THE NELSON INSTITUTE FOR ENVIRONMENTAL STUDIES
University of Wisconsin-Madison
Where Environmental Leadership Begins

CCR

Assessing Large-Scale Climate Feedback from the Observation ---- The GEFA Approach (Generalized Equilibrium Feedback Analysis)

Zhengyu Liu
Center for Climatic Research &
Dept. Atmospheric and Oceanic Sciences
University of Wisconsin-Madison

Tropical Ocean-Atmos. Interaction

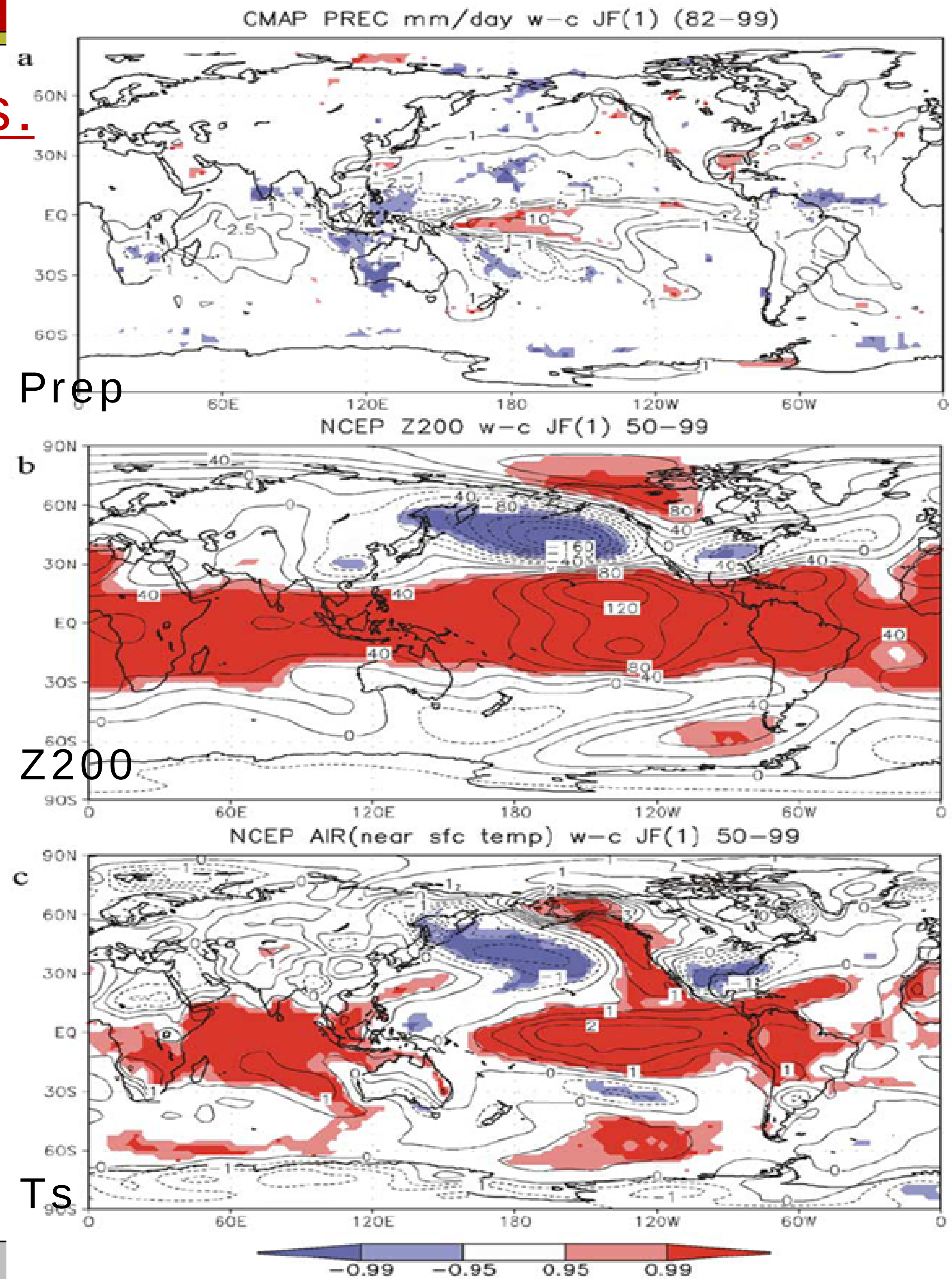
ENSO Impact !

Atm **SST** **Noise**

$$X(t)=BT(t)+N(t)$$

Strong Signal

$$BT \gg N$$



Motivation I: Extratropical Ocean-Atmos. Interaction

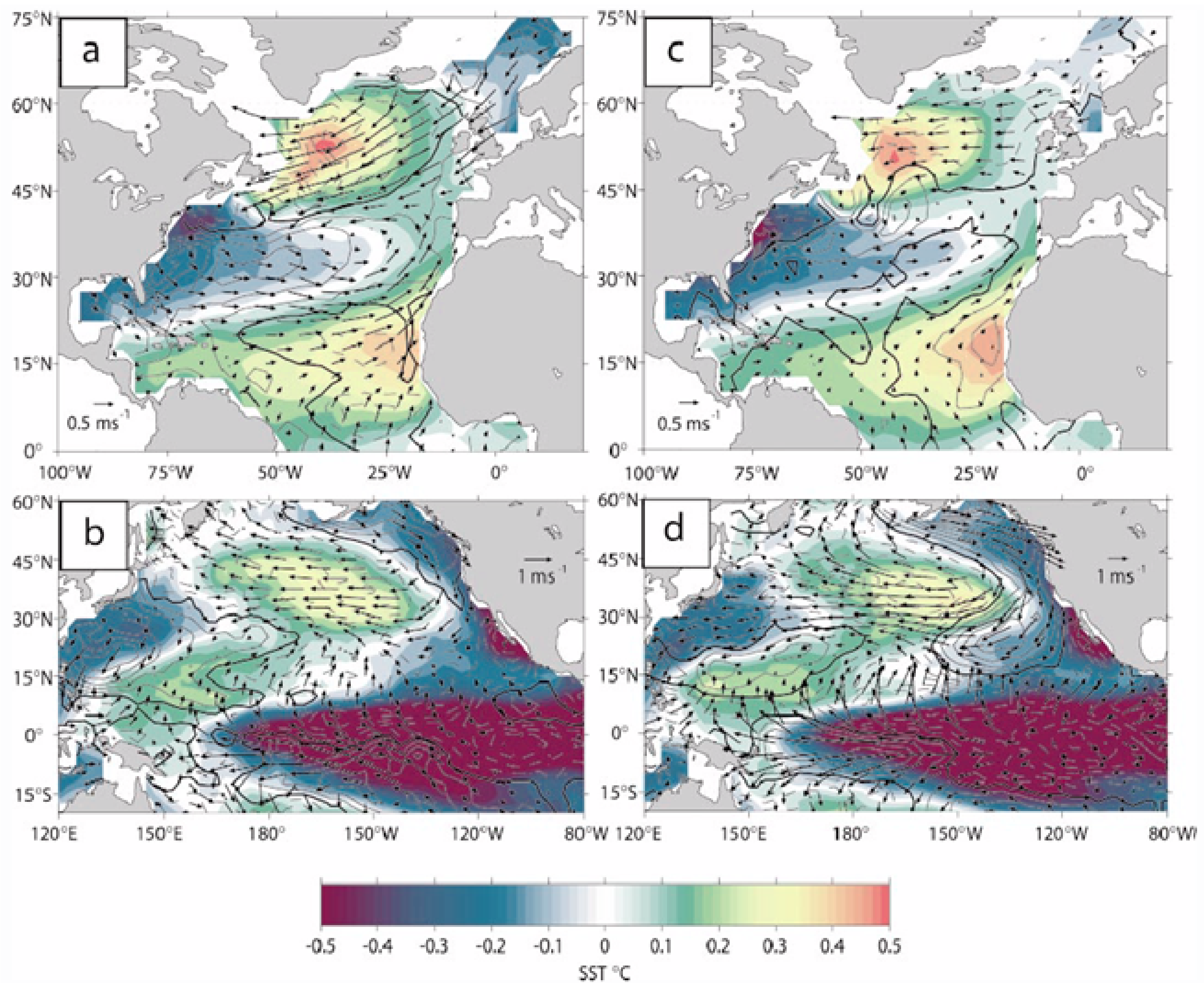
Regression/SVD (lag=0) Modeling

NP/NA Impact ?

X(t)=BT(t)+N(t)

Weak Signal

BT << N



Obs, mixes cause/effect, Model: diverse with different models and methods

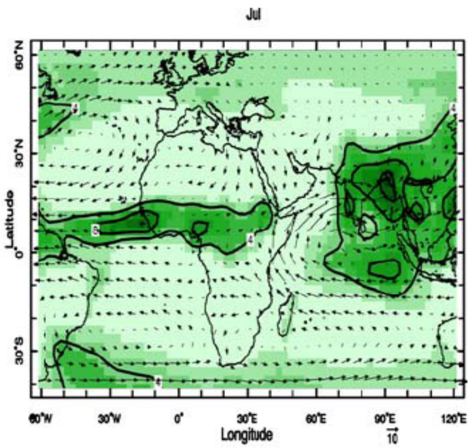
Kushnir et al., 2002, J. Climate

Modeling?

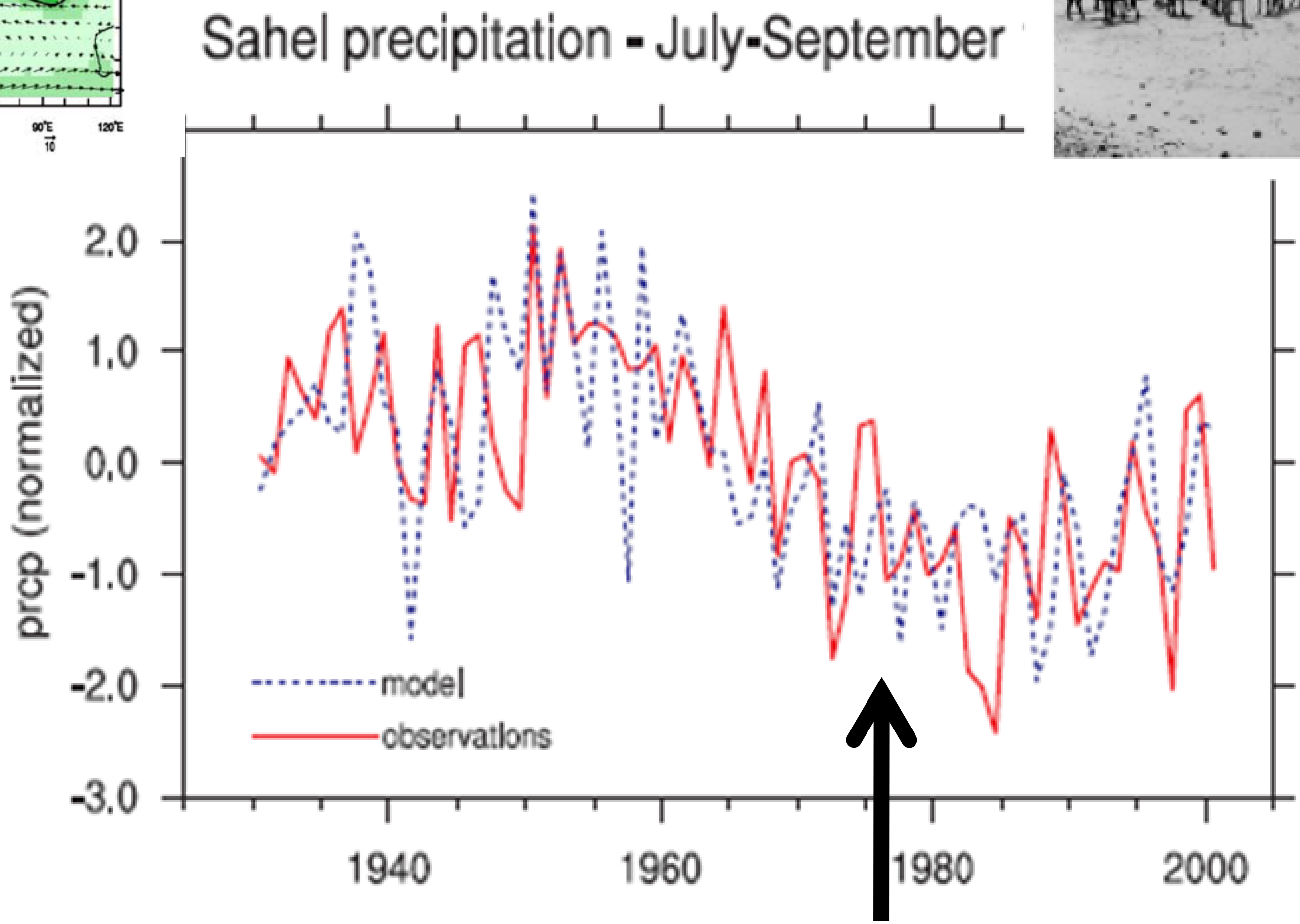
Reference	*Exp.*	*Resoln.*	*Response*
Palmer and Sun (1985)	**AMIP**	**350km*15**	**EqBt high**
Pitcher et al. (1988)	**AMIP**	**R15*9**	**EqBt low (W and C)**
Kushnir and Lau (1992)	**AMIP**	**R15*9**	**EqBt low (W and C)**
Ferranti et al. (1994)	**AMIP**	**R63*15**	**EqBt high**
Peng et al. (1995)	**AMIP**	**T42*21**	**EqBt high (Nov.)** **Baroclinic low (Jan.)**
Kushnir and Held (1996)	**AMIP**	**R15*9**	**Barclinic low**
Latif and Barnett (1995,96)	**AMIP**	**T42*19**	**EqBt high**
Peng et al. (1997)	**AMIP**	**T42*19**	**EqBt high (Feb.)** **Baroclinic low (Jan.)**

Yulaeva et al. (2001)	**FHXE**	**T42*19+slab**	**Baroclinic low**
Sutton and Mathieu (2002)	**FHXE**	**T42*19+slab**	**Baroclinic low**

Motivation II: Land-Atmosphere Interaction



Sahel Rainfall



Charney

Giannini et al., 2003: Science

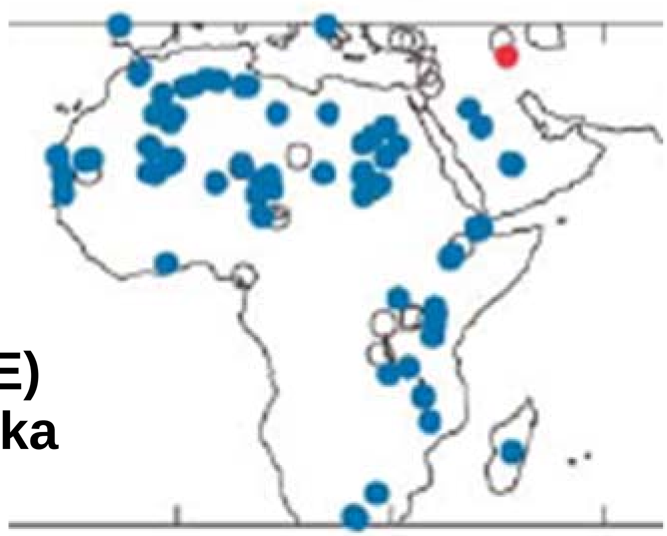
N. Africa Vegetation Impact ?

6000 years ago

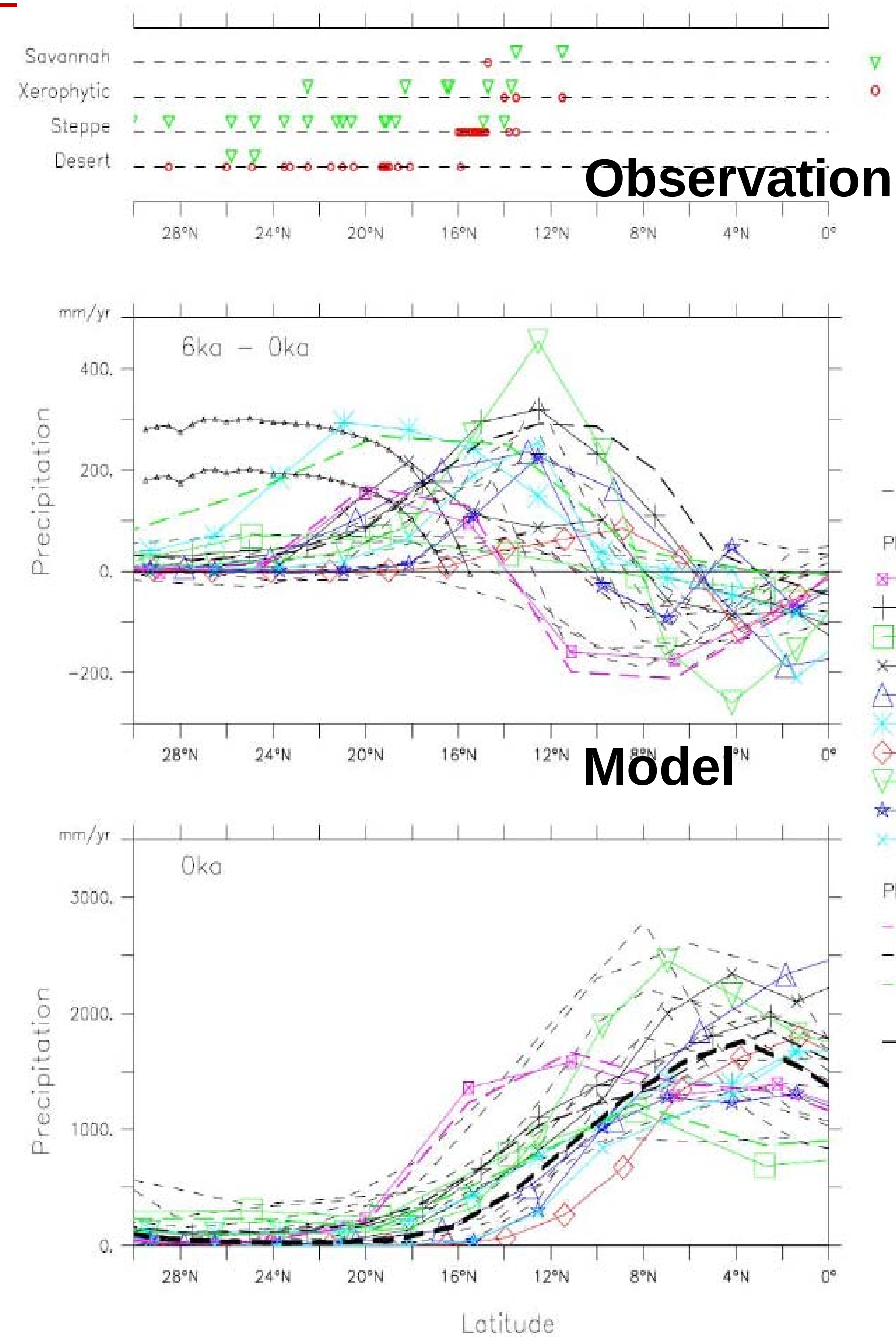
X(t)=BL(t)+N(t)

Weak Signal

BL < < N



Δ(P-E)
6ka-0ka



PMIP II: Vegetation Feedback

(OAV-OA)

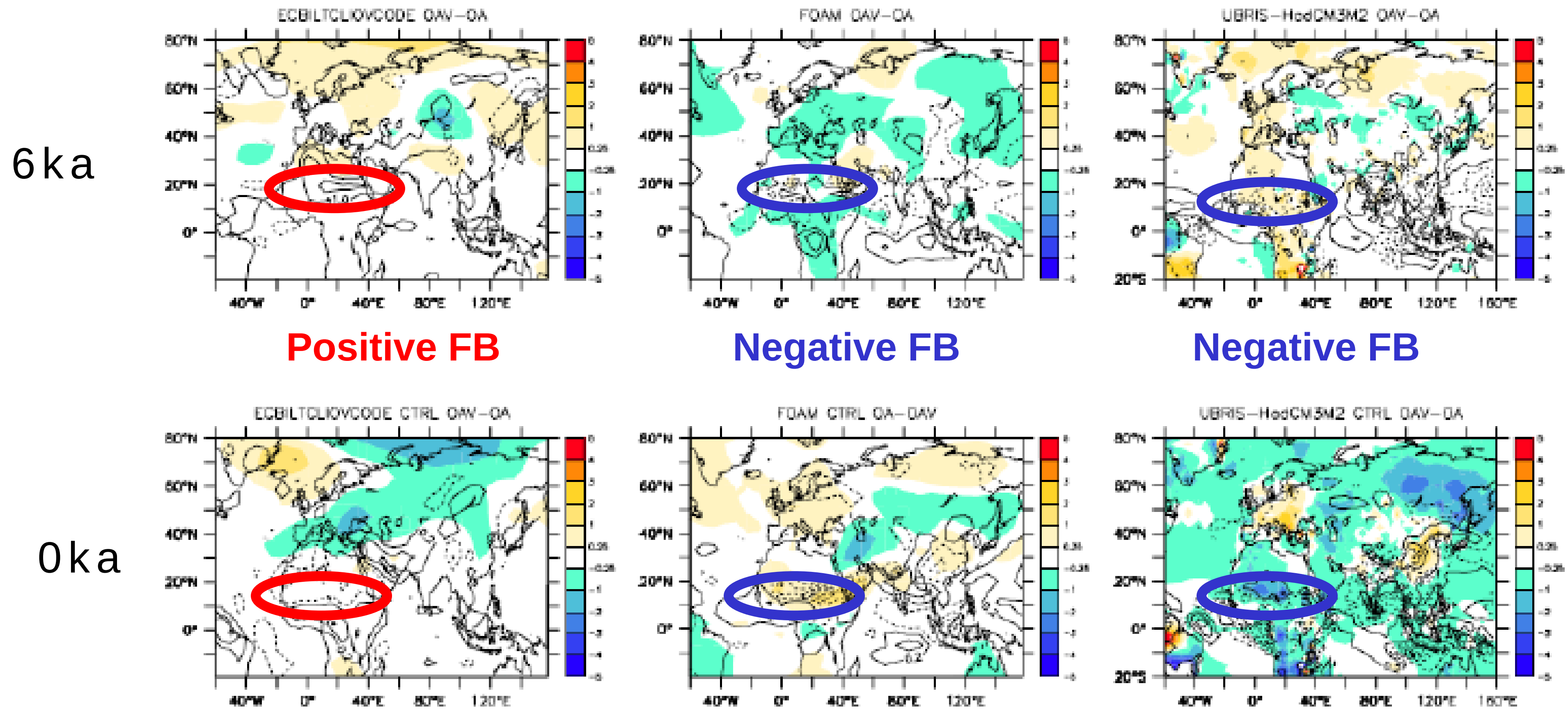


Fig. 5. MH JJAS difference in 2m air temperature (°C, color map) and precipitation (mm/d, isolines) for the three models for which OA and OAV simulations are available in the PMIP2 database. The first two lines represent the MH differences simulated by the OA and the OAV simulations respectively, the third lines is the difference between the first two, and the last line represents the differences between OAV and OA for the preindustrial simulations.

Braoconnot et al., 2007, Climate of Past

+CCSM2_LPJ

The Question ?

Climate impact of ocean/land on the atmosphere

in the observation?

EFA: Equilibrium Feedback Analysis

---- Univariate Statistical Assessment

GEFA: Generalized Equilibrium Feedback Analysis

---- Multivariate Statistical Assessment

Comparison with LIM/FDT

EFA: Equilibrium Feedback Analysis
---- Univariate Statistical Assessment

GEFA: Generalized Equilibrium Feedback Analysis
---- Multivariate Statistical Assessment

Comparison with LIM/FDT

Equilibrium Feedback

x: atmosphere (fast), *T*: ocean/land (slow)

$$\frac{dx}{dt} = ax + bT + n$$

$$\frac{dT}{dt} = cx + dT + N_T$$

Time average the atmosphere equation (>adjustment time of ***x***)

$$0 \approx \frac{d\overline{x}}{dt} = a\overline{x} + b\overline{T} + \overline{n}$$

Quasi Equilibrium Feedback Response

$$\overline{x}(t) = B\,\overline{T}(t) + N(t)$$

Feedback parameter

$$B = -\frac{b}{a}$$

EFA (Equilibrium Feedback Analysis)

Frankignoul et al., 1998, JPO

$$x(t) = BT(t) + N(t)$$

Since $< N(t), T(t-\tau) >= 0$

We have $< x(t), T(t-\tau) >= B < T(t), T(t-\tau) > + < N(t), T(t-\tau) >$

$$B = \frac{< x(t), T(t-\tau) >}{< T(t), T(t-\tau) >} = \frac{C_{xT}(\tau)}{C_{TT}(\tau)}$$

EFA response

$$= \frac{C_{xT}(\tau)}{C_{TT}(0)} \Big/ \frac{C_{TT}(\tau)}{C_{TT}(0)}$$

Alternative (AMIP exp.)

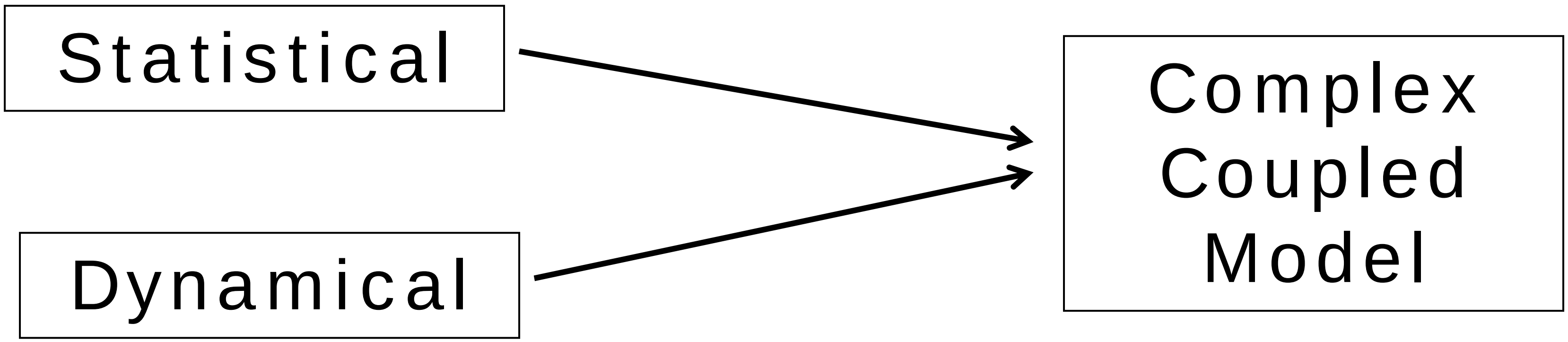
$$< x(t) >= B < T(t) > + < N(t) >$$

$$B =< x(t) > / < T(t) >$$

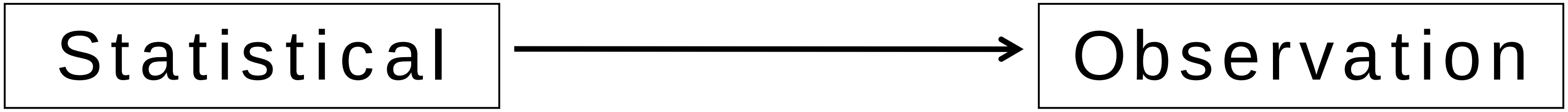
Dynamic Assessment

Combined Statistical-Dynamical Strategy

Step I: Validating Statistical Method
and Understanding Mechanism

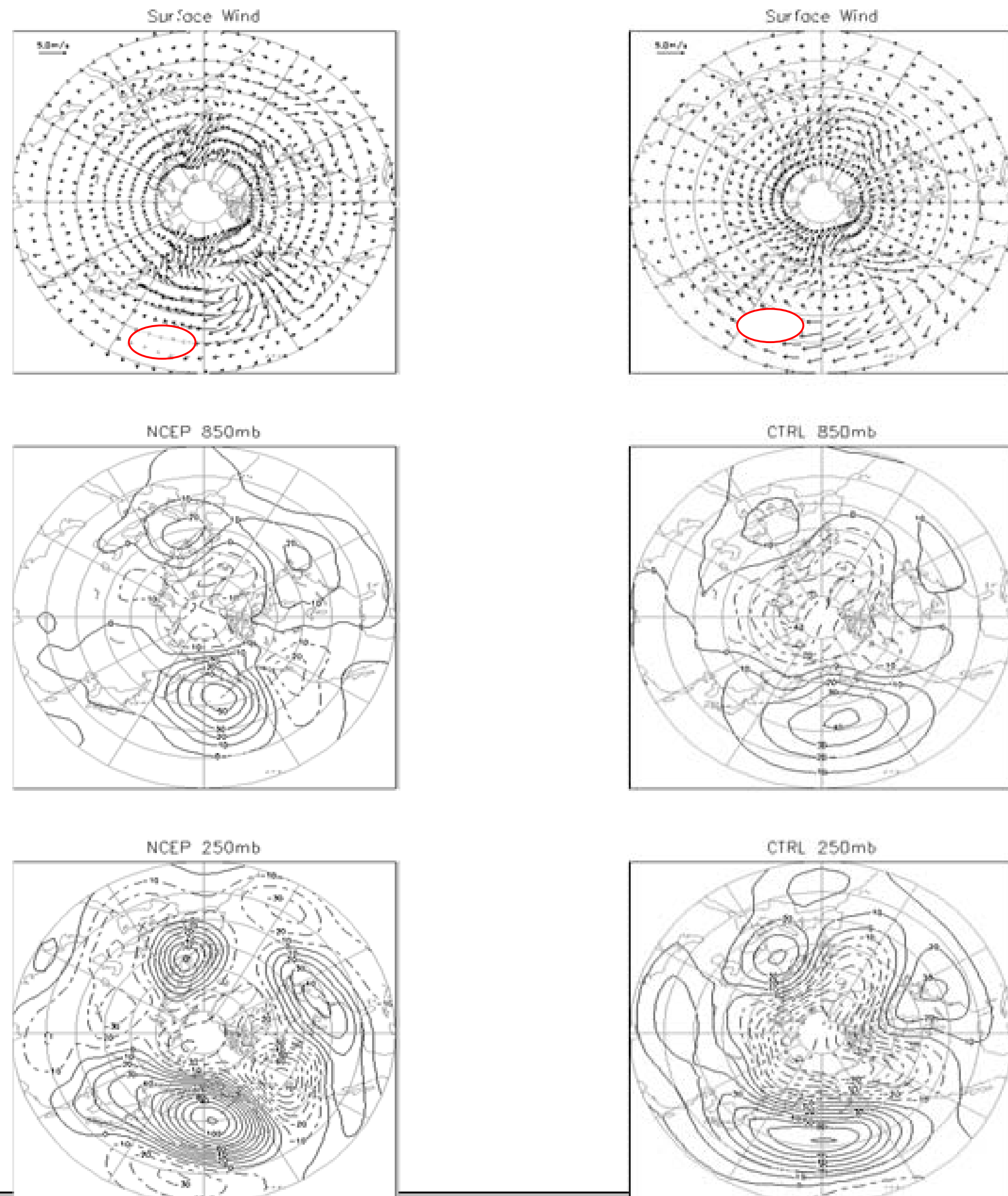


Step II: Statistical Assessment in Observation



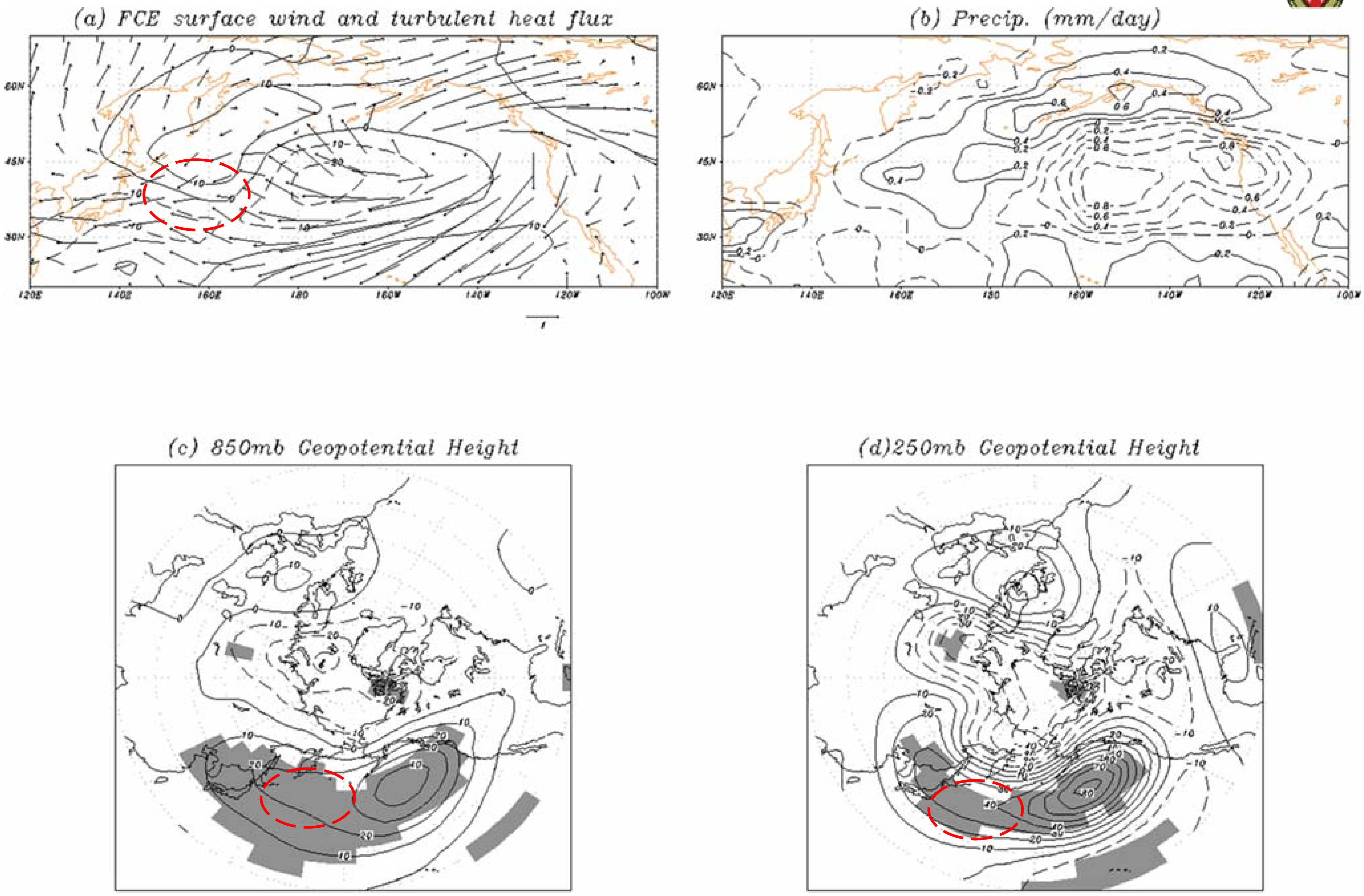
EFA Example I: Atmos. Response to KOE SST

Obs. | Model (FOAM)

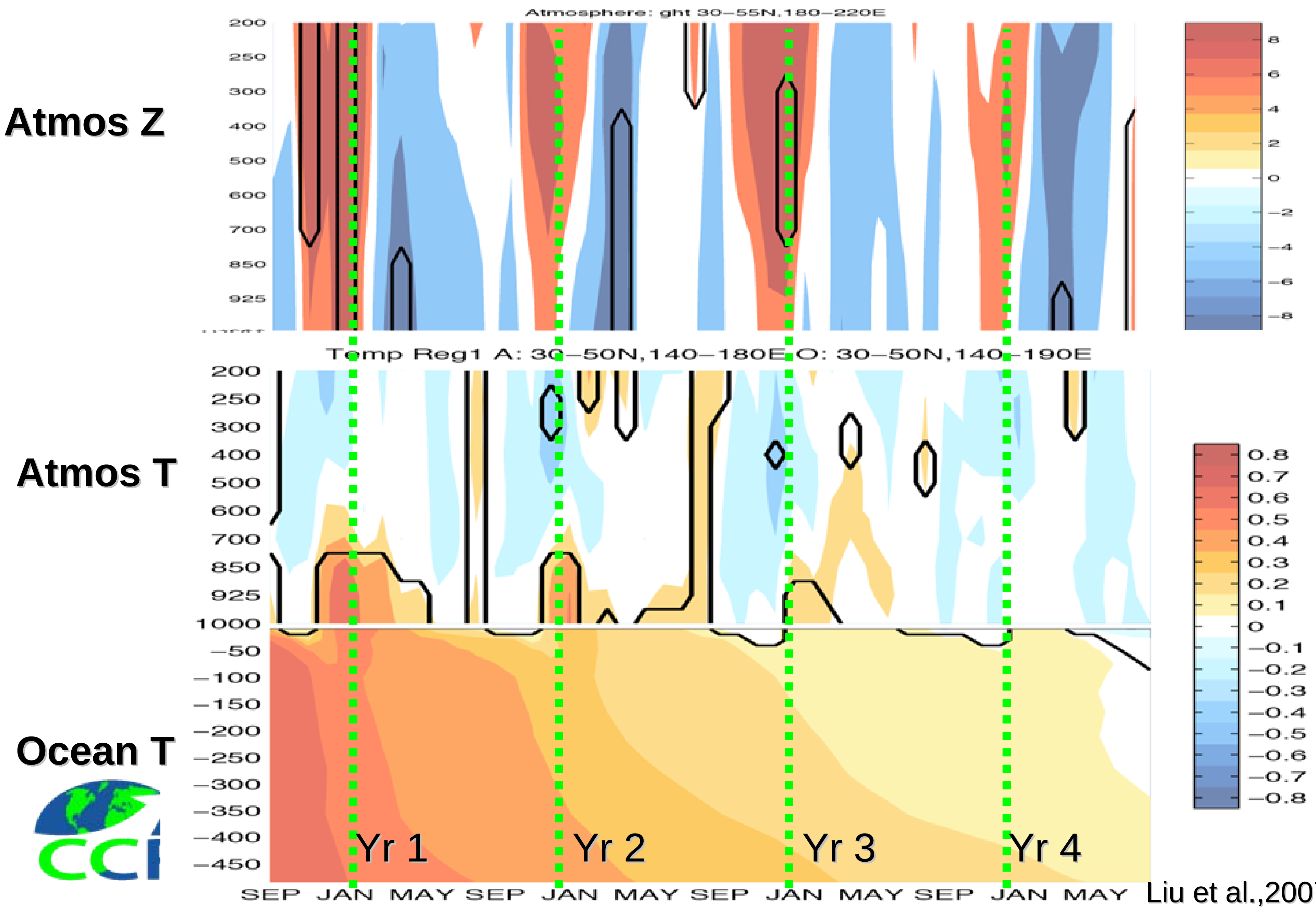


Liu and Wu, 2004, J. Climate

Fully Coupled Response (Dec)



Long Term Response: The Role of Ocean Memory



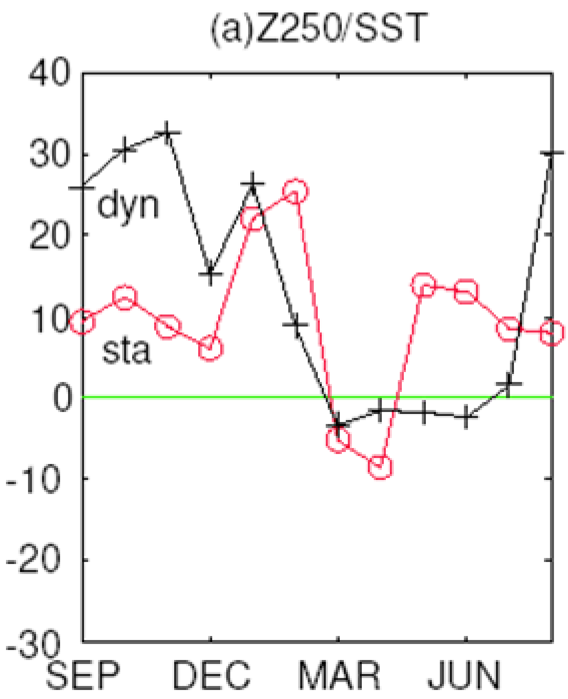
Liu et al.,2007, J. C

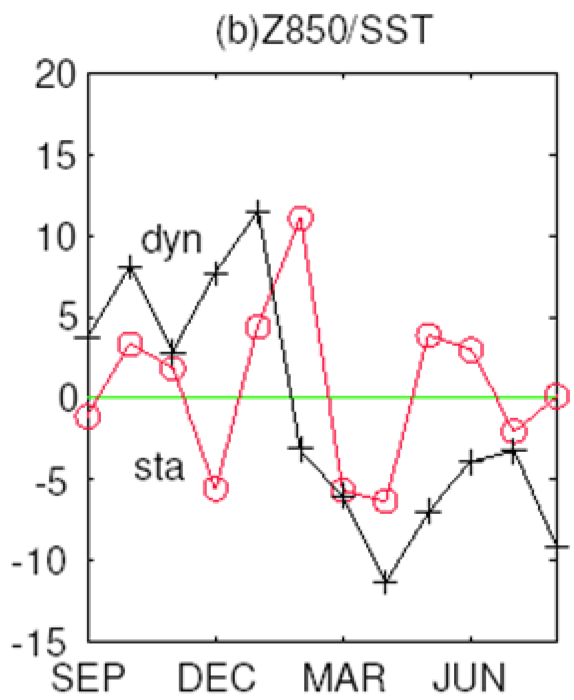
Atmospheric Response to KOE SST

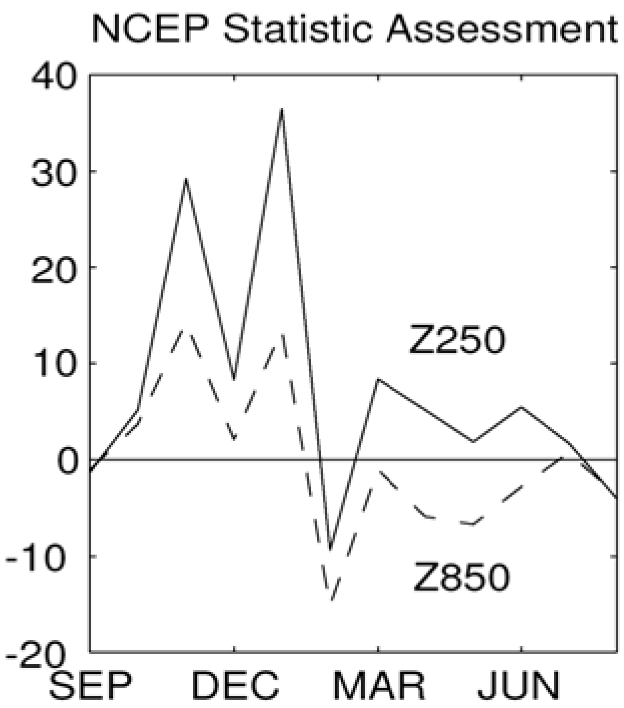
GEFA vs Dyn.

FOAM

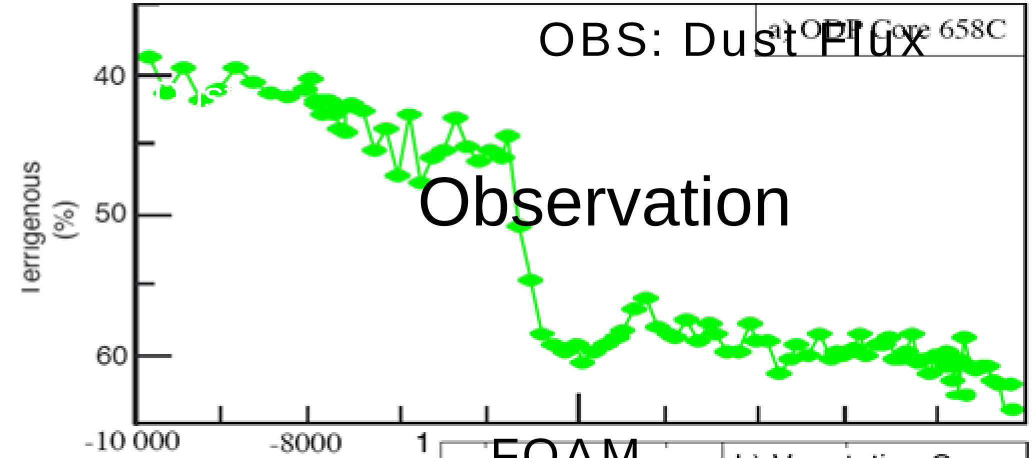
Obs



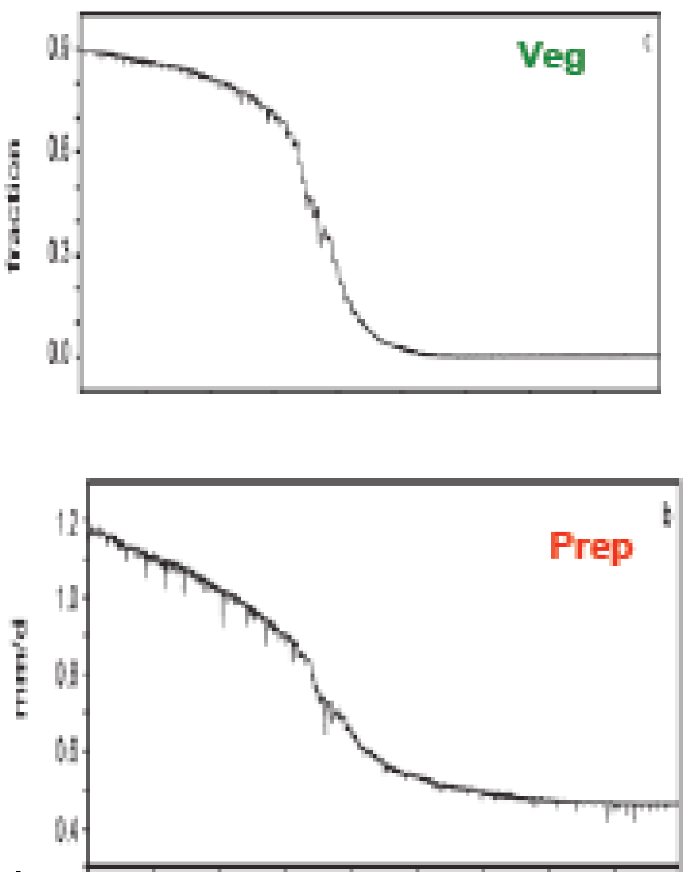




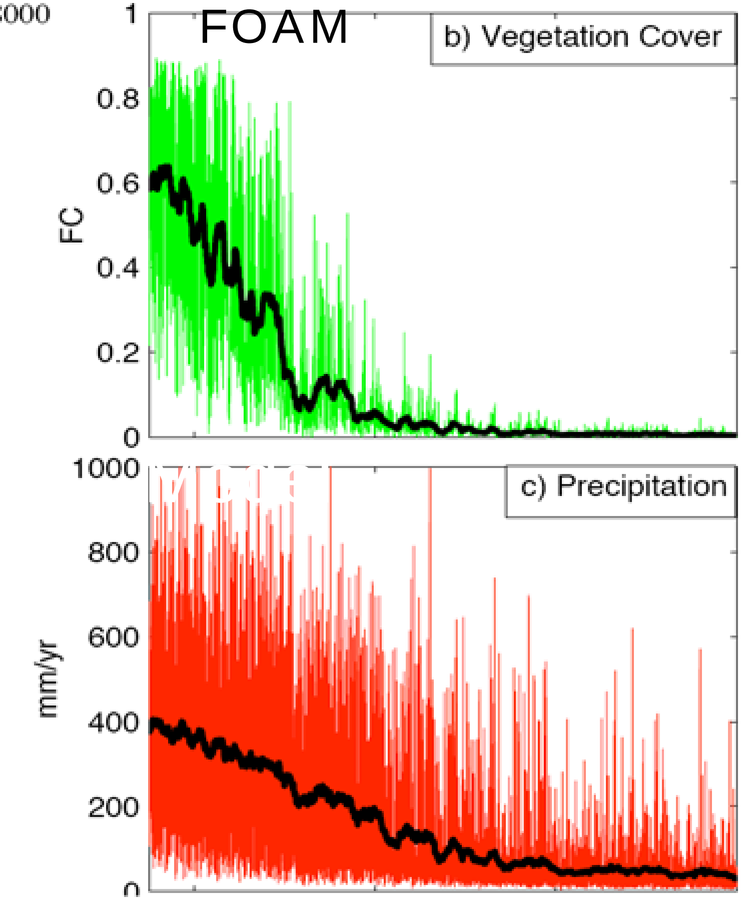
EFA Example II: N. Africa Abrupt Climate Change



CLIMBER-2



FOAM

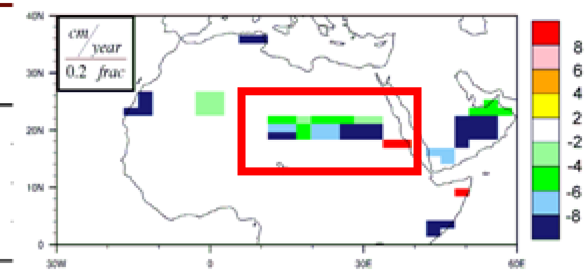


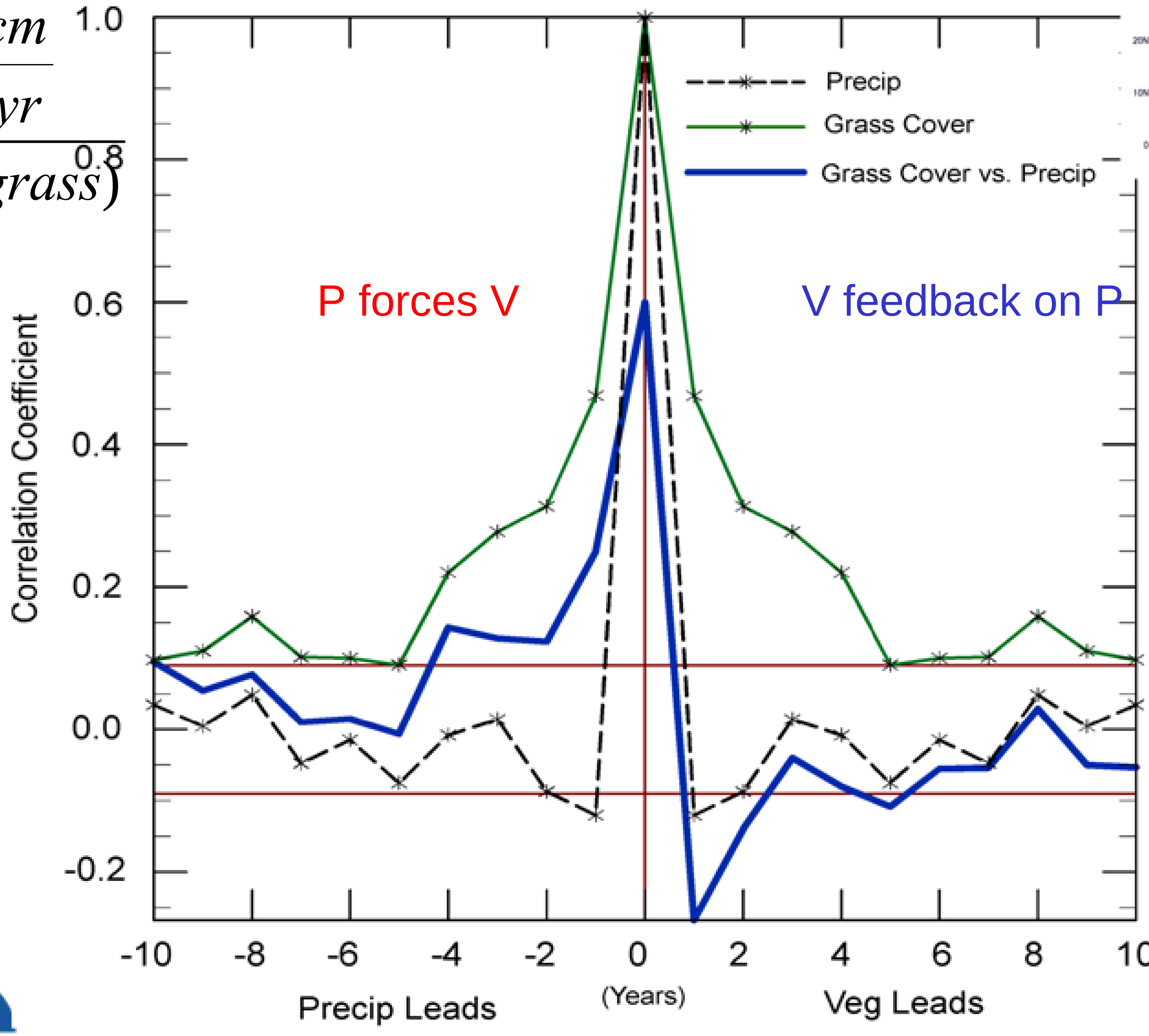
Claussin et al., 1999

Liu et al., 2006, GRL

Corr<grass cover, annual rainfall>

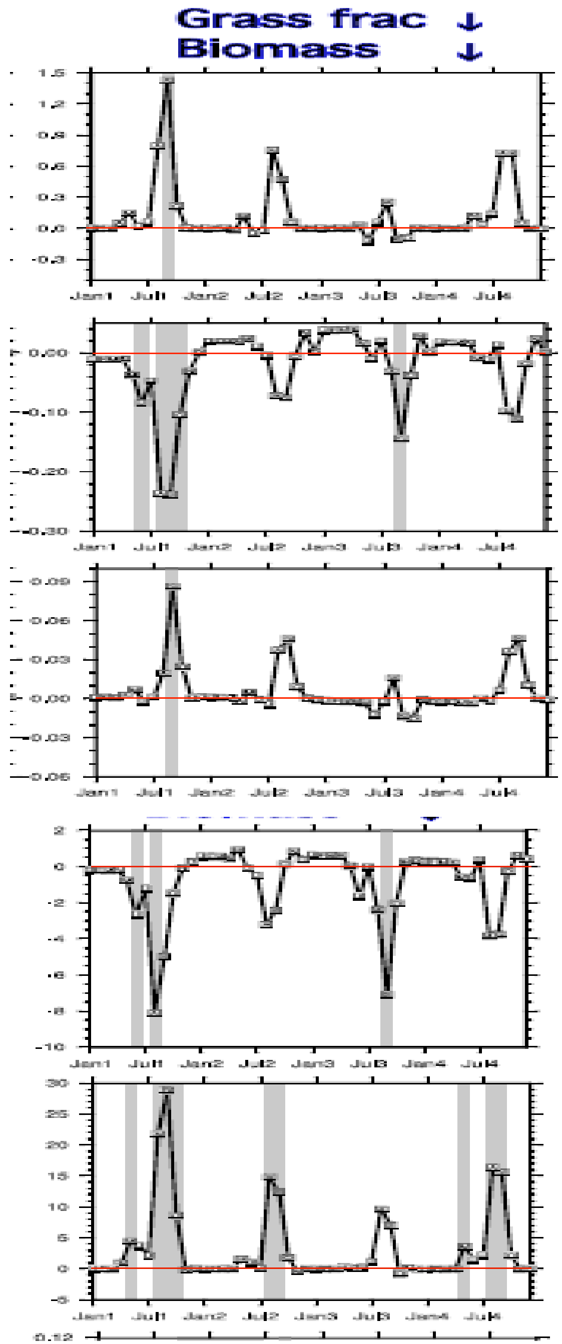
$$\frac{-9.2\frac{cm}{yr}}{0.2\,fpc(grass)}$$





Notaro et al., 2008, Glb Change Biology

Dynamic Assessment



Prep

Leaf Area Index

Top Soil Moisture

-10

Transpiration

+30

BareGround Evap

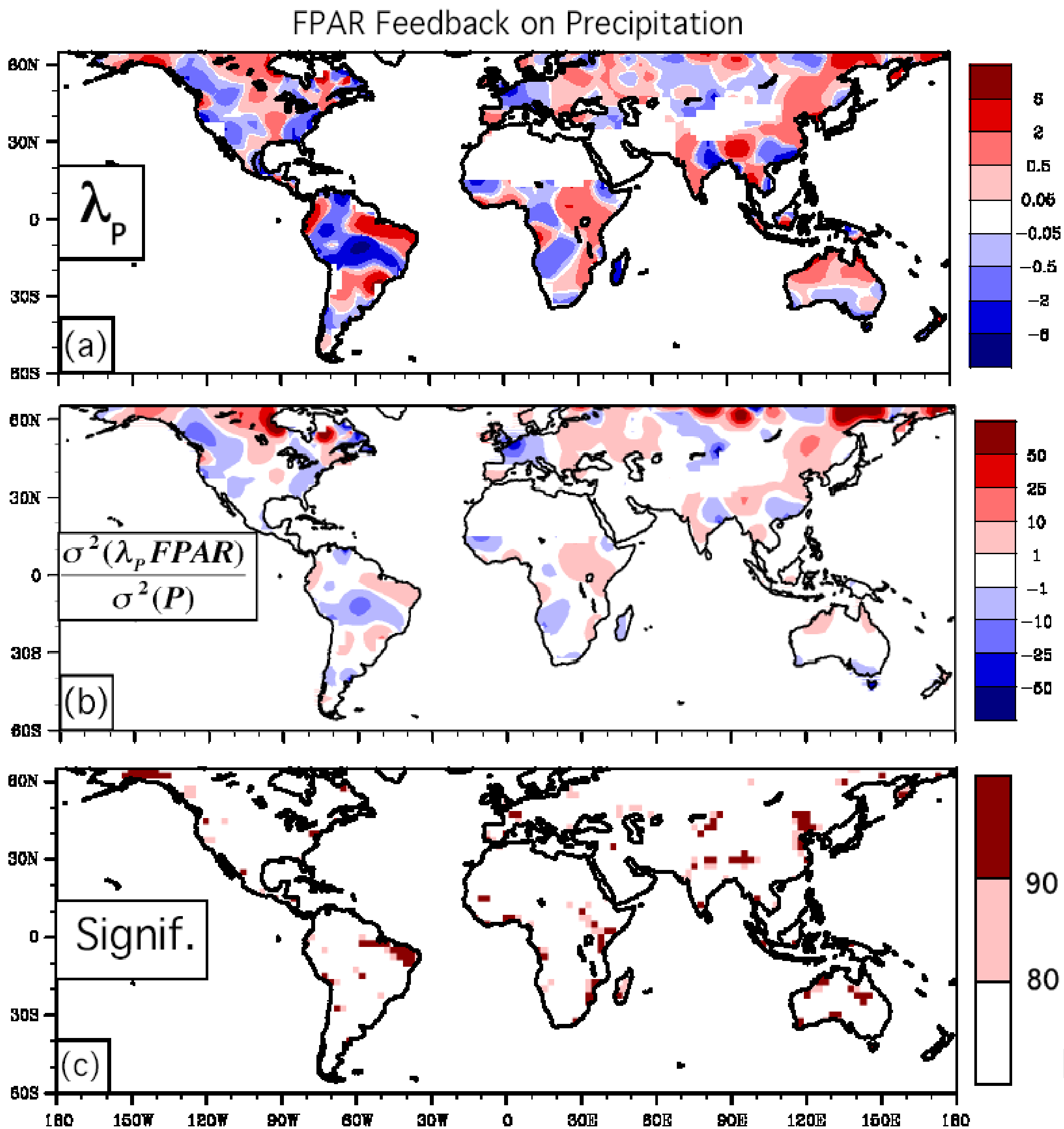
Notaro et al., 2008, Glb Change Biology

Statistical and Dynamical Response in Annual Variables to a Decrease in North African Grass Cover Fraction by 0.2

	Units	Statistical (FOAM)	Dynamical (FOAM)	Statistical (CCSM2)
Precipitation	cm/yr	+9.2	+9.7	+3.3
Evaporation	cm/yr	+4.7	+6.1	+0.7
Bare soil evaporation	cm/yr	+10.2	+8.6	+8.7
Transpiration	cm/yr	-5.5	-2.5	-8.0
Sfc specific humidity	g/kg	+0.19	+0.27	+0.08

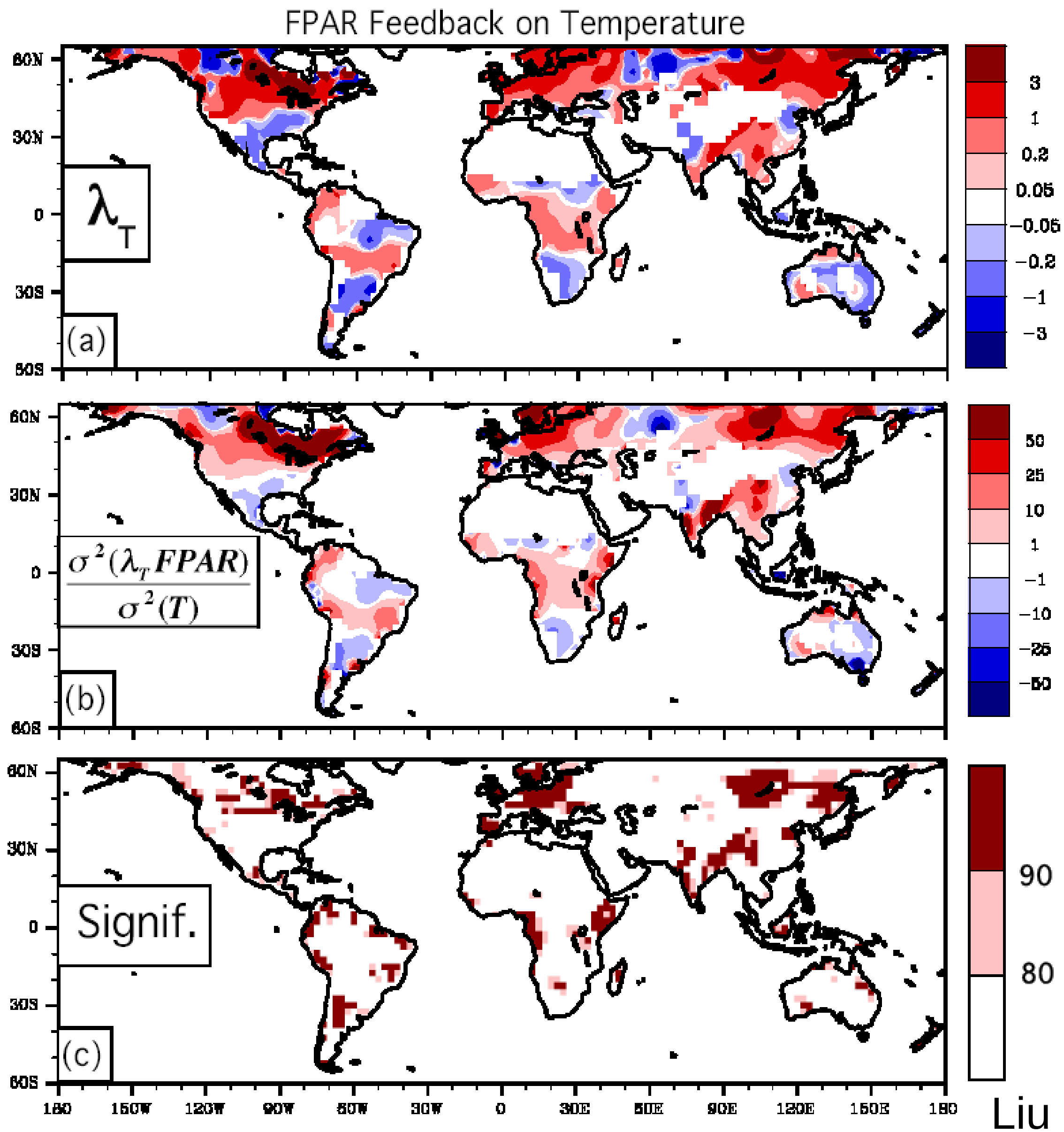
Notaro et al., 2008,
Glb Change Biology

EFA Vegetation feedback on Prep
Observation (1980-2000)



Liu et al., 2006, Climate

EFA Vegetation feedback on temperature
Observation (1980-2000)



Liu et al., 2006, J. Climate

EFA: Equilibrium Feedback Analysis
---- Univariate Statistical Assessment

GEFA: Generalized Equilibrium Feedback Analysis
---- Multivariate Statistical Assessment

Comparison with LIM/FDT

GEFA (Generalized EFA)

Liu et al., 2008, J. Climate

$$X(t) = \begin{bmatrix} b_1 & b_2 & \cdots & b_J \end{bmatrix} \begin{bmatrix} T_1(t) \\ T_2(t) \\ \cdots \\ T_J(t) \end{bmatrix} + N(t) \equiv \mathbf{B}\,T(t) + N(t)$$

GEFA response

$$\mathbf{B} = \mathbf{C}_{xT}(\tau)\mathbf{C}_{TT}^{-1}(\tau)$$

Testing GEFA:
Ocean feedback in the Advective Hasselman Model

Advective Hasselman Model

$$\frac{\partial T_a}{\partial t} + U\frac{\partial T_a}{\partial x} = \lambda(T - T_a) + N(t,x)$$

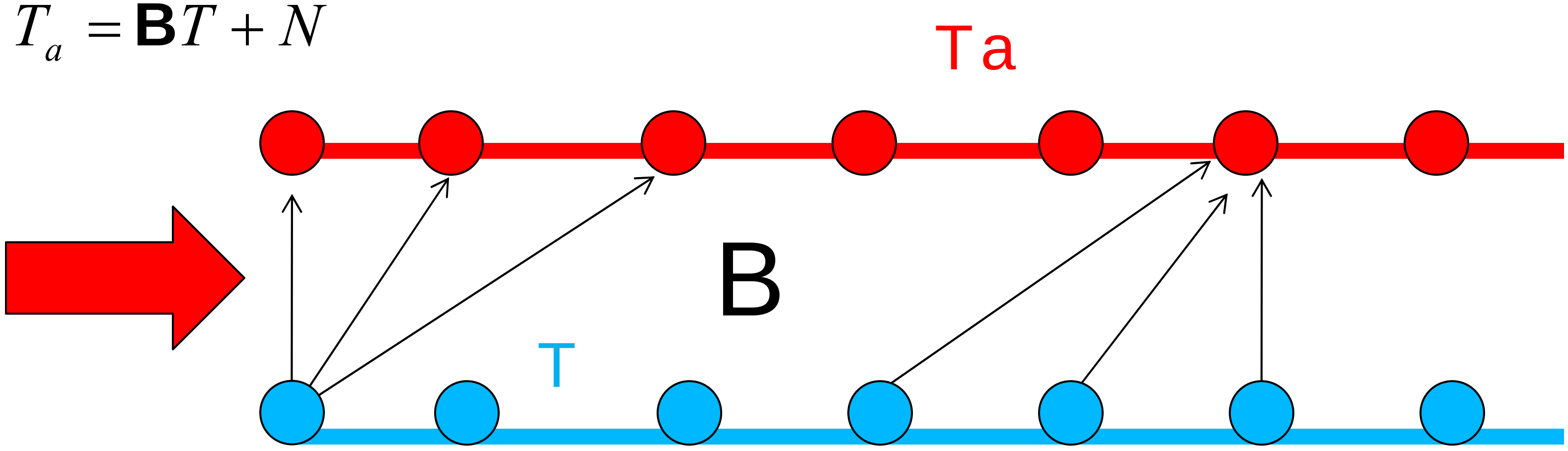
$$\frac{dT}{dt} = \lambda(T_a - T) - dT$$

Equilibrium Response

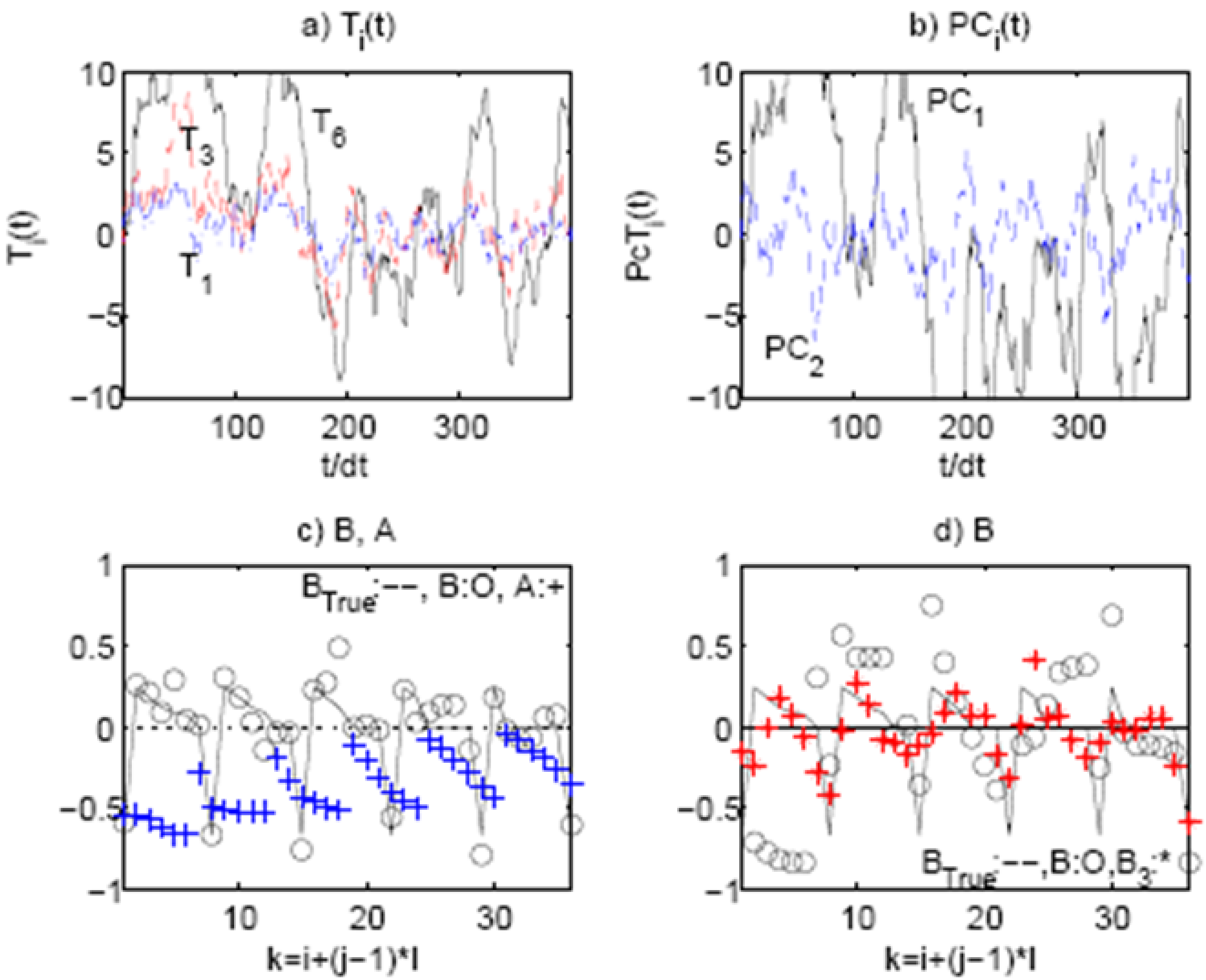
$$U\frac{\partial T_a}{\partial x} = \lambda(T - T_a) + N(t,x)$$

Finite difference

$$T_a = \mathbf{B}T + N$$



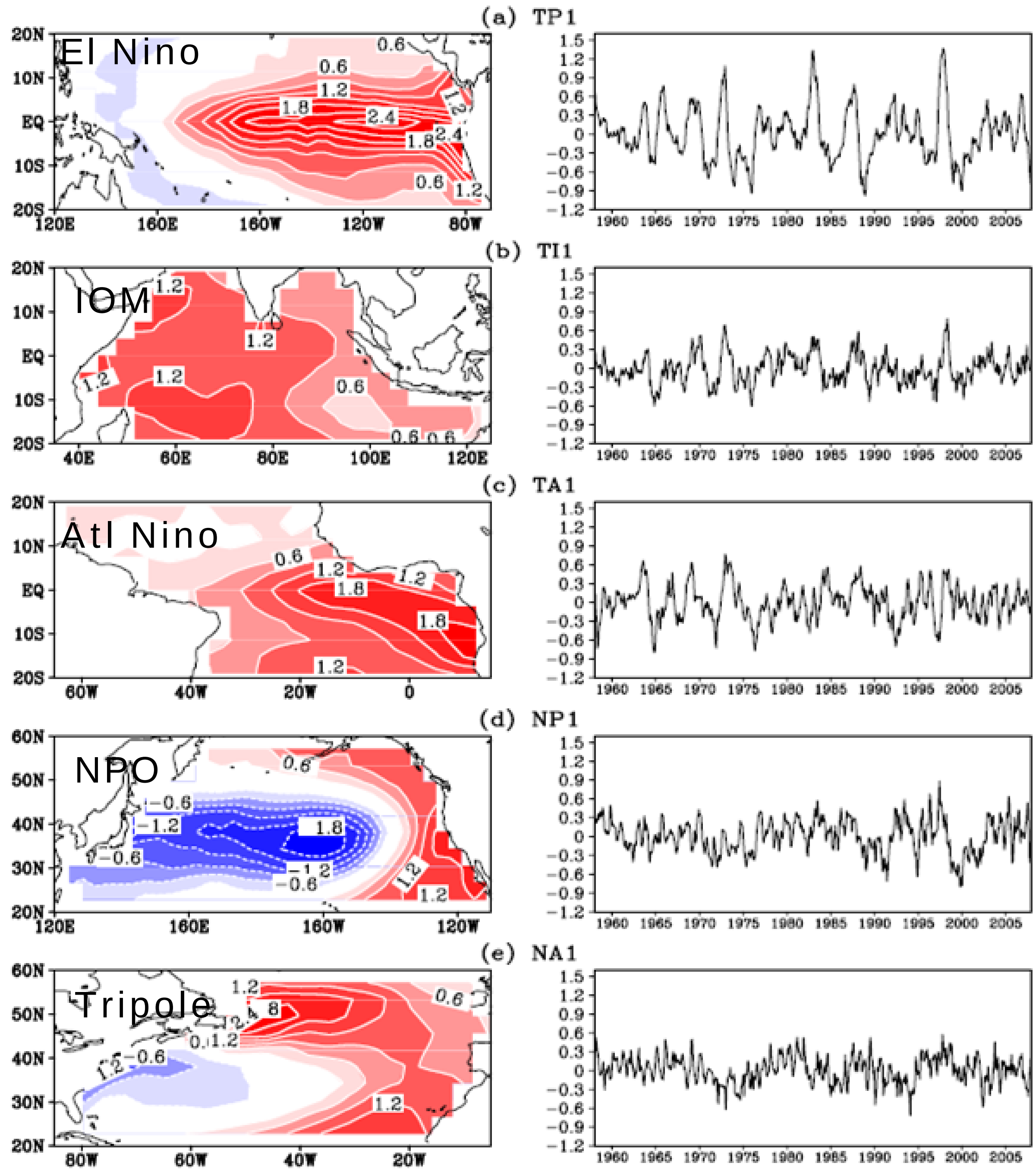
Ocean feedback in Advective Hasselman Model (6 points)



B and A

B and B3 (EOF)

Forcing:
Regional SST EOF1

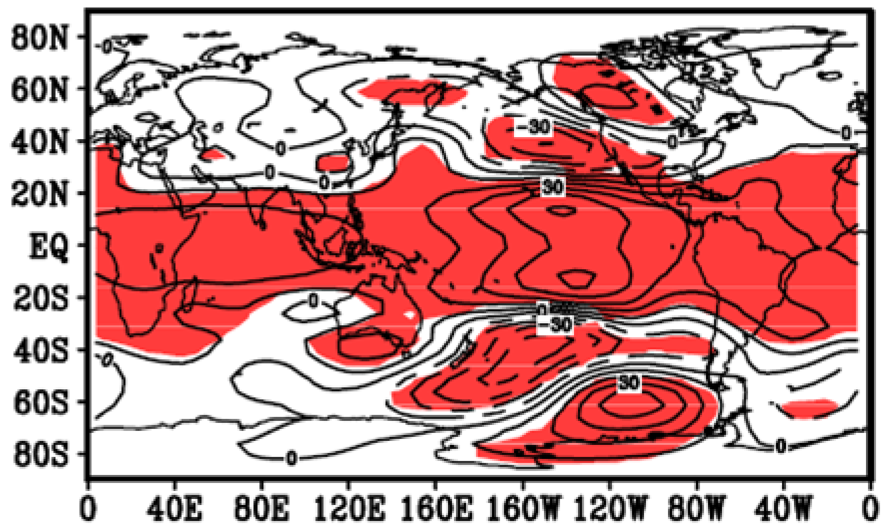


Wen et al., J. Climate, 2009, Submitted

GEFA Response to ENSO

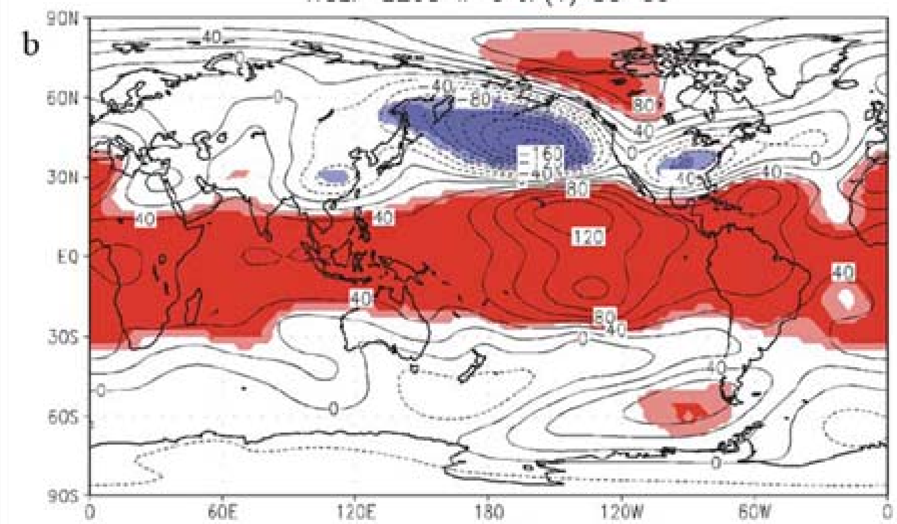
Tropical Pacific (3) x North Pacific (3)

a) GEFA Z250 Rsp to TP1, σ(TP1)=0.42°C

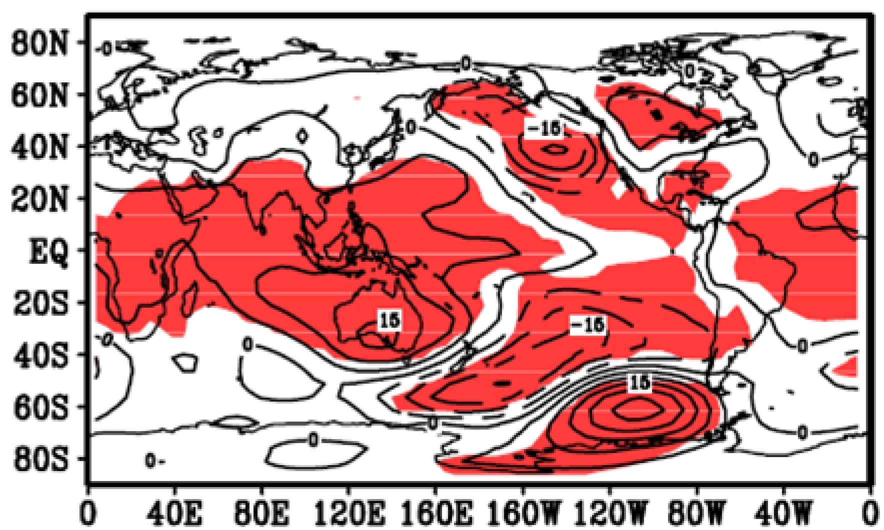


Composite

NCEP Z200 w-c JF(1) 50-99



b) GEFA Z850 Rsp to TP1, σ(TP1)=0.42°C

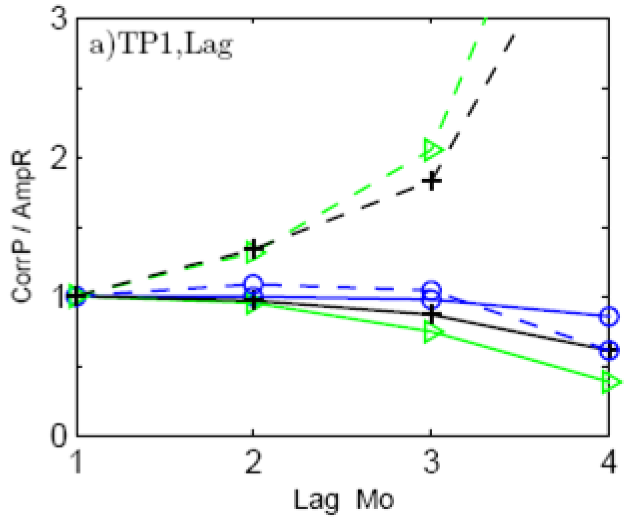


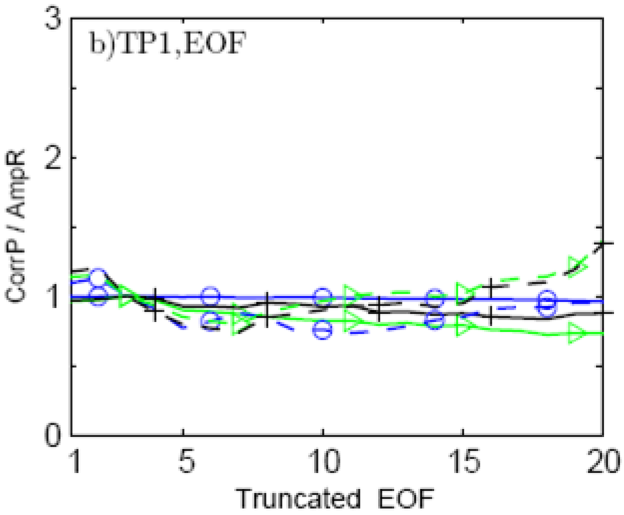
Sensitivity to lag and EOF truncation

Lag

EOFs

Tp1

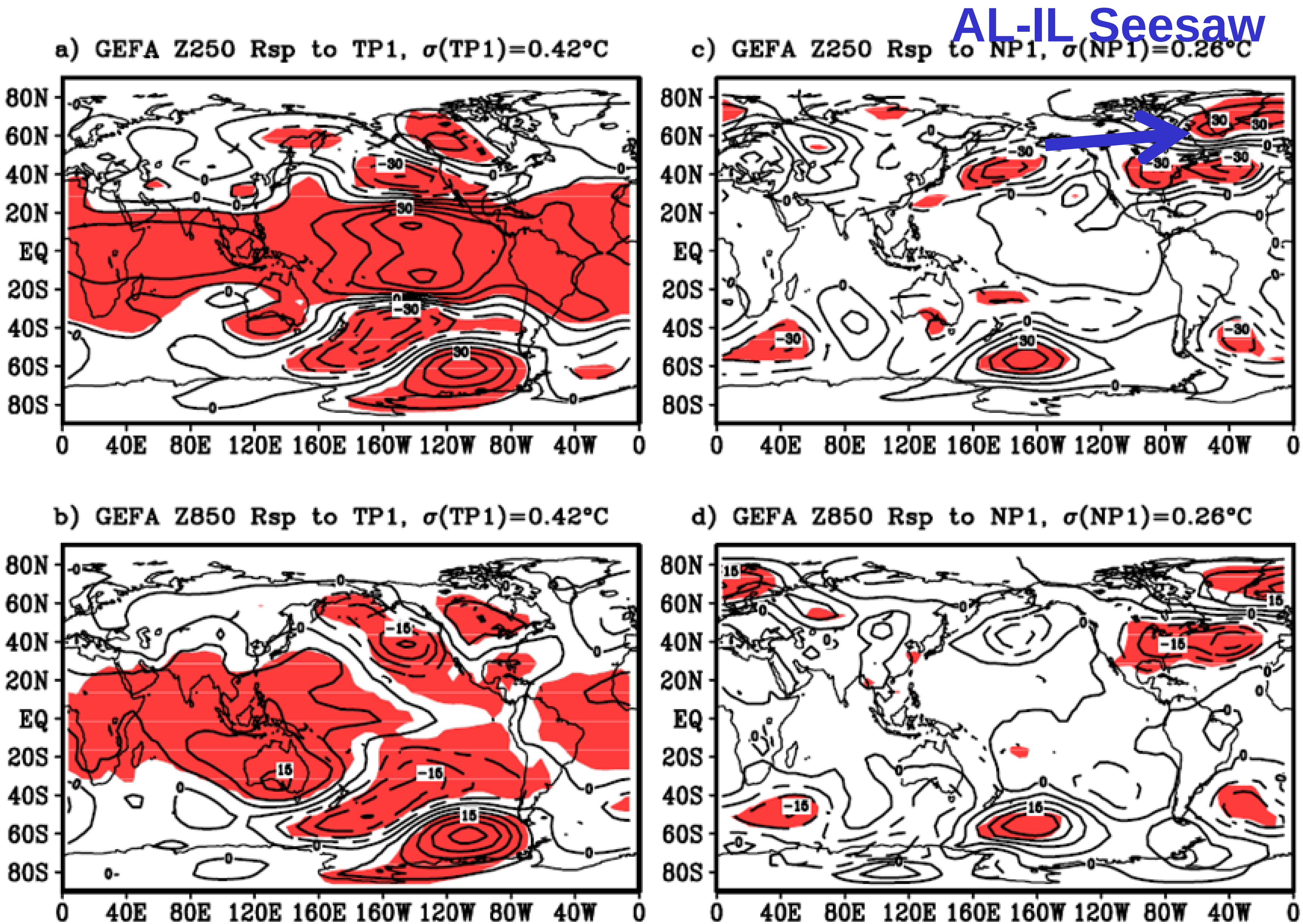




GEFA Response to TP1 and NP1

Trop Pac (3) x N. Pac (3)

TP1 **NP1**

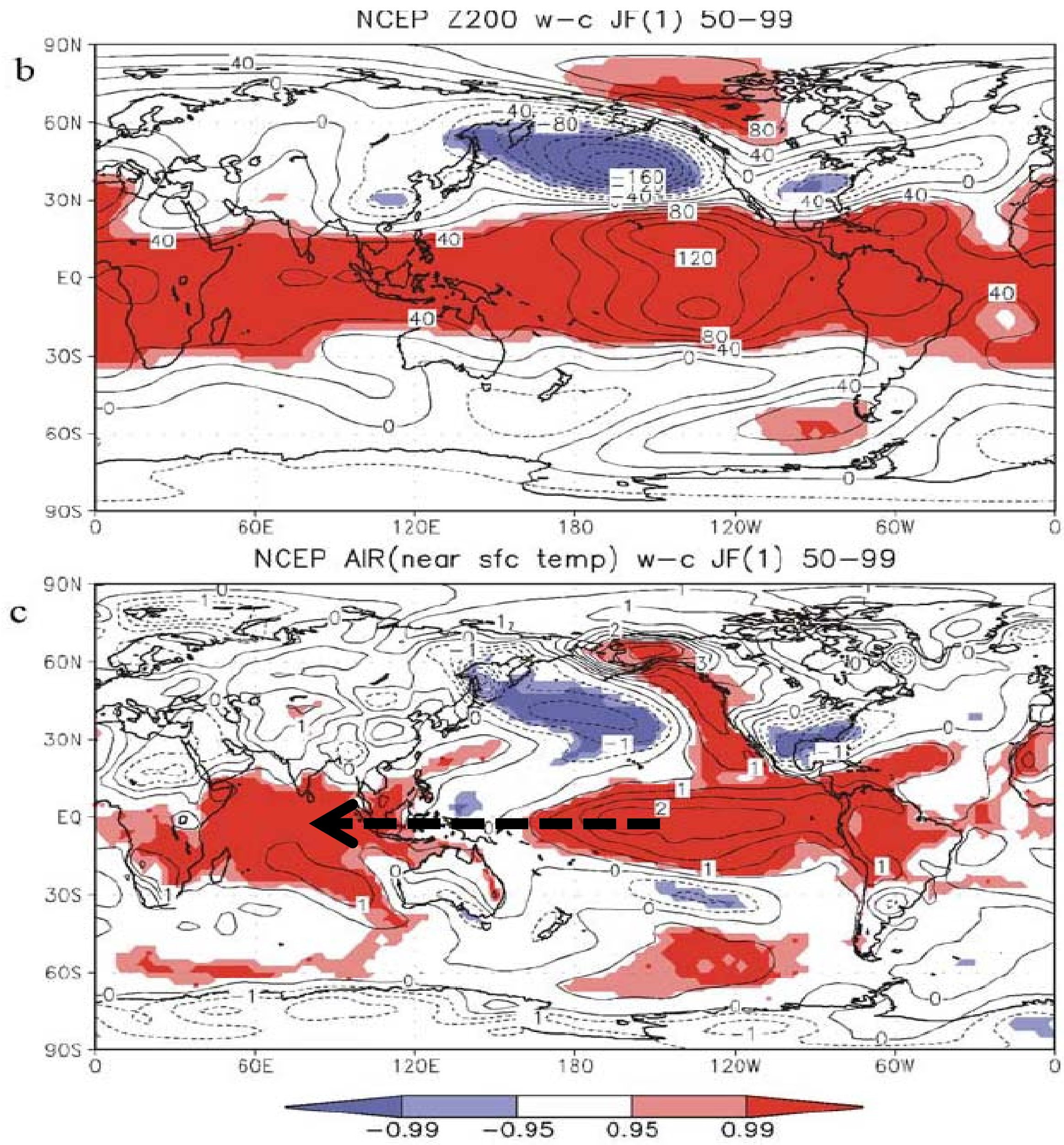


ENSO forcing? or Indian Ocean forcing?

Composite

Z200

Ts

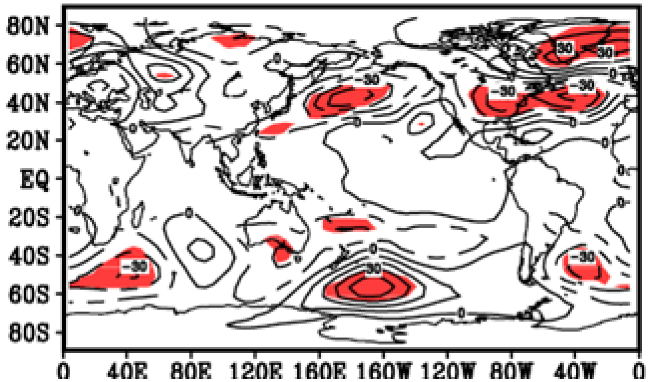


GEFA Z250 Response

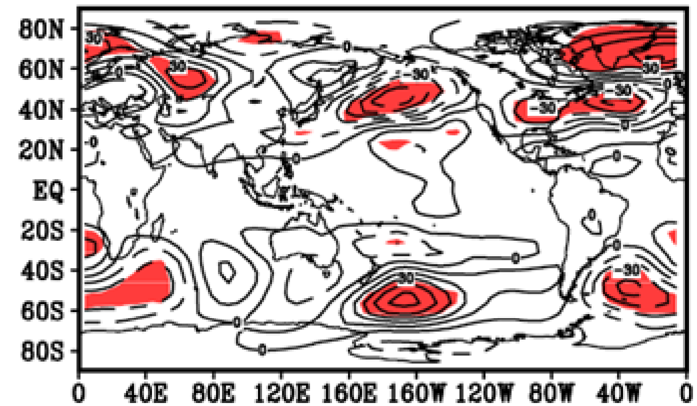
T. Pac(3)xN. Pac(3)

T. Pac(3)xN. Pac(3)xT. Ind(3)xN. Alt(3

c) GEFA Z250 Rsp to NP1, σ(NP1)=0.26°C

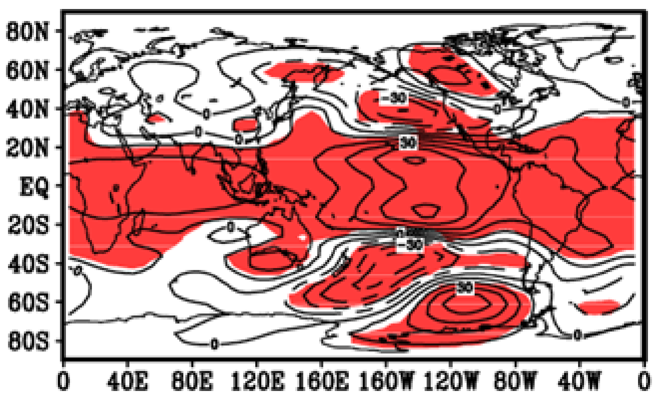


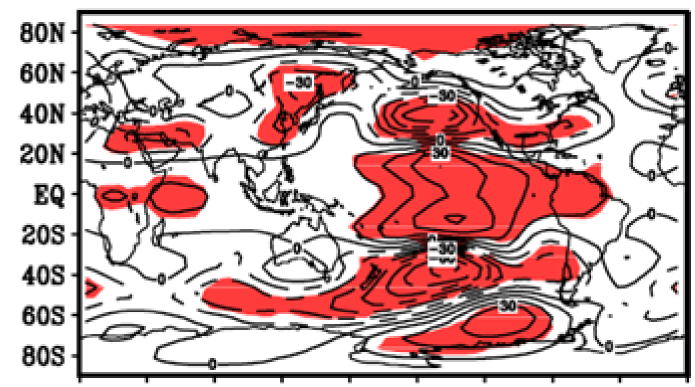
d) GEFA Z250 Rsp to NP1, σ(NP1)=0.26°C



NP1

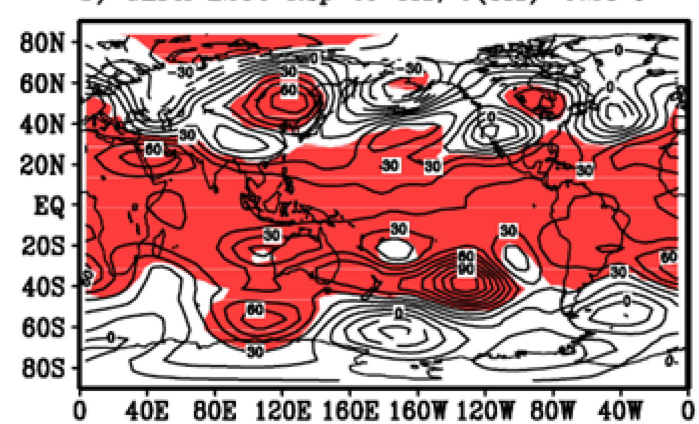
a) GEFA Z250 Rsp to TP1, σ(TP1)=0.42°C





TP1

b) GEFA Z250 Rsp to TI1, σ(TI1)=0.23°C



TI1

Lead-Lag Composite to ENSO forcing

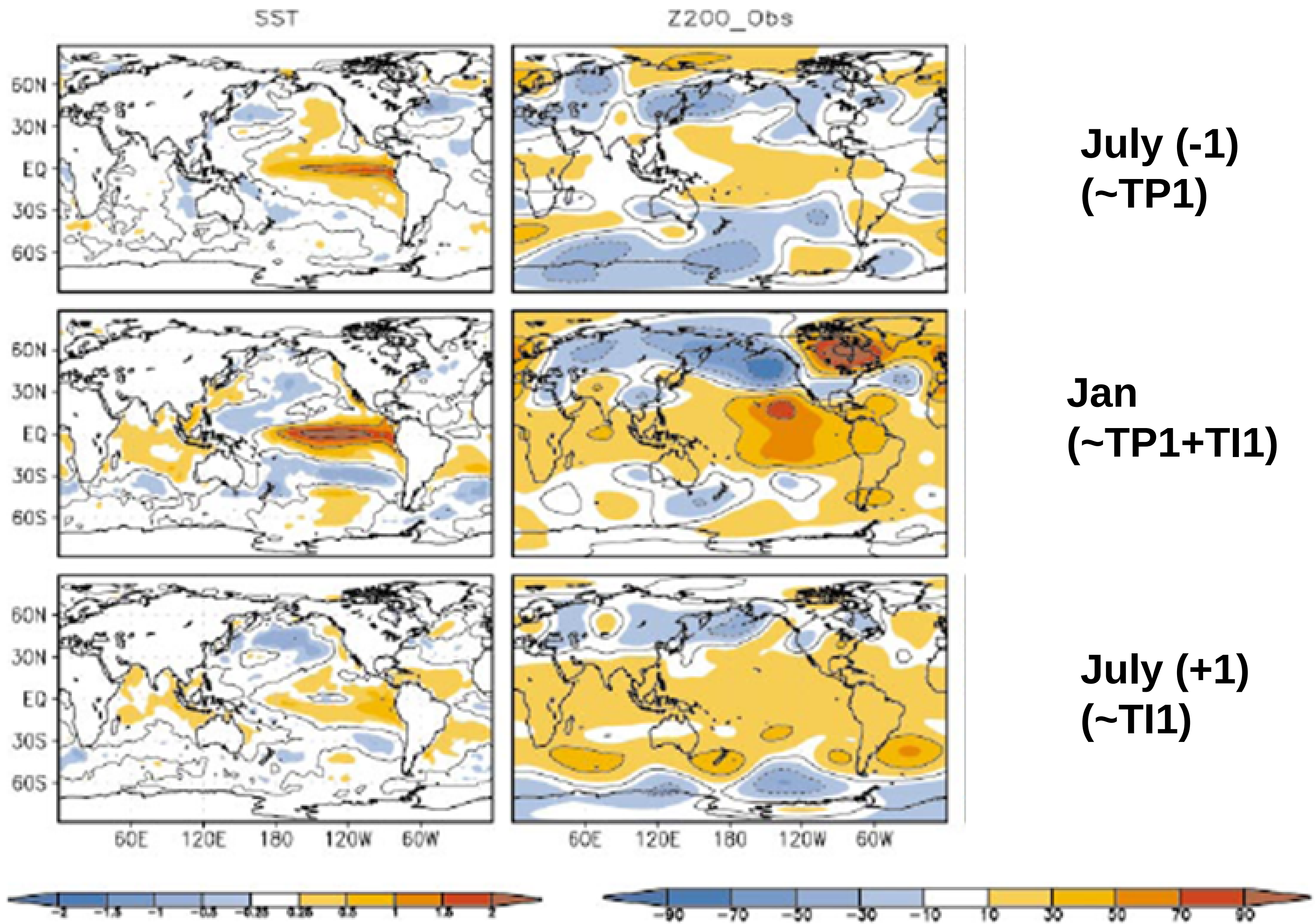


FIG. 5. The spatial maps of warm ENSO event composite anomalies for (left column) SST (°C), (middle column) observed 200-mb height (m), and (right column) CCM3 simulated 200-mb height (m). Warm events defined as in Fig. 3. The top (bottom) row shows Jul composites preceding (following) the Jan base month of the Niño-3.4 index. The middle row shows simultaneous composites for Jan. Negative anomalies are dashed.

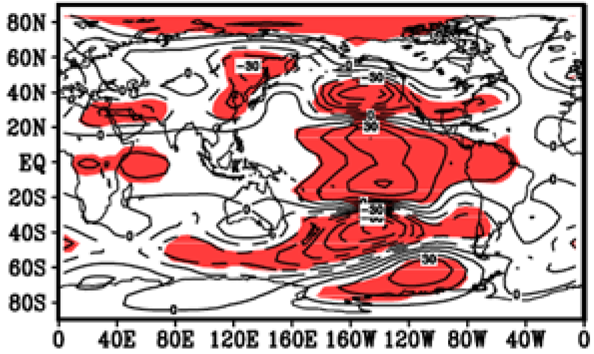
CCR

Kumar and Hoerling, 2003, J. Climate

GEFA Z250 Response to EOF1s

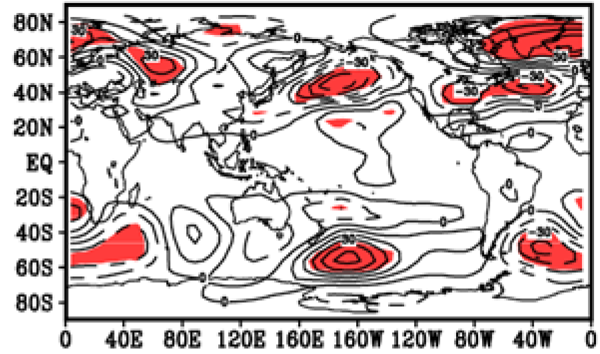
T. Pac(3)xN. Pac(3)xT. Ind(3)xN. Atl(3)xT. Atl (3)

a) GEFA Z250 Rsp to TP1, σ(TP1)=0.42°C



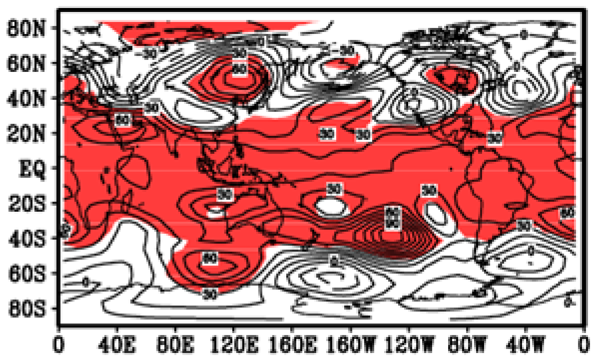
TP1

d) GEFA Z250 Rsp to NP1, σ(NP1)=0.26°C



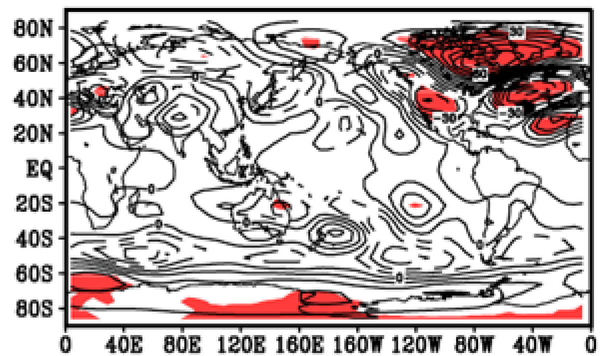
NP1

b) GEFA Z250 Rsp to TI1, σ(TI1)=0.23°C



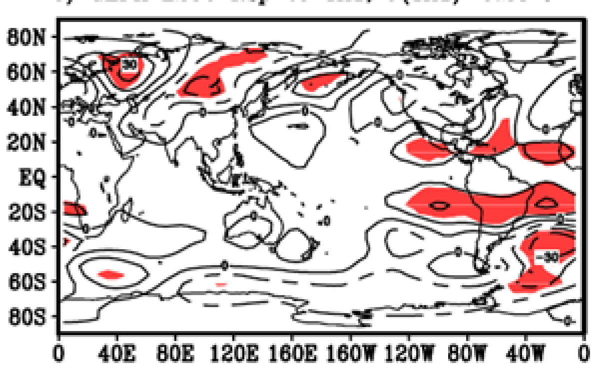
TI1

e) GEFA Z250 Rsp to NA1, σ(NA1)=0.22°C



NA1

c) GEFA Z250 Rsp to TA1, σ(TA1)=0.28°C



TA1

EFA: Equilibrium Feedback Analysis
---- Univariate Statistical Assessment

GEFA: Generalized Equilibrium Feedback Analysis
---- Multivariate Statistical Assessment

Comparison with LIM/FDT

Linear Inverse Modeling (LIM)/ Fluctuation-Dissipation Theorem(FDT)

Dynamic system
(N white, Gaussian)

$$\frac{dZ}{dt} = \mathbf{G}Z + N(t)$$

Most probable solution

$$\hat{Z}(t+\tau) = \exp(\mathbf{G}\tau)Z(t)$$

Matrix estimator

$$\mathbf{G} = \tau^{-1}\ln\{\mathbf{C}(\tau)\mathbf{C}(0)^{-1}\}, \qquad LIM$$

$$-\mathbf{G}^{-1} = \int_0^\infty \mathbf{C}(\tau)\mathbf{C}(0)^{-1}d\tau, \qquad FDT$$

$$where \quad \mathbf{C}(\tau) = < Z(t+\tau), Z^T(t) >$$

Forecast/prediction

$$Z(t+\tau_0) = \exp(\mathbf{G}\tau_0)Z(t) + \varepsilon$$

Penland, 1989, J. Climate

LIM/FDT

X : *atmosphere* (*fast*), T : *ocean / land* (*slow*)

$$\frac{dX}{dt} = aX + bT + N_X$$

$$\frac{dT}{dt} = cX + dT + N_T$$

GEFA

$$0 = \frac{dX}{dt} = aX + bT + N_X$$

$$X = \mathbf{B}\,T + N, \qquad \mathbf{B} = -a/b$$

$$Z = \begin{bmatrix} X \\ T \end{bmatrix}, \quad \mathbf{G} = \begin{bmatrix} a & b \\ c & d \end{bmatrix}, \quad N = \begin{bmatrix} N_X \\ N_T \end{bmatrix};$$

$$\frac{dZ}{dt} = \mathbf{G}Z + N(t) \;\Rightarrow\; \mathbf{B} = -a/b$$

Summary

- GEFA provides a potentially effective approach to assess and understand atmospheric response to SST/Land surface forcing, systematically.

- There is a modest but significant atmospheric response to extratropical SST anomaly

- There is no observational evidence of significant positive vegetation feedback on rainfall in N. Africa, yet.

Future Work

- GEFA modifications/applications

- GEFA + Dynamic assessment

- Prediction: GEFA(Atm)+LIM/FDT(SST)
  FDT(Atm+SST)

Acknowledgement

Wen Na	Nanjing Univ. of Information Science and Technology, China
Mike Notaro	Univ. Wisc-Madison
Yun Liu	Univ. Wisc-Madison
Yafang Zhong	Univ. Wisc-Madison
Lixin Wu	Ocean Univ. of China
Qinyu Liu	Ocean Univ. of China
Claude Frankignoul	Univ. Pierre et Marie Curie, France