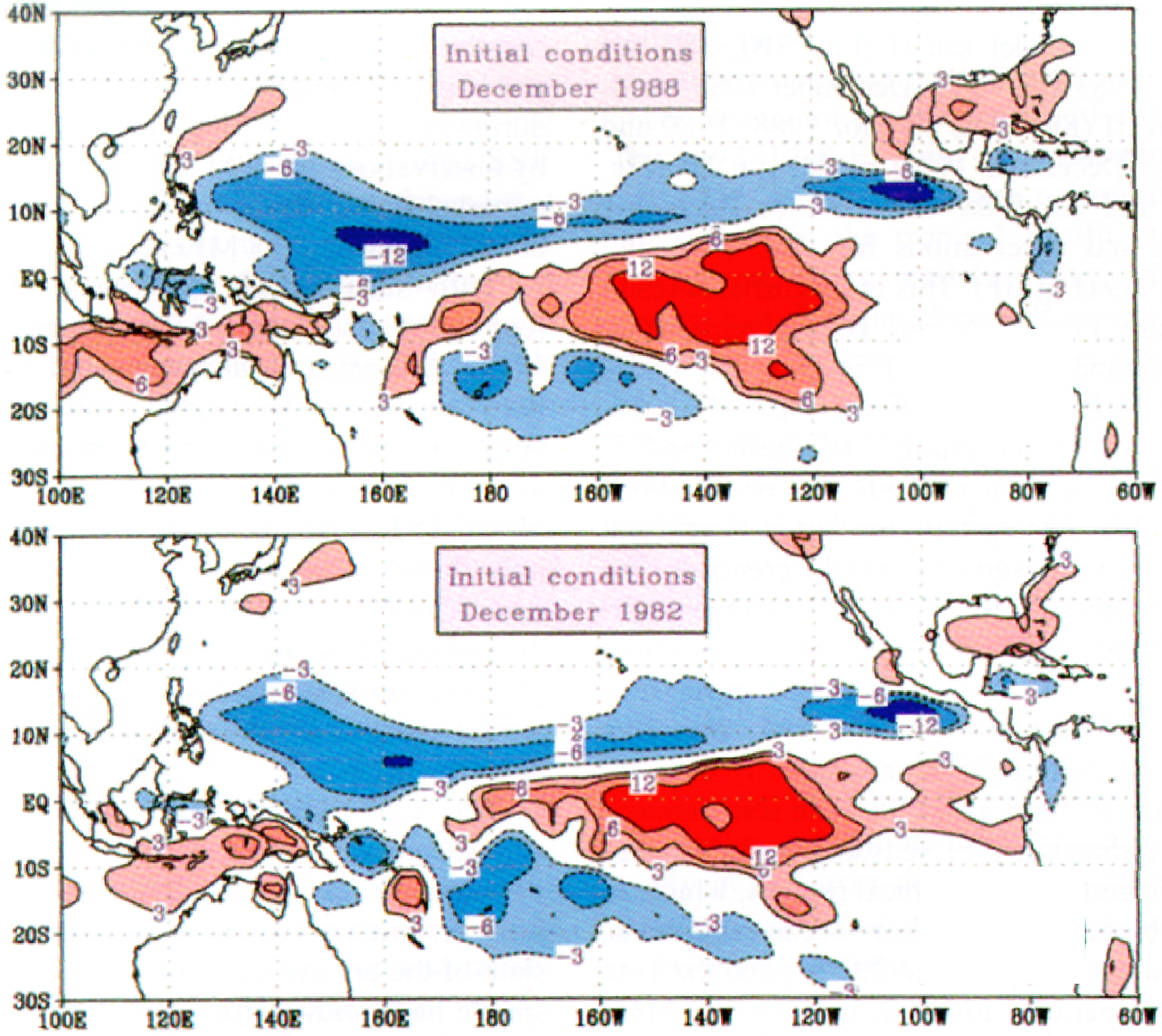
Predictability of Weather: Initial Condition Uncertainty



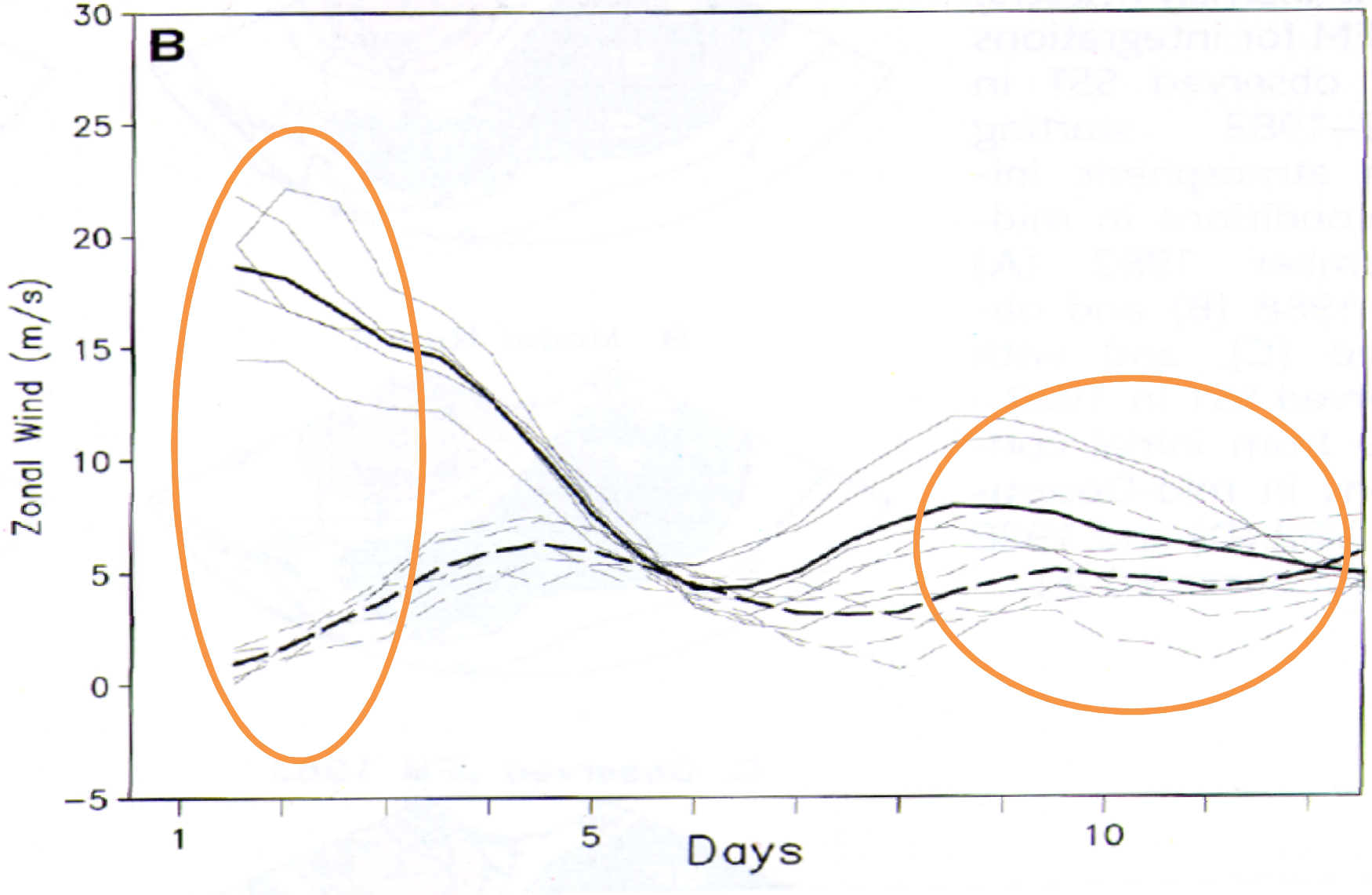
Prediction vs. Predictability

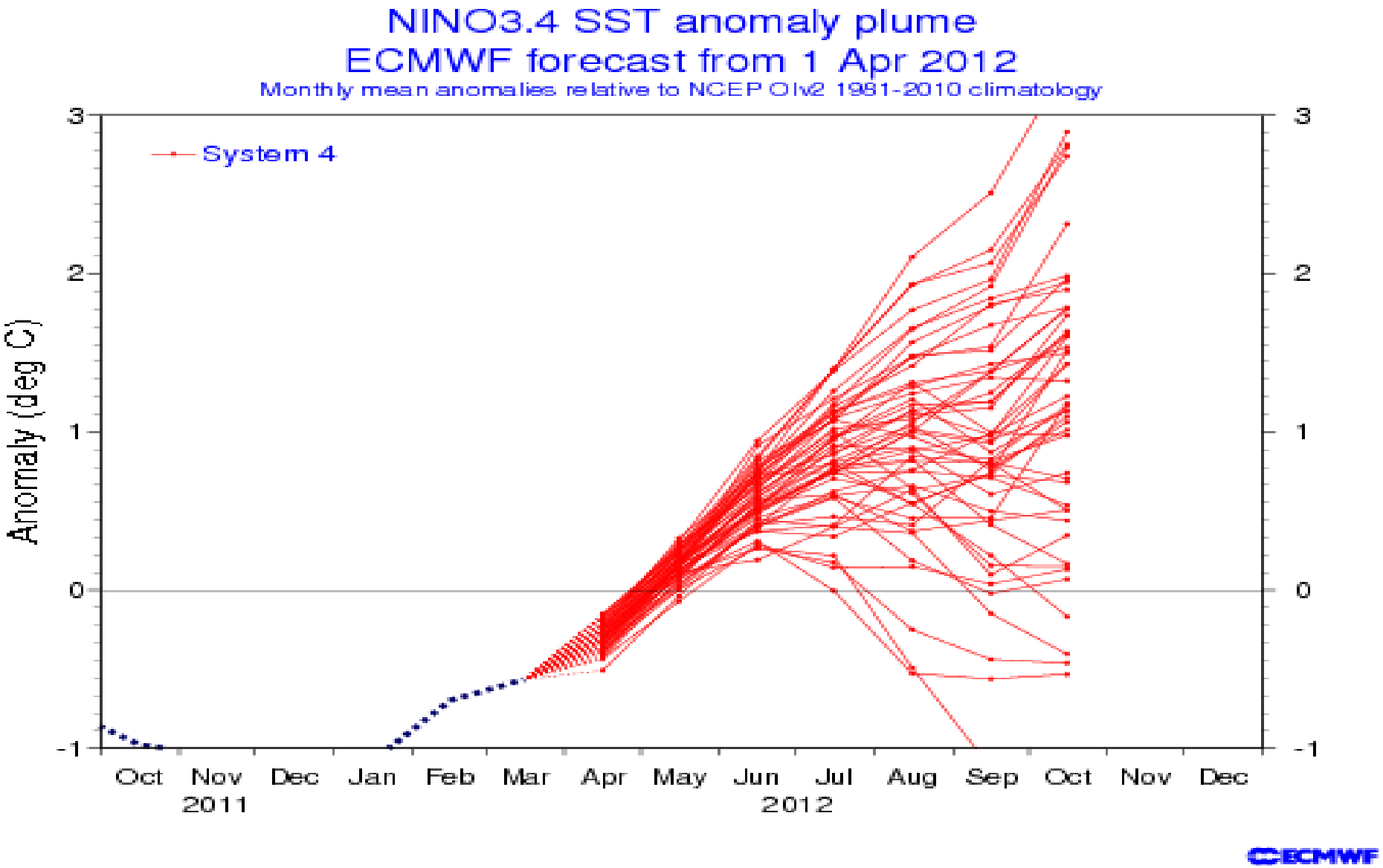


Distinction Between Weather and Climate Predictability: Boundary Forcing



Tropical Atmosphere with Prescribed SST: Initial Condition “Insensitivity”

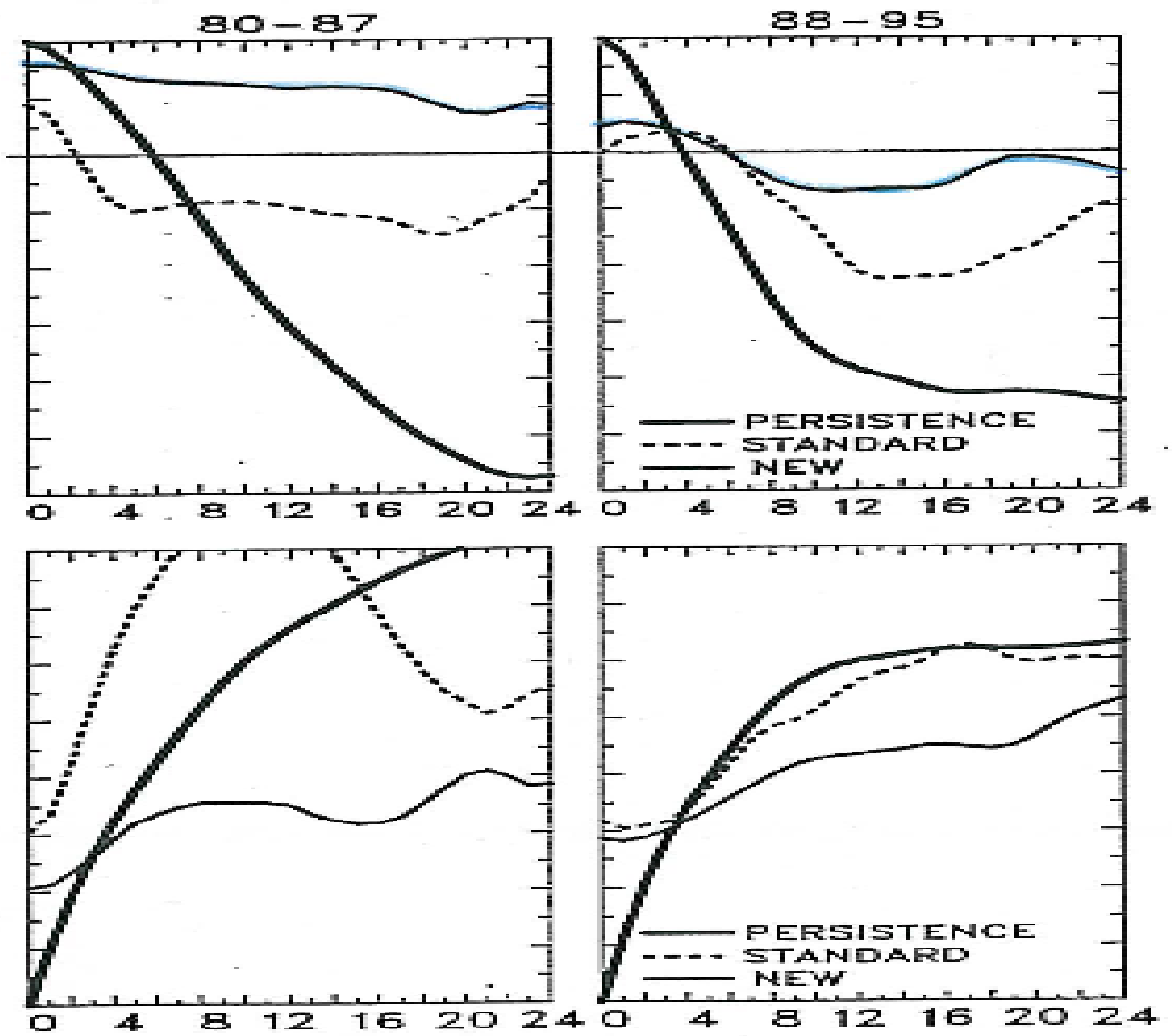



NINO3.4 SST anomaly plume
ECMWF forecast from 1 Apr 2012
Monthly mean anomalies relative to NCEP OIv2 1981-2010 climatology
System 4
Anomaly (deg C)
3
2
1
0
-1
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
2011
2012
ECMWF

Zebiak-Cane Intermediate Coupled Model

Correlation

RMSE



Chaos:

$$\frac{d\vec{X}}{dt} = G(\vec{X})$$ **Non-Linearity in G is Fundamental**

External Uncoupled Stochastic Forcing:

$$\frac{d\vec{X}}{dt} = L\vec{X} + \vec{N}$$ **Noise Not Predictable but Details Matter**

Multiplicative Noise Forcing:

$$\frac{d\vec{X}}{dt} = L\vec{X} + N\vec{X}$$ **Source of Skewness**

Non-Linearly Self Sustained:

$$\frac{d\vec{X}}{dt} = G(\vec{X}) + \vec{N}$$ **Non-Linearity Fundamental, but Details of Noise Not Important**

Chaos:

$$\frac{d\vec{X}}{dt} = G(\vec{X})$$

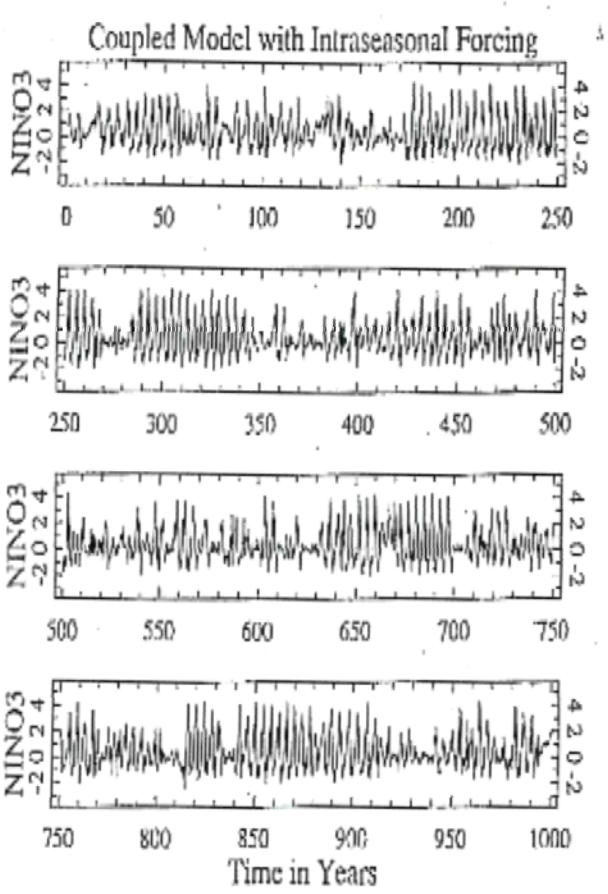


FIG. 4. As Fig. 3, except with added ISV forcing.

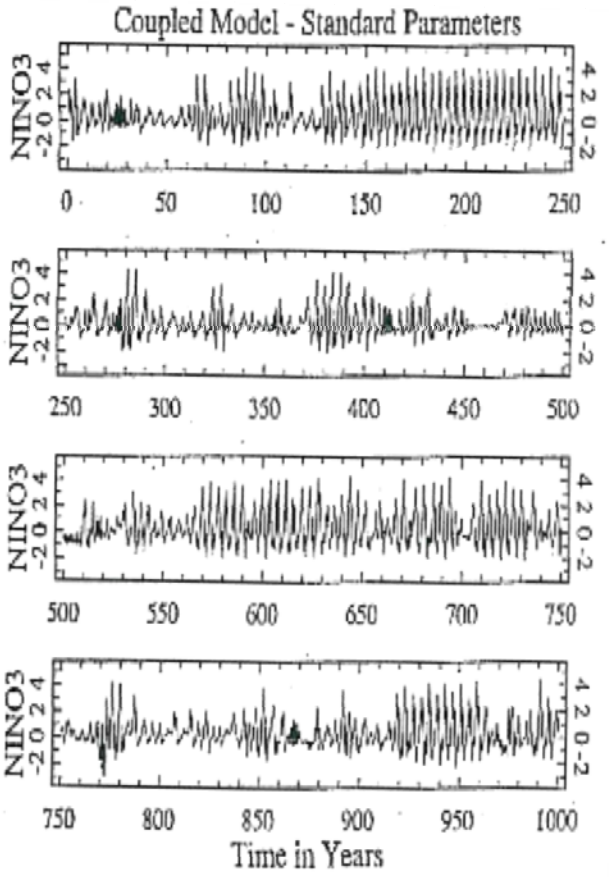
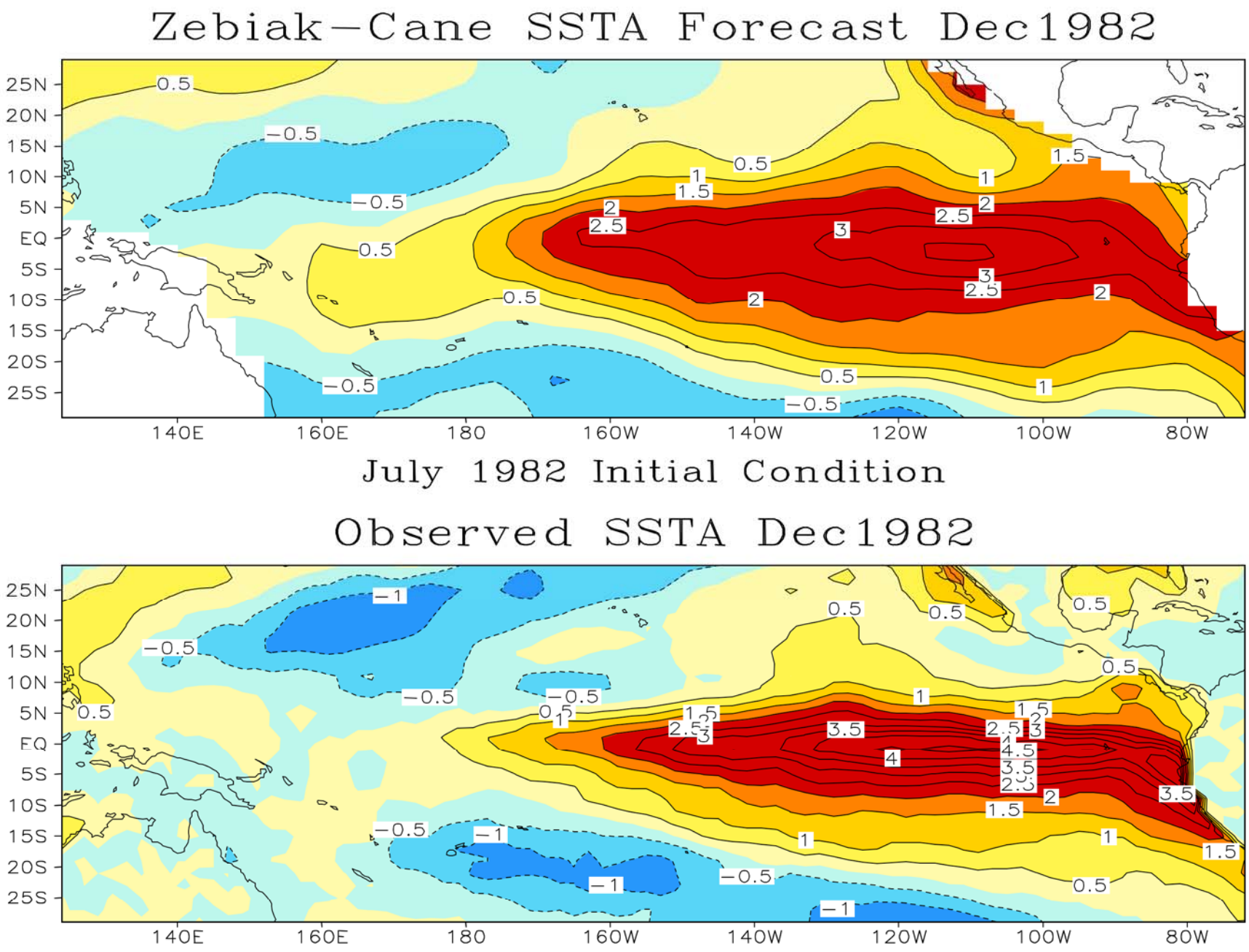


FIG. 3. NINO3 index from a 1000-year run of the coupled model with no ISV forcing.

Non-Linearity in G is Fundamental

Zebiak 1989



Cane, Zebiak and Dolan (1986); Zebiak and Cane (1987)

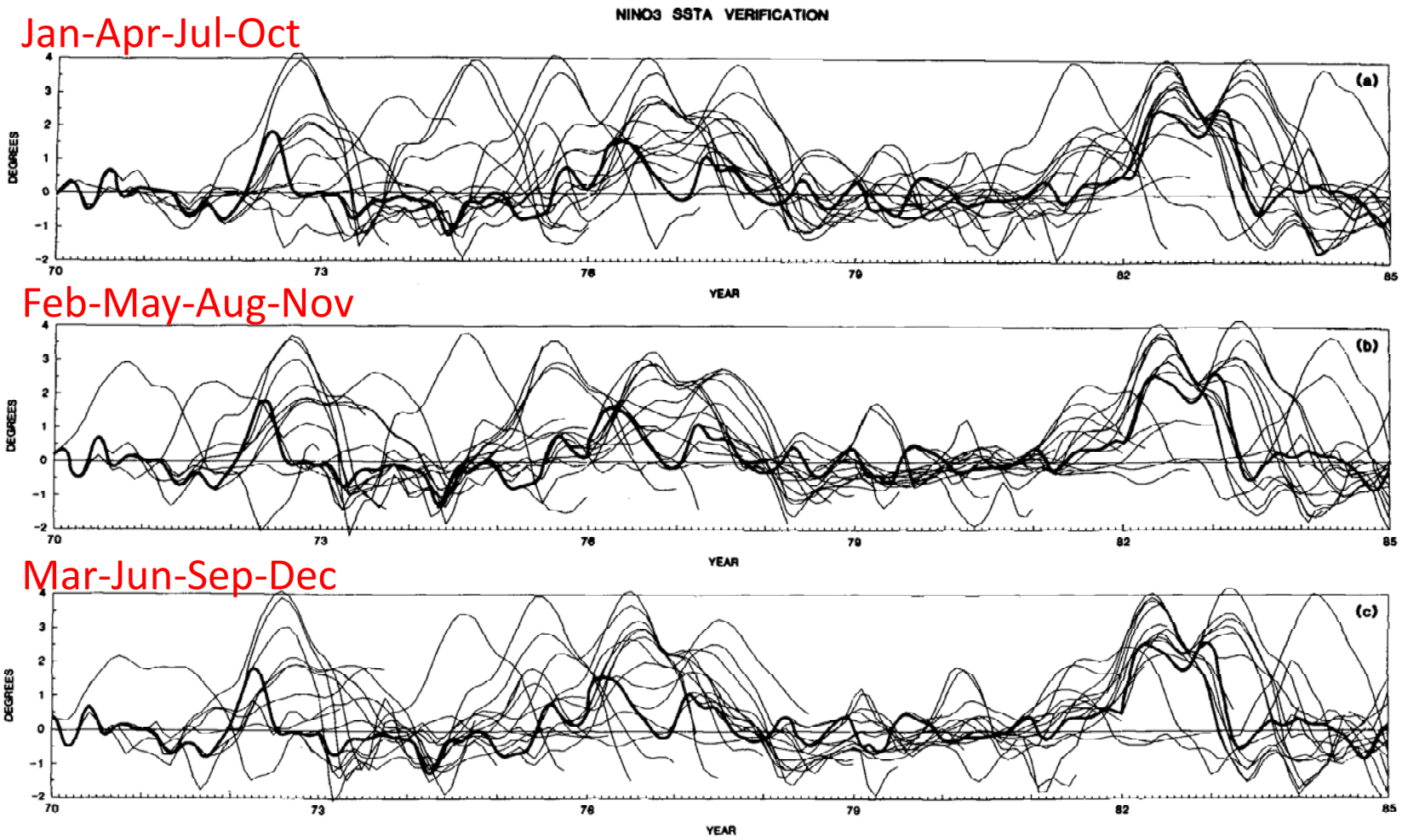
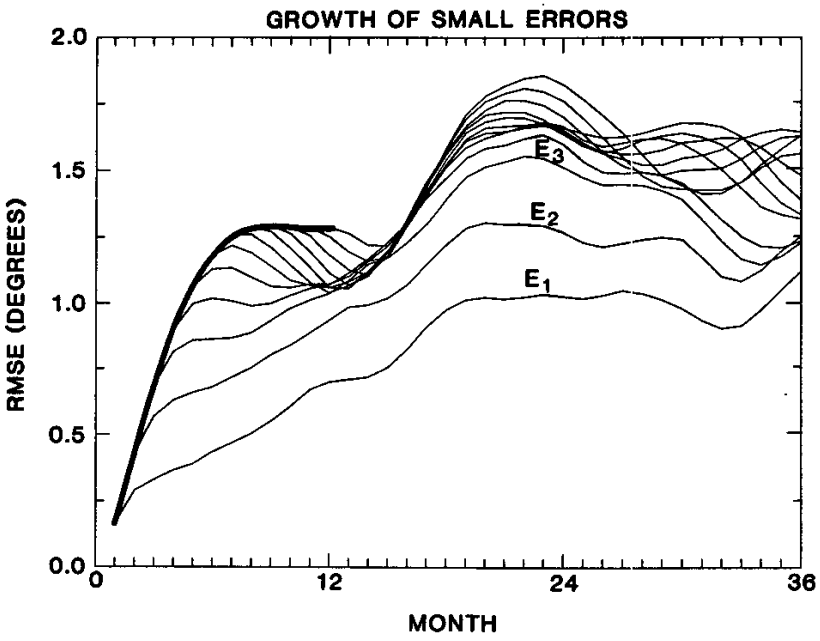
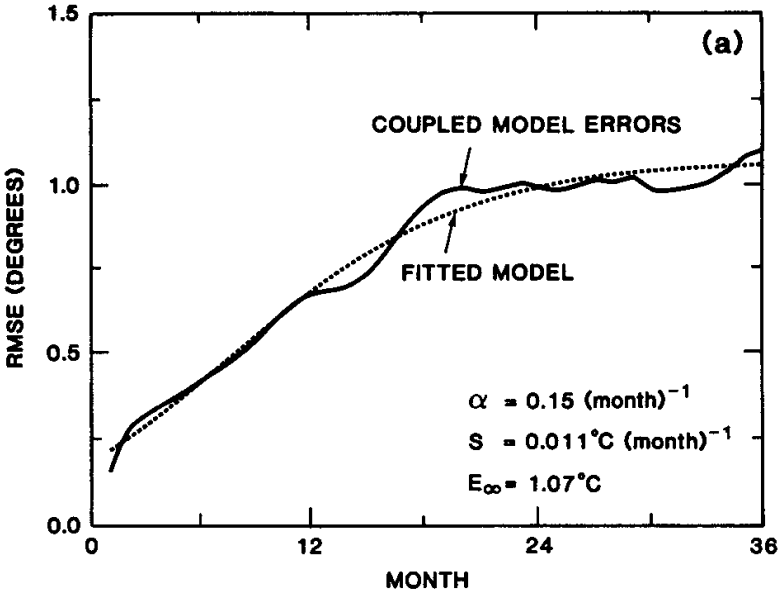


FIG. 2. The complete ensemble of predictions for NINO3 SSTA. The heavy curve represents the control, while the light curves are the predictions. Each panel contains one-third of the total predictions for clarity. (a) All predictions made from January, April, July, and October. (b) All predictions made from February, May, August, and November. (c) All predictions made from March, June, September, and December.

Growth of Small Initial Errors





Predictability Limited Due to Initial Condition Uncertainty

$$\frac{dE}{dt} = \alpha E - \alpha E^2 / E_\infty$$

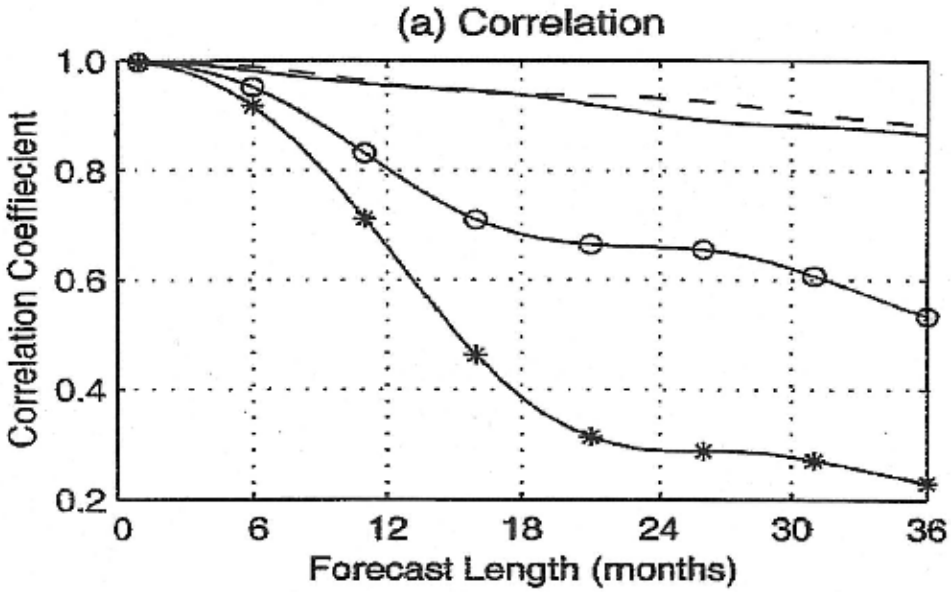
E- Error

α-Error Growth Rate

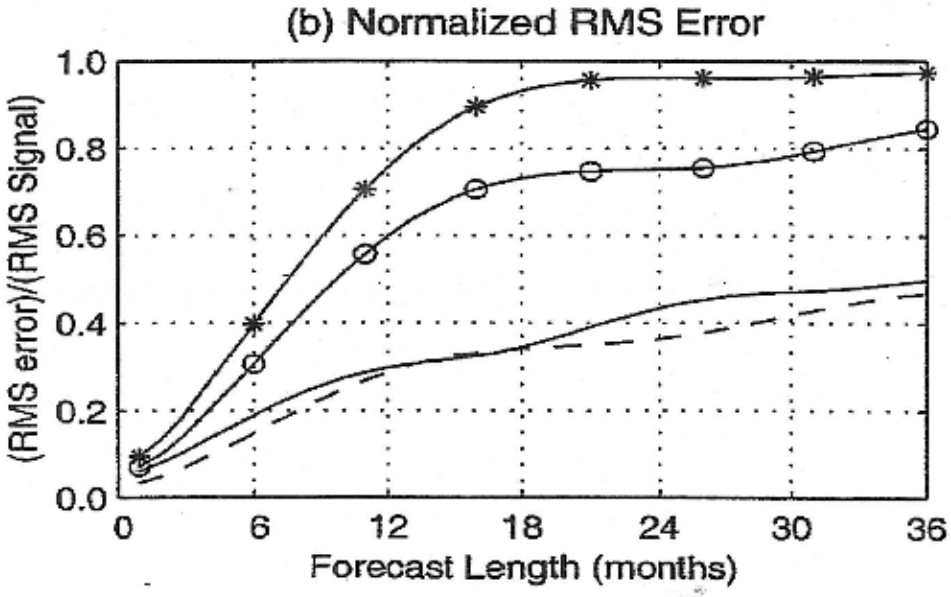
E_∞-Error Saturation

External Uncoupled Stochastic Forcing:

$$\frac{d\vec{X}}{dt} = L\vec{X} + \vec{N}$$



Noise Not Predictable but Details Matter



External Uncoupled Stochastic Forcing:

$$\frac{d\vec{X}}{dt} = L\vec{X} + \vec{N}$$

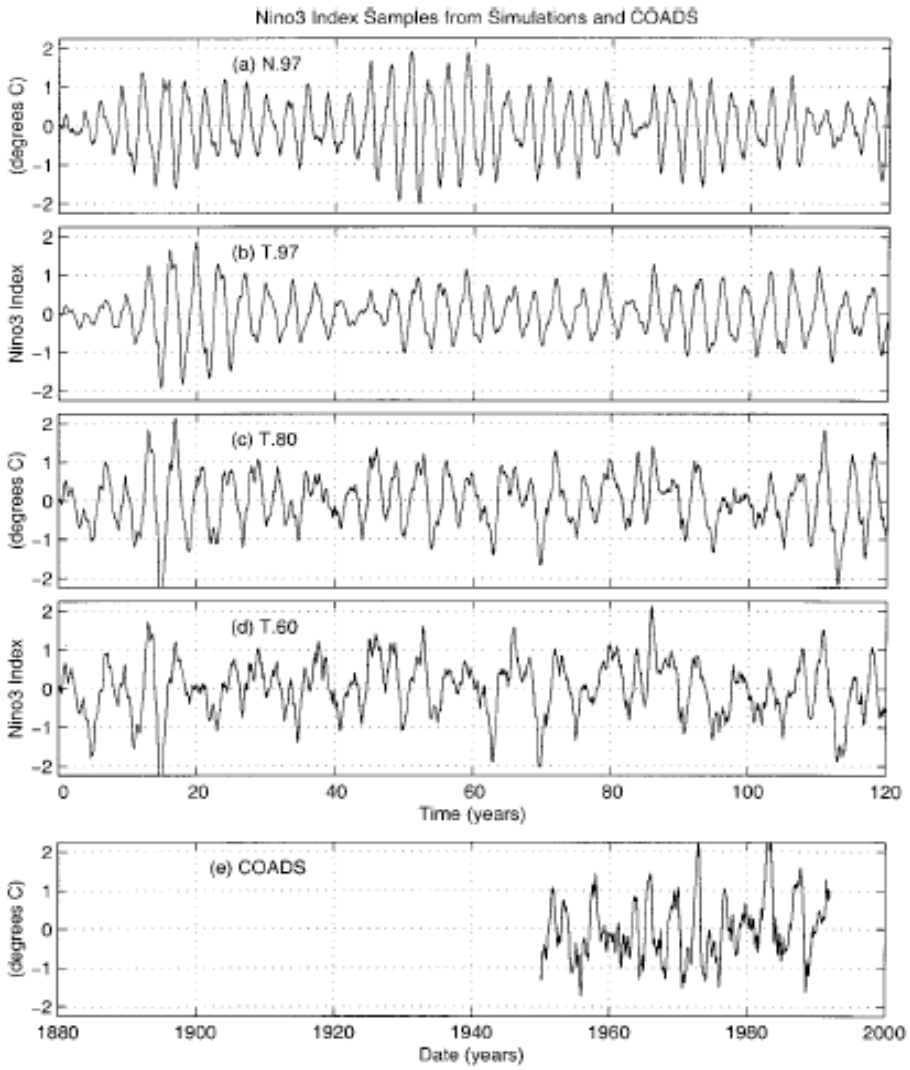


FIG. 2. Niño-3 index of first 120 yr of simulations plus COADS. (a)–(d) The Niño-3 index of the first 120 yr of the SSTA forced N.97, T.97, T.80, and T.60 simulations, respectively. (e) The Niño-3 index of the 42 yr of COADS data.

Noise Not Predictable but Details Matter

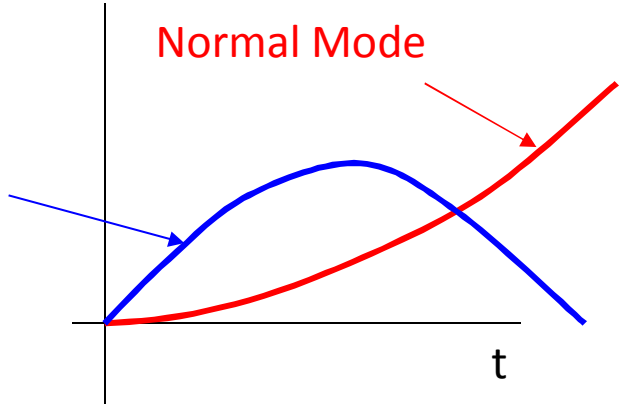
Thompson and Battisti 2001

Normality

$$\frac{d\vec{X}}{dt} = L\vec{X}$$

If *L* Normal then

$$L = S\Lambda S^T, S^T = S^{-1}, \Lambda = diag(\lambda_1, \ldots, \lambda_n)$$



$$S^T \vec{X}(t) = e^{\Lambda(t-t_o)} S^T \vec{X}(t_o)$$

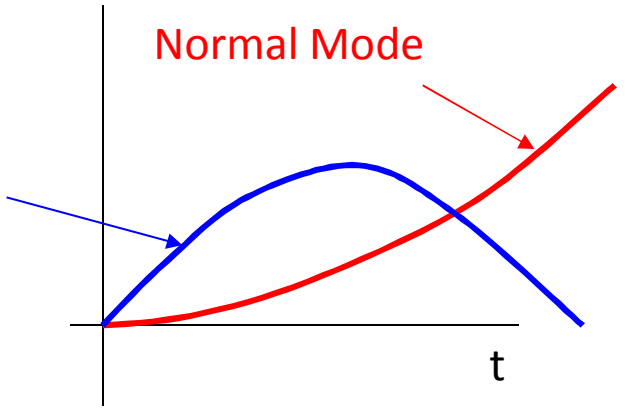
Fixed Spatial Structures Exponentially Growing in Time: Normal Modes

Non-Normality

$$\frac{d\vec{X}}{dt} = L\vec{X}$$

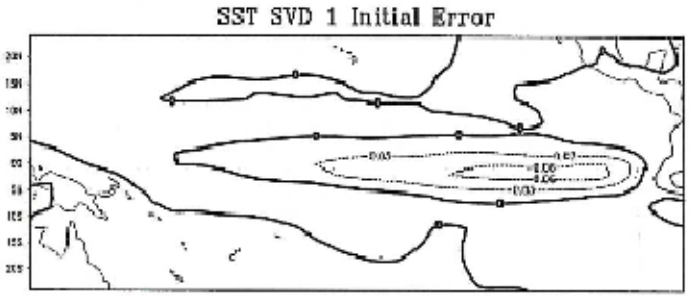
If *L* Non-Normal then

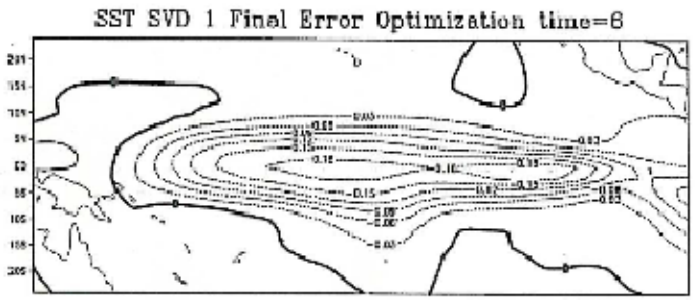
$$\vec{X}(t) = A\vec{X}(t_o),\ A \equiv e^{L(t-t_o)}$$



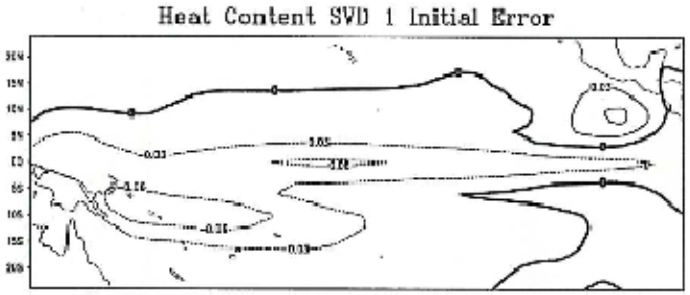
Eigenvalues of $A \neq L$ and Depend on $t\text{-}t_o$

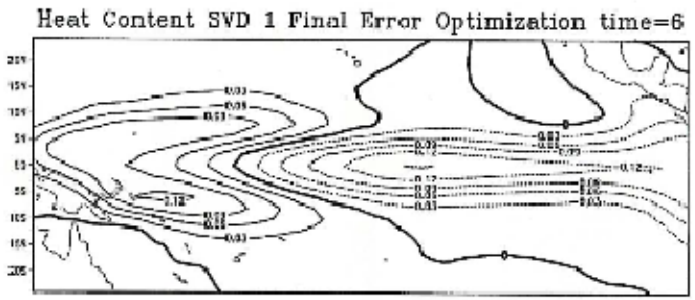
SST



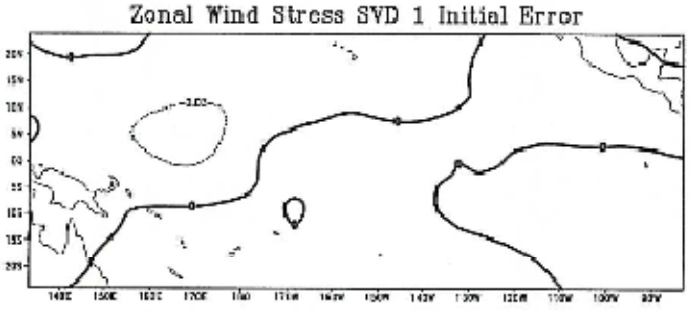


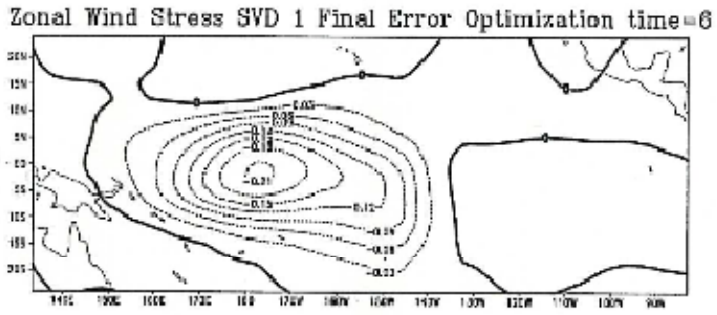
Heat Content





Zonal Stress



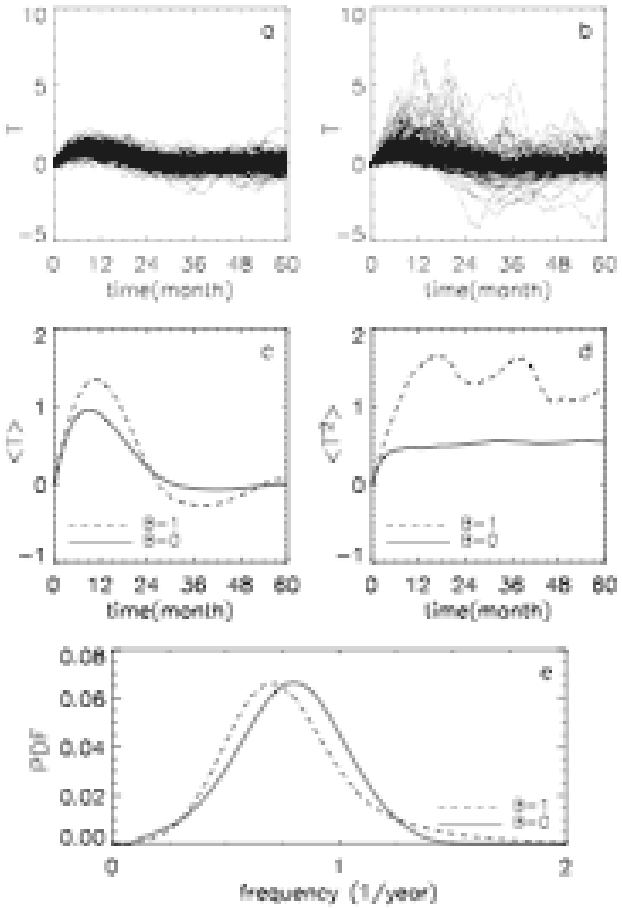


$$\frac{d\vec{X}}{dt} = L\vec{X}$$

L Non-Normal, Singular Vectors

Multiplicative Noise

$$\frac{d\vec{X}}{dt} = L\vec{X} + N\vec{X}$$

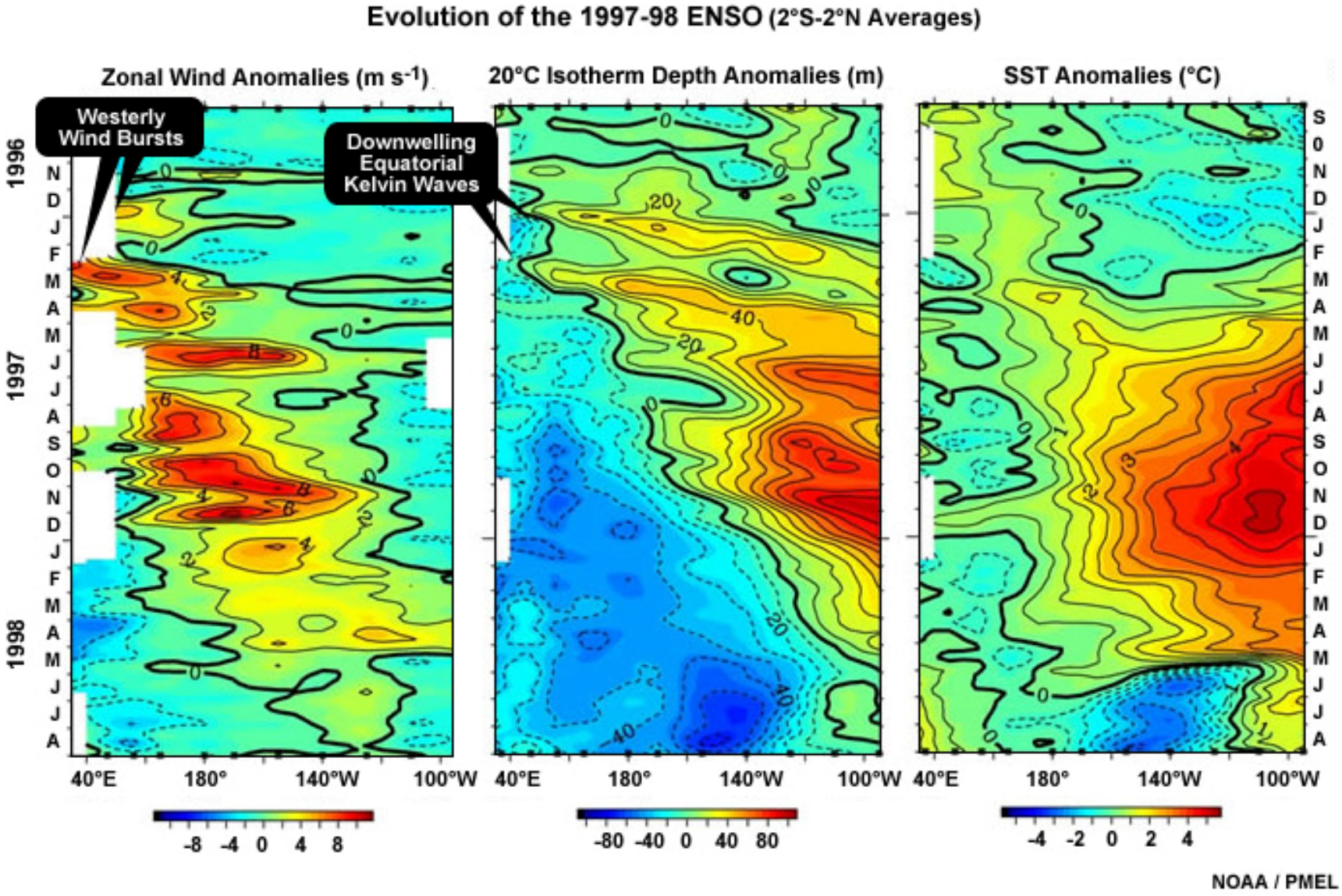


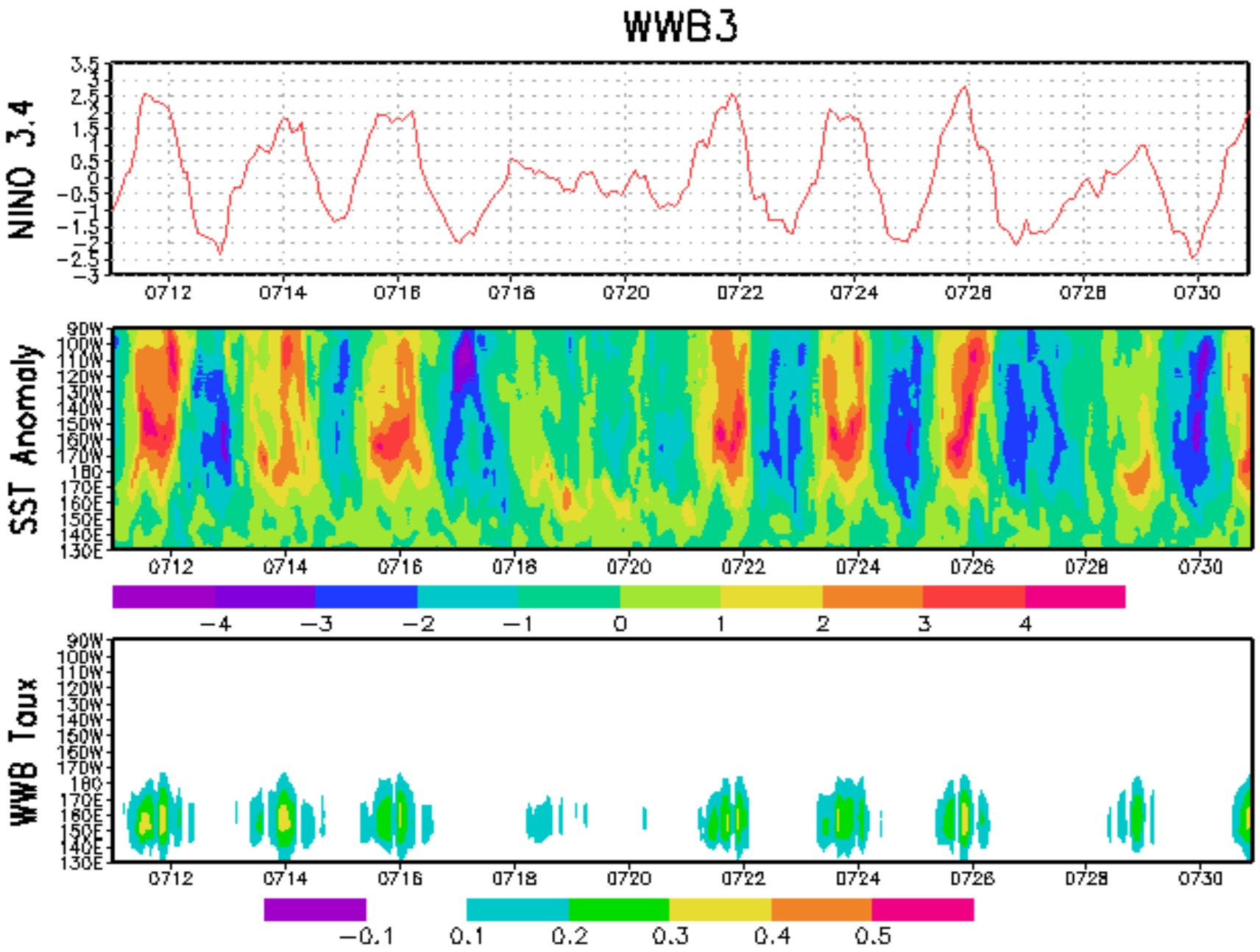
Increasing Spread and Skewness

Jin et al. 2007

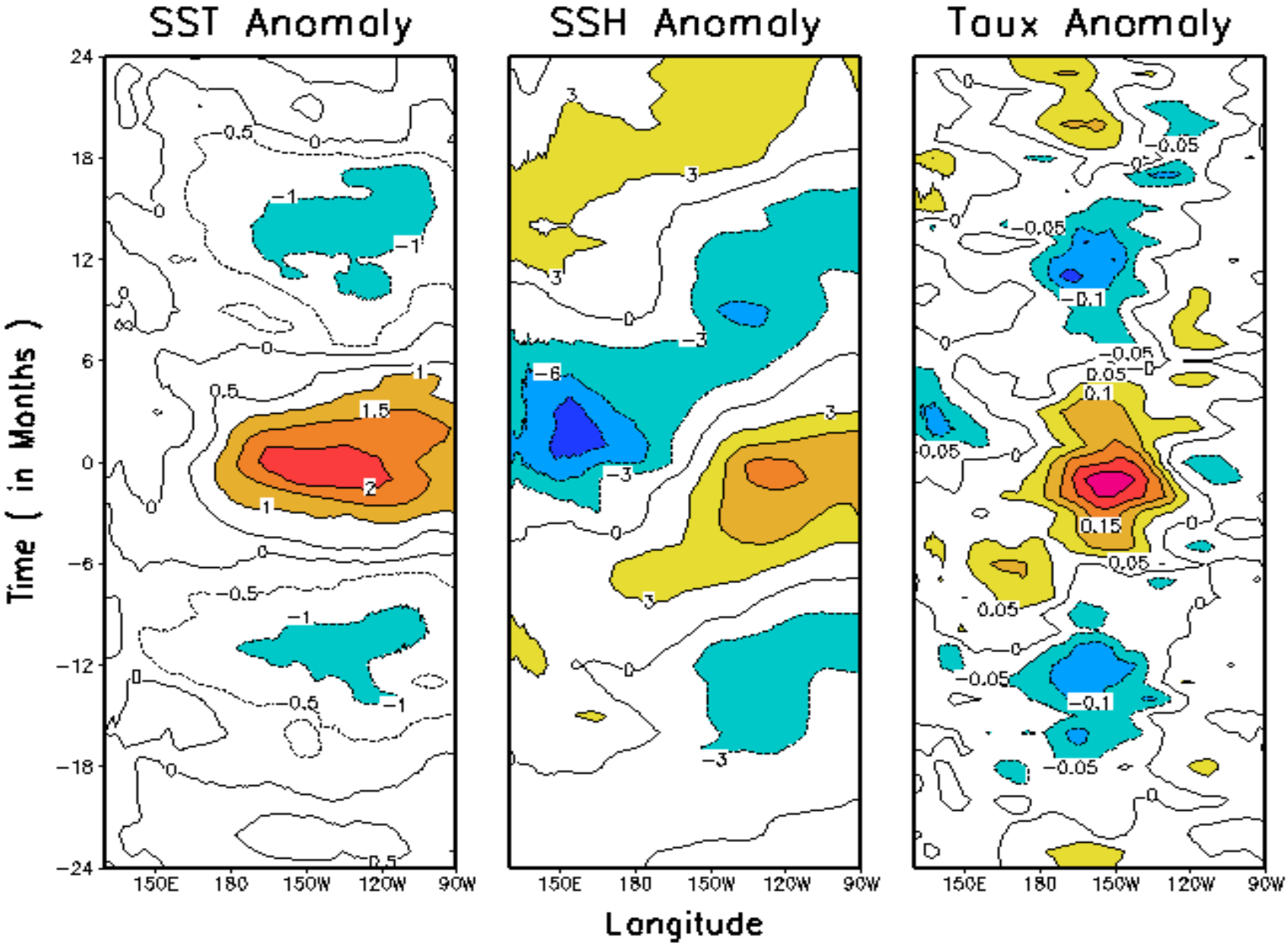
Westerly Wind Burst – Multiplicative Noise

$$\frac{d\vec{X}}{dt} = L\vec{X} + N\vec{X}$$

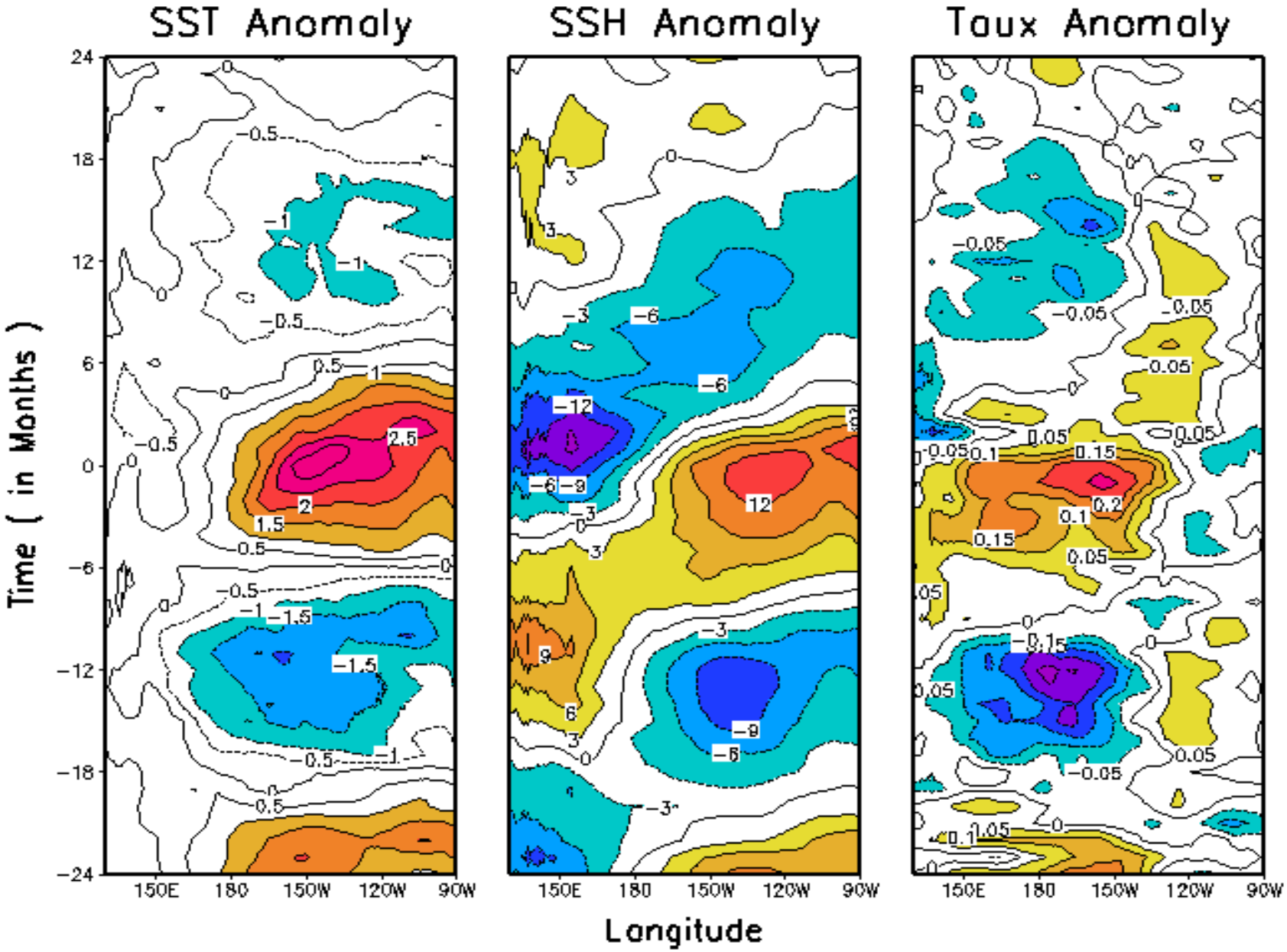


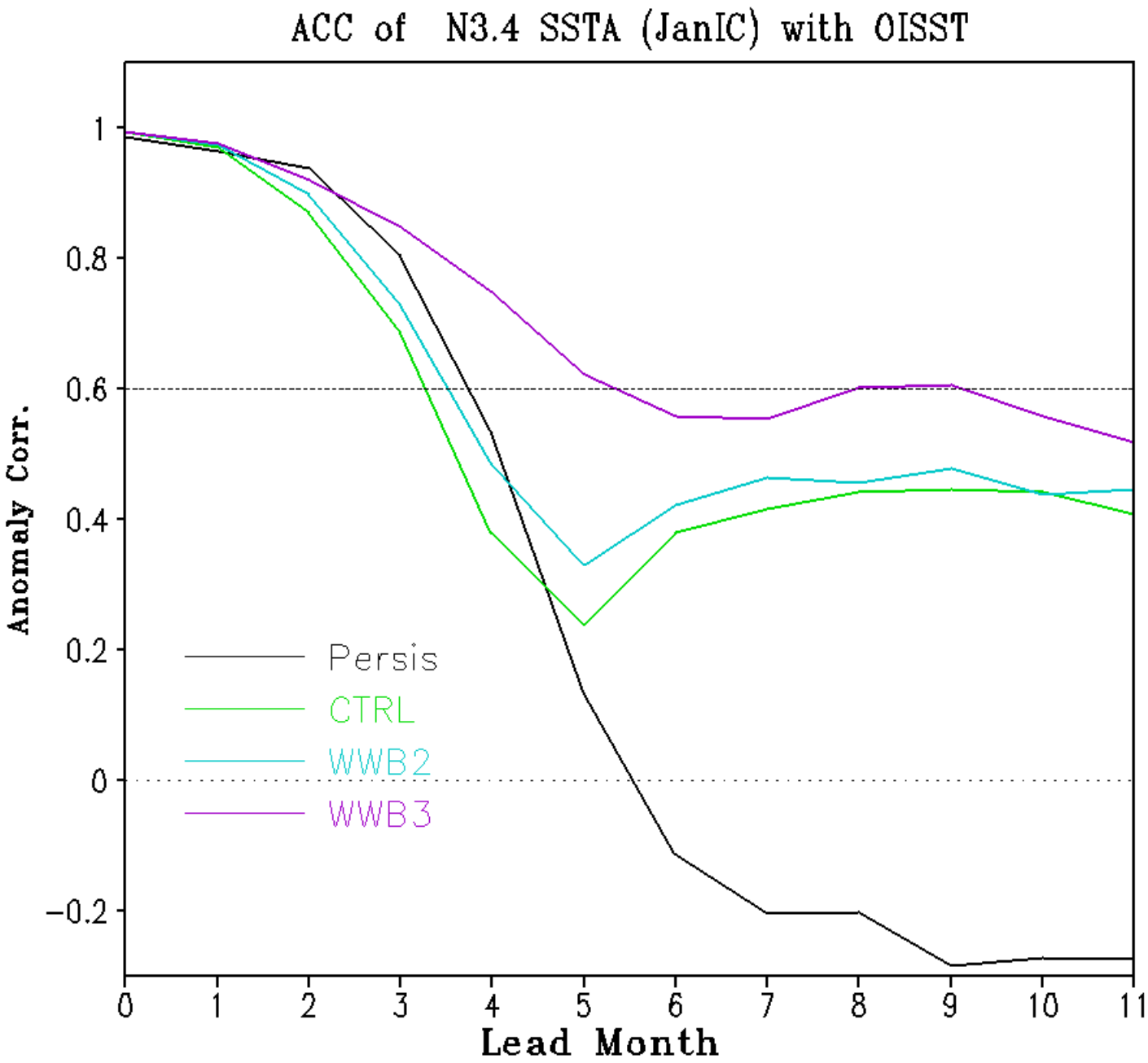

WWB3
NINO 3.4
3.5
2.5
1.5
0.5
-0.5
-1.5
-2.5
0712
0714
0716
0718
0720
0722
0724
0726
0728
0730
SST Anomaly
90W
100W
110W
120W
130W
140W
150W
160W
170W
180
170E
160E
150E
140E
130E
−4
−3
−2
−1
0
1
2
3
4
WWB Taux
−0.1
0.1
0.2
0.3
0.4
0.5

Top 5 Warm Events (Ensemble Mean) for NoOMP



Top 5 Warm Events (Ensemble Mean) for WWB3

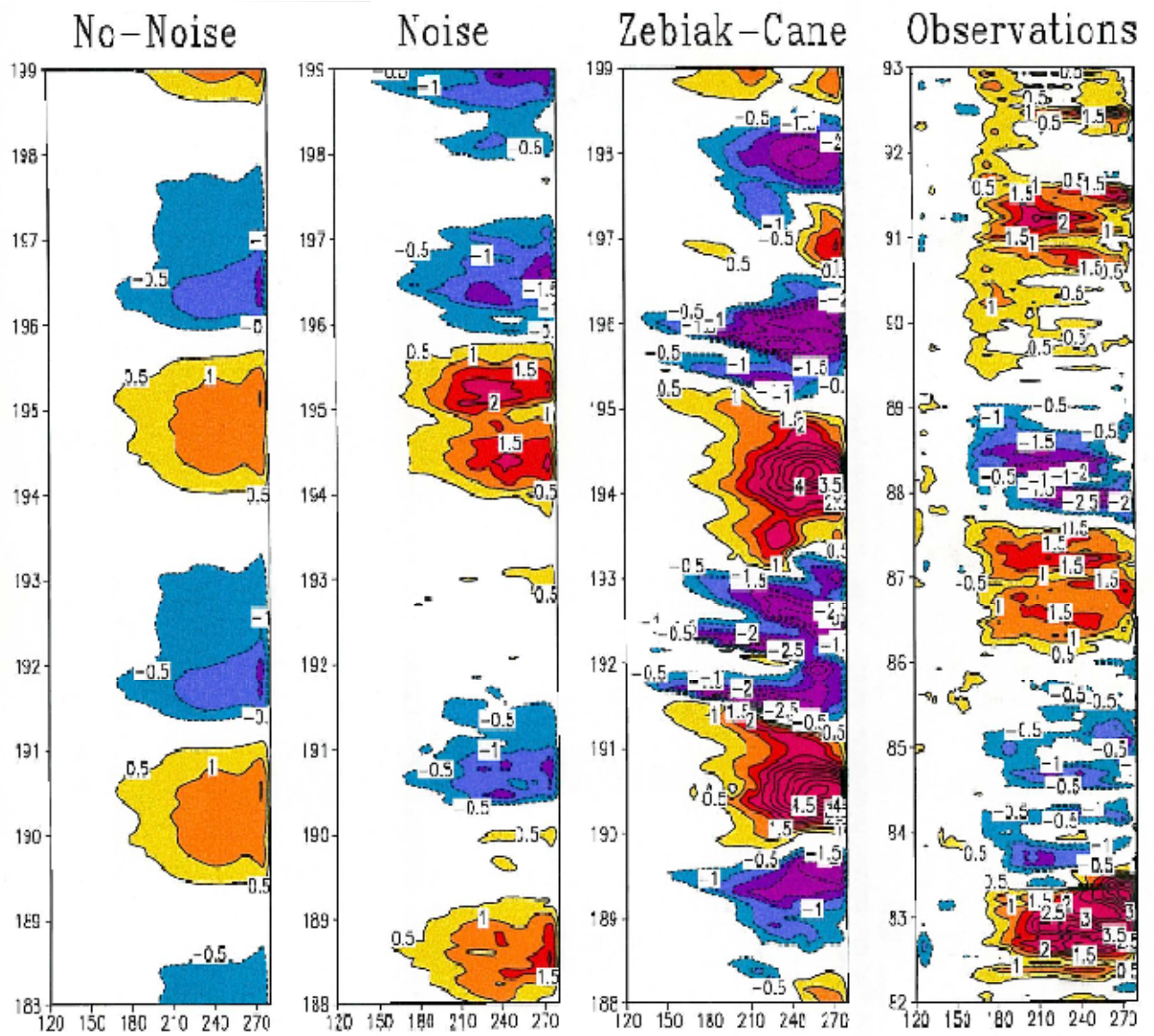



ACC of N3.4 SSTA (JanIC) with OISST
Anomaly Corr.
1
0.8
0.6
0.4
0.2
0
-0.2
0
1
2
3
4
5
6
7
8
9
10
11
Lead Month
Persis
CTRL
WWB2
WWB3

Non-Linearly Self Sustained:

$$\frac{d\vec{X}}{dt} = G(\vec{X}) + \vec{N}$$

Non-Linearity Fundamental, but Details of Noise Not Important

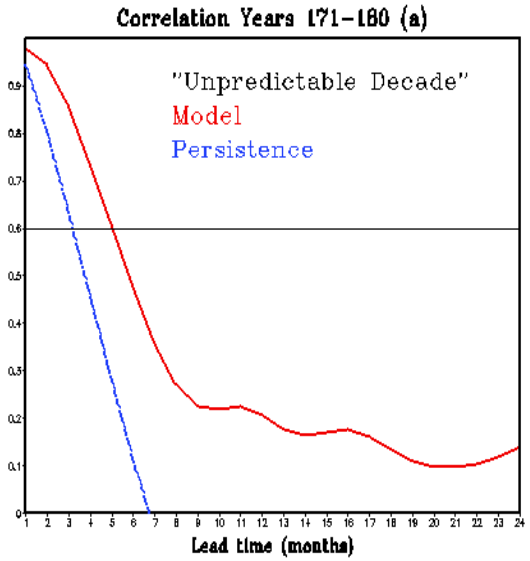


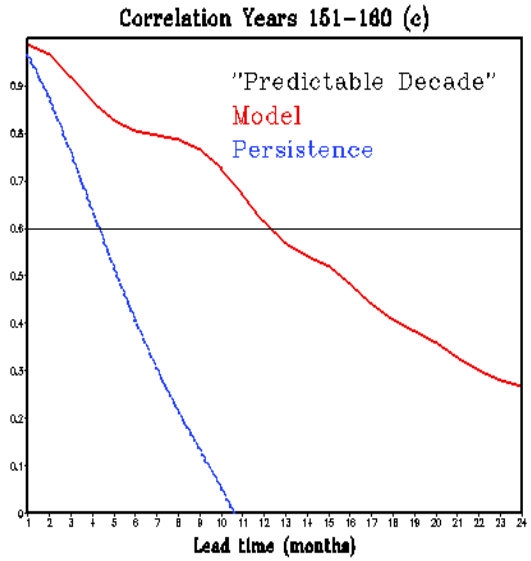
Kirtman and Schopf 1998

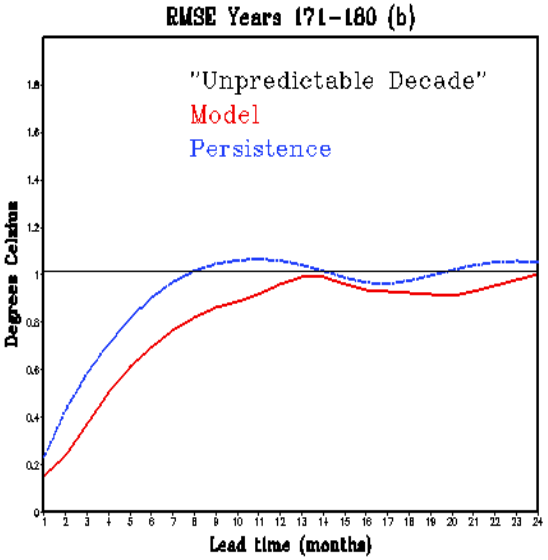
Middle Ground:

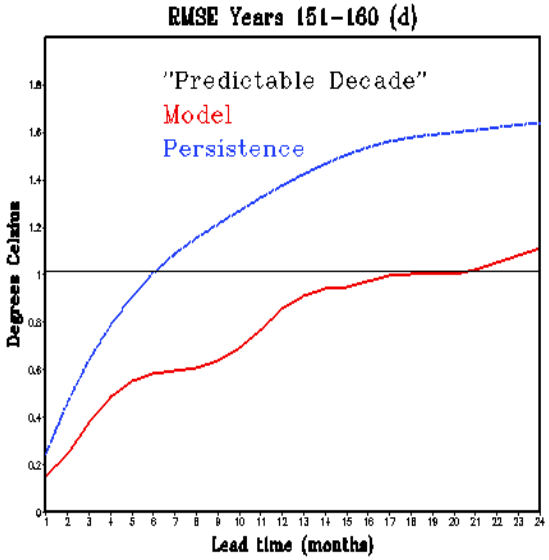
$$\frac{d\vec{X}}{dt} = G(\vec{X}) + \vec{N}$$

Non-Linearity Fundamental, but Details of Noise Not Important



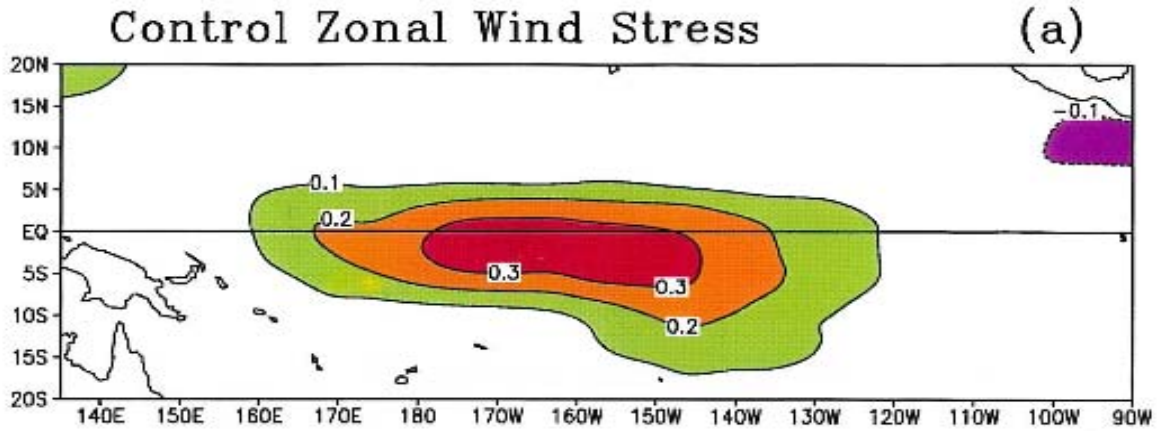




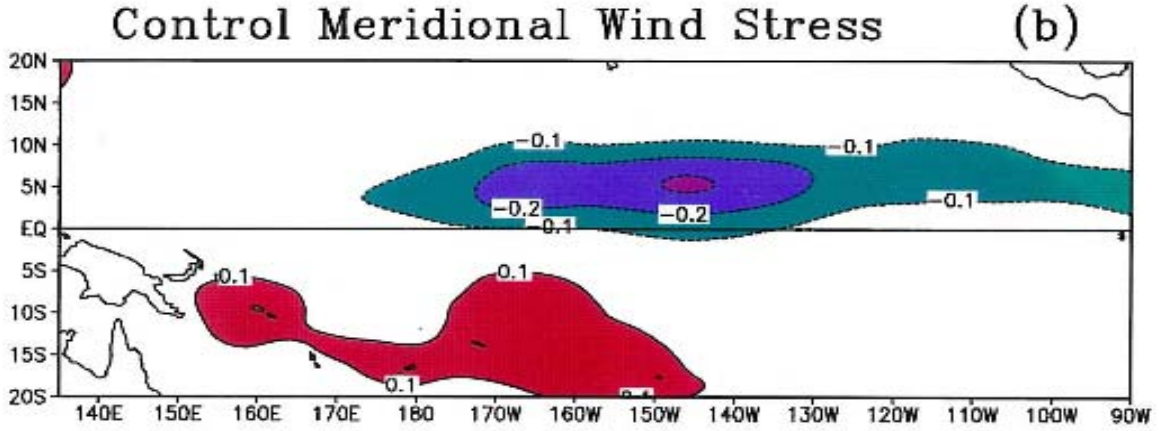


An Even Simpler Coupled Model

α(x,y)



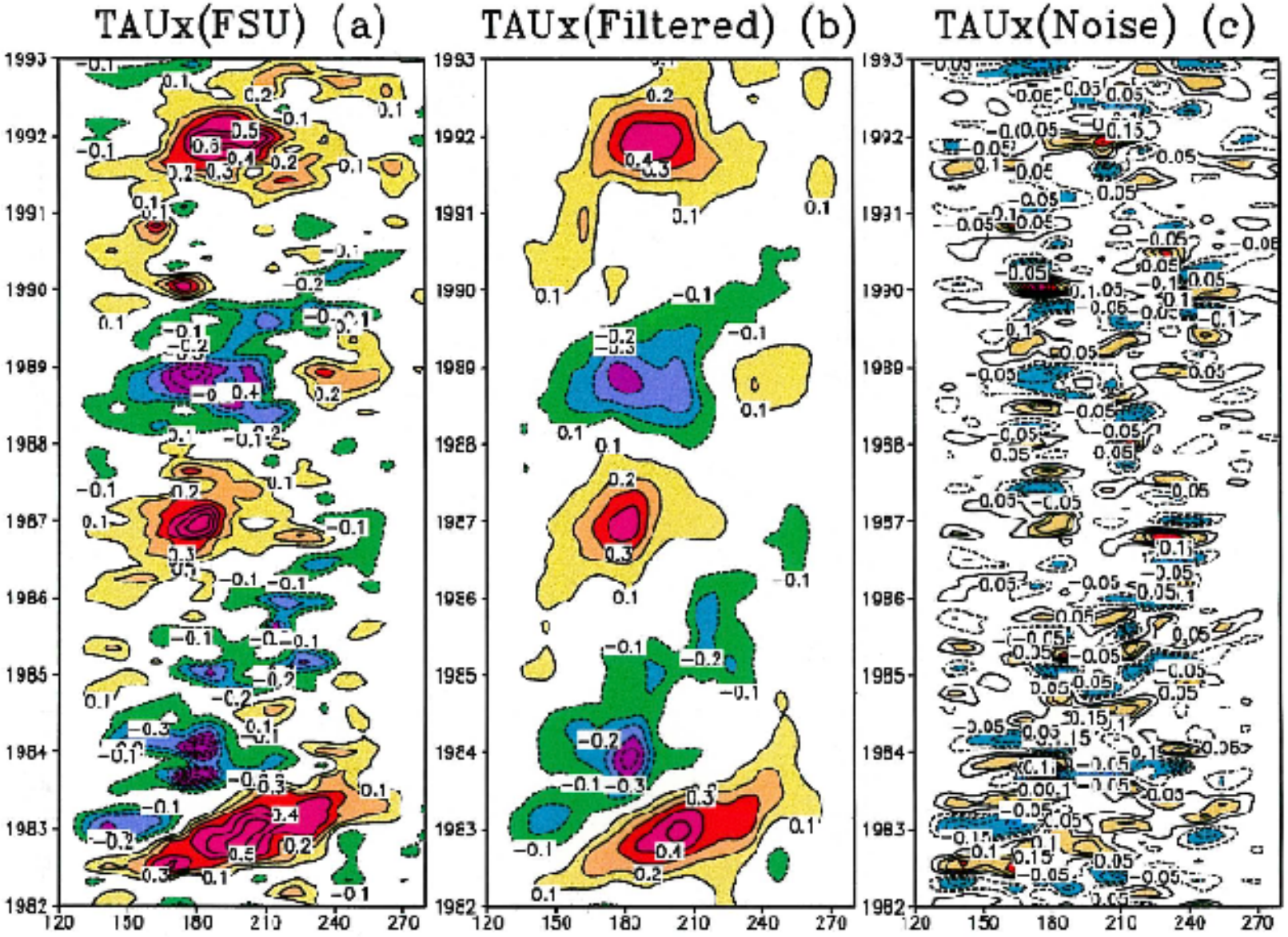
β(x,y)

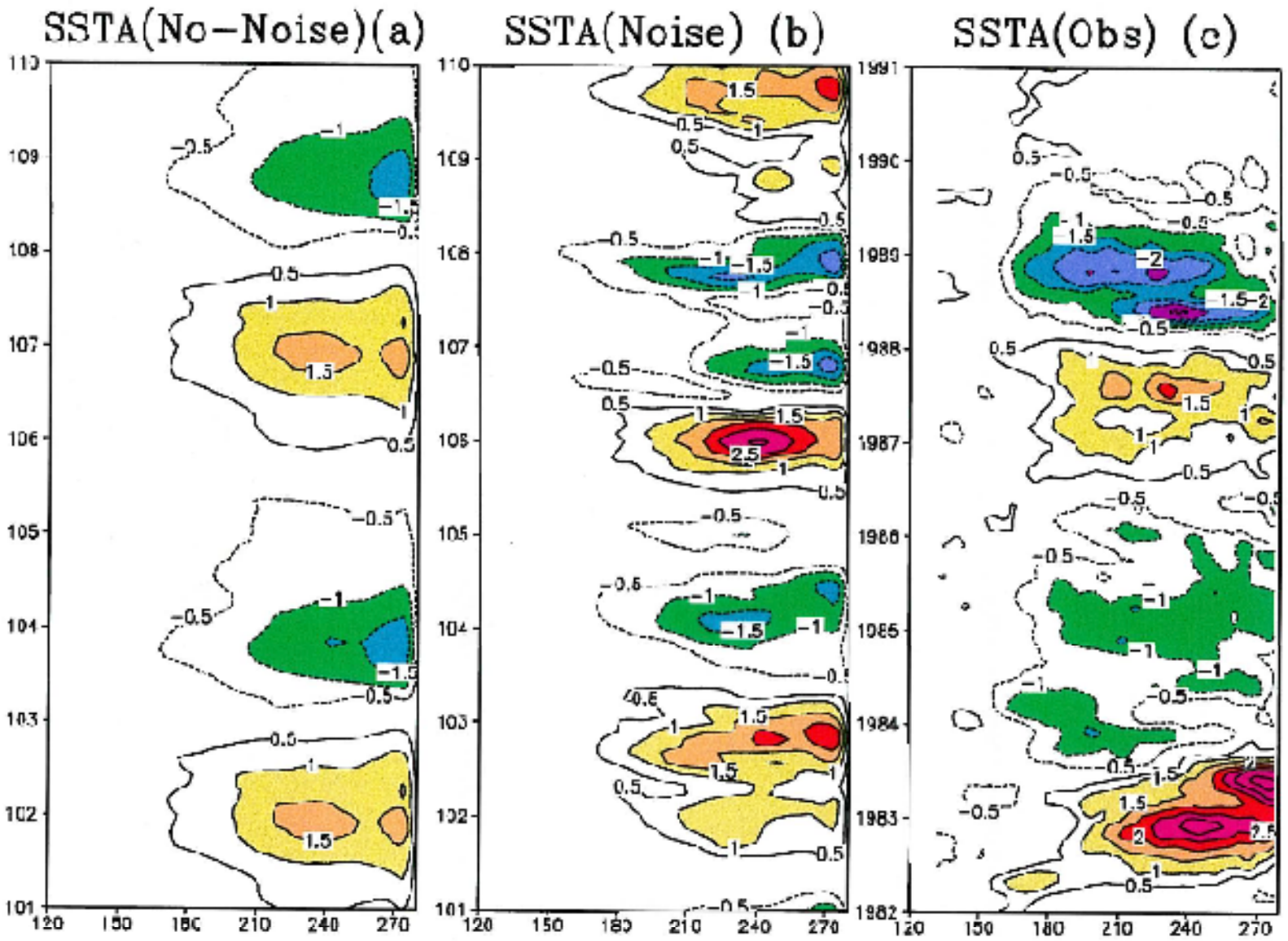


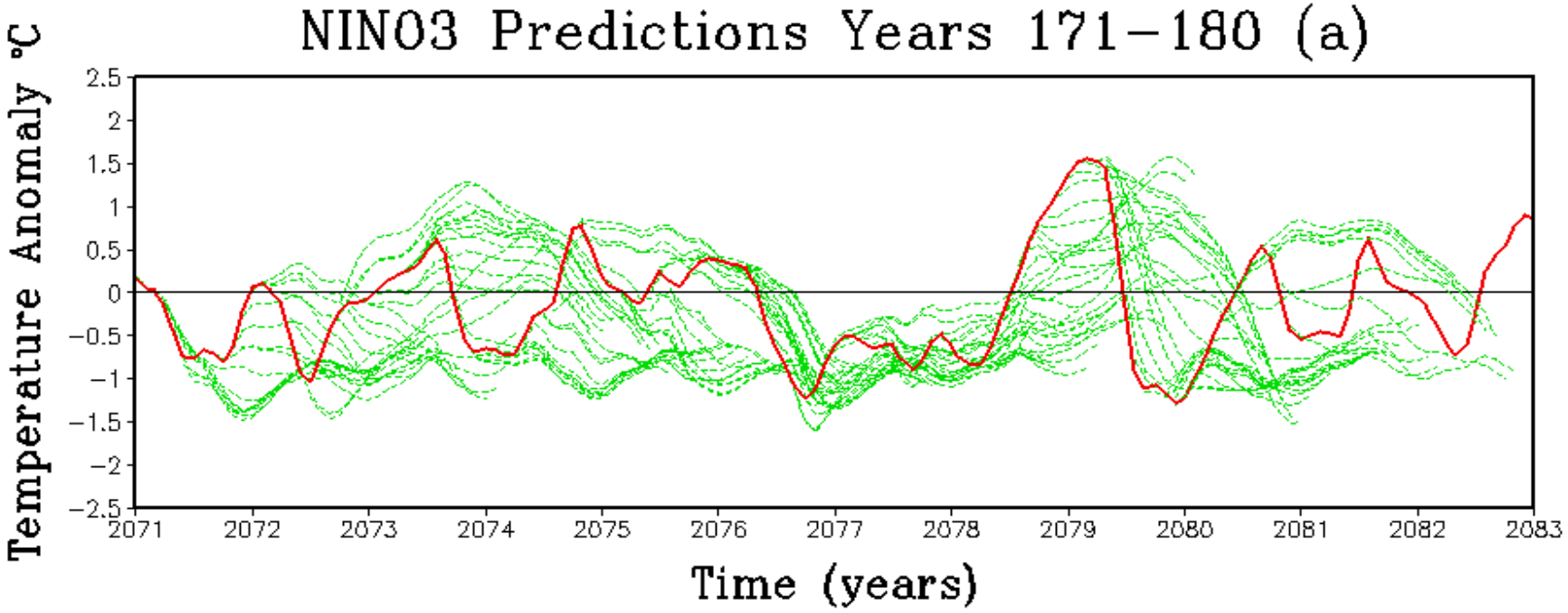
$$\tau_x(x,y) = \alpha(x,y) * NINO3$$

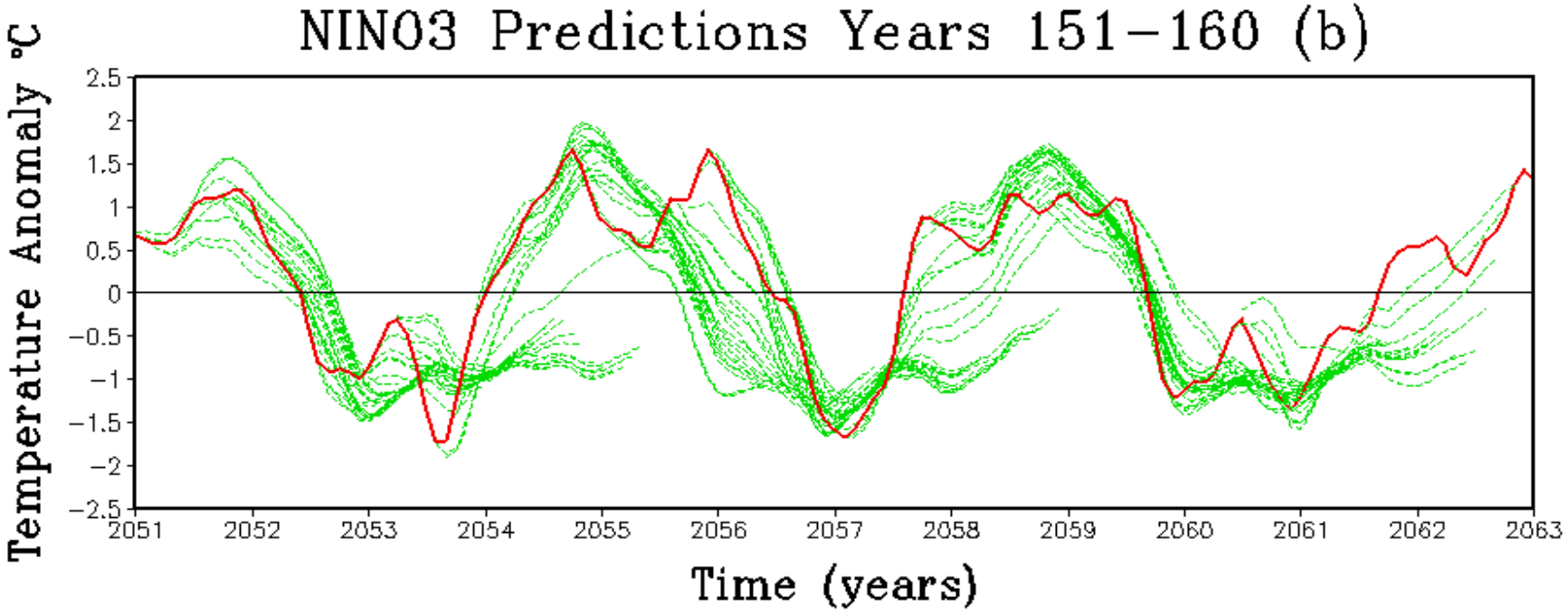
$$\tau_y(x,y) = \beta(x,y) * NINO3$$

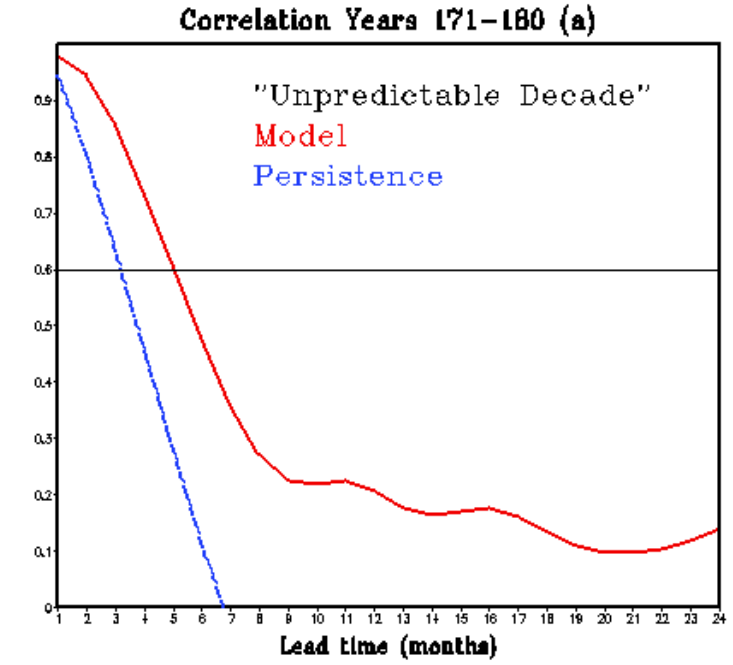
Estimating the "Noise"

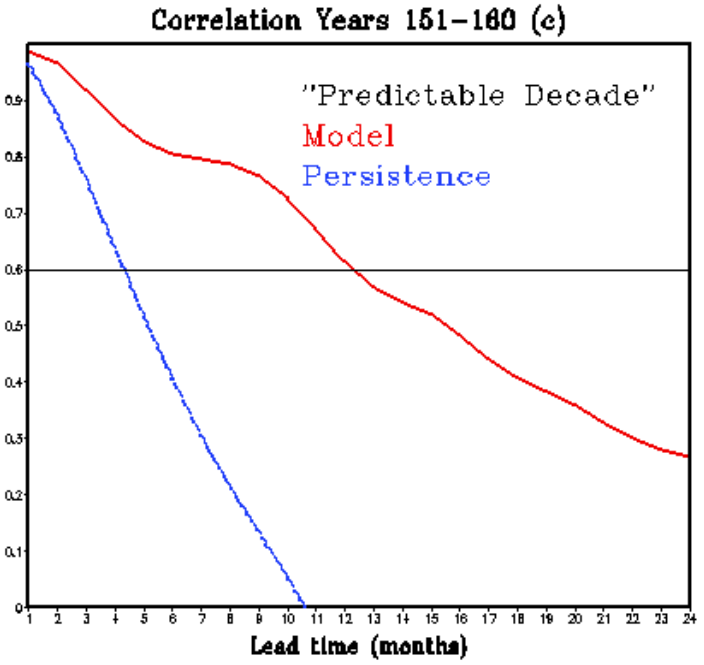


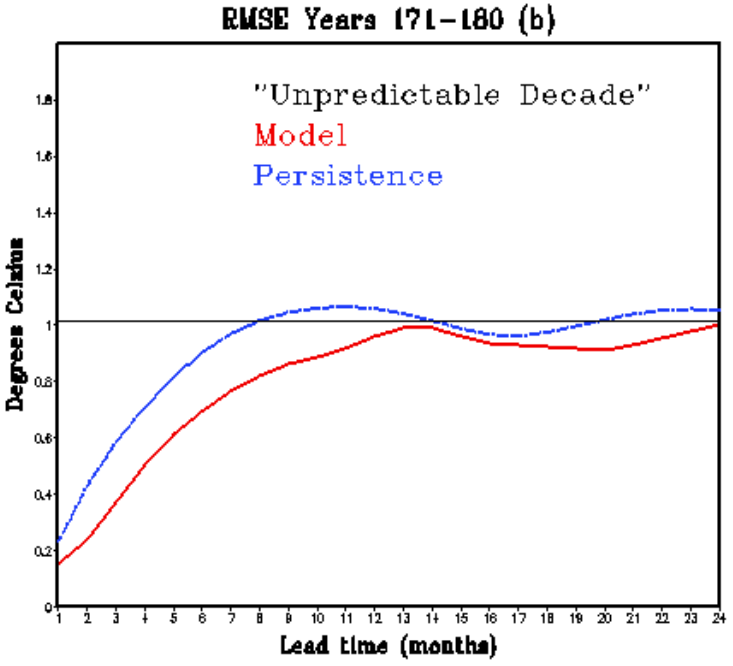

SSTA(No-Noise)(a)
SSTA(Noise) (b)
SSTA(Obs) (c)
120
150
180
210
240
270

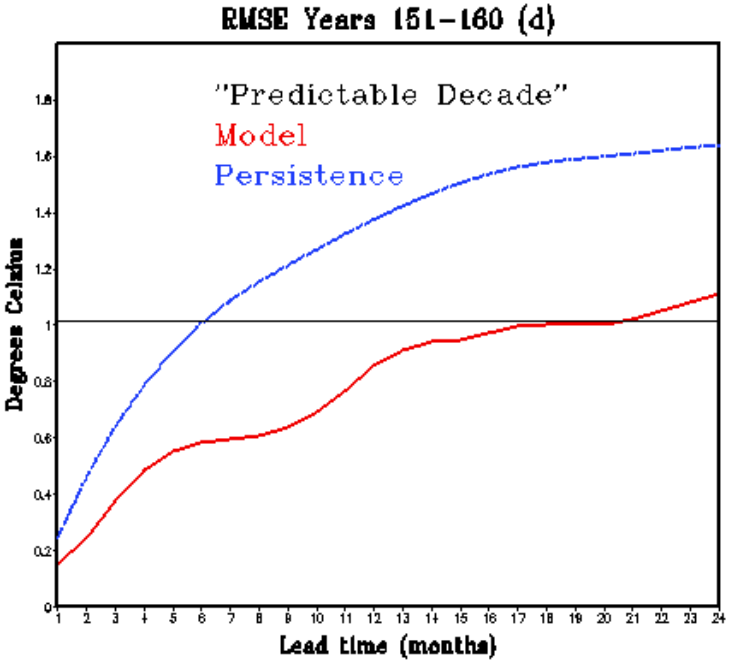

NINO3 Predictions Years 171–180 (a)
Temperature Anomaly °C
2.5
2
1.5
1
0.5
0
−0.5
−1
−1.5
−2
−2.5
2071
2072
2073
2074
2075
2076
2077
2078
2079
2080
2081
2082
2083
Time (years)


NINO3 Predictions Years 151–160 (b)
Temperature Anomaly °C
2.5
2
1.5
1
0.5
0
−0.5
−1
−1.5
−2
−2.5
2051
2052
2053
2054
2055
2056
2057
2058
2059
2060
2061
2062
2063
Time (years)

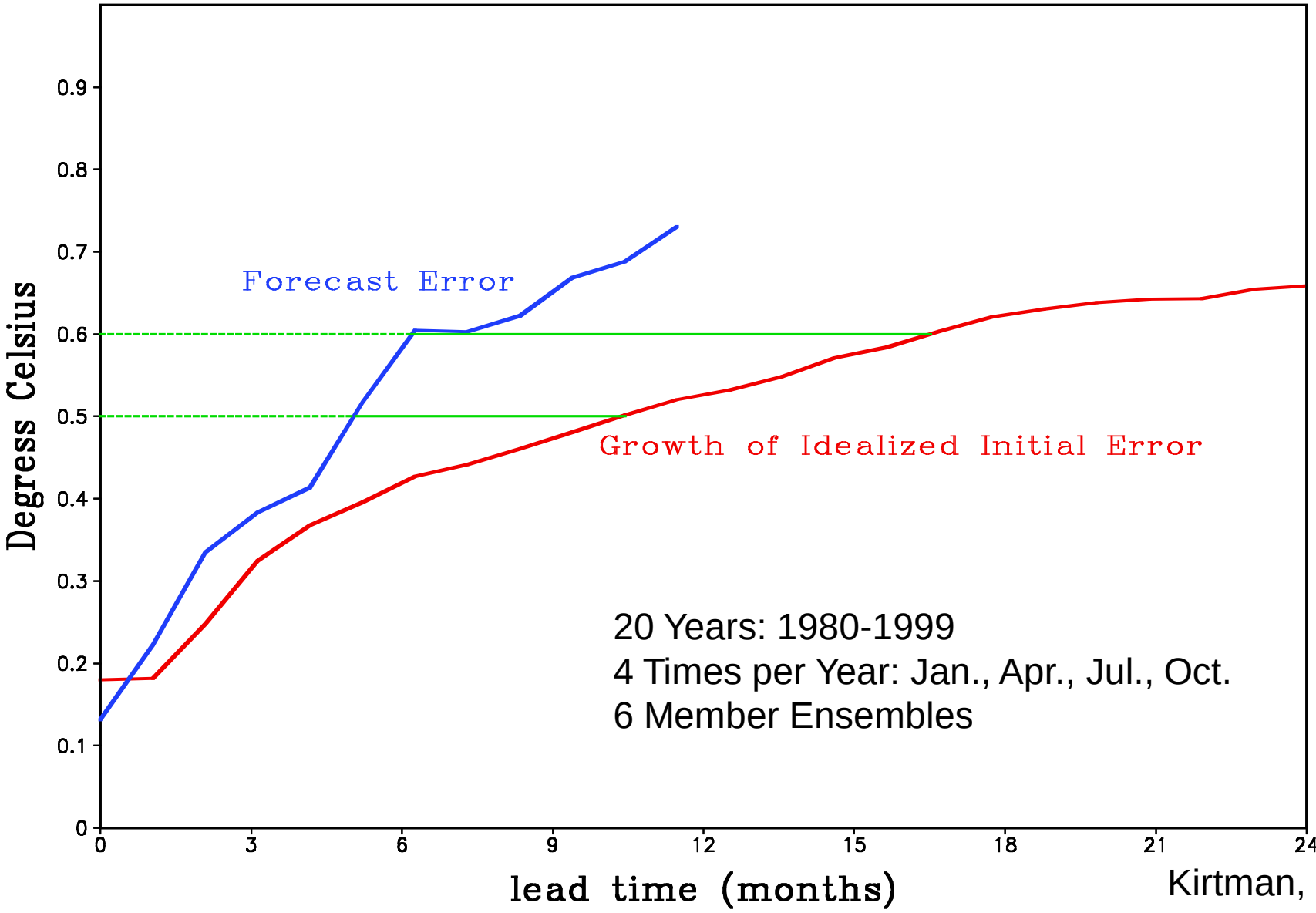

Correlation Years 171-180 (a)
"Unpredictable Decade"
Model
Persistence
Lead time (months)


Correlation Years 151-160 (c)
"Predictable Decade"
Model
Persistence
Lead time (months)


RMSE Years 171-180 (b)
"Unpredictable Decade"
Model
Persistence
Degrees Celsius
Lead time (months)


RMSE Years 151-160 (d)
"Predictable Decade"
Model
Persistence
Degrees Celsius
Lead time (months)

Current Limit of Predictability of ENSO (Nino3.4)
Potential Limit of Predictability of ENSO



Kirtman, 2003

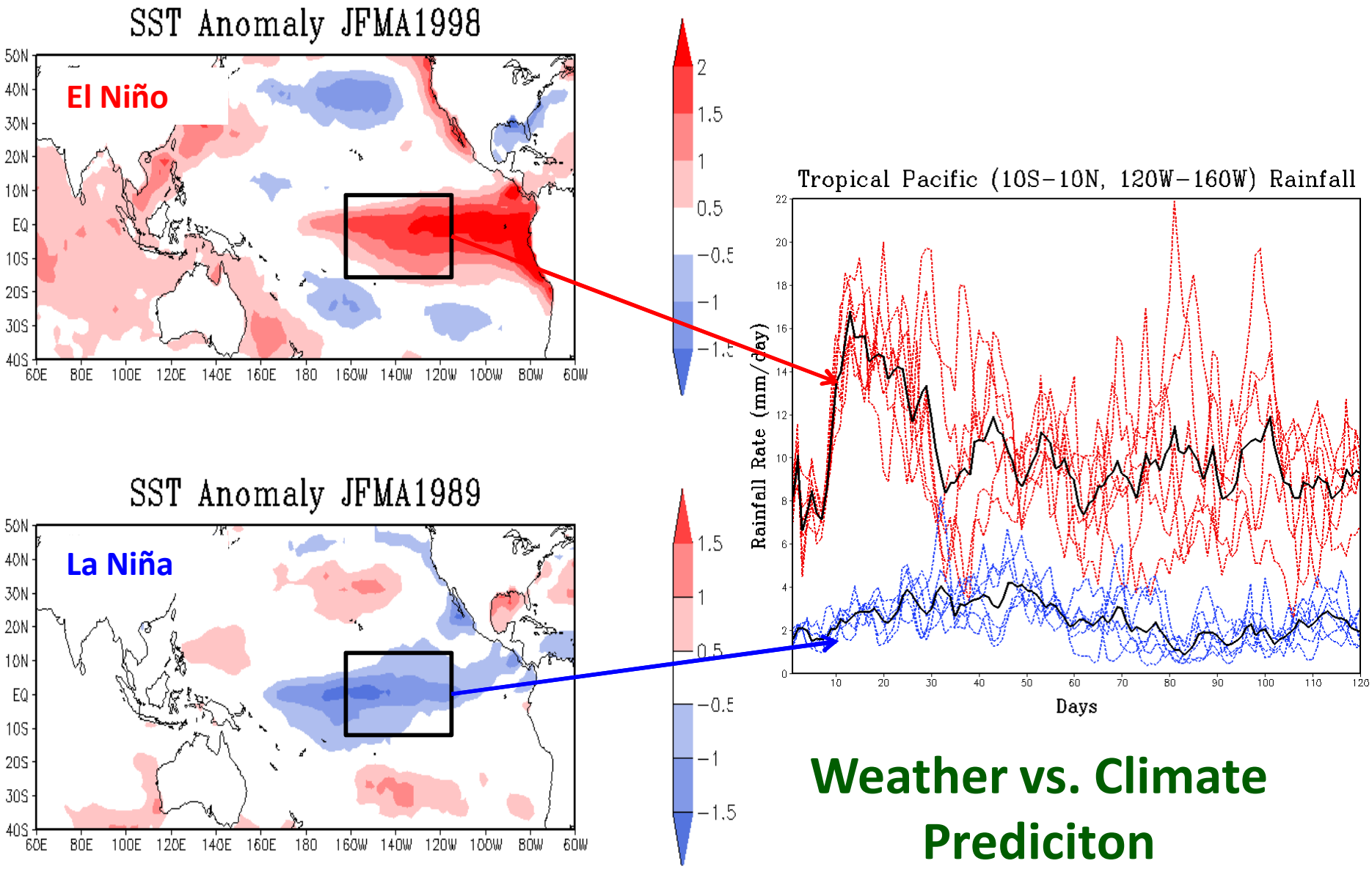
ENSO: Chaotic or Stochastically Forced?

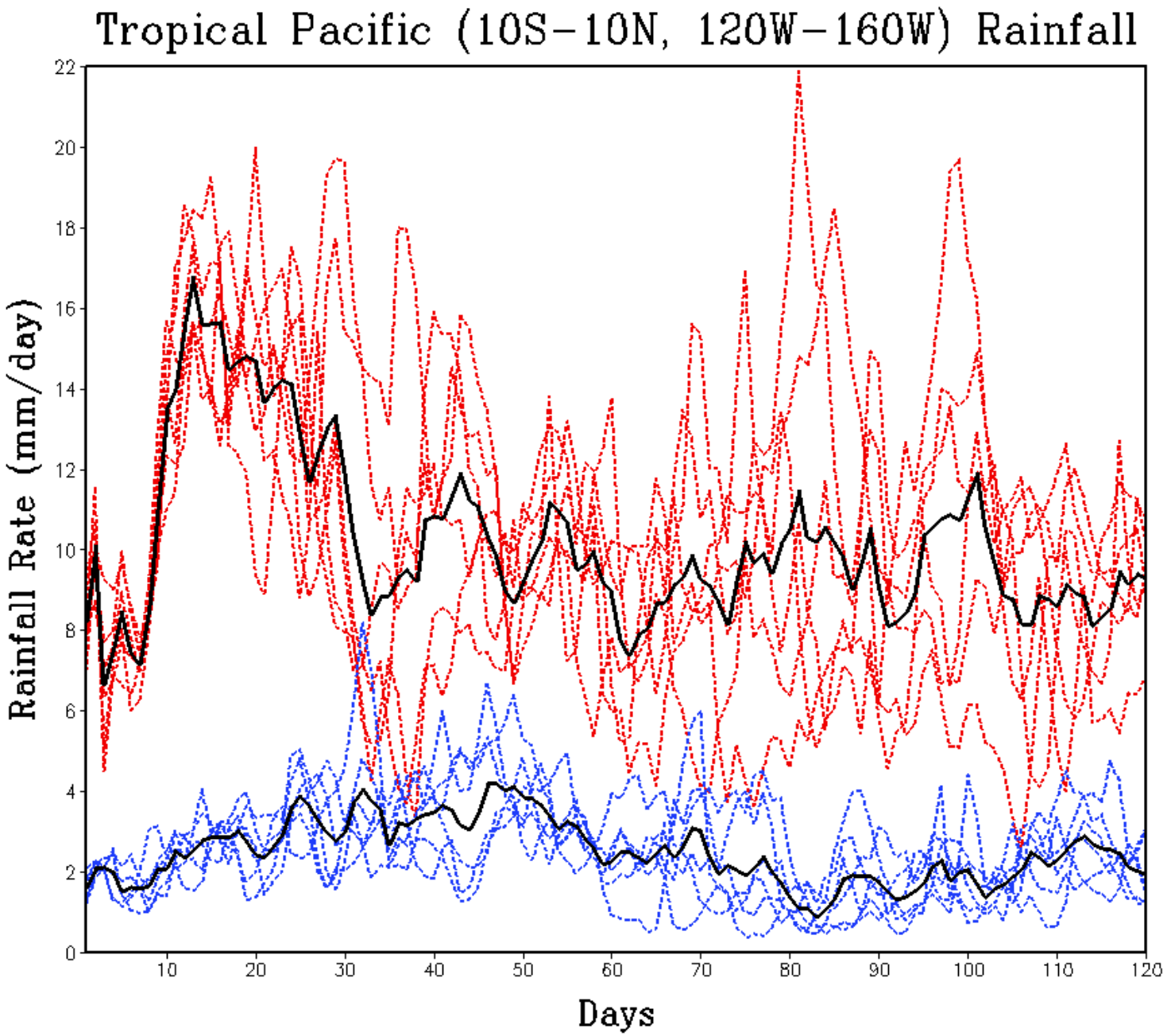
- **Stochastically Forced**
  - Linear Dynamics
  - Non-Linearity → Noise
  - Noise Amplitude Unrelated to Signal
  - Non-Normality and Spatial Structure of Noise
- **Limit of Predictability (~12 Months)**
- **Variations in Predictability and ENSO Amplitude Modulation Random**

- **Chaotic**
  - Fundamental Non-Linearity
  - Non-Linear Control of Growth
  - Details of Noise Relatively Unimportant
  - Signal and Noise Amplitude Dependence
- **Limit of Predictability (~18 Months)**
- **Variations in Predictability and ENSO Amplitude Modulation Fundamental**

Prediction

- What Do We Mean By Climate Prediction?
- What Are The Ingredients Of A Climate Prediction System?
- Example: CCSM3 and CFS – Initial Condition Uncertainty
- Example: NMME – Initial Condition Uncertainty and Model Formulation Uncertainty


SST Anomaly JFMA1998
El Niño
SST Anomaly JFMA1989
La Niña
Tropical Pacific (10S-10N, 120W-160W) Rainfall
Rainfall Rate (mm/day)
Days
Weather vs. Climate
Prediciton


Tropical Pacific (10S-10N, 120W-160W) Rainfall
Rainfall Rate (mm/day)
Days
0
2
4
6
8
10
12
14
16
18
20
22
10
20
30
40
50
60
70
80
90
100
110
120

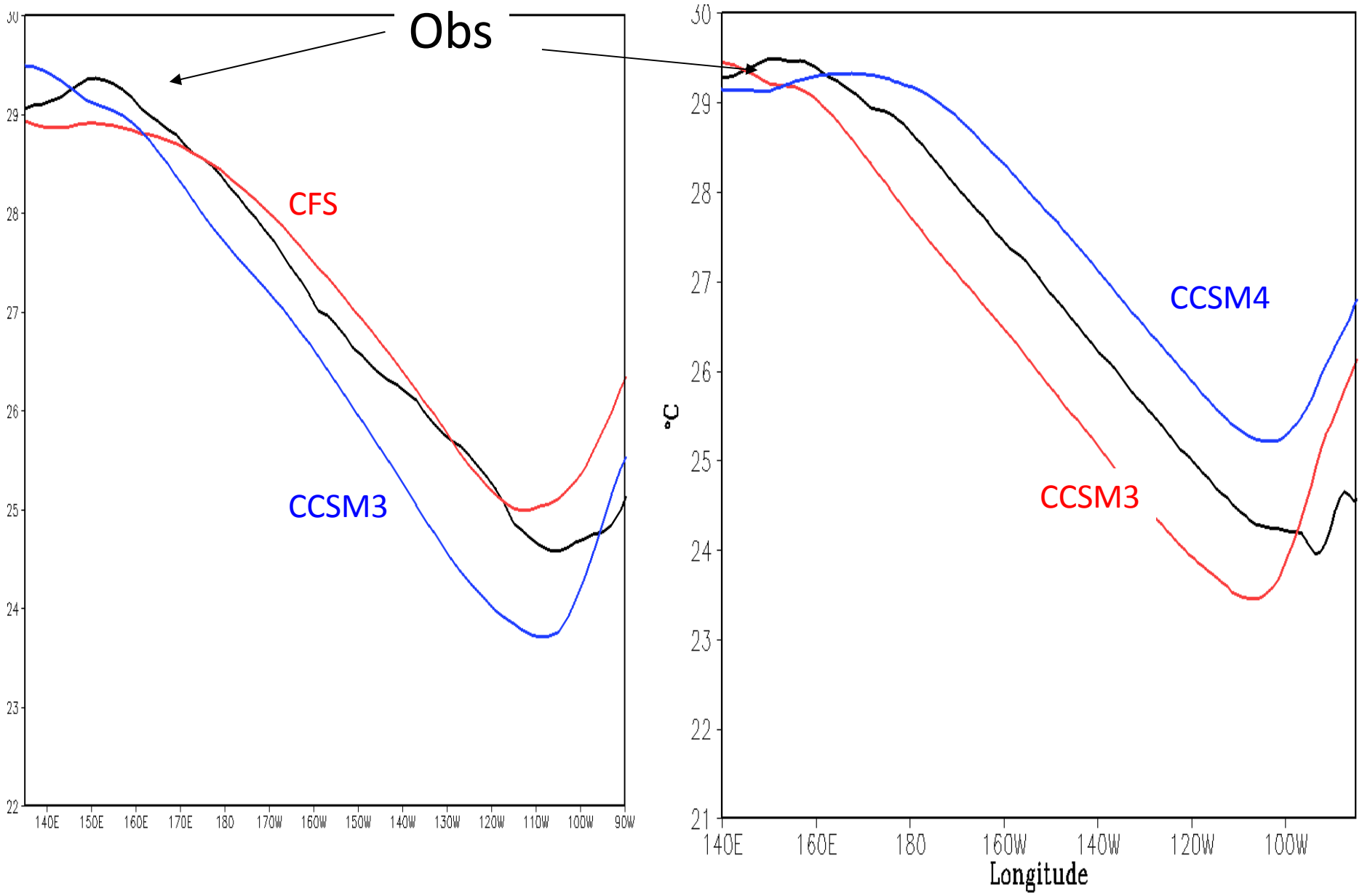
What is a Climate Prediction System?

- **Models**
  - Atmosphere-Ocean-Land-Ice
  - Fidelity of the Model
- **Data for Initial Conditions and Verification**
  - Observing System (i.e., the data)
  - Techniques for Using the Data as Initial Conditions
    - Data Assimilation (uncoupled and coupled)
- **Quantifying Uncertainty in Forecast**
  - Initial Condition Uncertainty: Ensembles
  - Model Formulation Uncertainty: Multi-Model Ensembles
    - Perturbed Physics, Stochastic Physics, …
- **Retrospective Forecasts!**
  - Assessing Forecast Quality

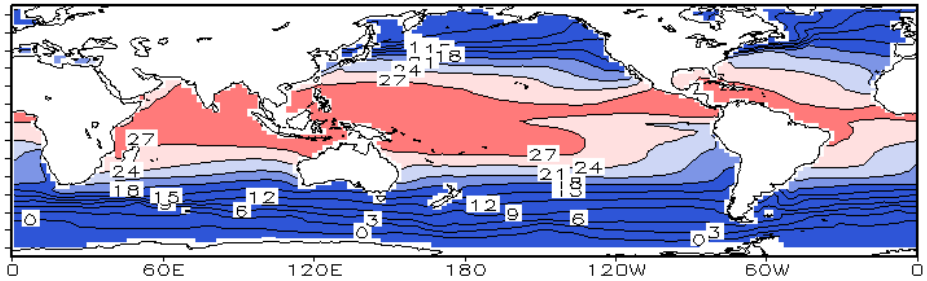
Comparing Two Prediction Systems

- CCSM3 ⟹ CCSM4 (NCAR Model)
- CFS (NOAA Climate Forecast System)
- Six Member Ensembles … Quantifying Initial Condition Uncertainty

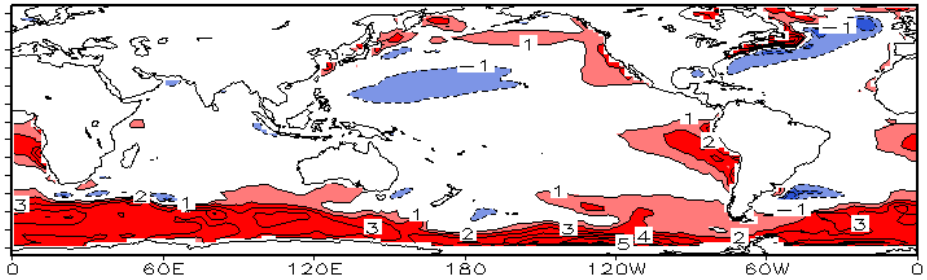
Equatorial Pacific SST



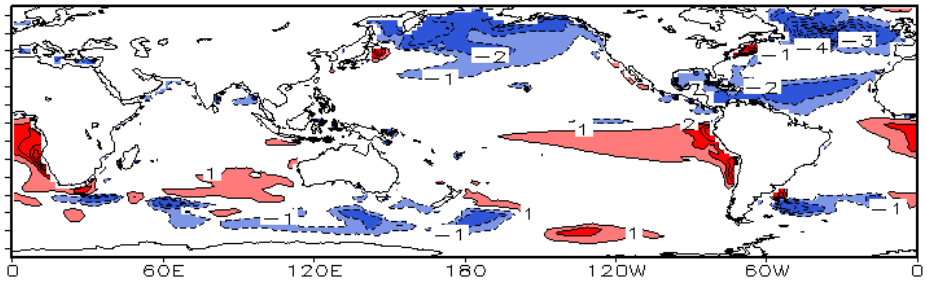
Annual Mean Sea Surface Temperature



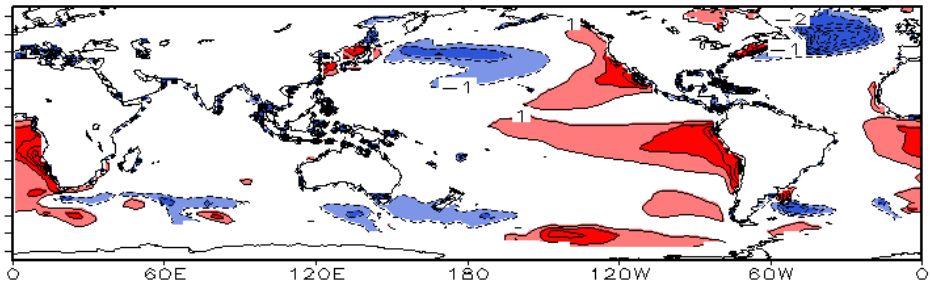
Observational Estimate



CFS



CCSM3

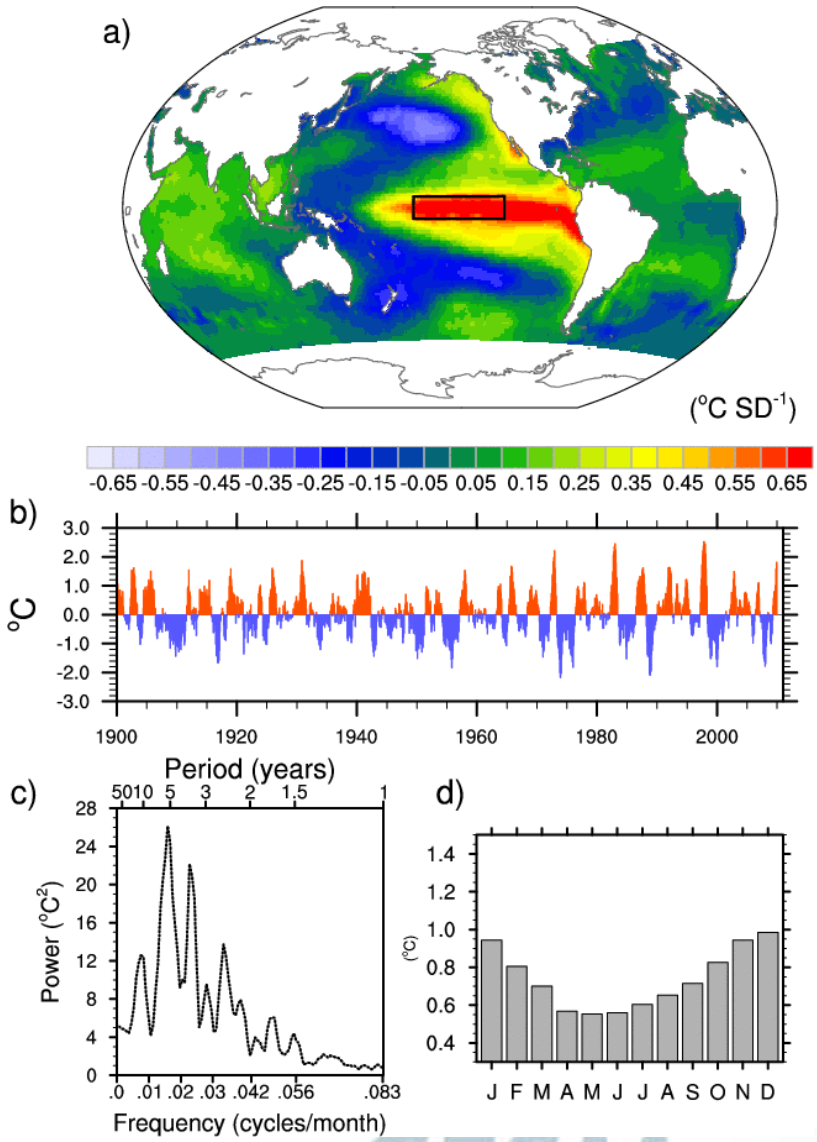


CCSM4

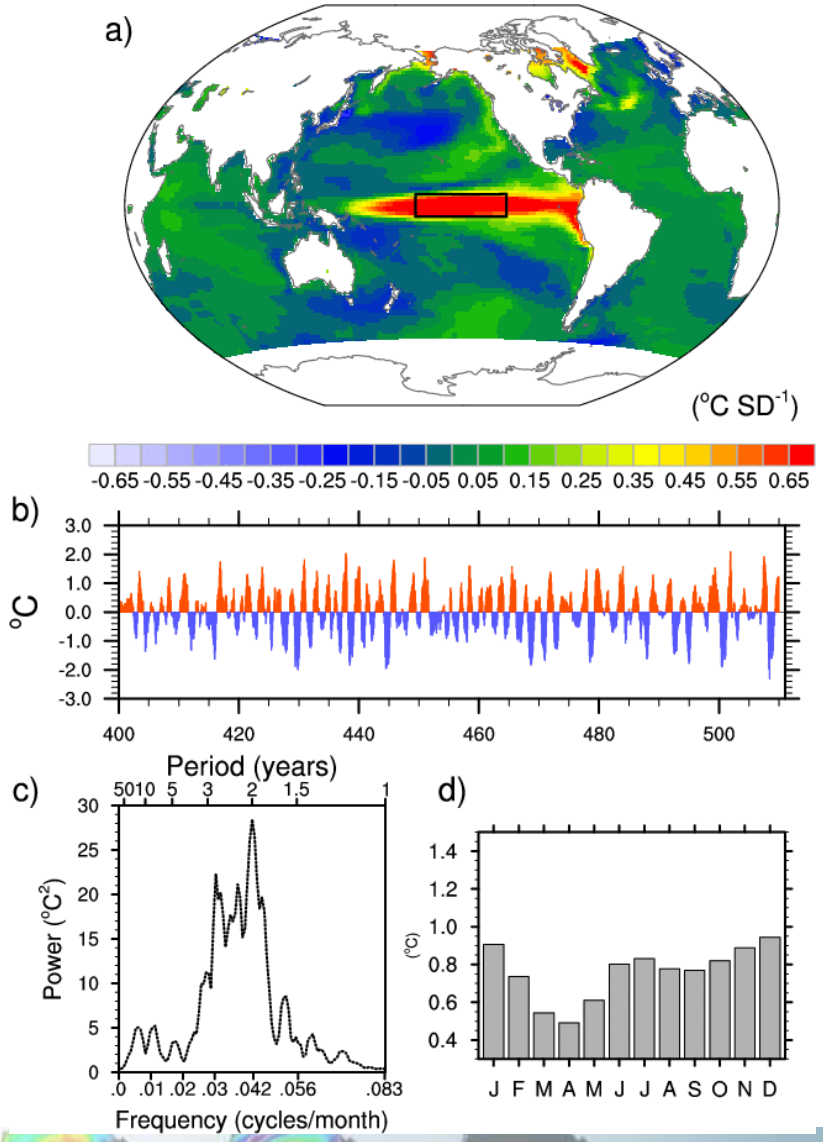
Leading Mode of Global SST Variability

Seasonal Capability

Observations



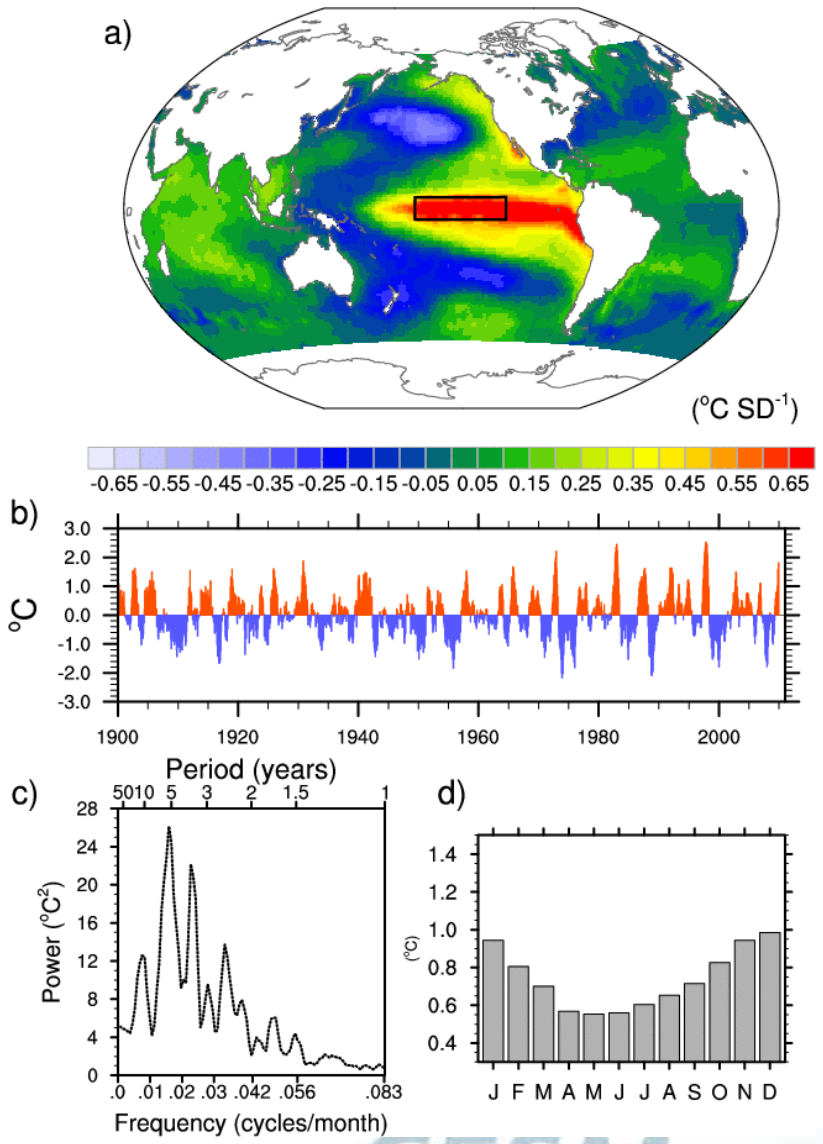
CCSM3



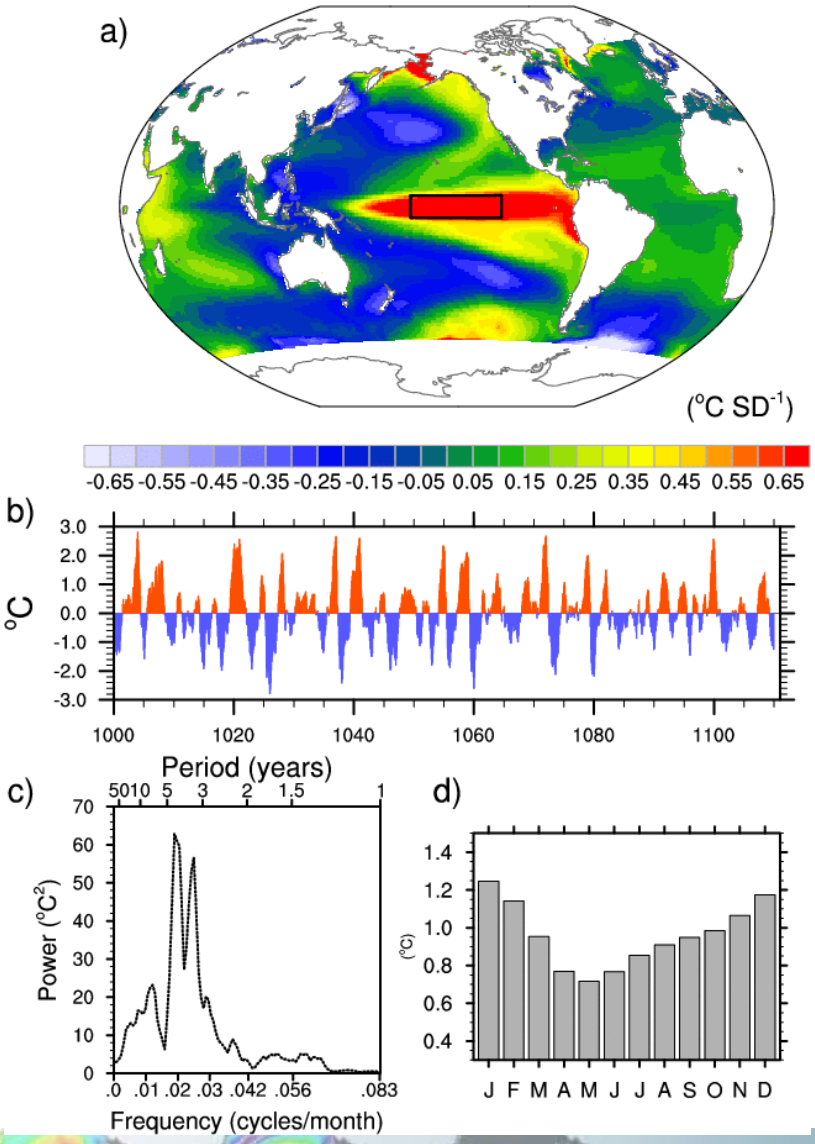
Leading Mode of Global SST Variability

Seasonal Capability

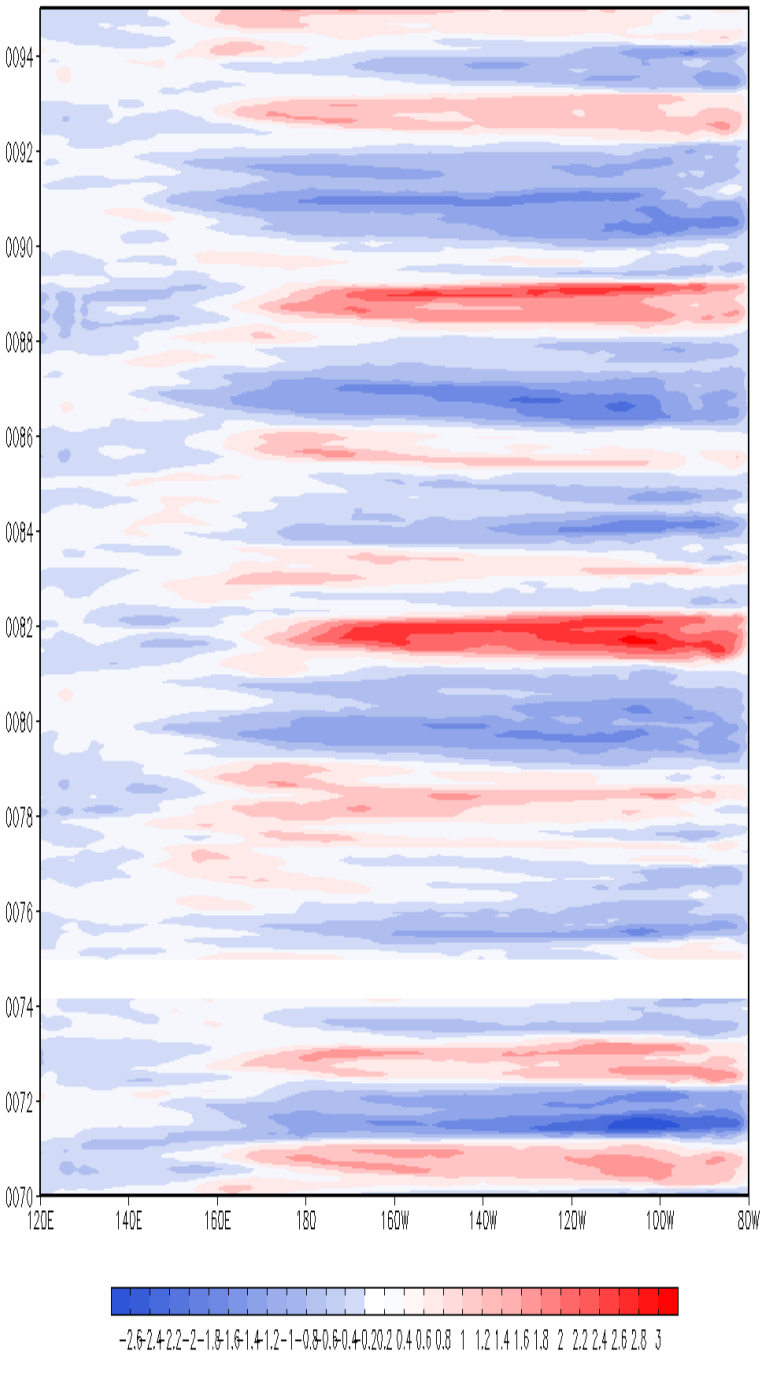
Observations



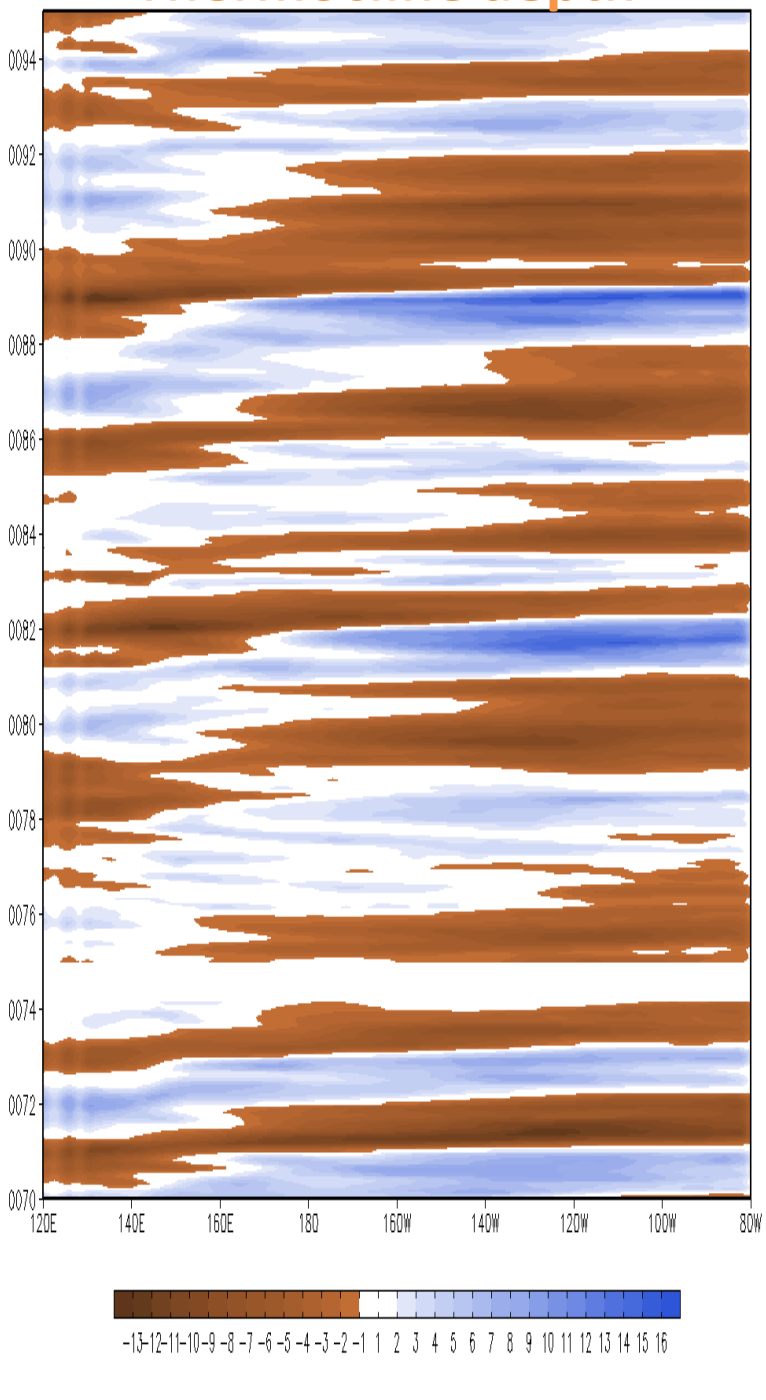
CCSM4

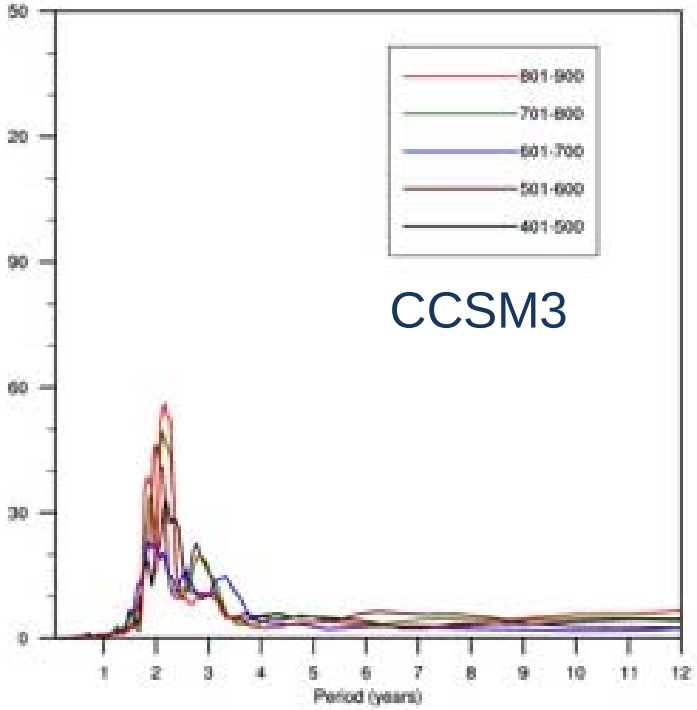


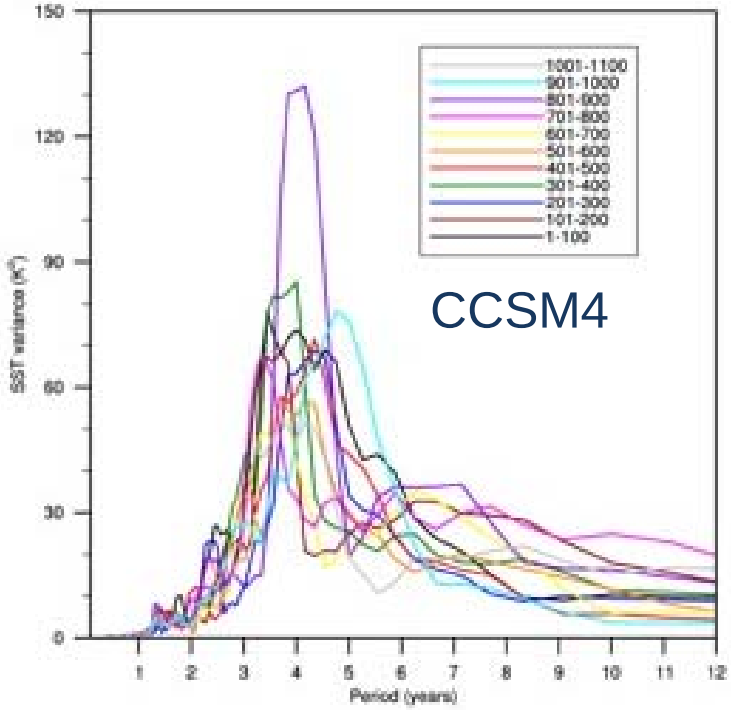
SST



Thermocline depth

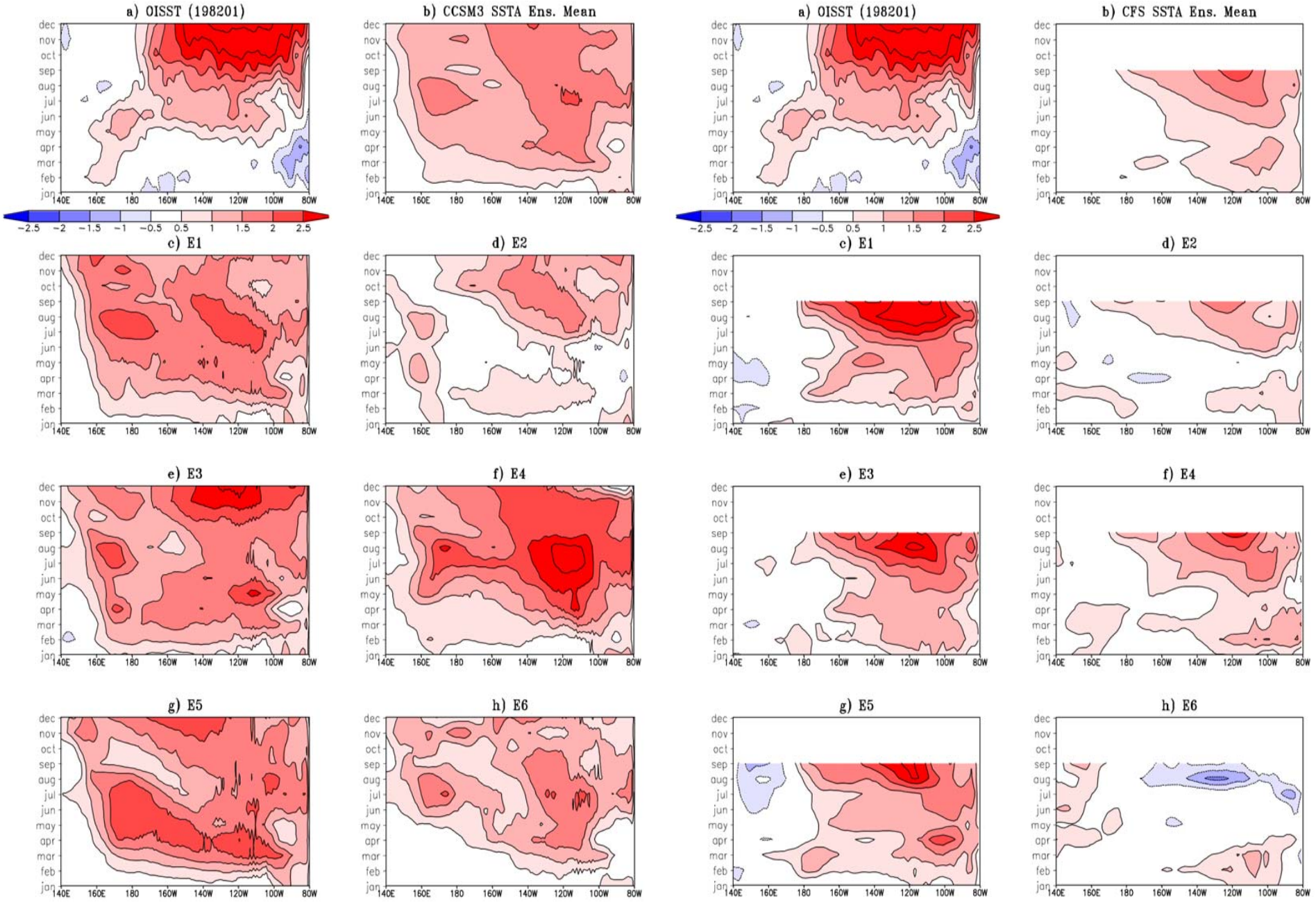



801-900
701-800
601-700
501-600
401-500
CCSM3
Period (years)

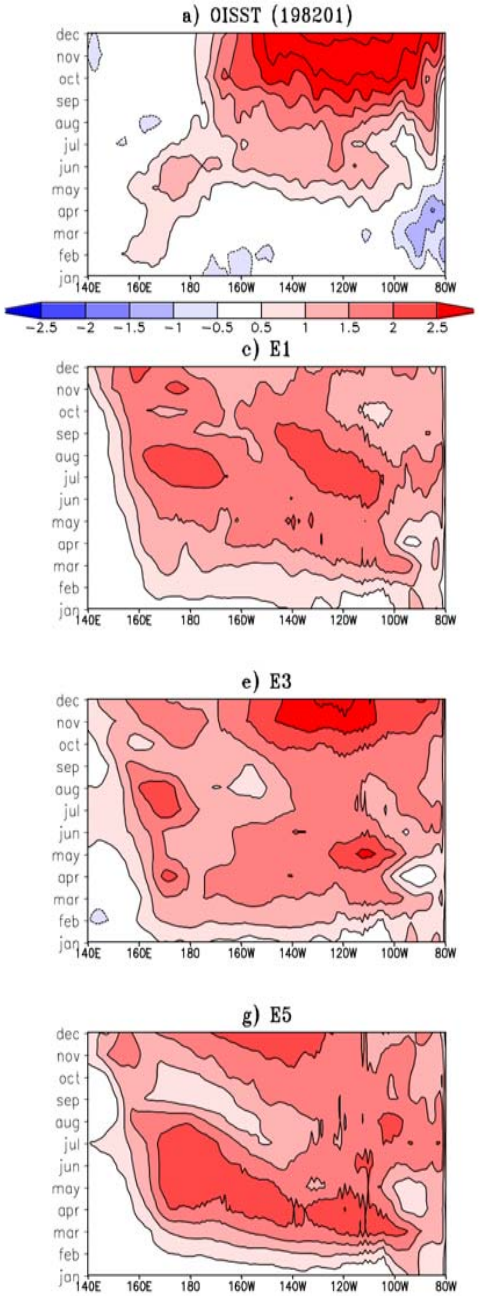

1001-1100
901-1000
801-900
701-800
601-700
501-600
401-500
301-400
201-300
101-200
1-100
CCSM4
SST variance (K²)
Period (years)

CCSM3.0 Jan 1982 IC

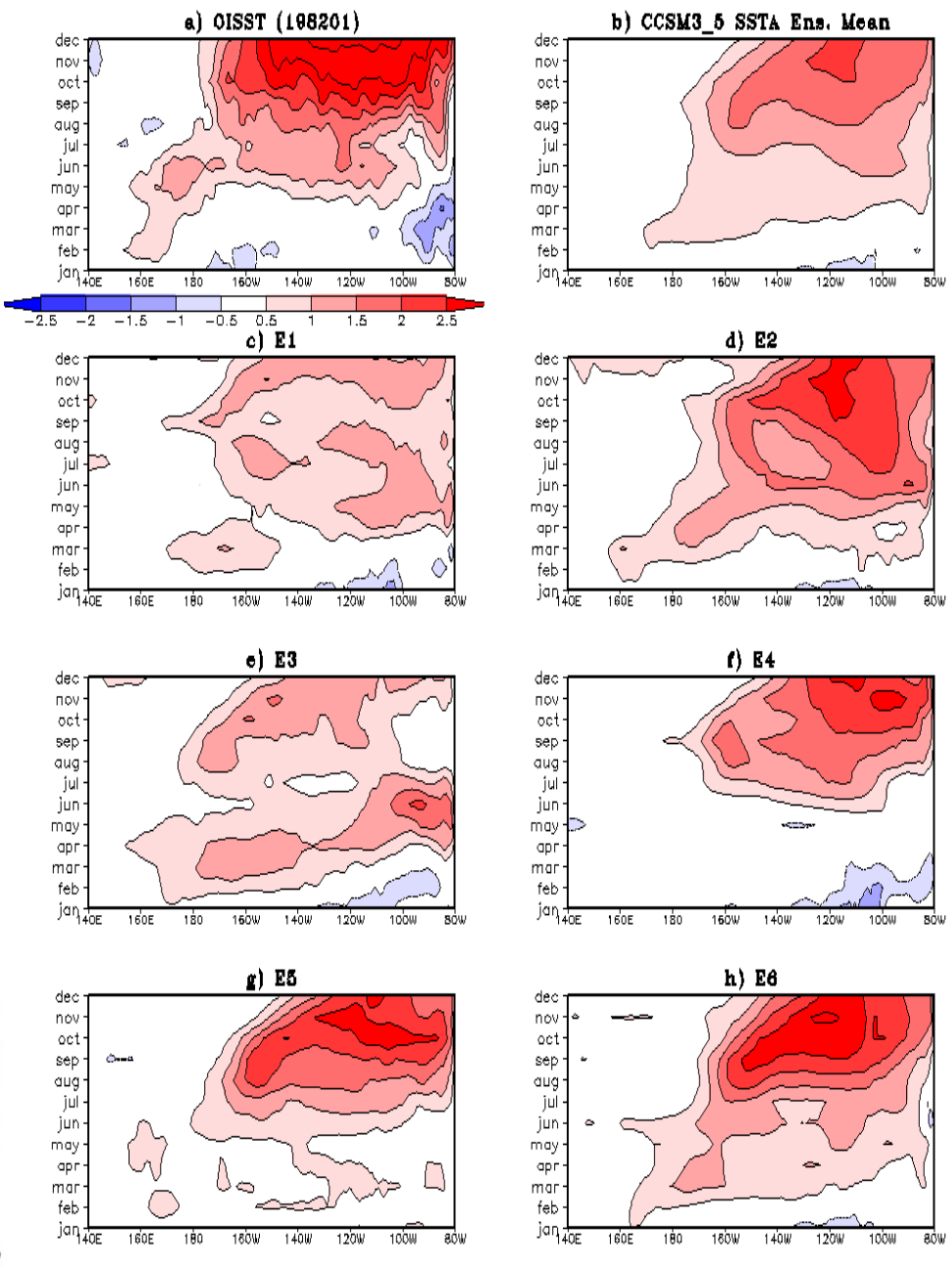
CFS Jan 1982 IC



CCSM3.0 Jan 1982 IC

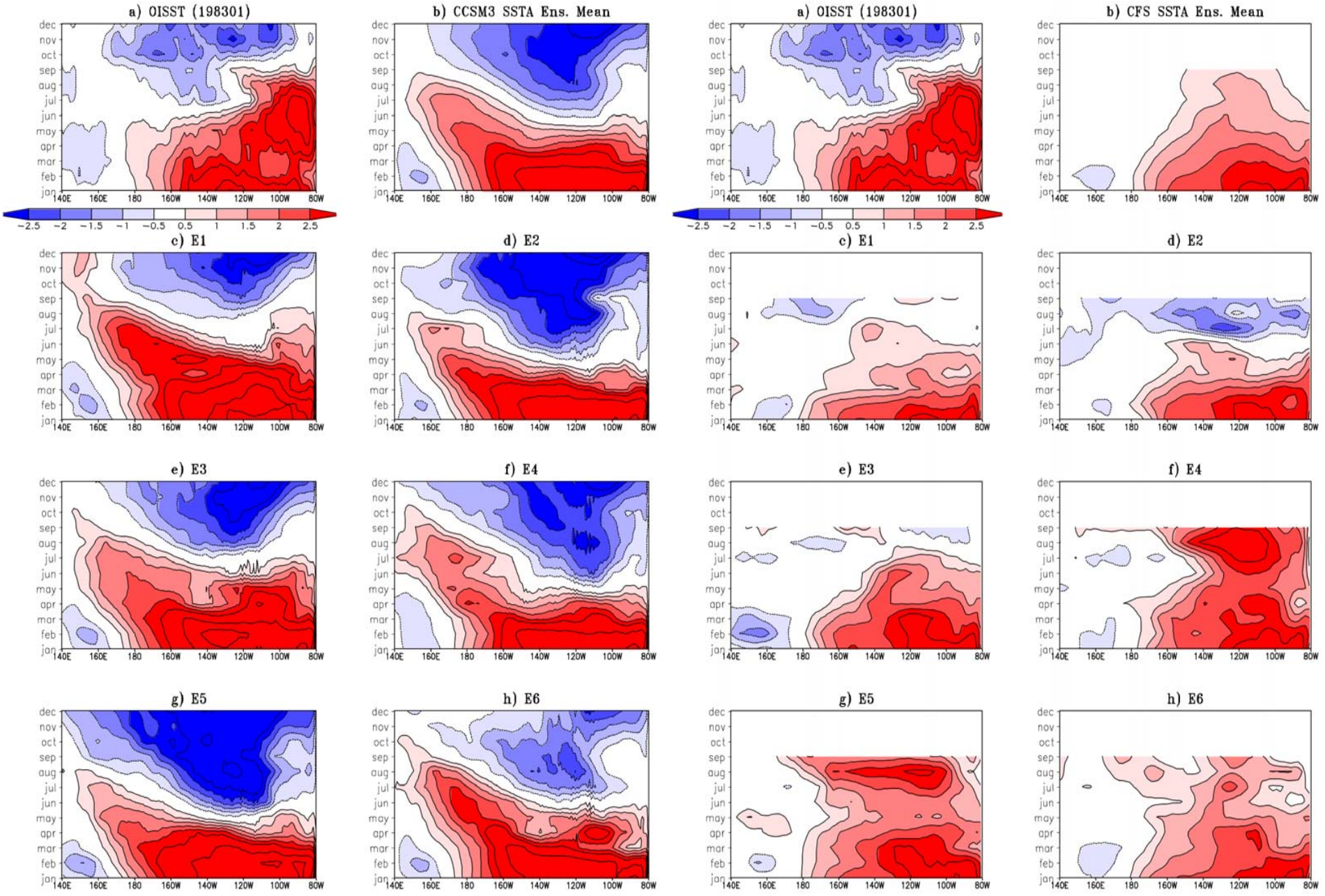


CCSM4.0 Jan 1982 IC

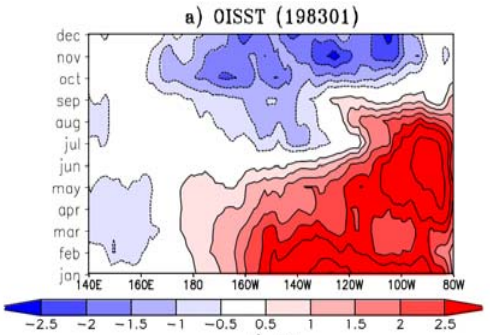


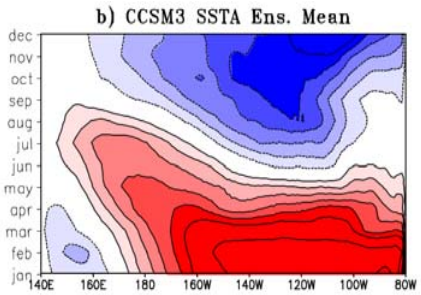
CCSM3.0 Jan 1983 IC

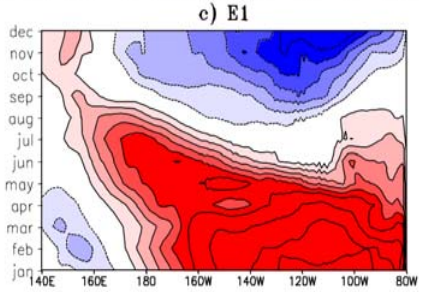
CFS Jan 1983 IC

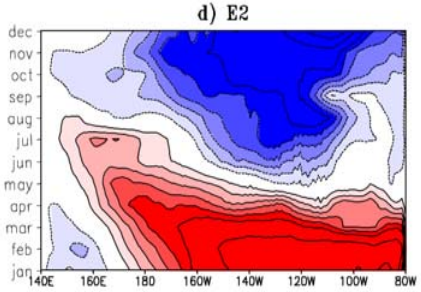


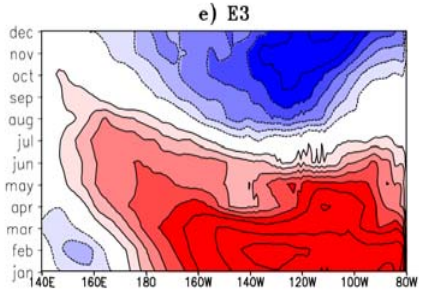
CCSM3.0 Jan 1983 IC

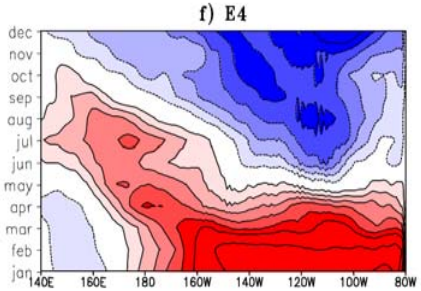


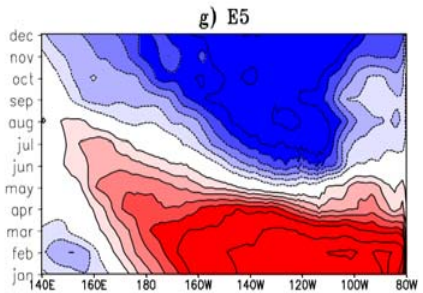


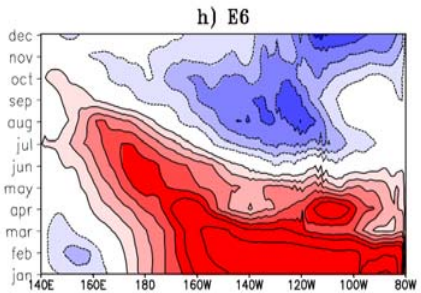




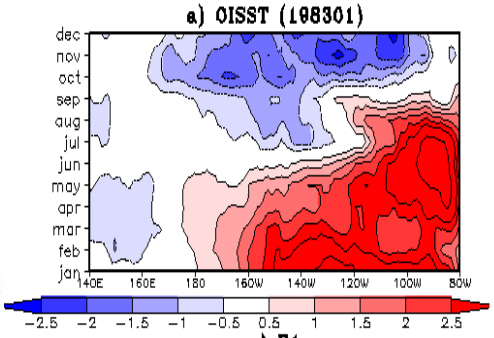


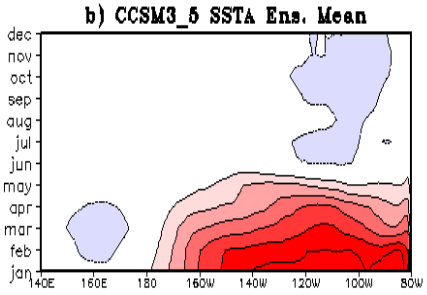


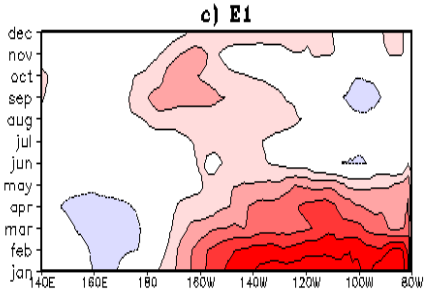


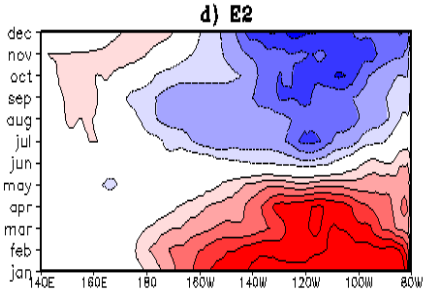


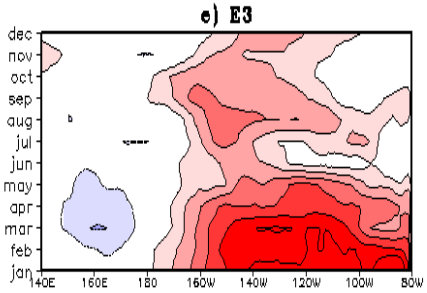
CCSM4.0 Jan 1983 IC

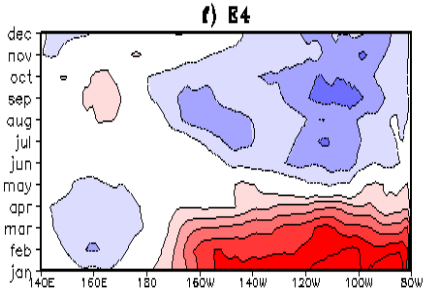


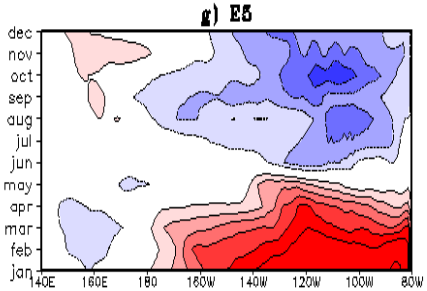


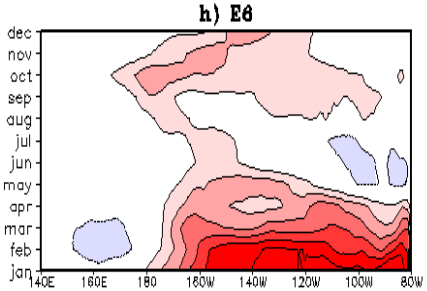




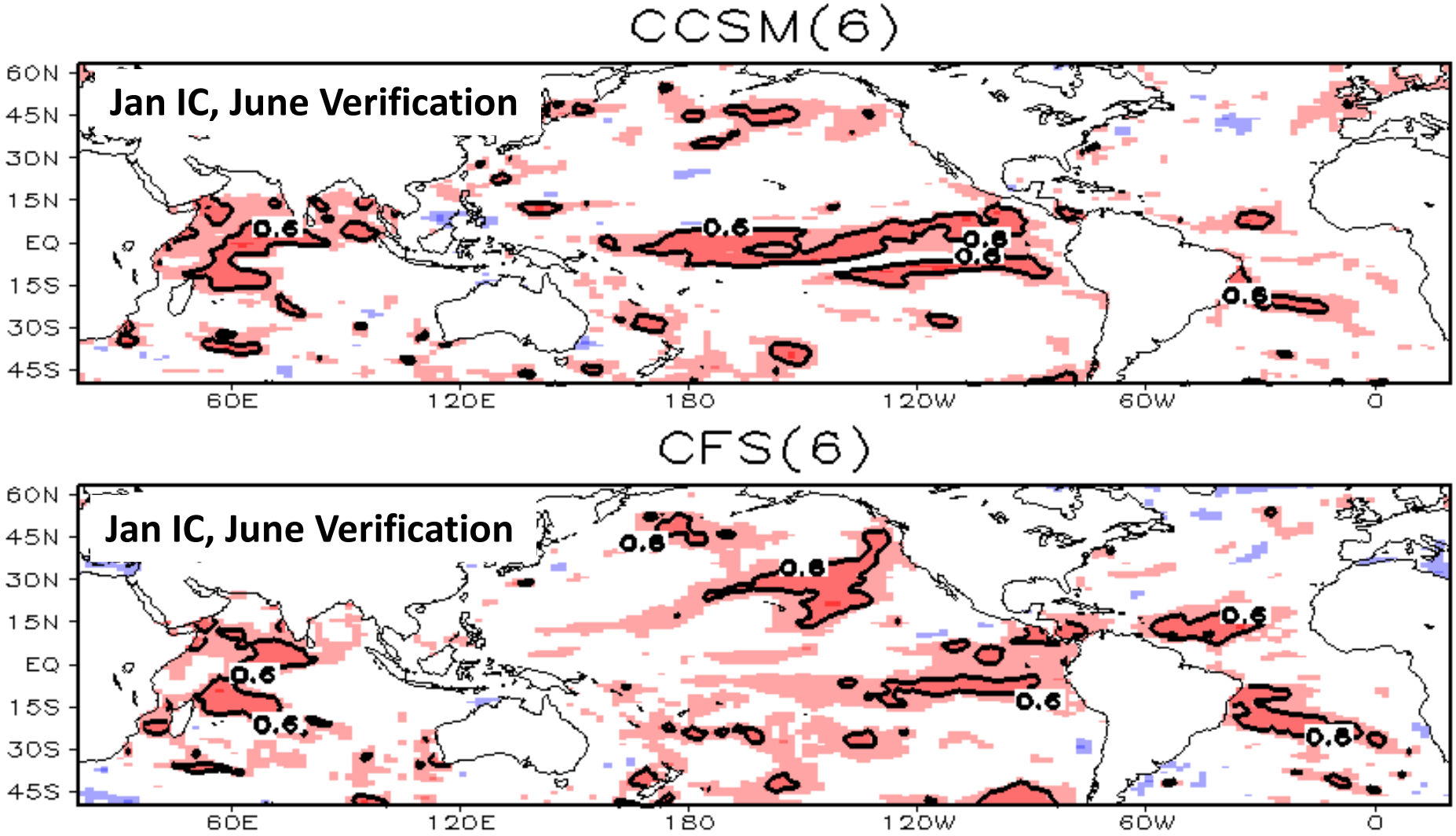








How Well Do These Models Predict SST?
Deterministic Verification: SST Correlation Forecast vs. Observations



How Well Do These Models Predict SST?
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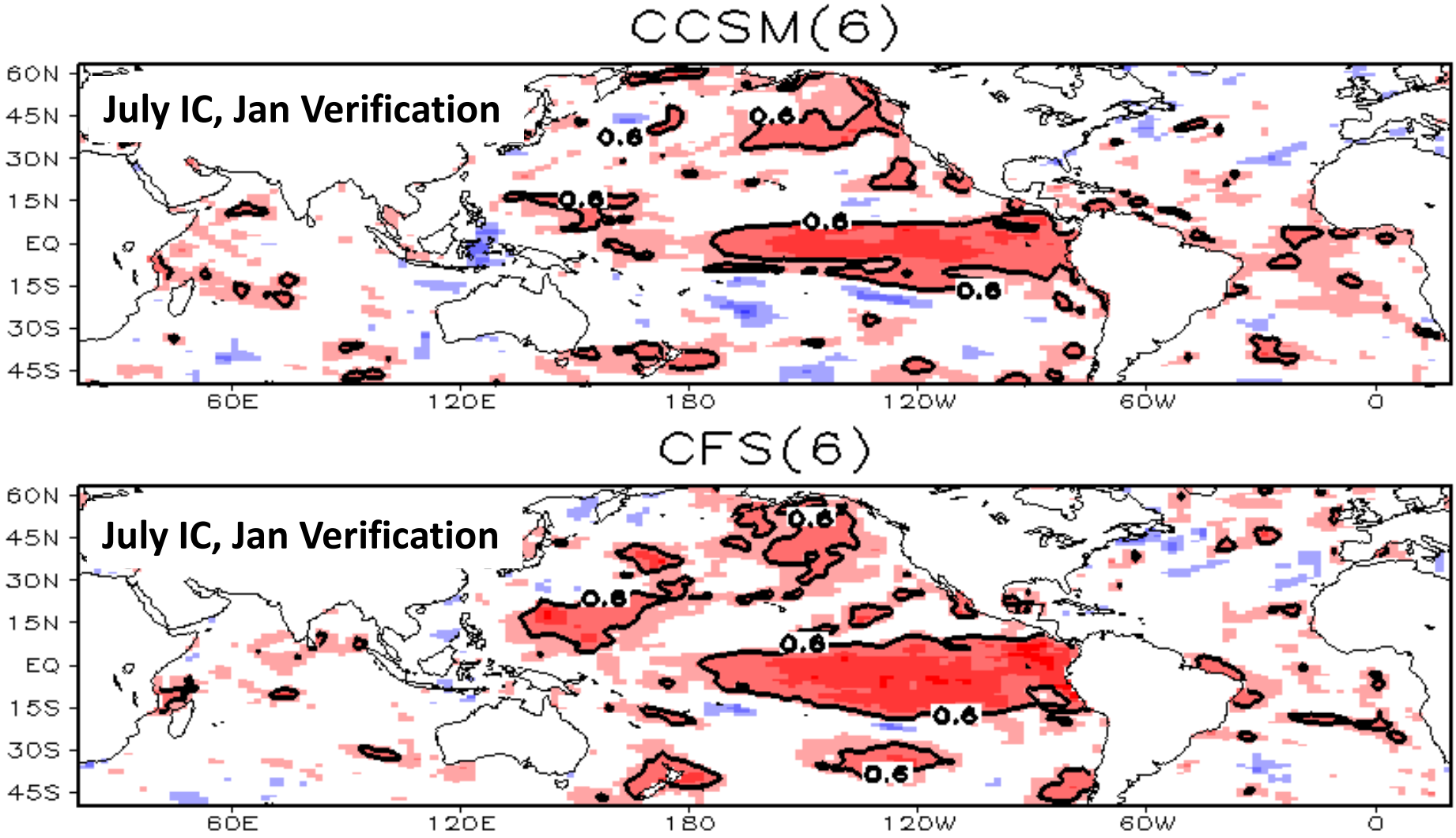
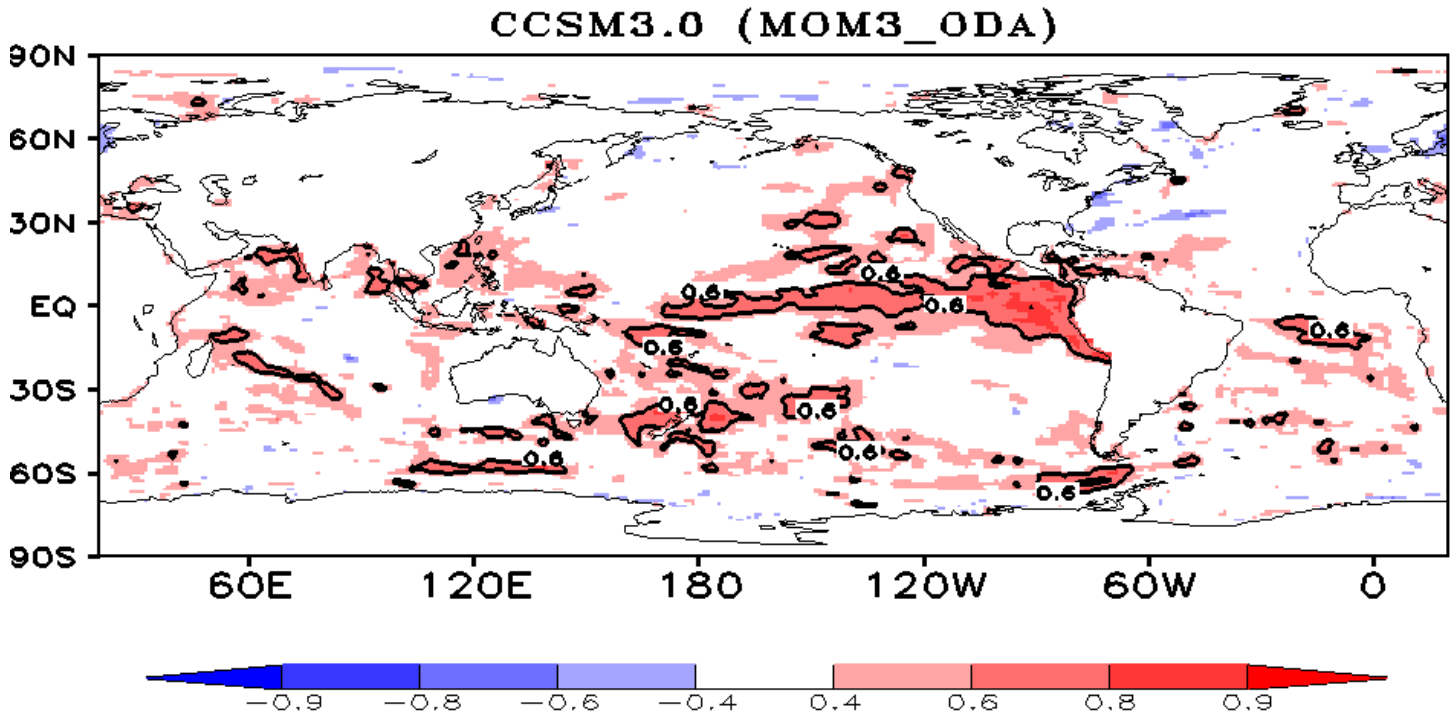
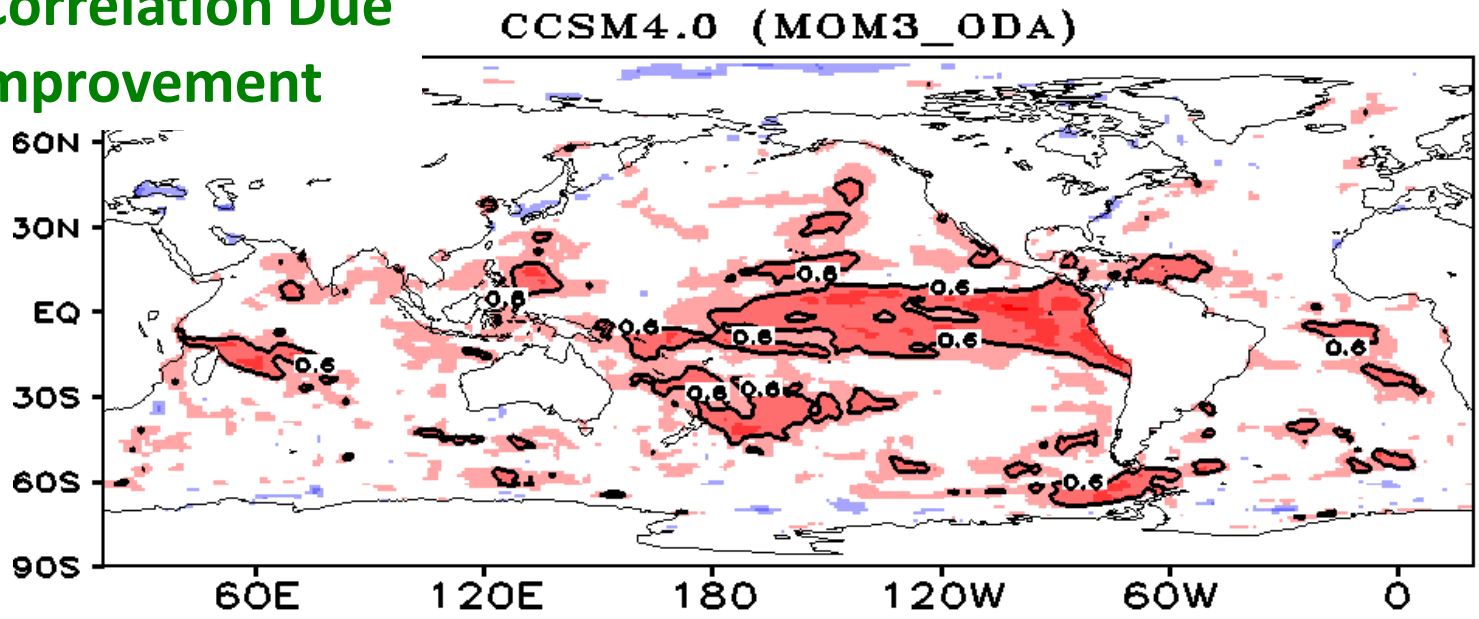


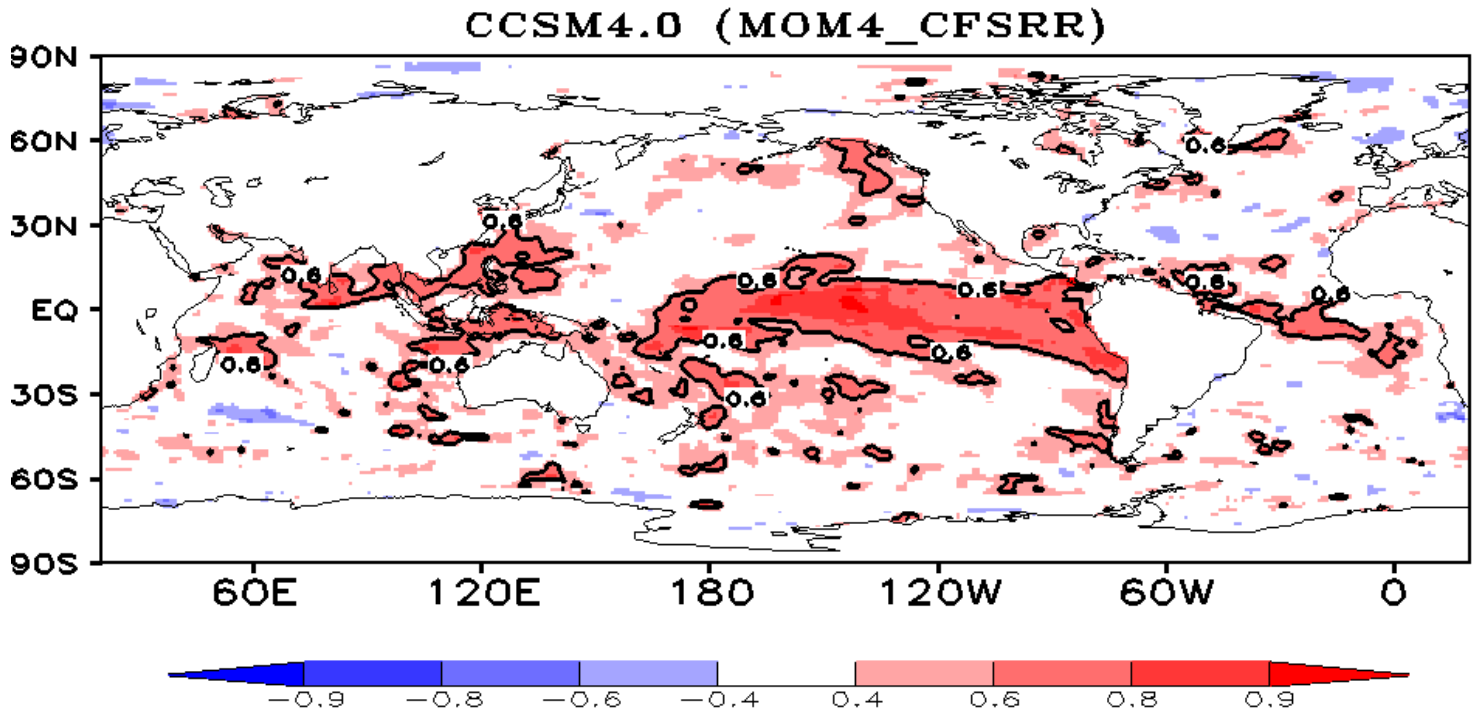
May Initial Conditions 3-Months Lead



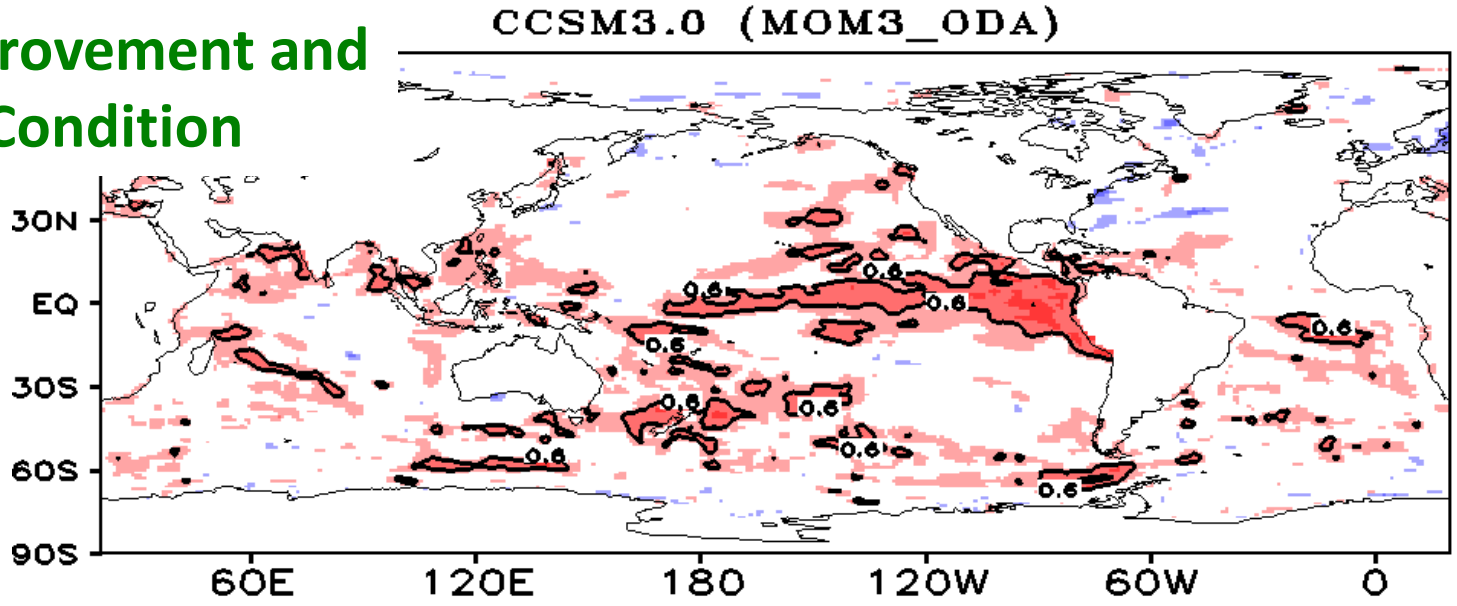
Improved Correlation Due to Model Improvement



May Initial Conditions 3-Months Lead



Improved Correlation Due to Model Improvement and Better Initial Condition



National Multi-Model Ensemble (NMME): Quantifying Initial Condition Uncertainty and Model Formulation Uncertainty

- University of Miami – RSMAS
- Nation Center for Atmospheric Research (NCAR)
- Center for Ocean-Land-Atmosphere Studies (COLA)
- International Research Institute for Climate and Society (IRI)
- University of Colorado – CIRES
- NASA – GMAO
- NOAA/NCEP/EMC/CPC
- NOAA/GFDL
- Canadian Meteorological Centre (Soon)

home tippett NMME

home tippett NMME.

Documents

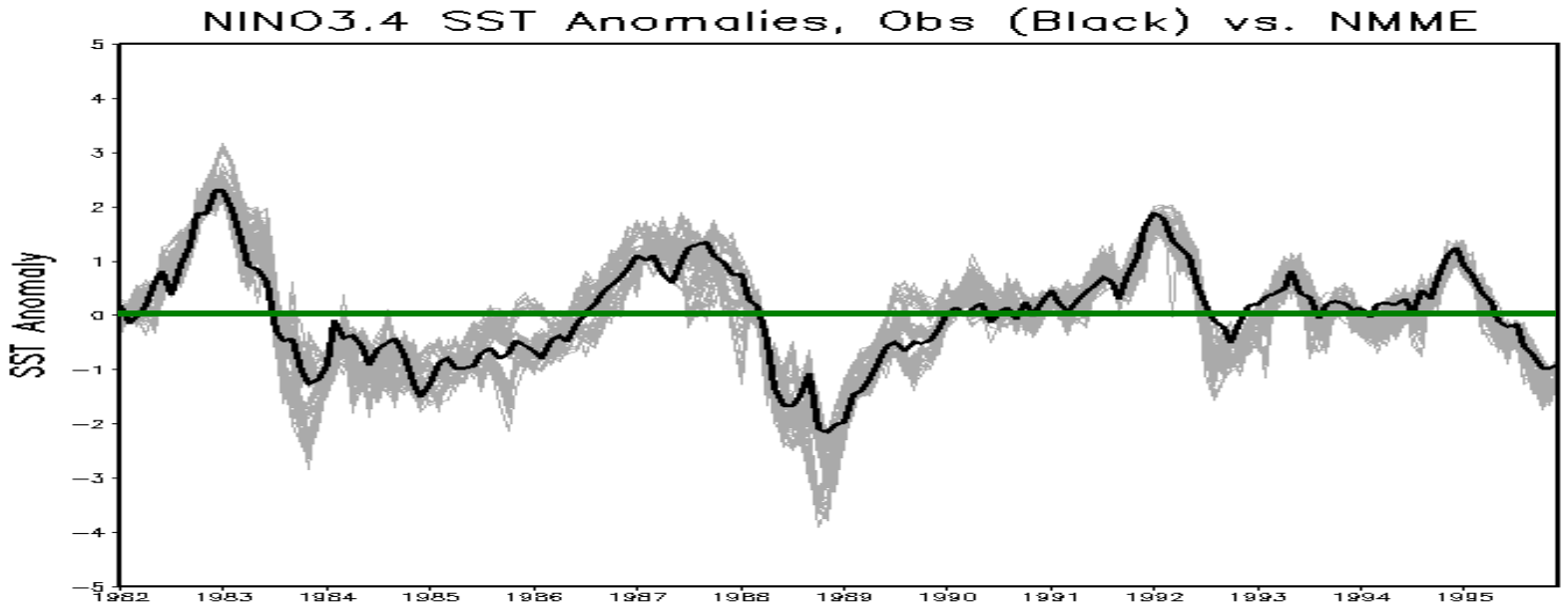
outline an outline showing all sub-datasets and variables contained in this dataset

Datasets and variables

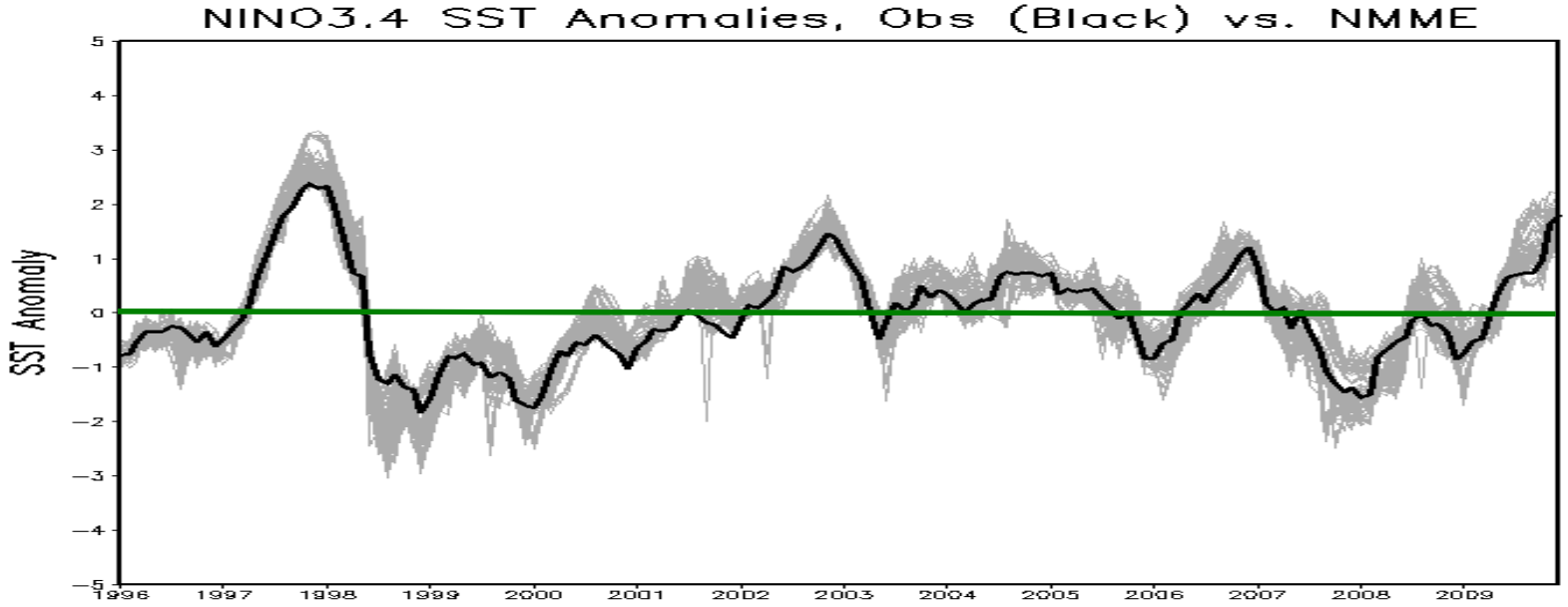
land mask	home tippett NMME Lmask[X Y]
nino34	home tippett NMME nino34[**AC Normal Above Dominant Mean rpss RPSS Below**]
ocean mask	home tippett NMME Omask[X Y]
prec	home tippett NMME prec[**AC Normal Above Dominant Mean RPSS rpss Below**]
sst	home tippett NMME sst[**AC Normal Above Dominant Mean RPSS rpss Below**]
tref	home tippett NMME tref[**AC Normal Above Dominant Mean rpss RPSS Below**]

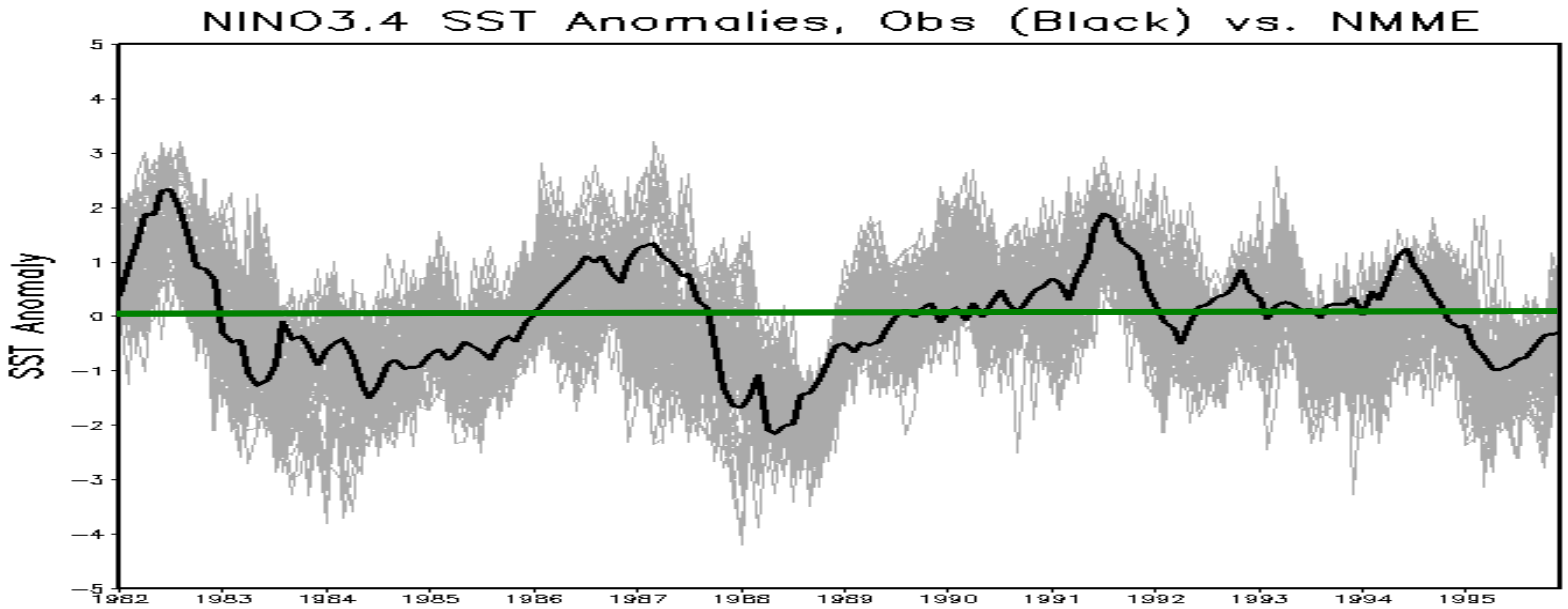
Independent Variables (Grids)

lead	grid: /L (months) ordered (1.5 months) to (10.5 months) by 1.0 N= 10 pts :grid
start	grid: /S (months since 1960-01-01) ordered (0000 1 Jan 1982) to (0000 1 Dec 2010) by 1.0 N= 348 pts :grid
Longitude	grid: /X (degree_east) periodic (0.0) to (1W) by 1.0 N= 360 pts :grid
Latitude	grid: /Y (degree_north) ordered (90S) to (90N) by 1.0 N= 181 pts :grid

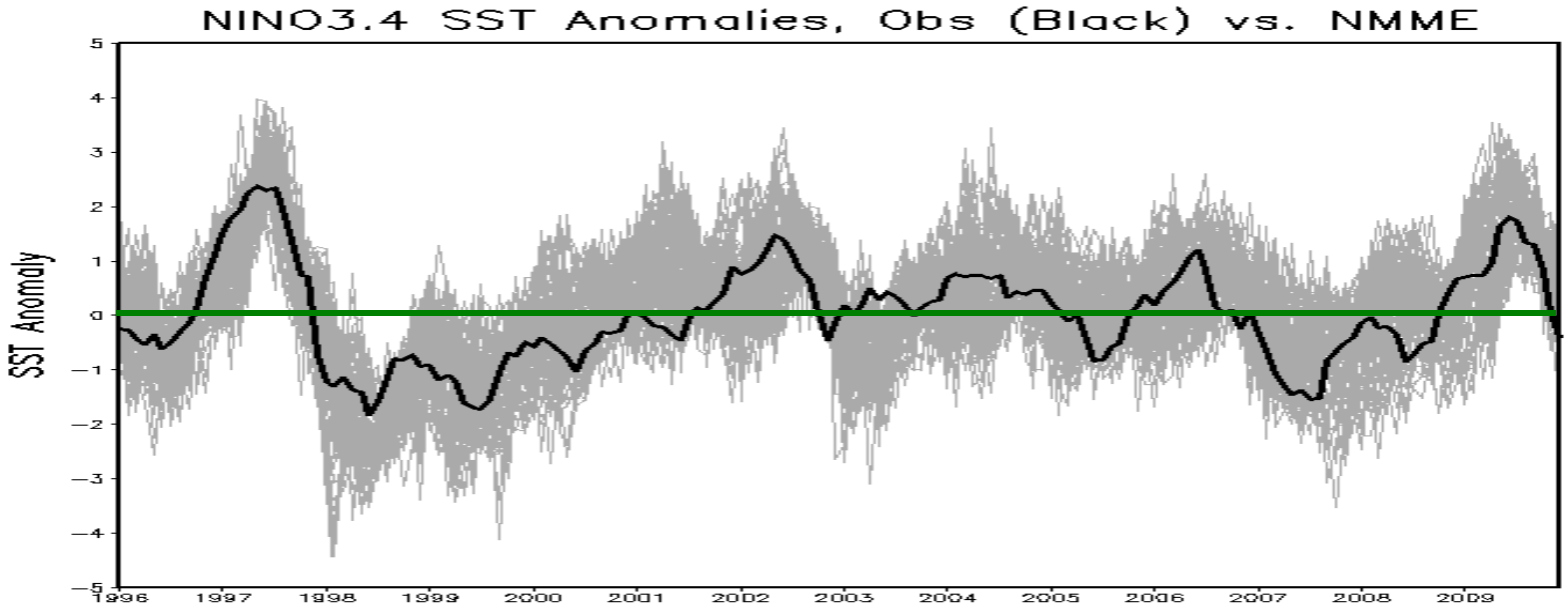

NINO3.4 SST Anomalies, Obs (Black) vs. NMME
SST Anomaly
5
4
3
2
1
0
−1
−2
−3
−4
−5
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995

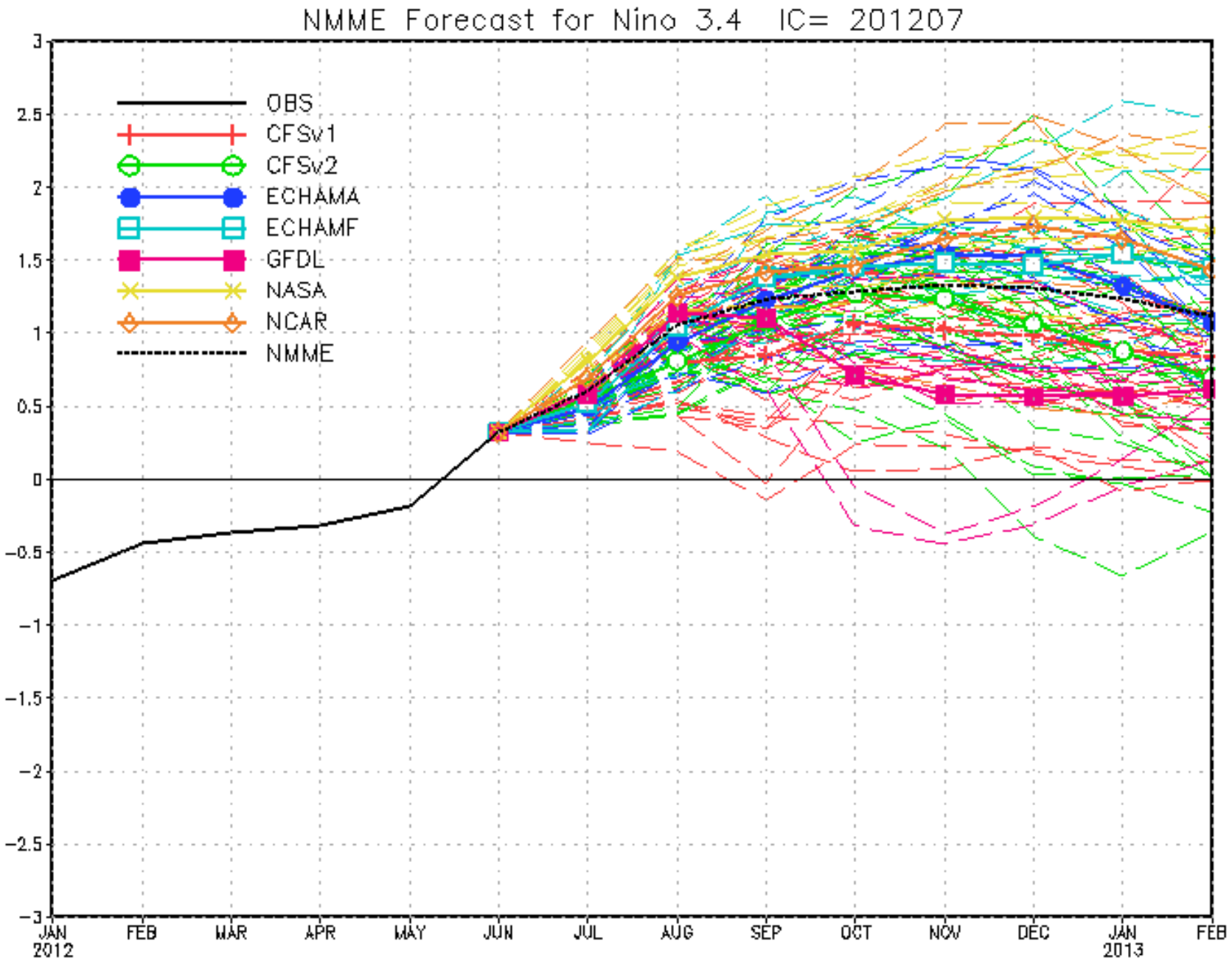
1-month Lead


NINO3.4 SST Anomalies, Obs (Black) vs. NMME
SST Anomaly
5
4
3
2
1
0
−1
−2
−3
−4
−5
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009


NINO3.4 SST Anomalies, Obs (Black) vs. NMME
SST Anomaly
5
4
3
2
1
0
−1
−2
−3
−4
−5
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995

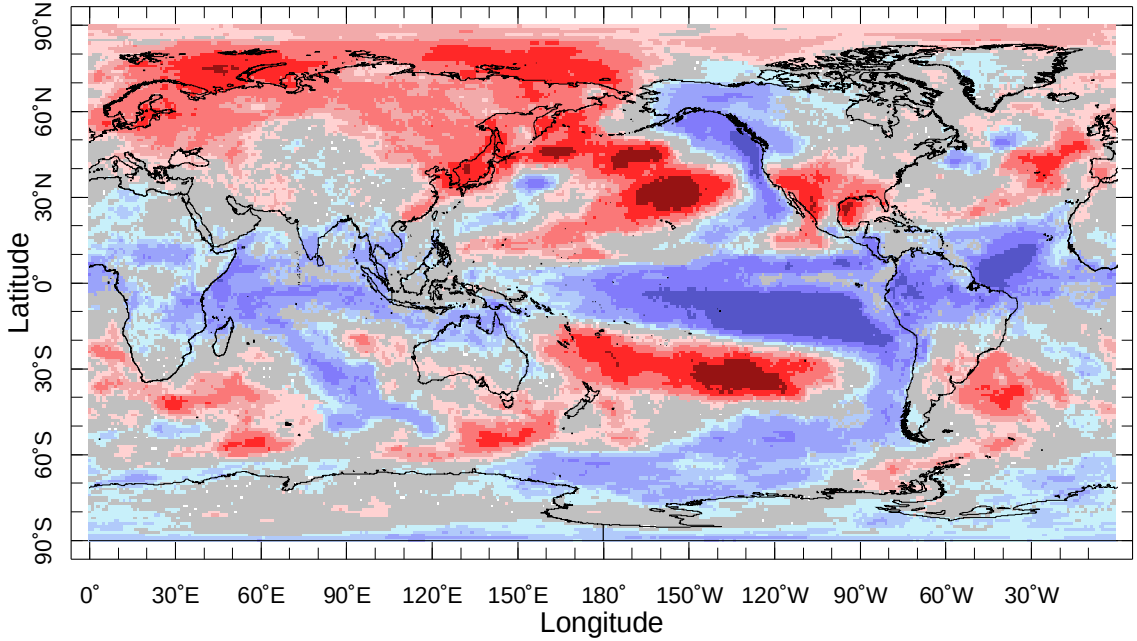
6-month Lead


NINO3.4 SST Anomalies, Obs (Black) vs. NMME
SST Anomaly
5
4
3
2
1
0
−1
−2
−3
−4
−5
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009

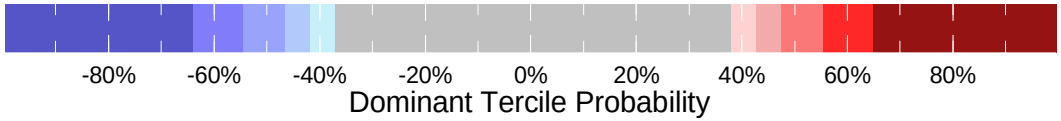

NMME Forecast for Nino 3.4 IC= 201207
OBS
CFSv1
CFSv2
ECHAMA
ECHAMF
GFDL
NASA
NCAR
NMME
3
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
JAN 2012
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
JAN 2013
FEB

Tercile category probability forecasts

- Pool forecast anomalies
- Compute fraction of ensemble members in each category
- Tref
- Oct 1, 2007
- Lead 6.5
- MAM



lead 6.5 months start 0000 1 Oct 2007

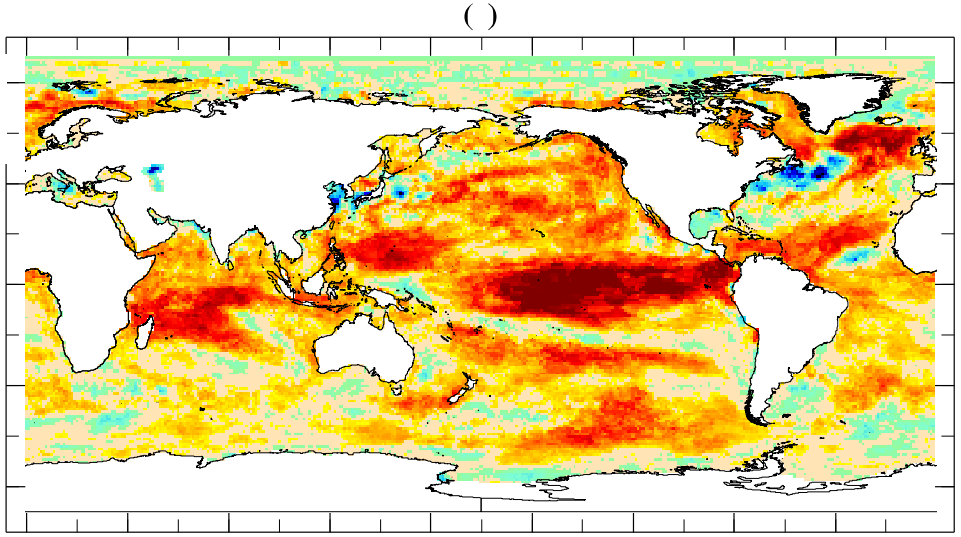


Ranked Probability Skill Score (RPSS) review

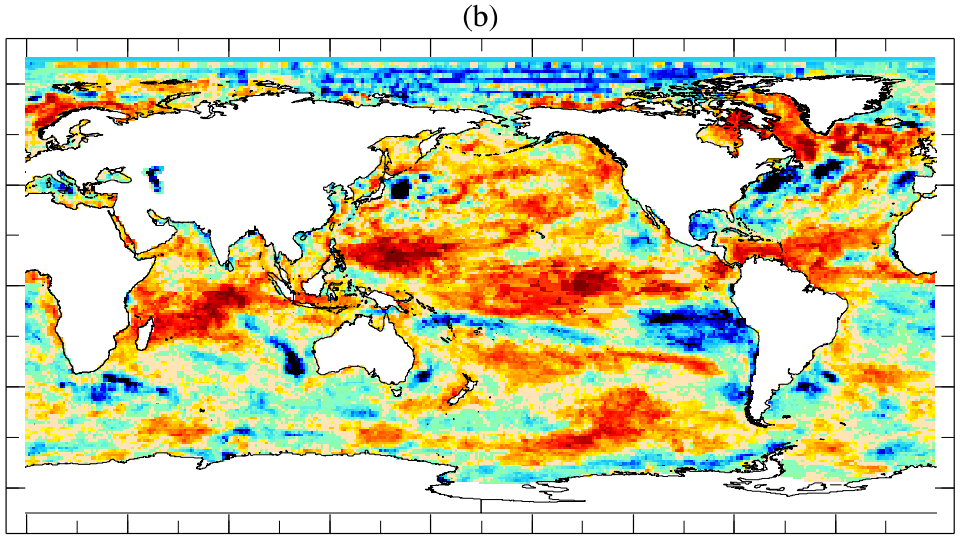
- RPS = $(Pa - Oa)^2 + (Pb\text{-}Ob)^2$
- RPS_clim = RPS(Pa=1/3,Pb=1/3)
- RPSS = average RPS/average RPS_clim
- RPSS ~ $1 - \text{sqrt}(1\text{-}r^2) \sim r^2/2$
- **r=0.4 -> RPSS =0.08**

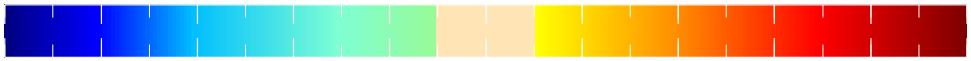
July IC – January Verification

Multi-Model



Single-Model

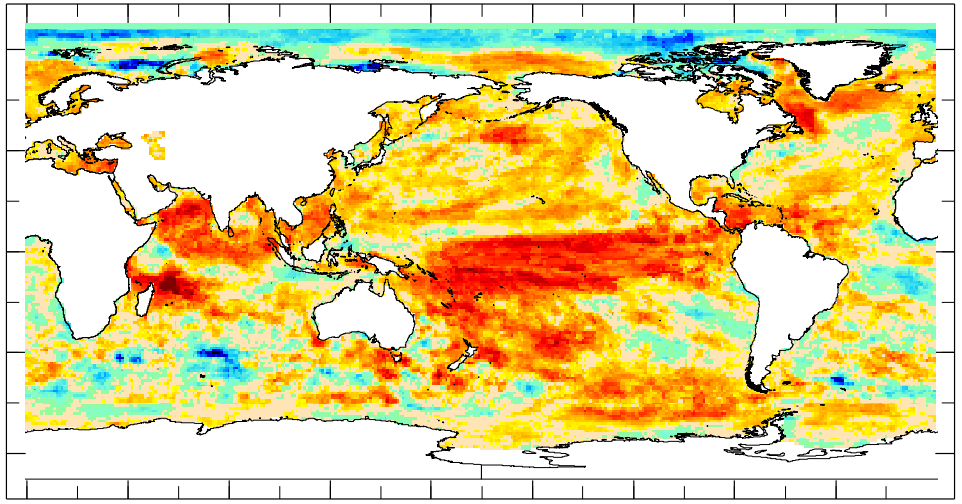




January IC – July Verification

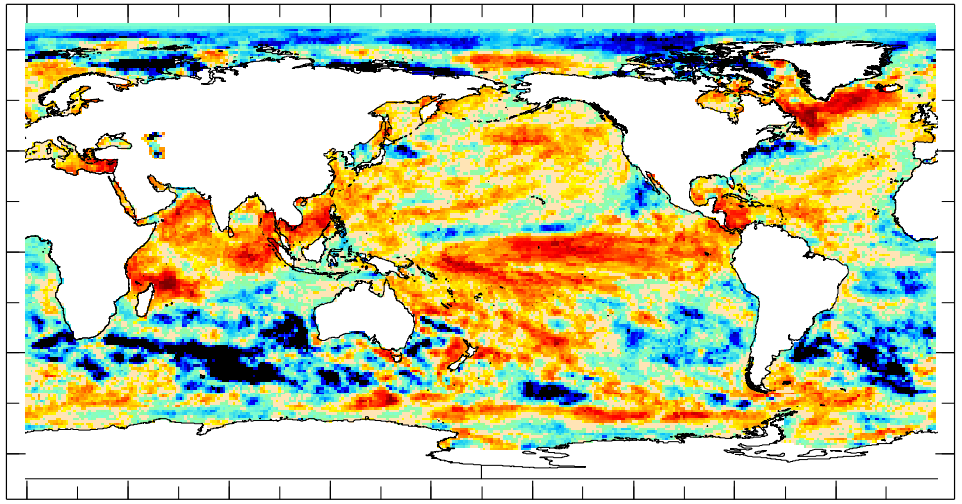
Multi-Model

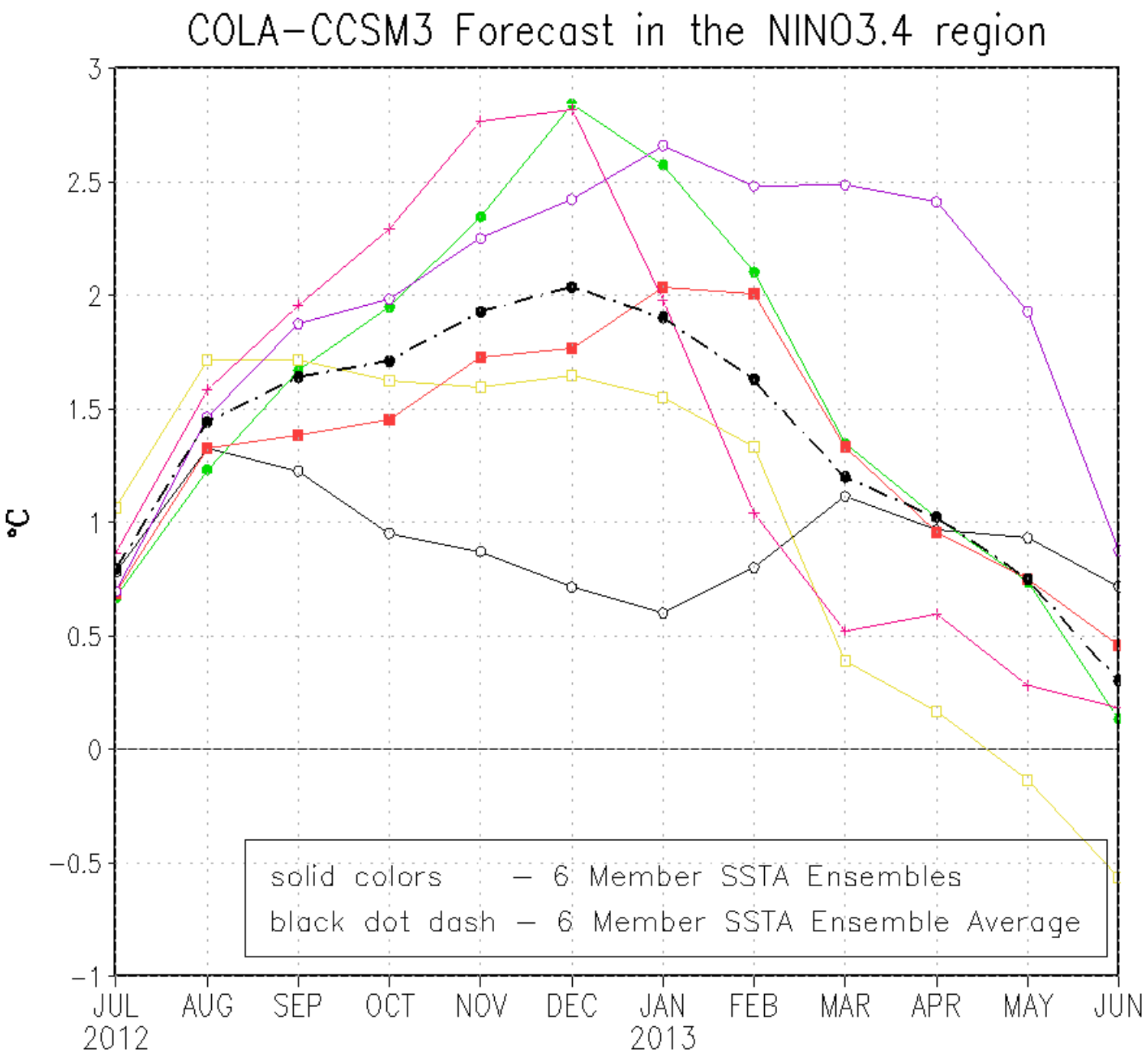
(a)



Single-Model

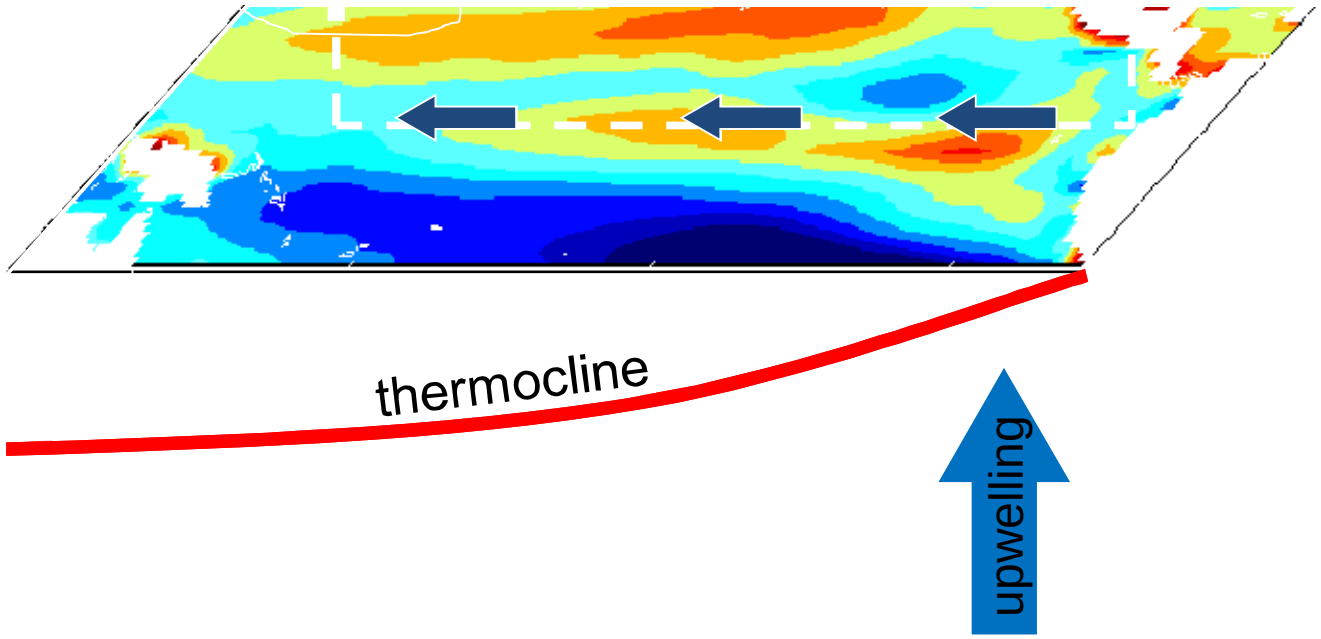
(b)



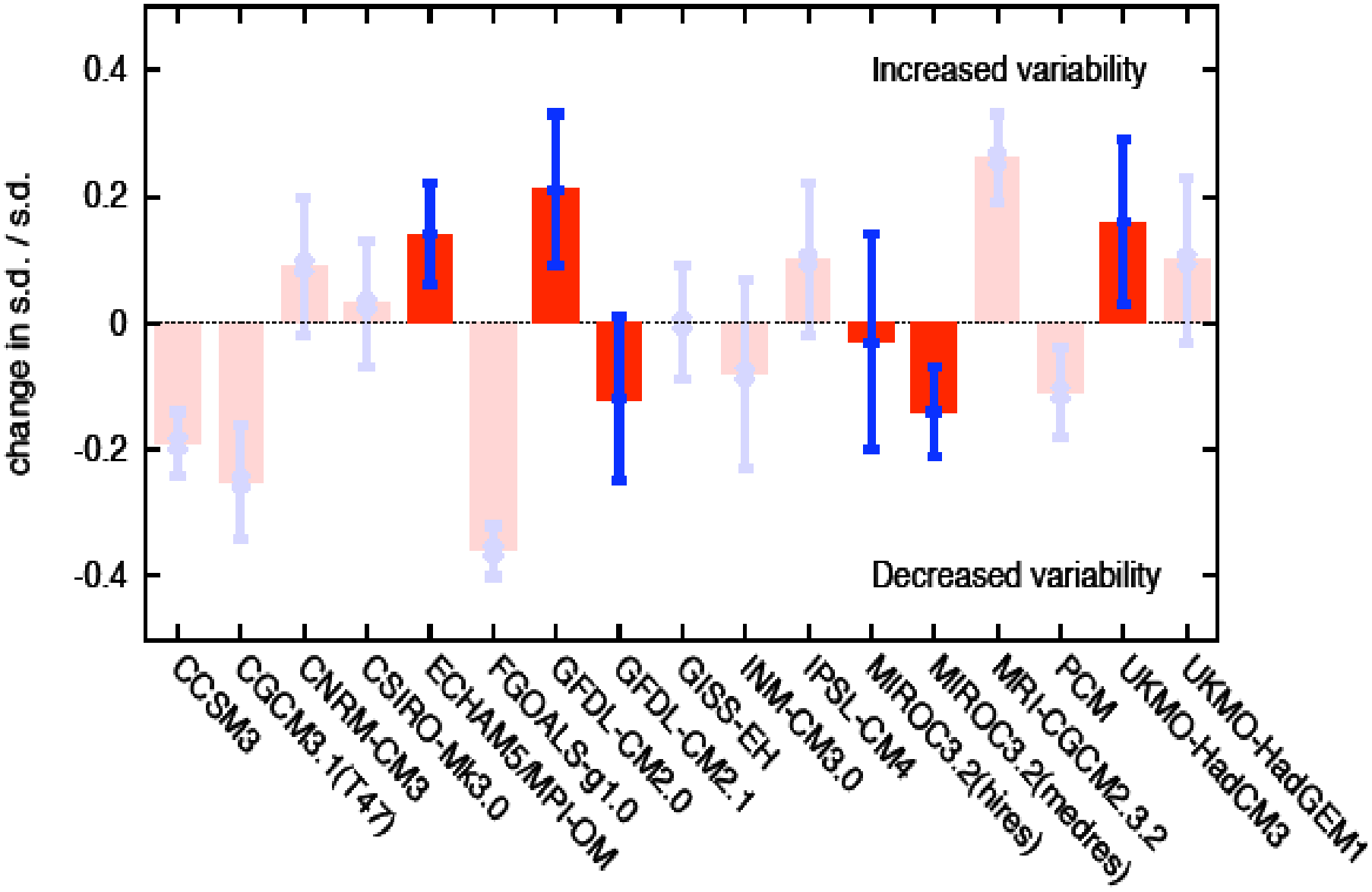

COLA-CCSM3 Forecast in the NINO3.4 region
°C
3
2.5
2
1.5
1
0.5
0
-0.5
-1
JUL
2012
AUG
SEP
OCT
NOV
DEC
JAN
2013
FEB
MAR
APR
MAY
JUN
solid colors — 6 Member SSTA Ensembles
black dot dash — 6 Member SSTA Ensemble Average

- Not “El Nino-like”
- Trade winds weaken
- SSTs warm more on the equator than off
- The equatorial thermocline shoals and the stratification increase
- Upwelling weakens

Climate Change
(SST Anomalies)



Changes in ENSO variability 2050-2100 in CMIP3 A1B experiments



El Niño Features and Processes