Bred Vectors in Coupled Ocean-Atmosphere Models

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With thanks to Michele Rienecker

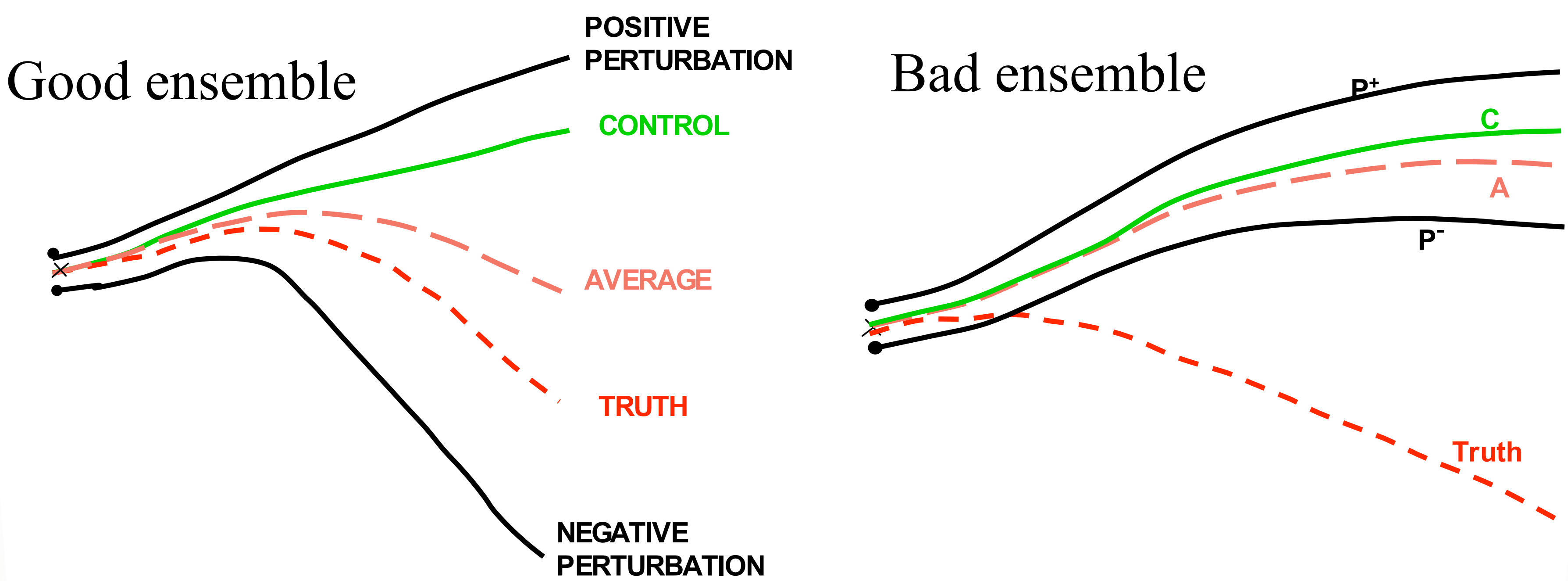
Content

- ENSO is a slow instability, weather noise is fast…How to create coupled slow perturbations for ENSO ensemble forecasting and data assimilation?
- Breeding is a nonlinear approach and allows for saturation of fast noise (unlike linear Singular Vectors)
- Breeding in the Cane-Zebiak model
- Breeding in the NASA coupled GCM; comparison with the NCEP coupled GCM
- Breeding in the operational NASA NSIPP data assimilation/forecasting system
- Bred vectors and forecast errors (analysis increments). Preliminary ensemble forecasting results

The atmosphere has coupled instabilities that span many time scales:

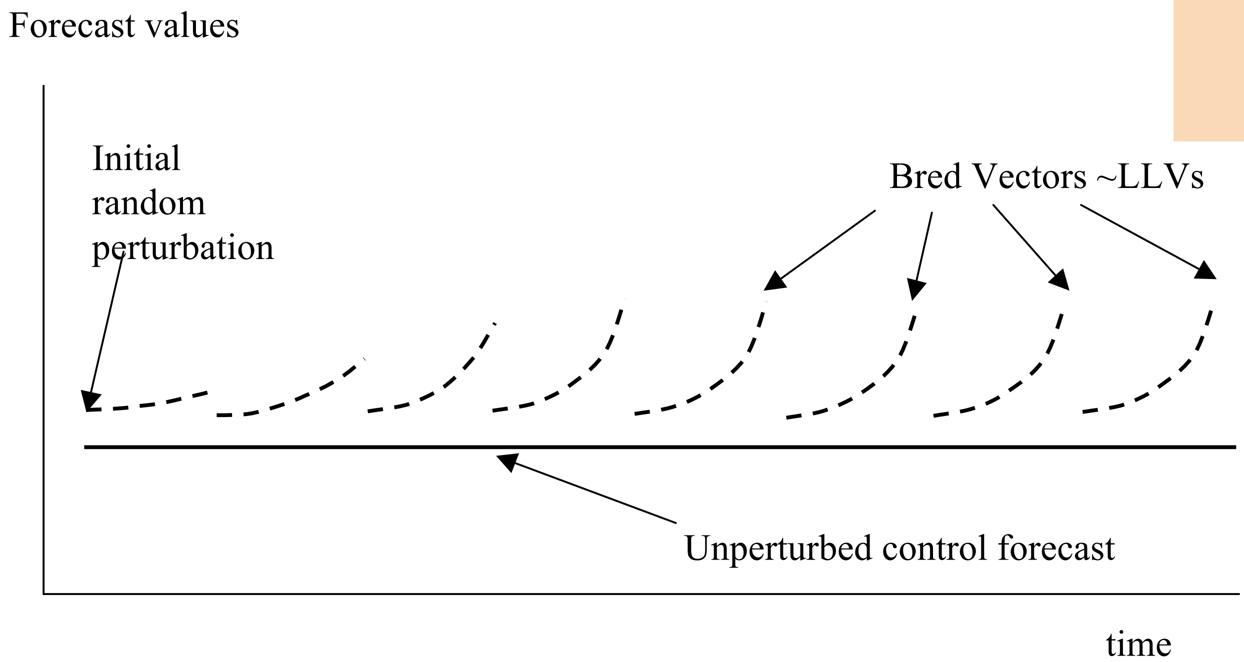
- ENSO has a doubling time of about one month,
- Baroclinic waves about 2 days,
- Cumulus convection about 10 minutes,
- Brownian motion…
- Linear approaches (like Singular Vectors and Lyapunov Vectors) can only handle the fastest instability.
- Nonlinear model integrations (like Bred Vectors, EnKF) allow fast instabilities to saturate, they can filter fast instabilities !!

A good ensemble should *contain relevant unstable perturbations:* an ensemble for seasonal prediction should have initial perturbations with coupled instabilities.



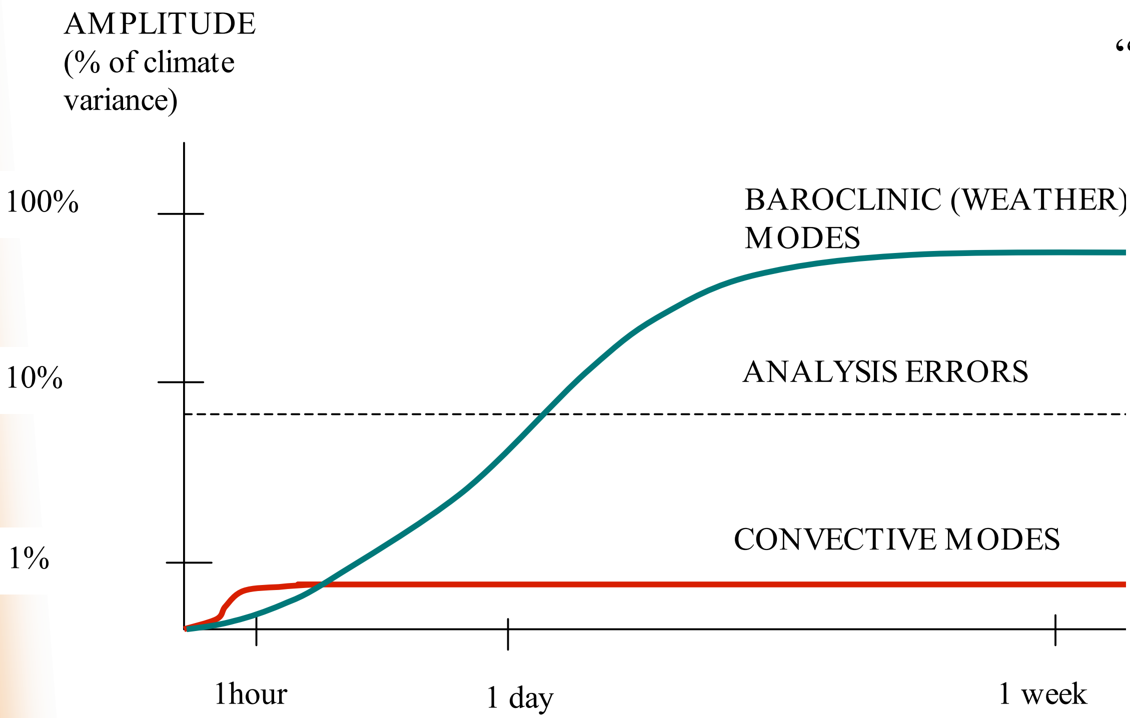
Breeding: simply running the nonlinear model a second time, from perturbed initial conditions.

Only two tuning parameters: rescaling amplitude and time interval

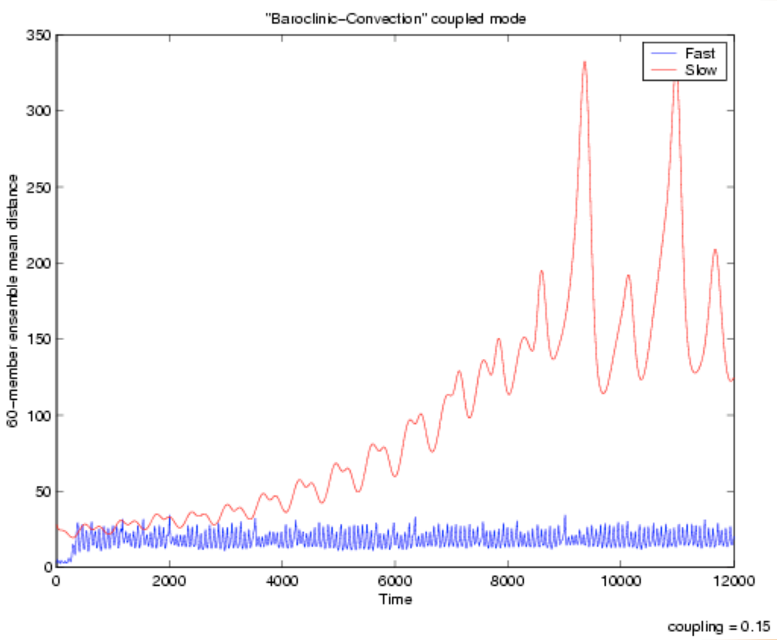


Local breeding growth rate: $$g(t) = \frac{1}{n\Delta t} \ln\left(\left|\delta \mathbf{x}\right| / \left|\delta \mathbf{x}_0\right| \right)$$

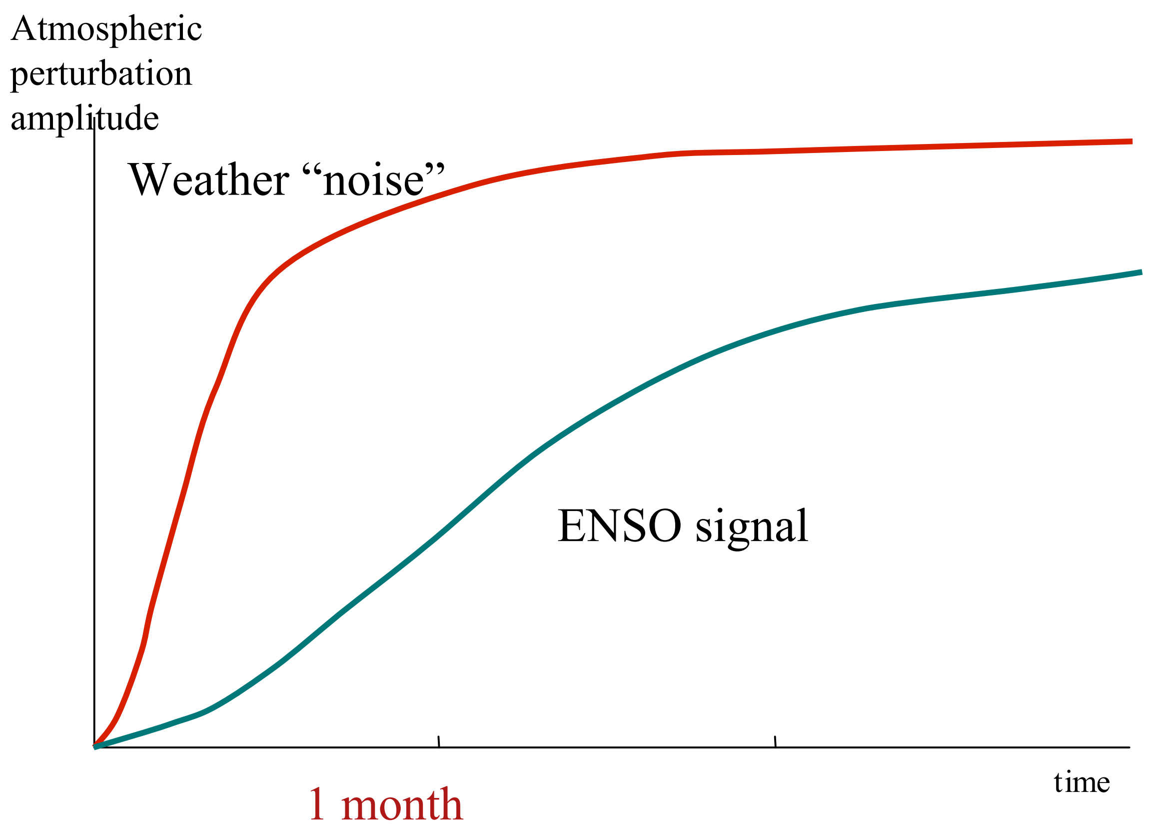
Nonlinear saturation allows filtering unwanted fast, small amplitude, growing instabilities like convection (Toth & Kalnay, 1993, Peña & Kalnay, 2003, NPG)



“weather + convection” coupled model

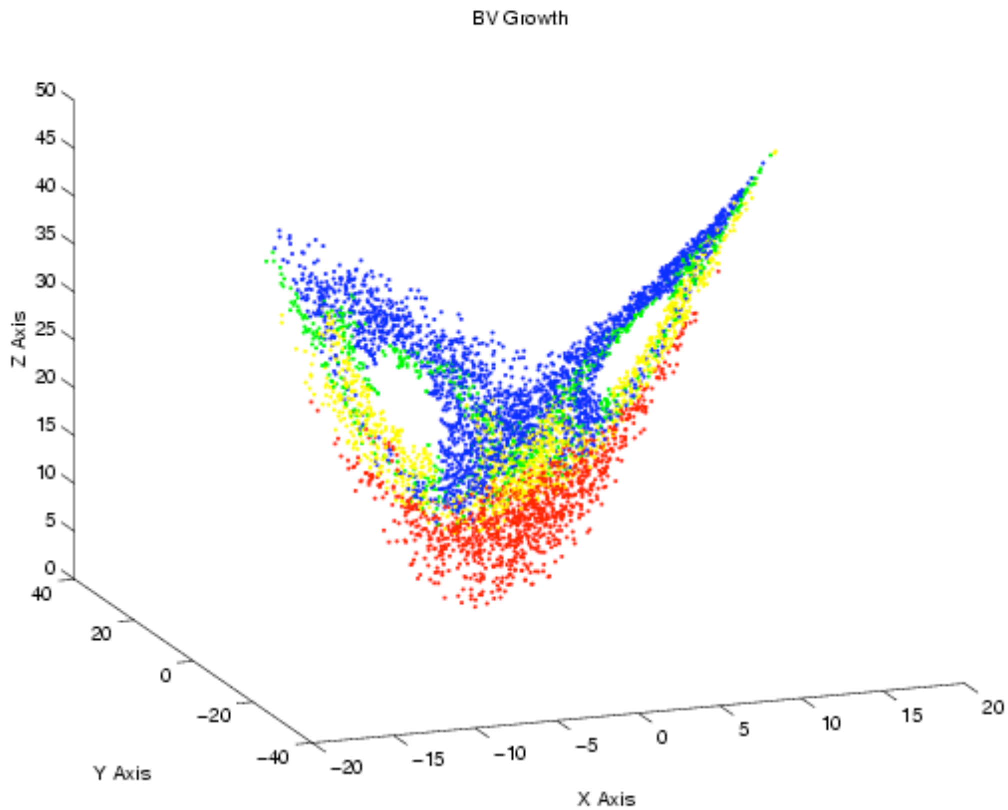


In the case of coupled ocean-atmosphere modes, we cannot take advantage of the small amplitude of the “weather noise”! Must use the fact that the coupled ocean modes are slower…



Need a long rescaling interval, like 2 weeks or one month

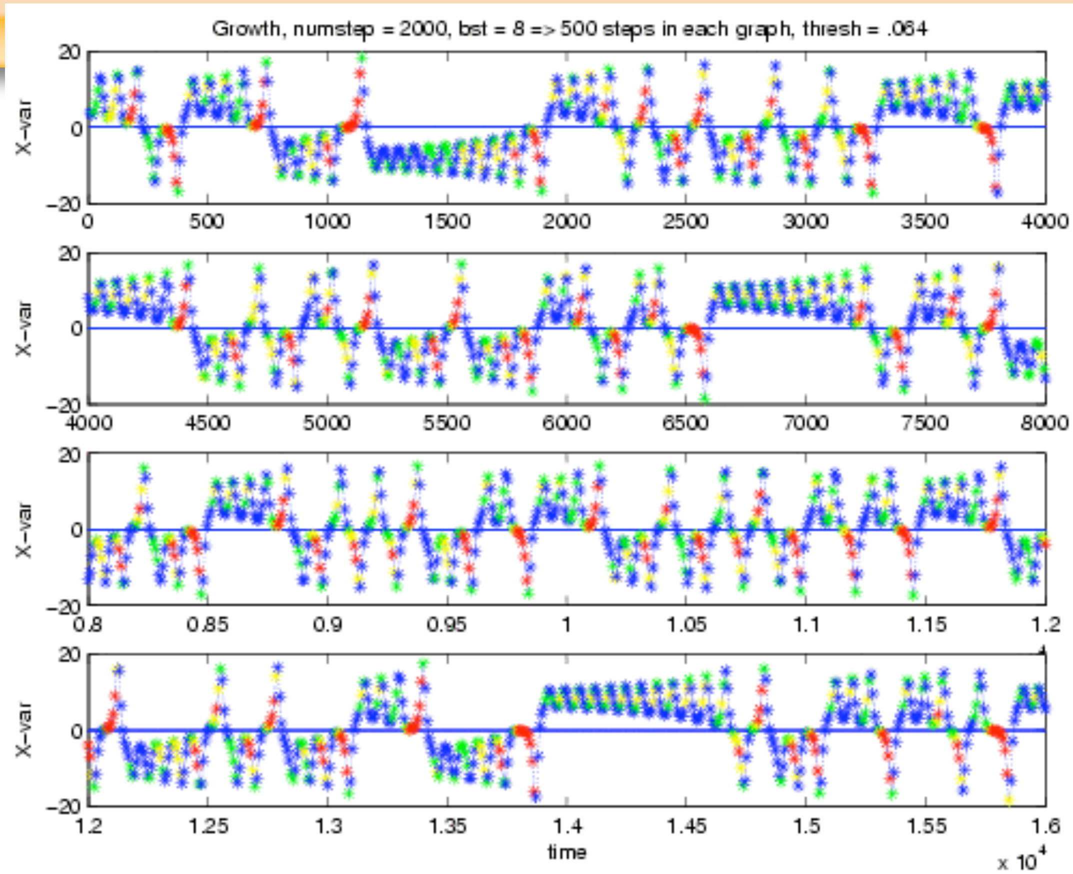
In the 3-variable Lorenz (1963) model we used breeding to estimate the local growth of perturbations:



Bred Vector Growth:
red, high growth;
yellow, medium;
green, low growth;
blue, decay

With just a single breeding cycle, we can estimate the stability of the attractor (Evans et al, 2004)

We found two rules for a forecaster living in the Lorenz attractor:



Bred Vector Growth:
red, high growth;
yellow, medium;
green, low growth;
blue, decay

1. Regime change: The presence of red stars (fast BV growth) indicates that the next orbit will be the last one in the present regime.
2. Regime duration: One or two red stars, next regime will be short. Several red stars: the next regime will be long lasting.

Breeding in a coupled system

- Breeding: finite-amplitude, finite-time instabilities of the system (~Lyapunov vectors)
- In a coupled system there are fast and slow modes, and a **linear** Lyapunov approach (like Singular Vectors) will only capture fast modes.
- Can we do breeding of the slow modes?

We coupled slow and a fast Lorenz (1963) 3-variable models (Peña and Kalnay, 2004)

Fast equations

$$\frac{dx_1}{dt} = \sigma(y_1 - x_1) - C_1(Sx_2 + O)$$

$$\frac{dy_1}{dt} = rx_1 - y_1 - x_1 z_1 + C_1(Sy_2 + O)$$

$$\frac{dz_1}{dt} = x_1 y_1 - bz_1 + C_1(Sz_2)$$

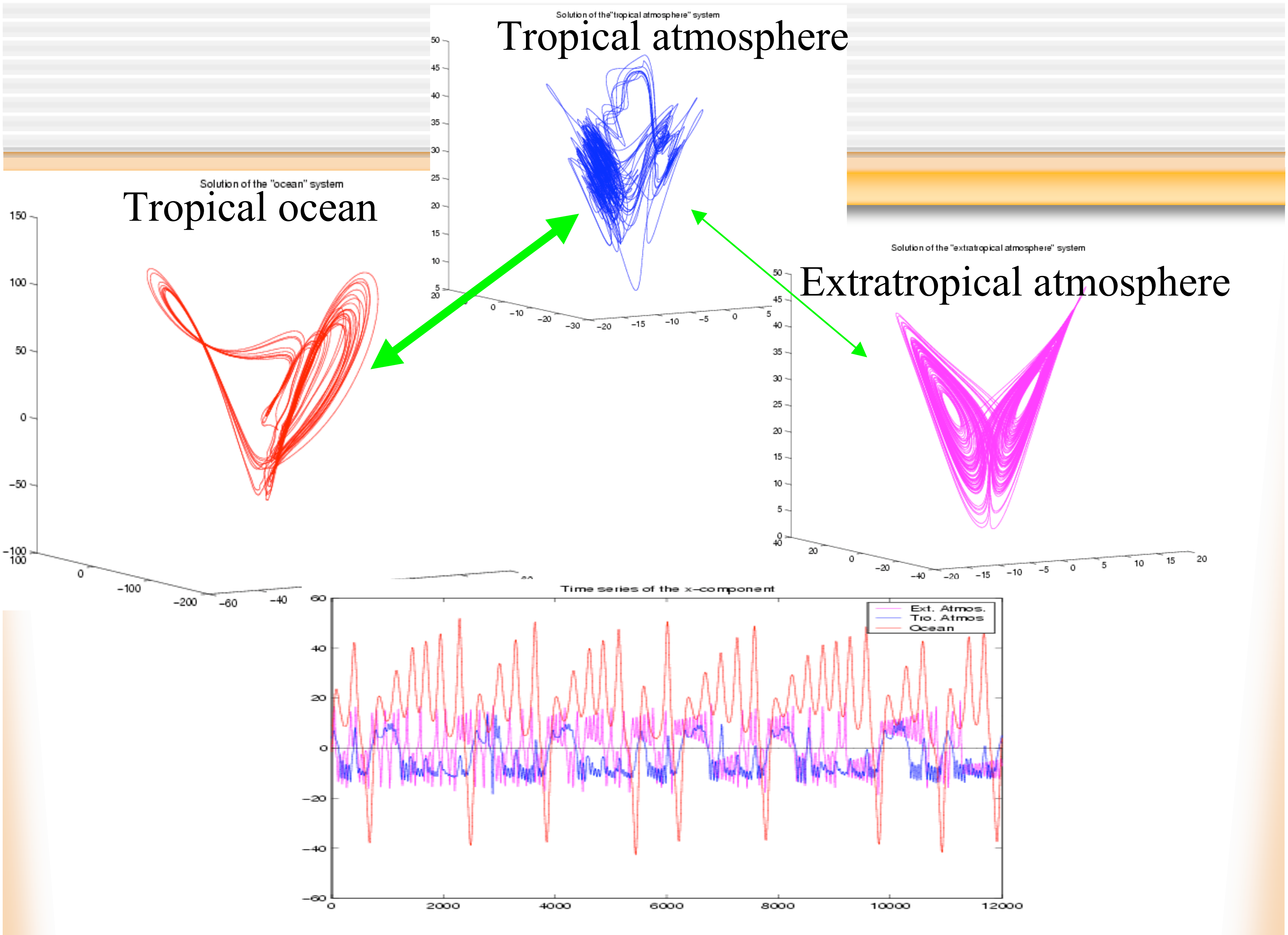
Slow equations

$$\frac{1}{\tau}\frac{dx_2}{dt} = \sigma(y_2 - x_2) - C_2(x_1 + O)$$

$$\frac{1}{\tau}\frac{dy_2}{dt} = rx_2 - y_2 - Sx_2 z_2 + C_2(y_1 + O)$$

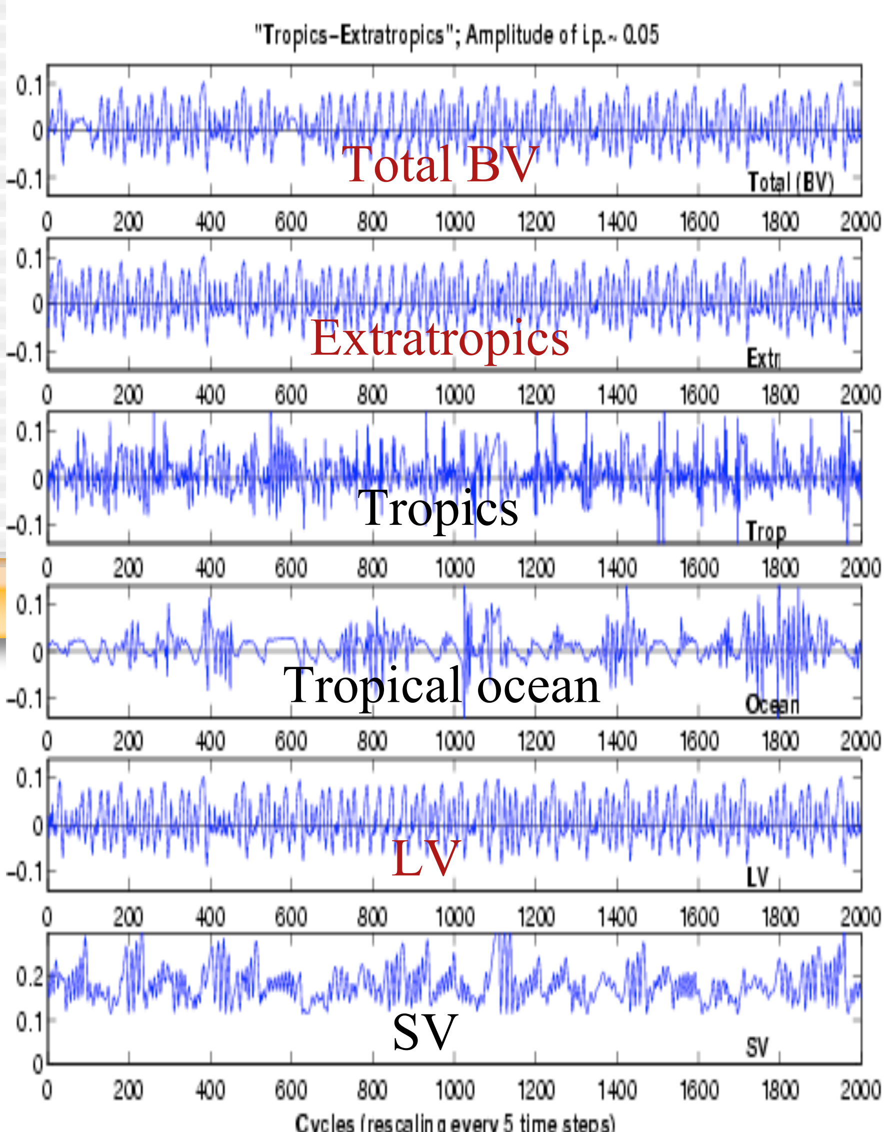
$$\frac{1}{\tau}\frac{dz_2}{dt} = Sx_2 y_2 - bz_2 + C_2(z_1)$$

“Tropical-extratropical” (triply-coupled) system: the ENSO tropical atmosphere is weakly coupled to a fast “extratropical atmosphere” with weather noise

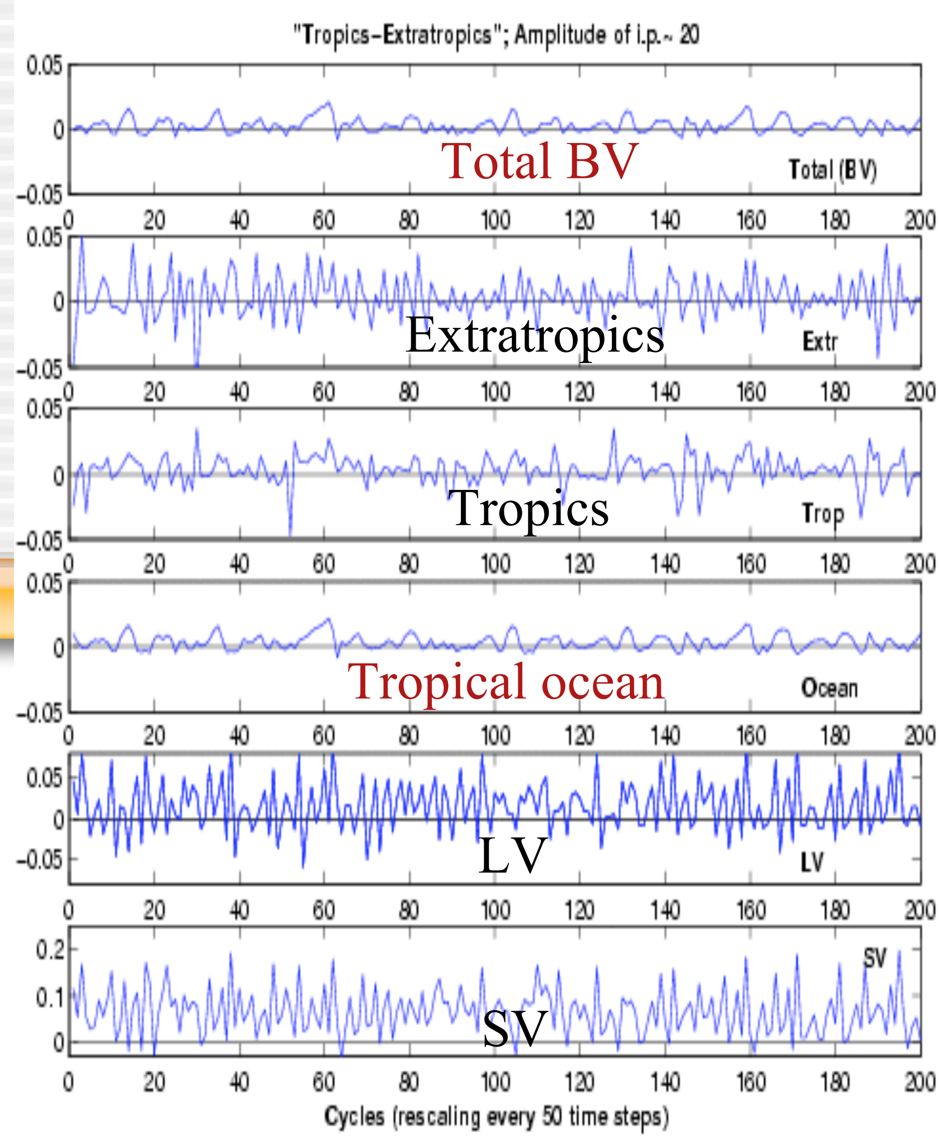


Tropical atmosphere
Solution of the"tropical atmosphere" system
Tropical ocean
Solution of the "ocean" system
Extratropical atmosphere
Solution of the "extratropical atmosphere" system
Time series of the x-component
Ext. Atmos.
Tro. Atmos
Ocean

WEATHER - ENSO - breeding with different time intervals



$\delta = 0.05, \Delta = 5$ steps

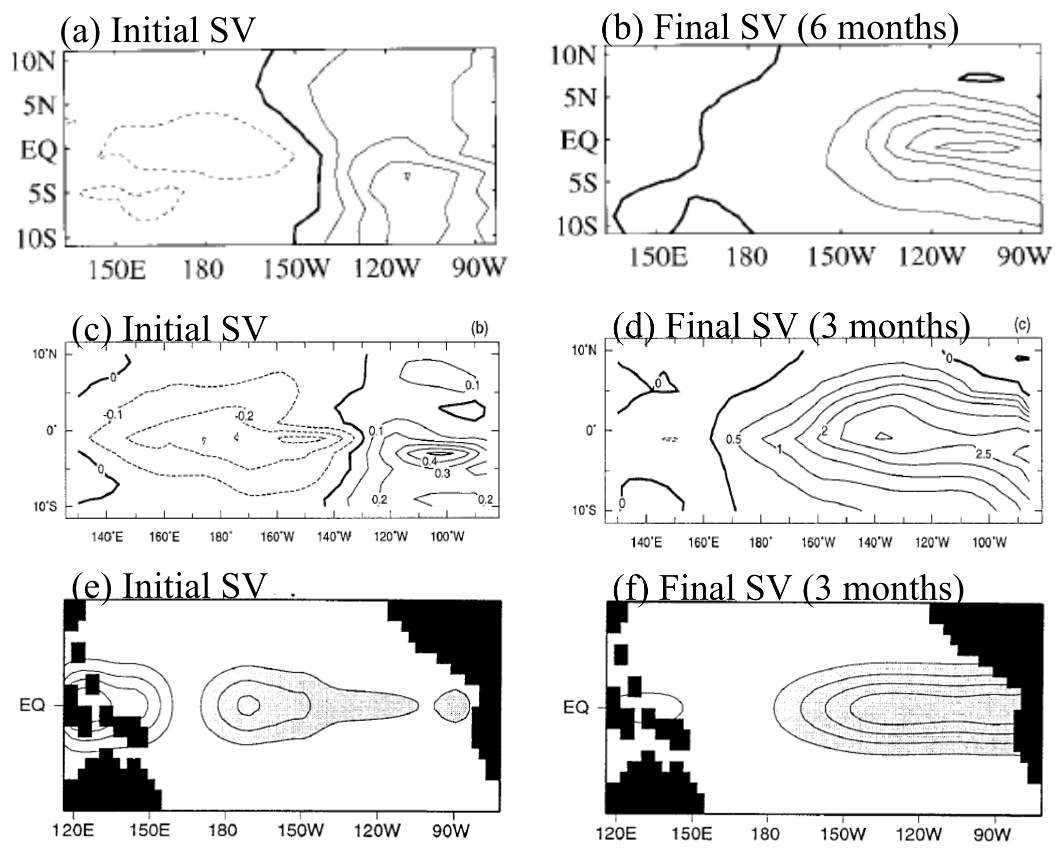


$\delta = 20, \Delta = 50$ steps

From Lorenz coupled models:

- In coupled fast/slow models, we can do breeding to isolate the slow modes
- We have to choose a slow variable and a long interval for the rescaling
- This is true for nonlinear approaches (e.g., EnKF) but not for linear approaches (e.g., SVs, LVs)
- We apply this to ENSO coupled instabilities:
  - Cane-Zebiak model (Cai et al, 2003)
  - NASA full coupled GCM (Yang et al, 2005)
  - NASA operational system with real observations

Initial and Final Singular Vector with a SST norm and an optimization time of 3-6 months



Chen et al. (1997)

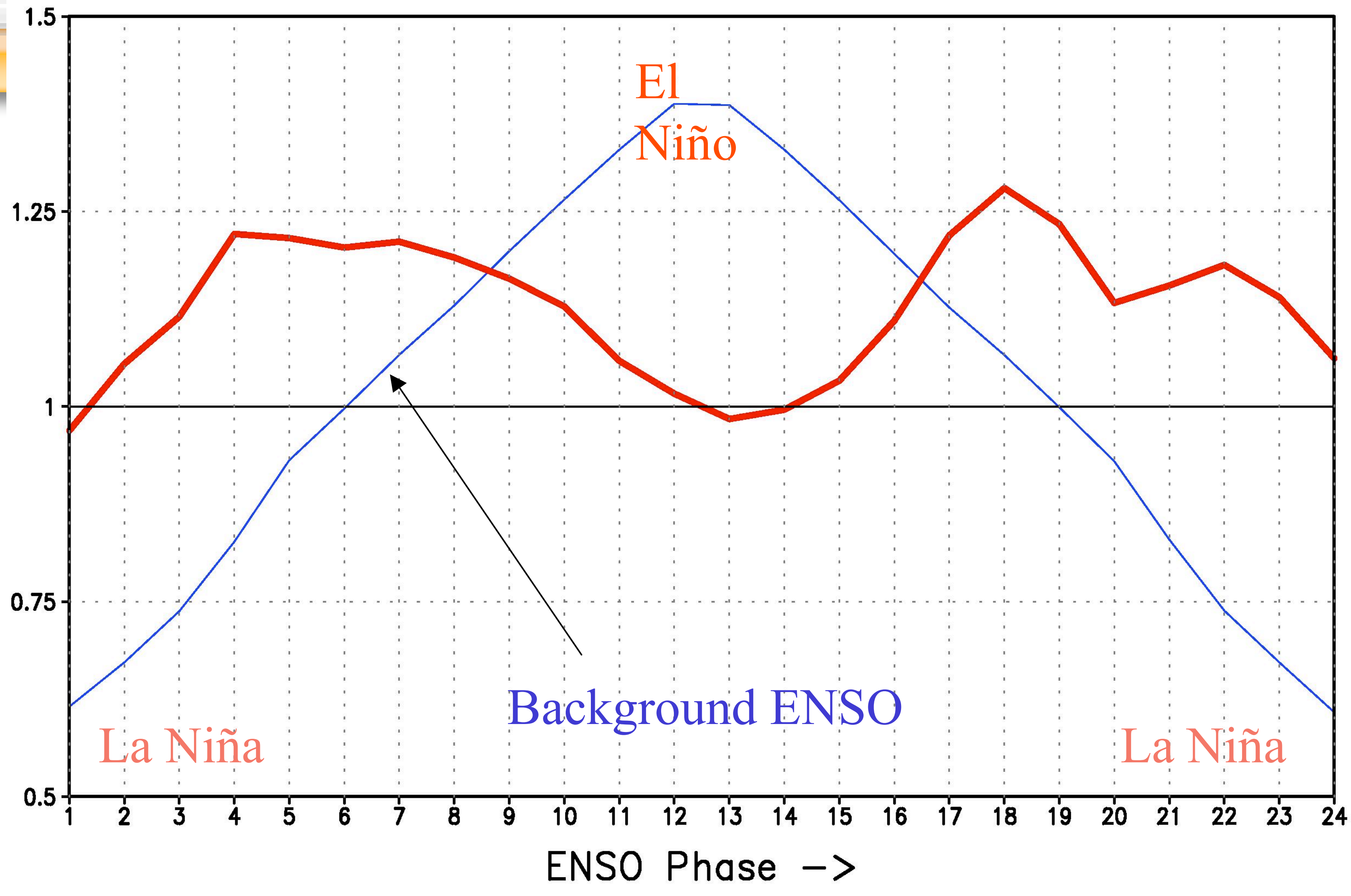
Xue et al.(1997)

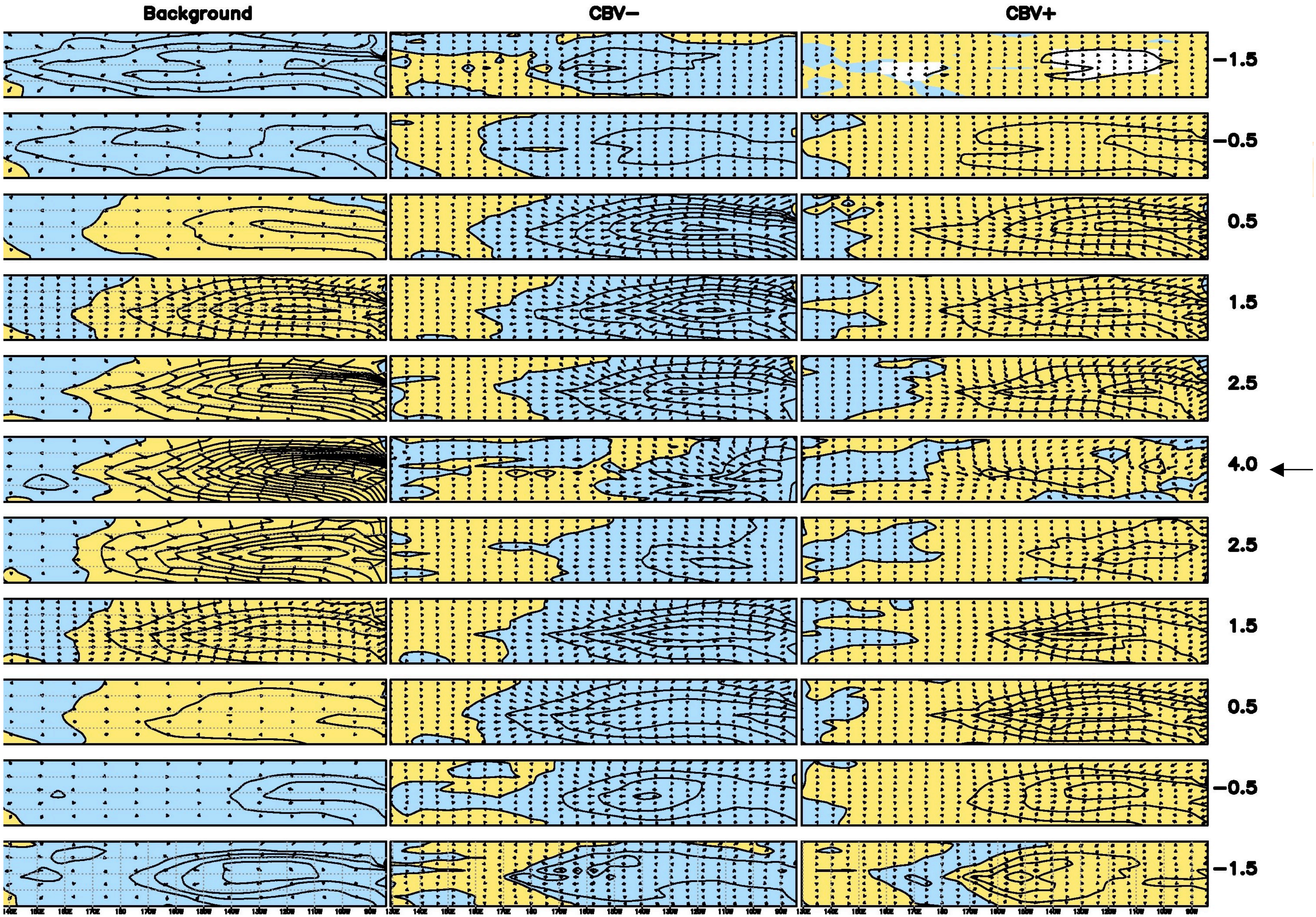
Moore and Kleeman (2001)

Cai et al. (2003) results with Cane and Zebiak model:

- Rescaling done every 1-3 months (insensitive to interval and to norm)
- Bred Vector growth rate is strongest before and after ENSO events.
- Bred Vectors can be applied to improve the forecast skill and reduce the impact of the "spring-barrier".
- The results show the potential impact for ensemble forecast and data assimilation

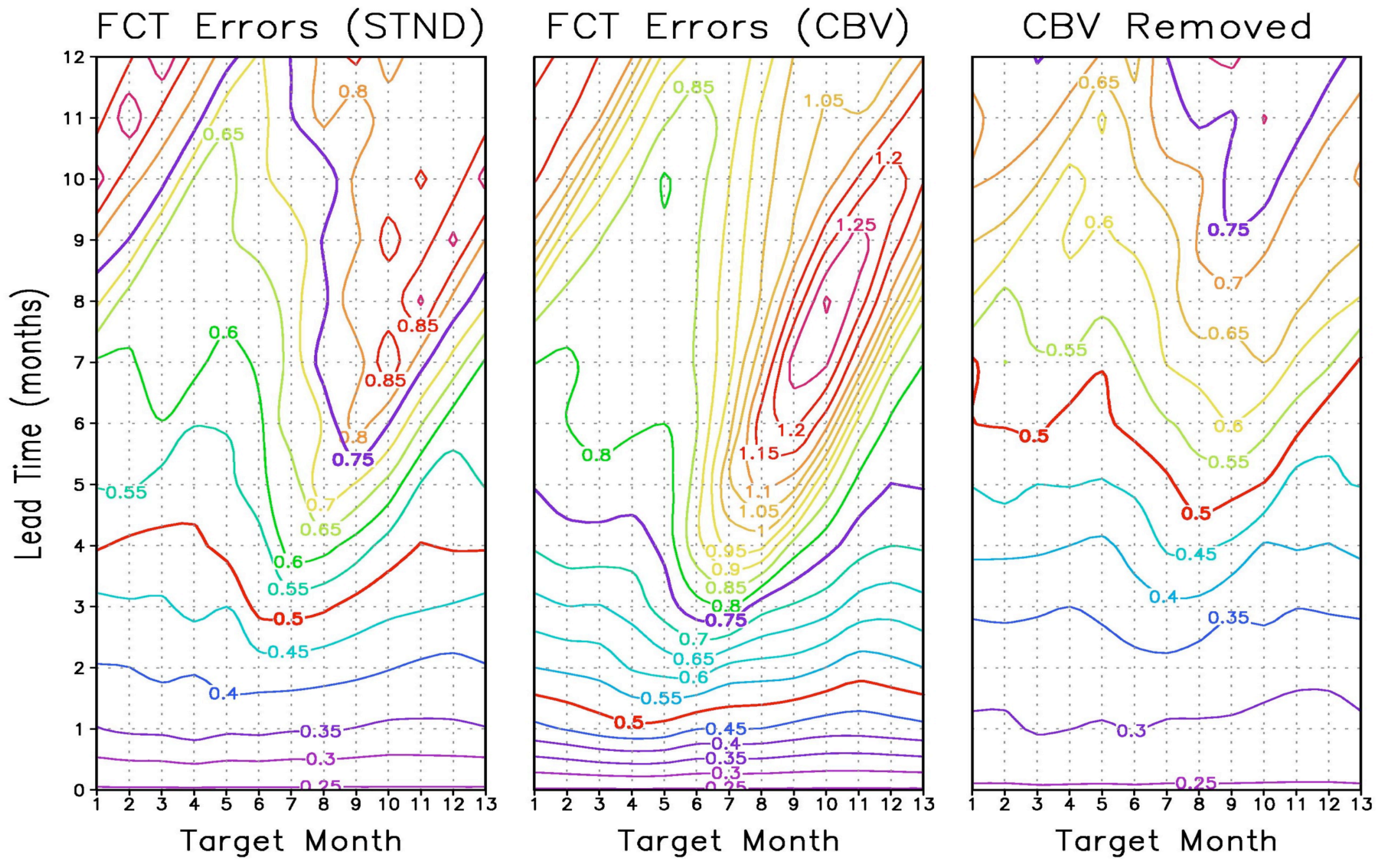
Monthly Amplification Factor of Bred Vector





Background
CBV−
CBV+
−1.5
−0.5
0.5
1.5
2.5
4.0
2.5
1.5
0.5
−0.5
−1.5

Forecast error growth



"Spring Barrier": The "dip" in the error growth chart indicates a large error growth for the forecast that begins in the spring and passes through the summer. Removing the projection of the composite BV from the initial conditions (one d.o.f.) wipes it out.

NASA Seasonal-to Interannual Prediction (NSIPP) coupled GCM

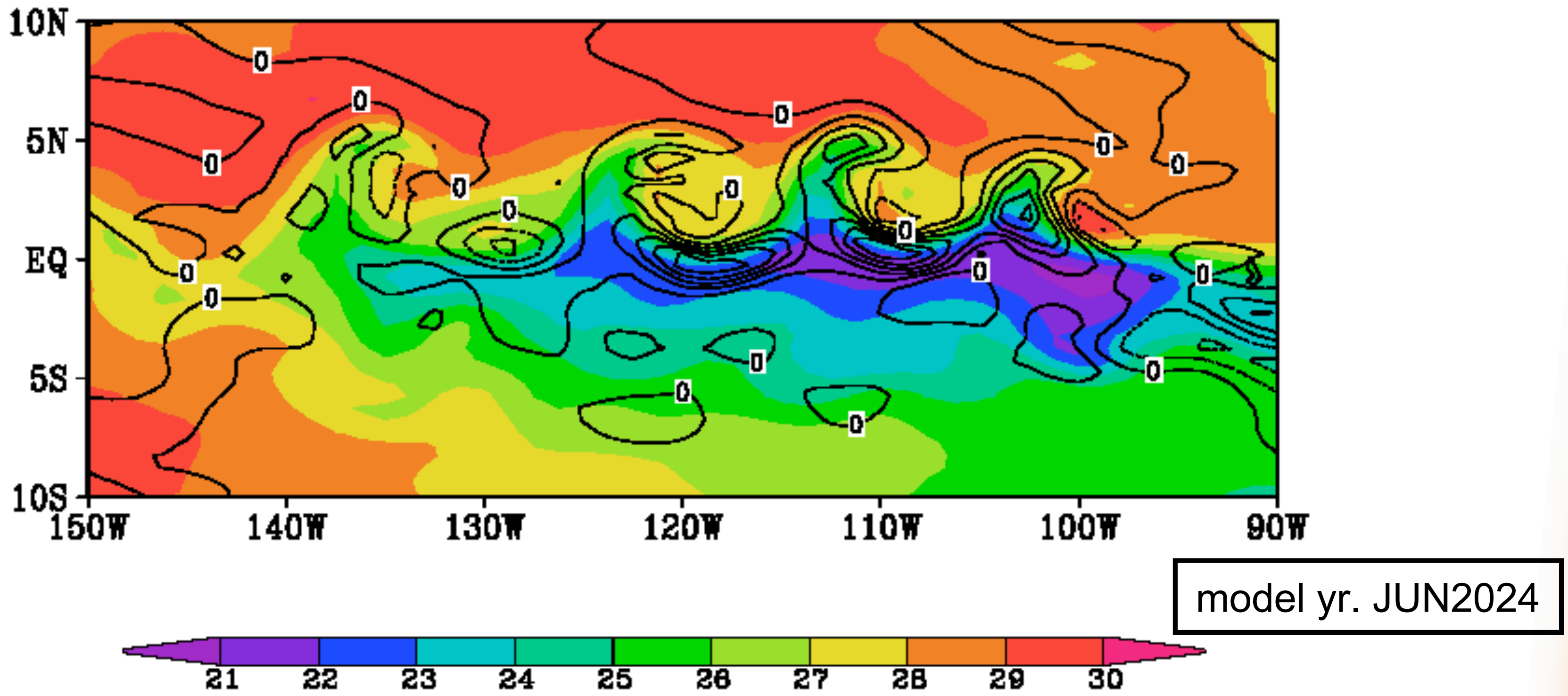
Components	•AGCM ◆Developed by Suarez (1996) ◆Resolution: 2°× 2.5°×34 levels •OGCM/Poseidon V4 ◆Developed by Schopf and Loughe (1995) ◆Resolution: 1/3°× 5/8°× 27 layers •Mosaic LSM

- Full globally coupled
- AGCM and OGCM coupled everyday
- Current prediction skill (El Niño hindcasts) is up to 9 months

Breeding method

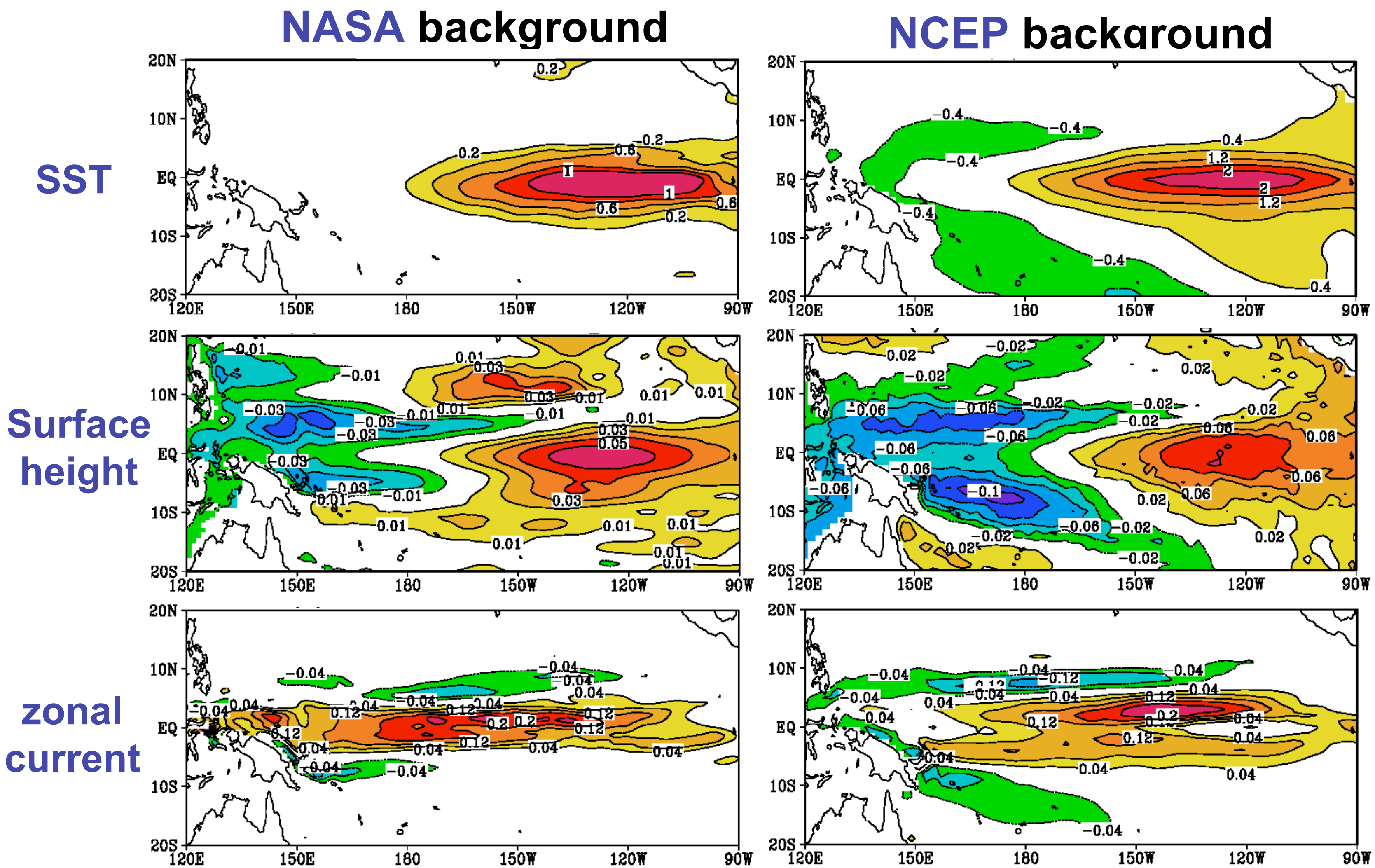
- **Bred vectors** :
  The differences between the control forecast and perturbed runs
- **Tuning parameters**
  - Size of perturbation (e.g., Niño-3 SST)
  - Rescaling period: one month
- **Advantages**
  - Low computational cost
  - Easy to apply to Coupled GCMs
  - Captures coupled instabilities

Example of instantaneous background SST (color) and bred vector SST (contours)



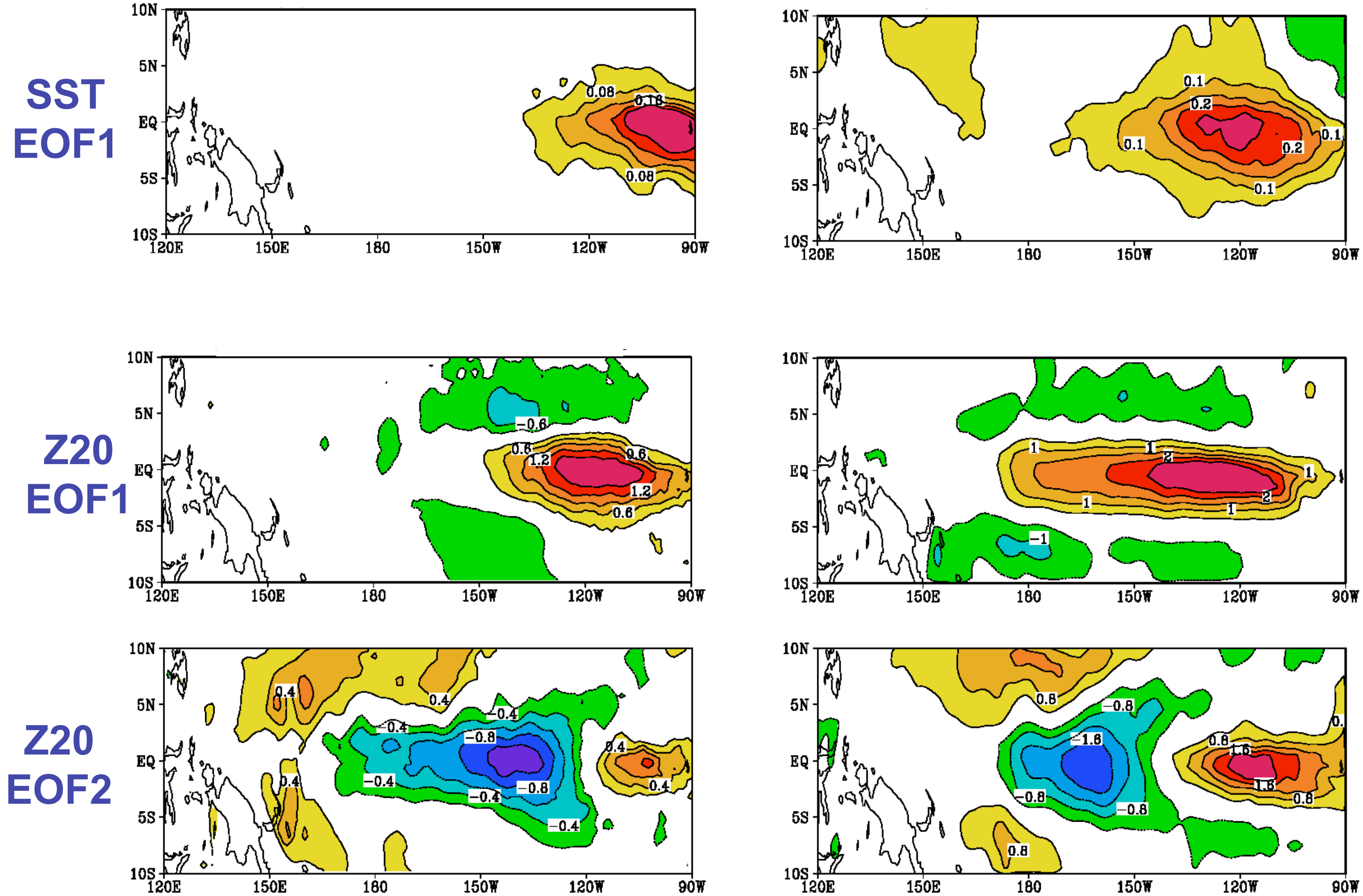
Instabilities associated with the equatorial waves in the NSIPP coupled model are naturally captured by the breeding method!

NASA vs. NCEP Coupled GCMs (regressed with Niño-3 SST)



These two coupled models have slightly different ENSOs…

NASA Bred Vector vs. NCEP Bred Vector

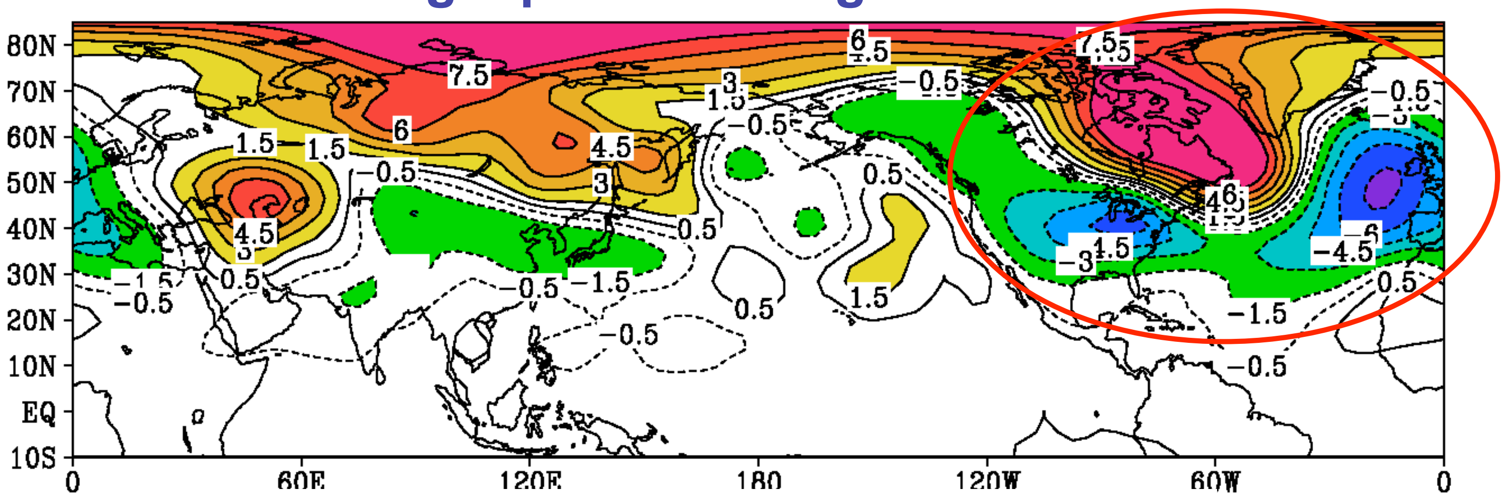


Bred vectors obtained with an 8-year NCEP run are extremely similar to the NASA's 20-year run!!!

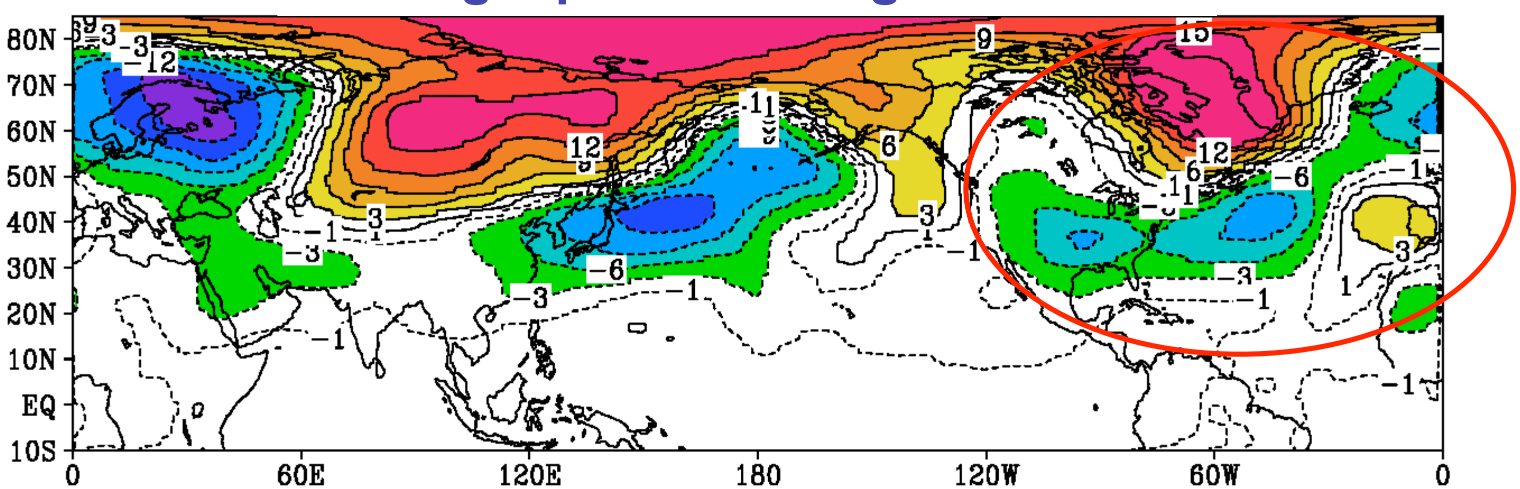
NASA BV vs. NCEP BV

Northern Hemisphere

NASA geopotential height at 500mb



NCEP geopotential height at 500mb



Even the PNA atmospheric teleconnections are similar!!

Summary: perfect model experiments

- Nonlinear methods, like breeding and EnKF, can take advantage of the saturation of fast weather noise. Linear systems cannot.
- Coupled Lorenz model experiments show that for slow modes the rescaling in breeding has to be done using slow variables and long rescaling intervals
- Cane-Zebiak breeding experiments show that the BV growth depends on season and ENSO phase, and that they can be used for data assimilation and ensemble forecasting
- “Perfect model” experiments with the NASA coupled GCM show a robust dominant coupled ocean/atmosphere bred vector.
- The NASA and the NCEP coupled models show similar but not identical ENSO evolutions
- The dominant BVs in these two systems are also very similar.
- They show similar extratropical teleconnections in the PNA region
- Results generally agree with those obtained with the C-Z model

Breeding in the operational NASA system with data assimilation and forecasts

- The operational system assimilates **ocean observations (analysis)**.
- The ocean **analysis increments** (analysis minus forecast) measure the growing **forecast errors**
- **Bred Vectors** are designed to estimate the growing **forecast errors.**
- If **BVs are similar to analysis increments** (without knowing about the new observations) then they have potential for use in ensemble forecasting and data assimilation:
- **BVs provide information on the coupled “errors of the month”**

Breeding experiments

– Rescaling parameters

BVa: BV SST in Niño3 region (rescaling size=0.1°C, standard run)

BVb: BV thermocline (Z20) in tropical Pacific (size=2m)

BVc: BV SST in Niño3 region as in (1). Breed in tropical region only and damp perturbations beyond 30°N/S

– The structures of the bred vectors from the 3 experiments are very similar. So, we show results from BVa.

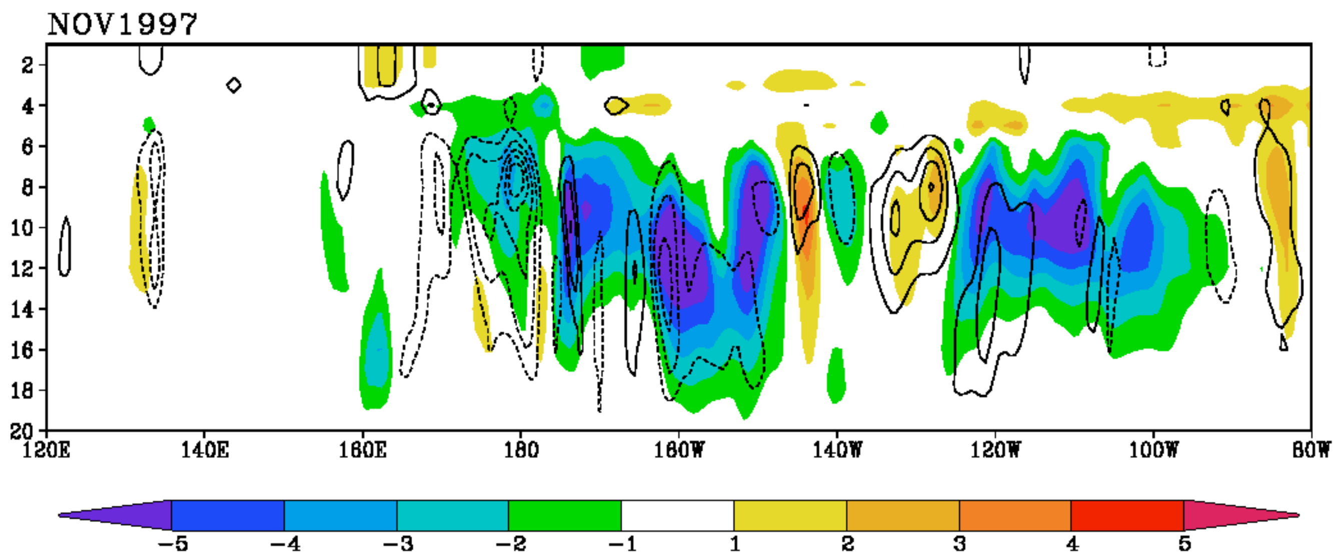
Vertical cross-section at Equator for Bred Vector and Analysis Increment

Bred vector (contour):

rescaled difference between control forecast and perturbed runs

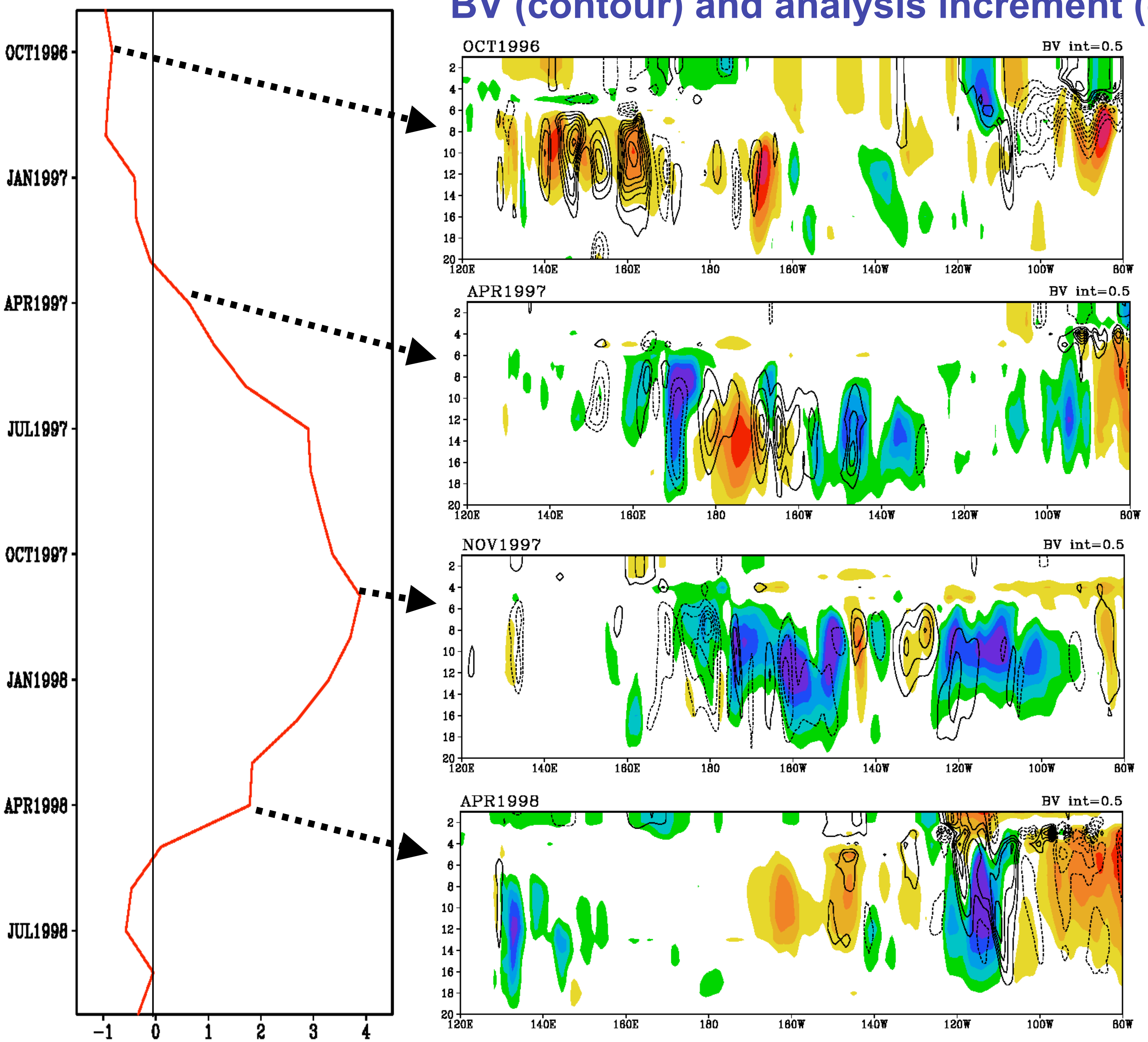
Analysis increment (color shading):

Difference between analysis and one-month foreacst



Niño3 index

Vertical cross-section at Equator for BV (contour) and analysis increment (color)

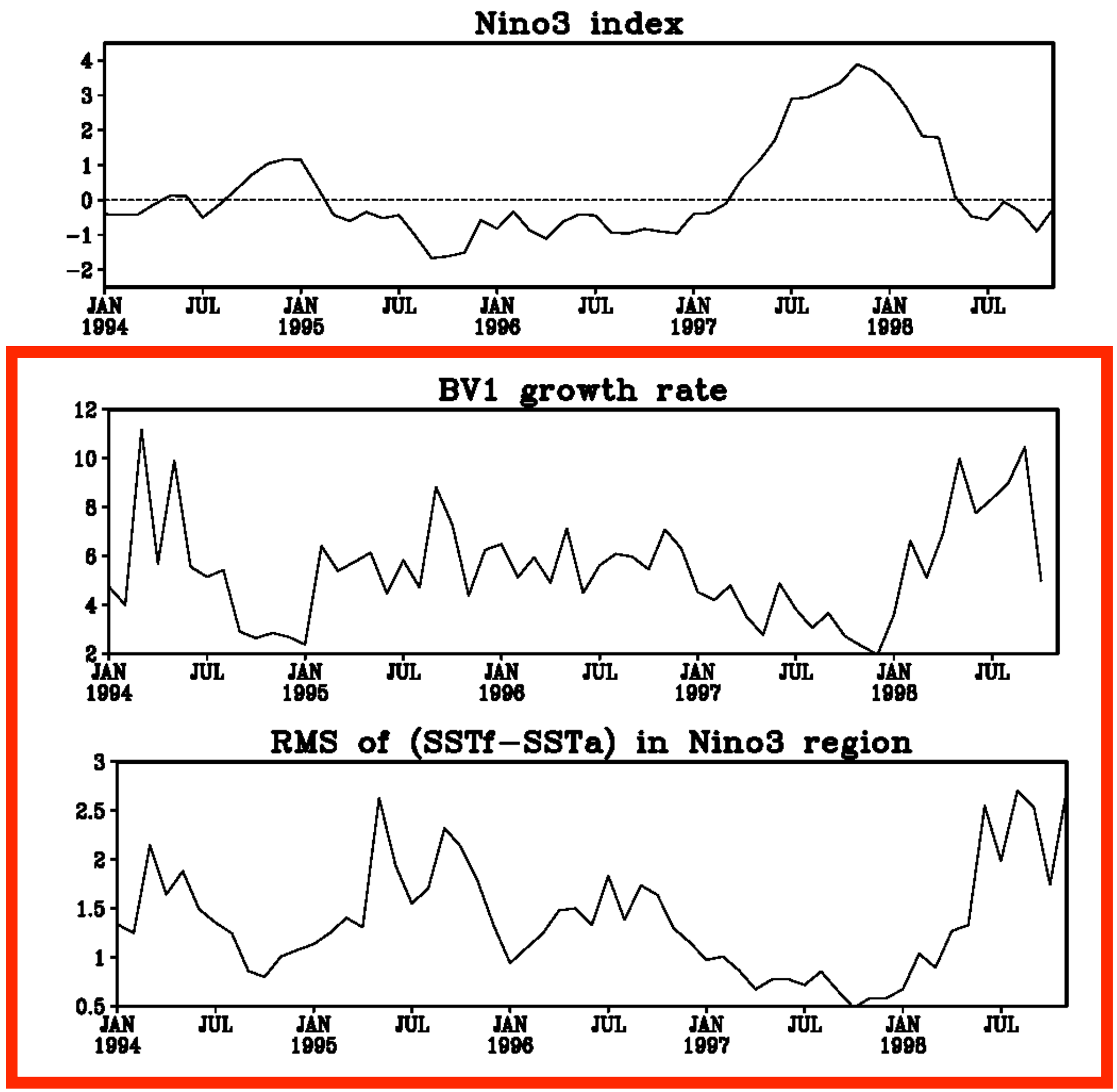


Before 97' El Niño, An.Inc. is located in W. Pacific and near coast region

During development, An.Inc. shifts to lower levels of C. Pacific.

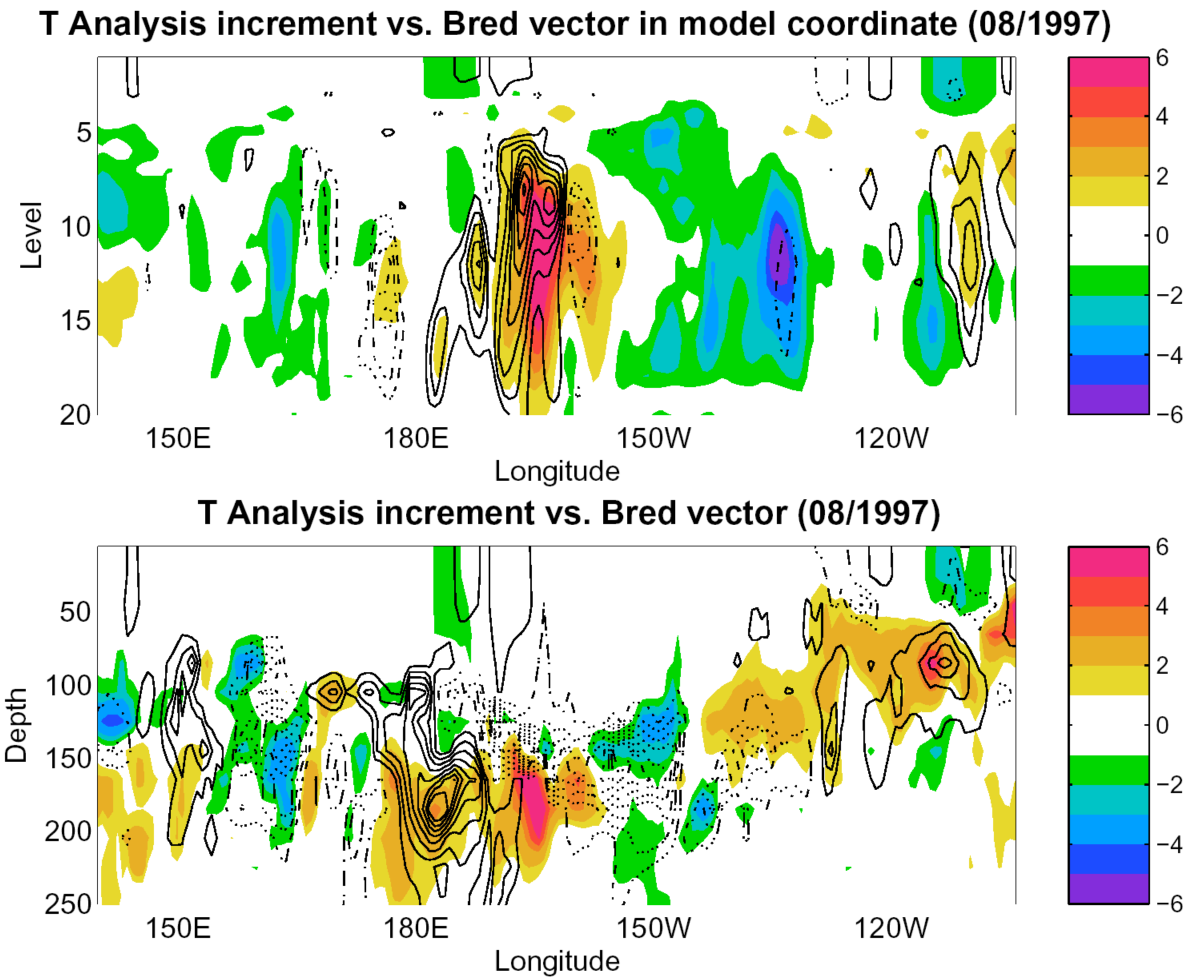
At mature stage, An.Inc. shifts further east and it is smallest near the coast.

After the event, An.Inc. is located mostly in E. Pacific.



Variations of temperature analysis increment in eastern Pacific are strongly related to BV growth rate

Analysis increment (color) vs. Bred vector (contour)



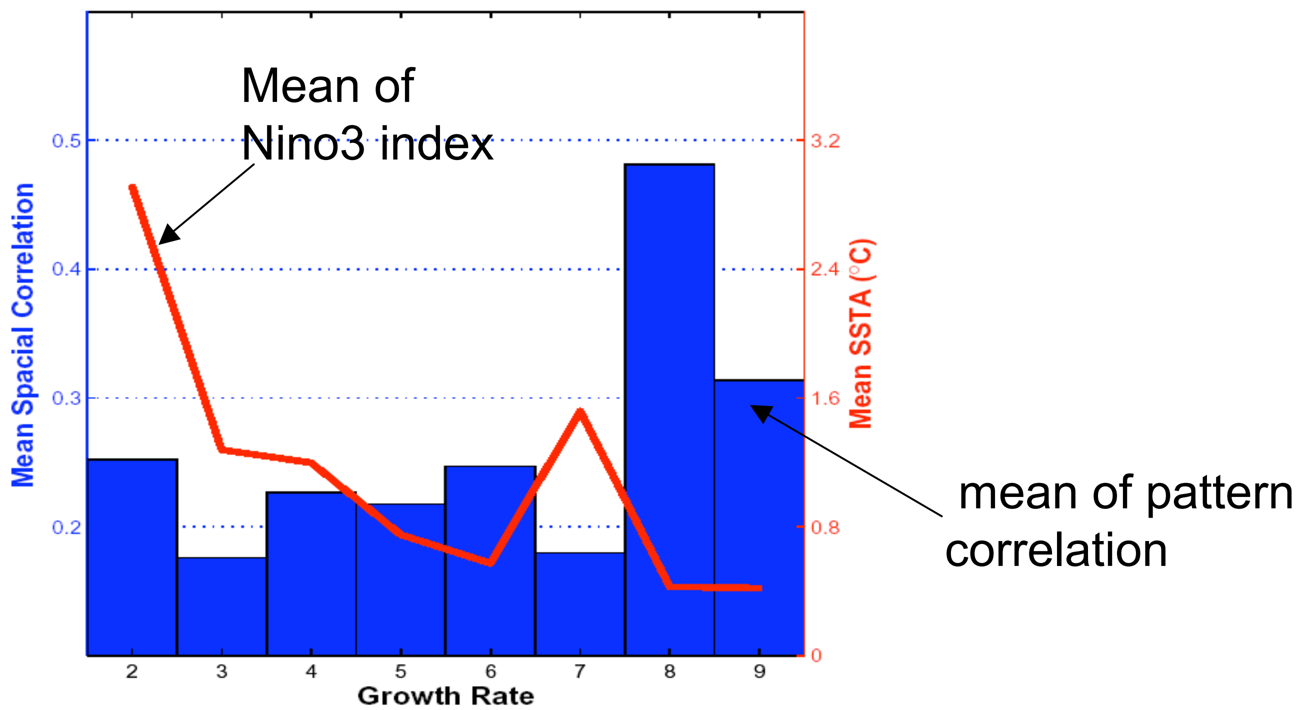
Temperature profile in model levels

Temperature profile in depth (meters)

- Bred vector captures large dynamic errors, located mostly near the thermocline.
- Good agreement between BV and An.Inc. on model levels suggests their potential application in DA background error covariance.

For standard breeding experiment

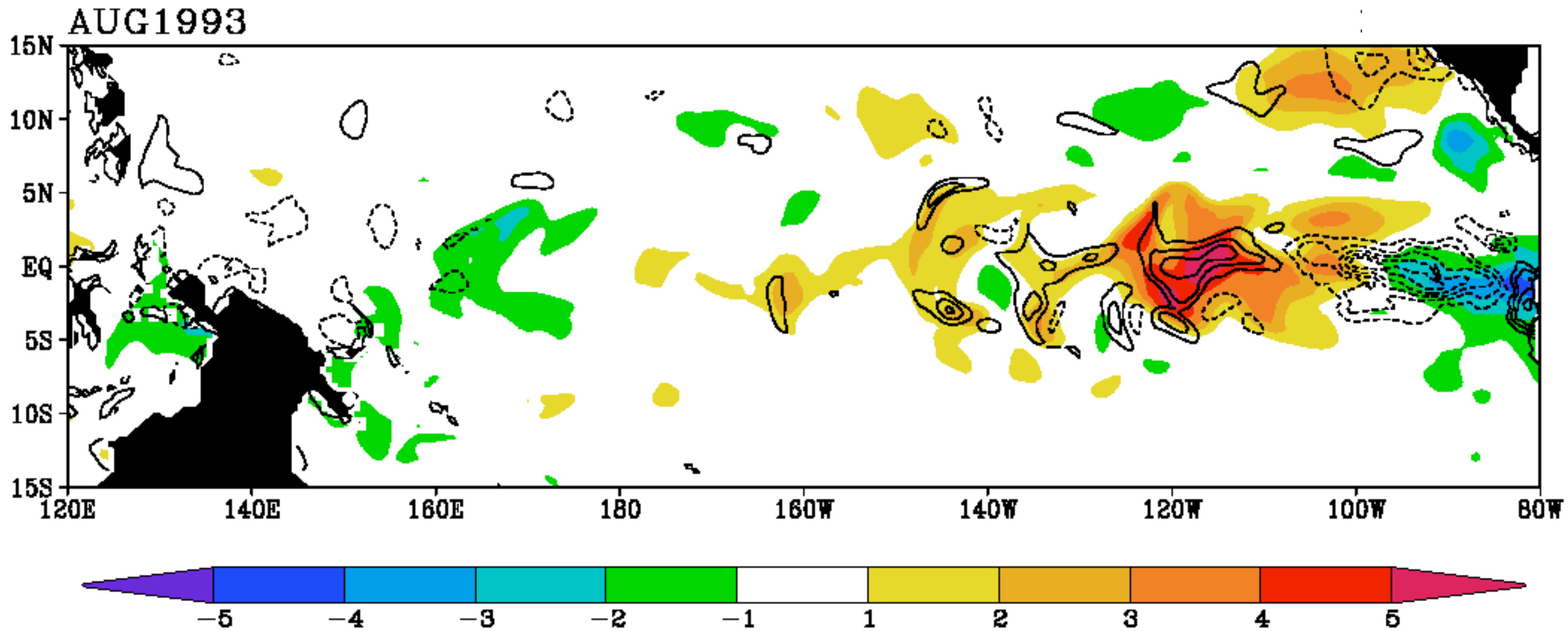
- We binned results (68 months) based on the BV growth rate, and compared An. Inc. pattern correlations and Nino3 index.



- **During an event (large Niño3 index), the growth rate is smallest.**
- **For large growth rate, the BV has large projection on analysis increments (pattern correlation).**

[SSTa-SSTf] vs. BV SST (contour) in tropical Pacific

(cases when pattern correlation is large)



For large BV growth, agreement of BV with analysis increment (forecast error) is very good

The equatorial temperature structure
Climate variability vs. Error structure

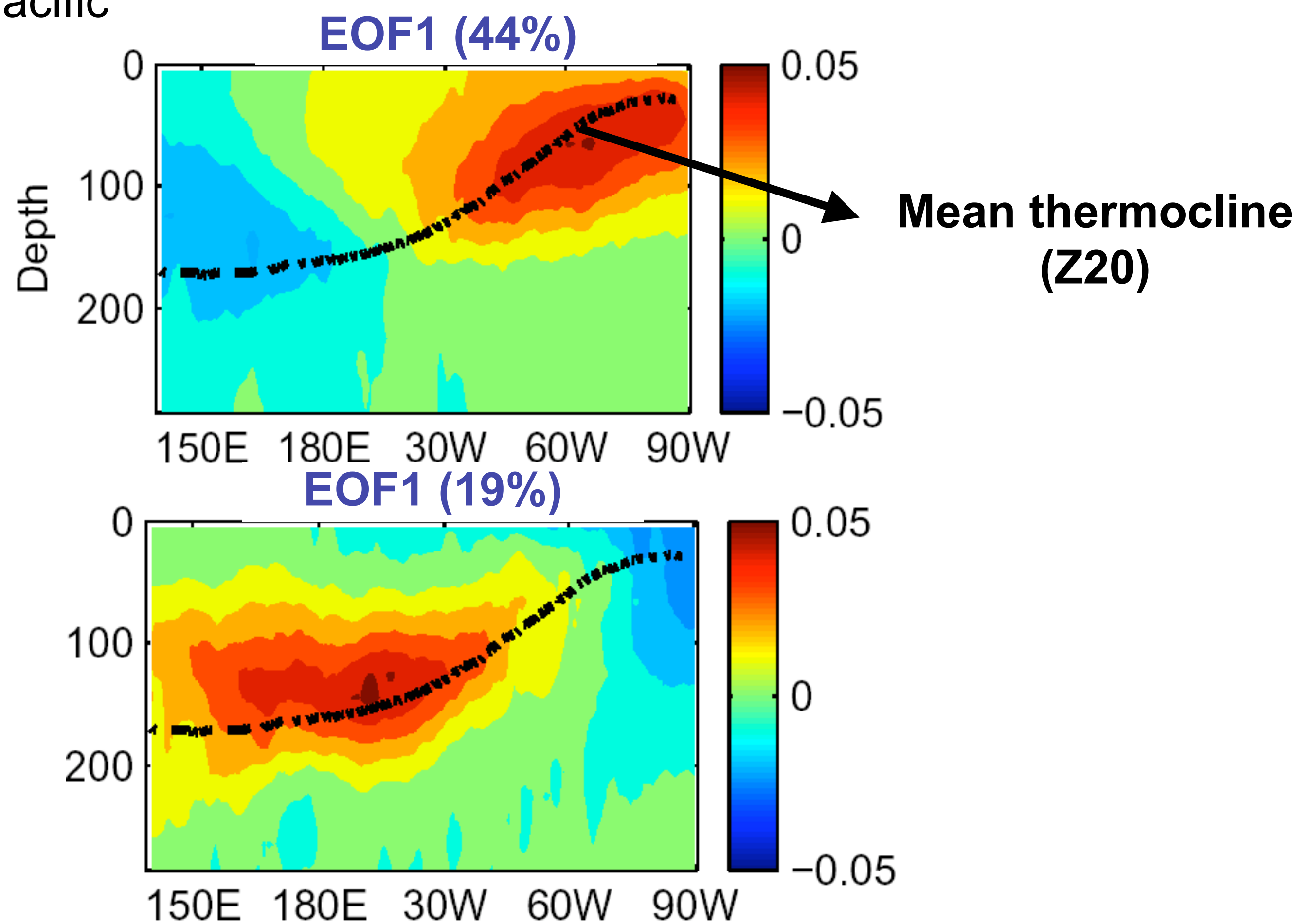
- **Observations:**
  - EOF analysis for temperature anomalies from NSIPP ocean reanalysis

- **Dominant error structure in equatorial subsurface**
  - EOF analysis for analysis increment and bred vector
    - Period (Feb1993-Nov1998, 69 months)
    - Time means are removed

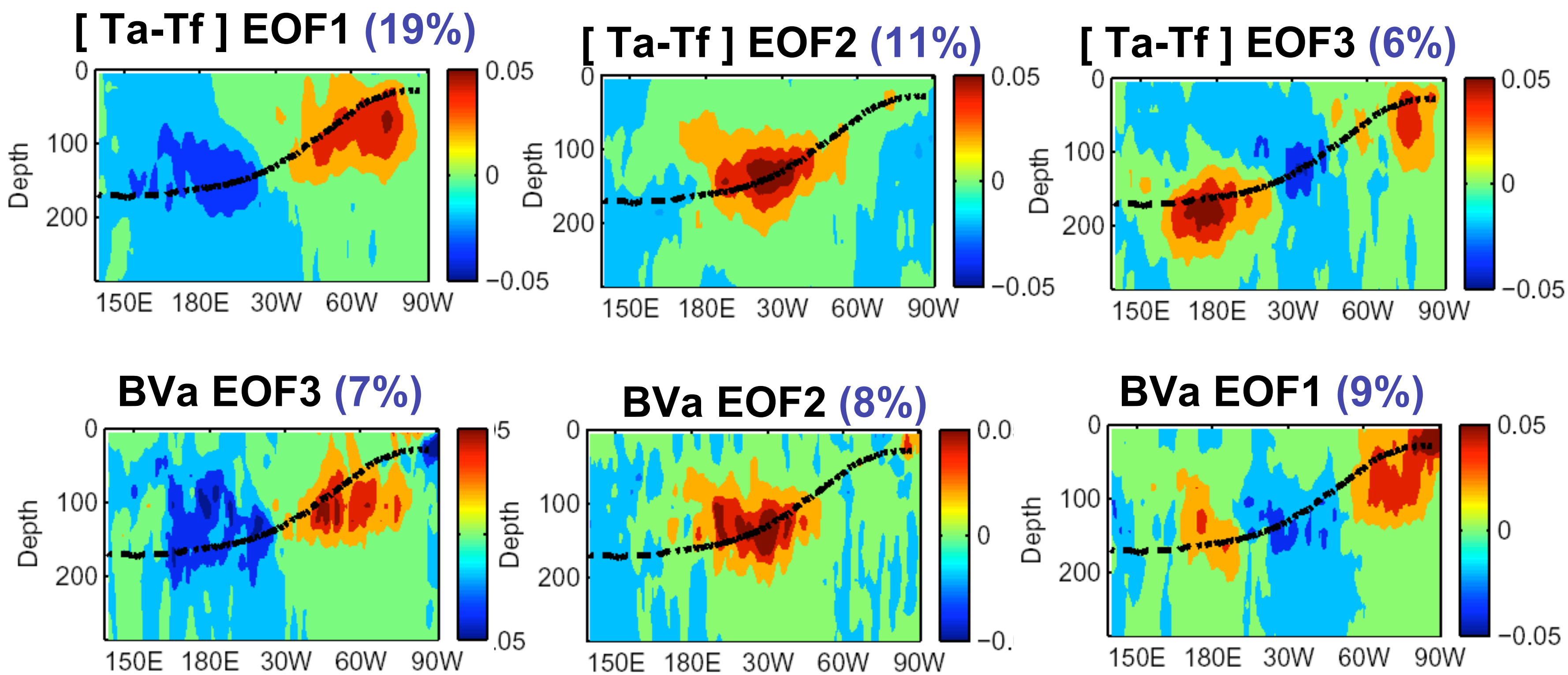
Climate variability in subsurface

- **First two EOF modes relate to ENSO evolution**

Temperature anomalies first appear in W. Pacific, and propagate eastward along the thermocline and amplify in the E. Pacific



The equatorial temperature error structure



Analysis increments and BV have very similar subsurface thermal structure

Correlations between analysis increment and bred vectors

Total correlation between first three EOF modes

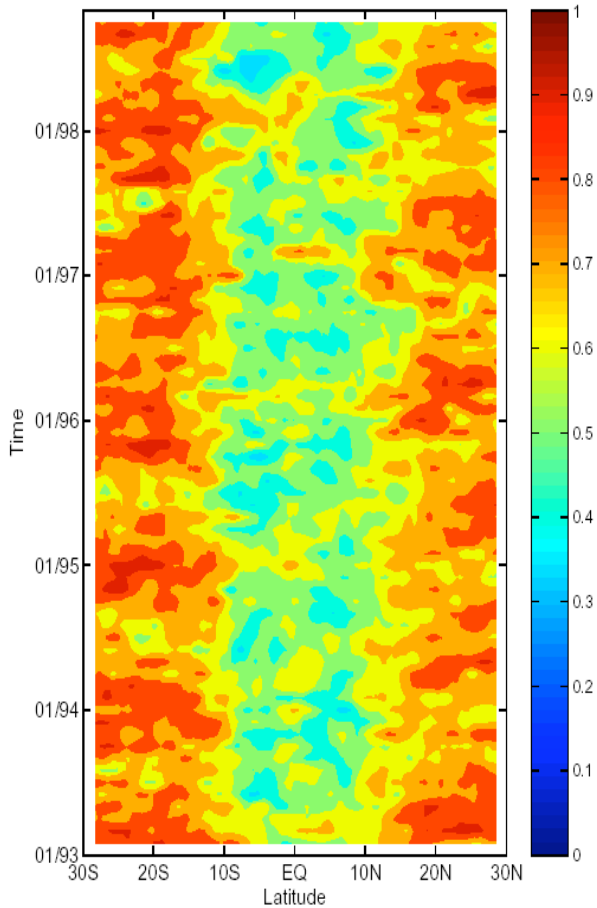
	An.Inc EOF_1	An.Inc EOF_2	An.Inc EOF_3
BV_a	0.80	0.84	0.62
BV_b	0.84	0.75	0.49
BV_c	0.80	0.64	0.50

- The first three EOF modes of analysis increment strongly project on the first two BV's EOF space.
- BV's EOF modes are similar, suggesting BV subsurface structure is insensitive to the chosen rescaling parameter.

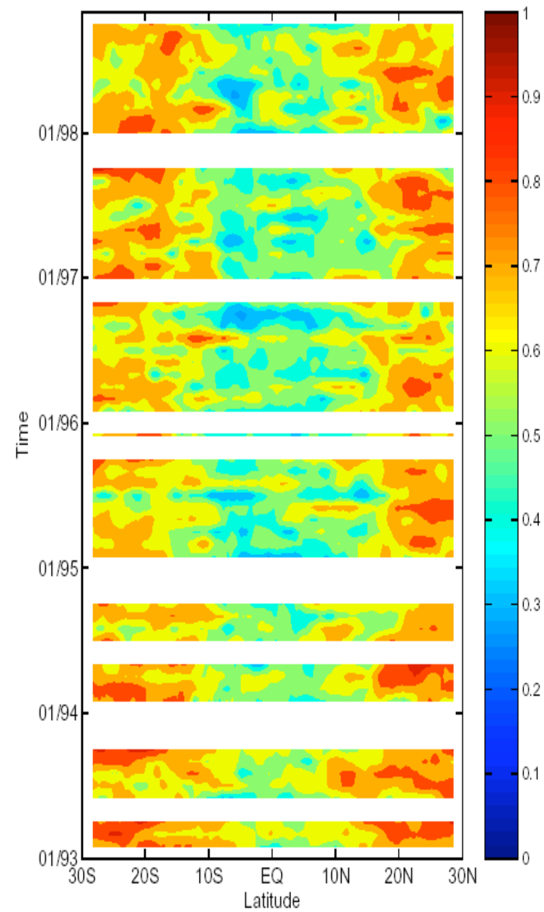
Local analysis increment projection on ensemble perturbations

- Ensemble perturbations
  - Three dynamic perturbations (BVa, BVb, and BVc)
  - Three operational perturbations
    - Differences between two analysis state, one is a randomly chosen analysis with 15 days of initialization time, and the other one is 3 days after the first one.
- Project local analysis increment on local space spanned by 3 ensemble perturbations (as in Patil et al, 2000).
  - Local domain (11x11 grid points)

SST analysis increment projection on bred vectors

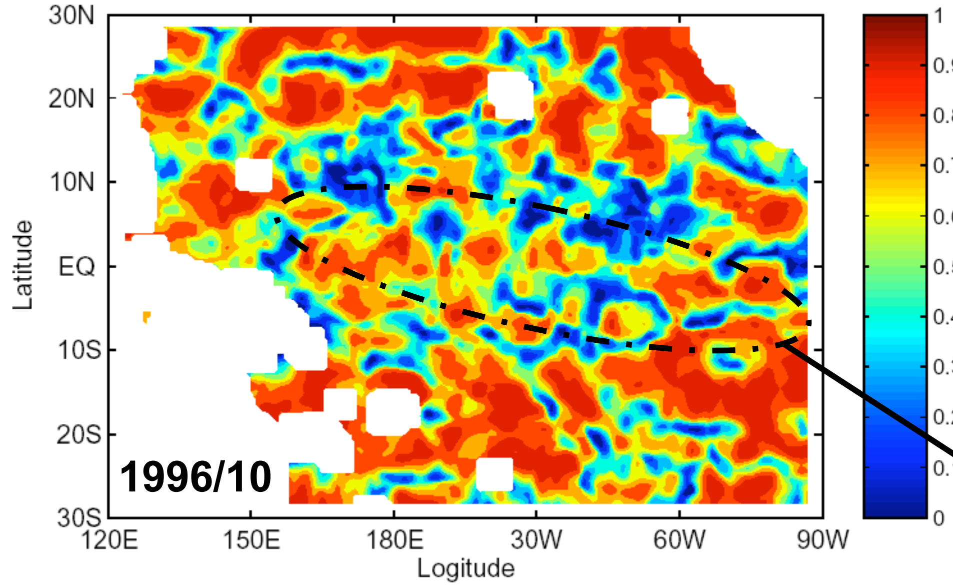


SST analysis increment projection on operational perturbations

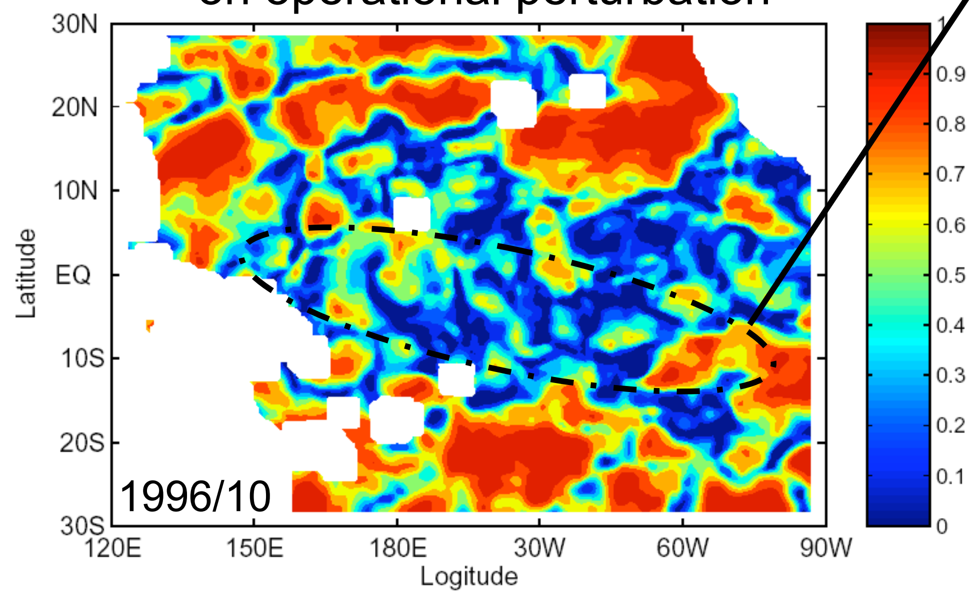


- Generally, the projection amount on bred vector is higher than operational perturbations, especially during 1997-1998 El Nino event
- Operational perturbations know the observations and therefore still contain oceanic memory.

SST analysis increment projection on BV



SST analysis increment projection
on operational perturbation



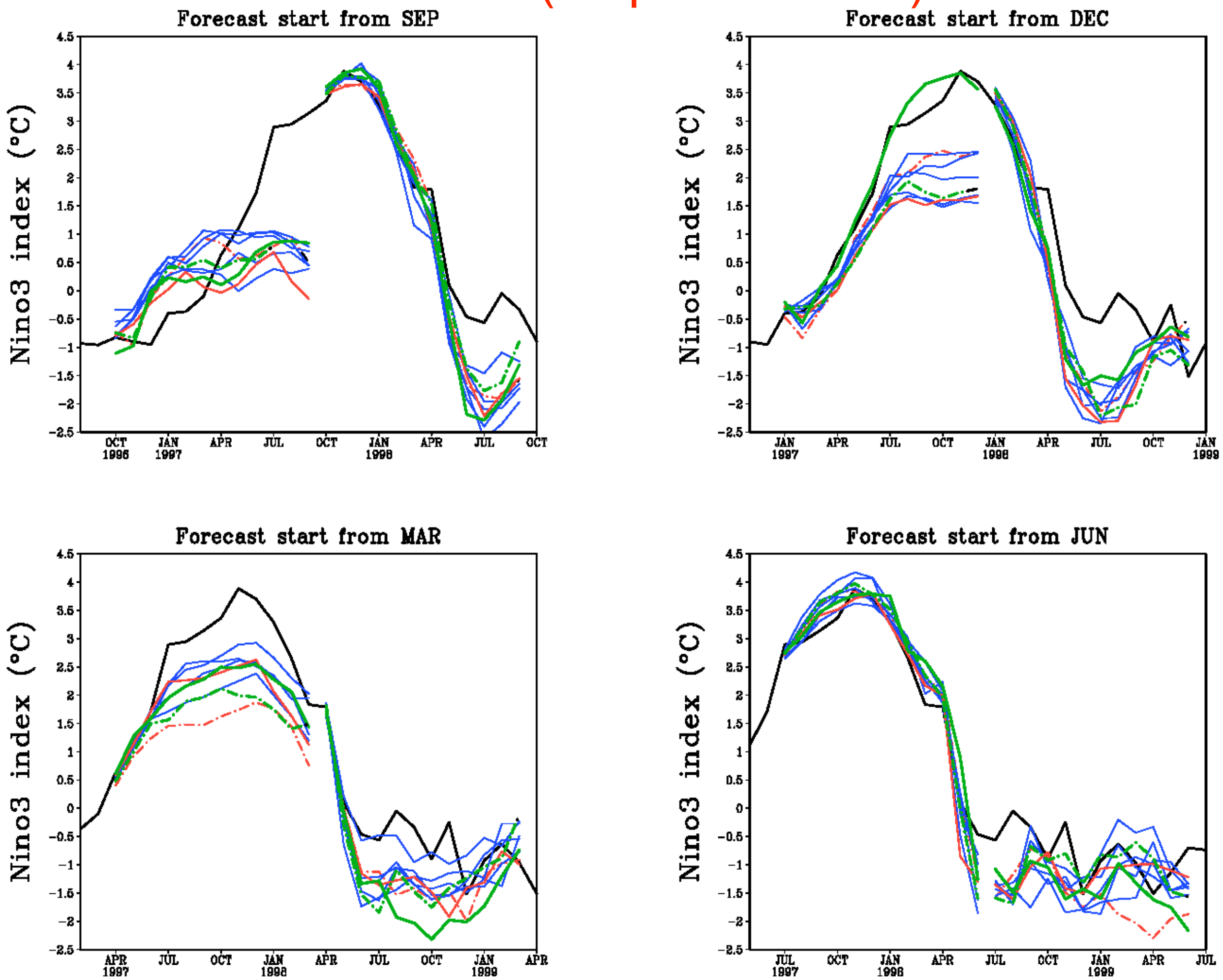
- Both analysis increment and BV growth rate are large
- Larger projection appear in the tropical Pacific before the anomalous warming ('97 El Nino) starts.

Ensemble forecasting experiments

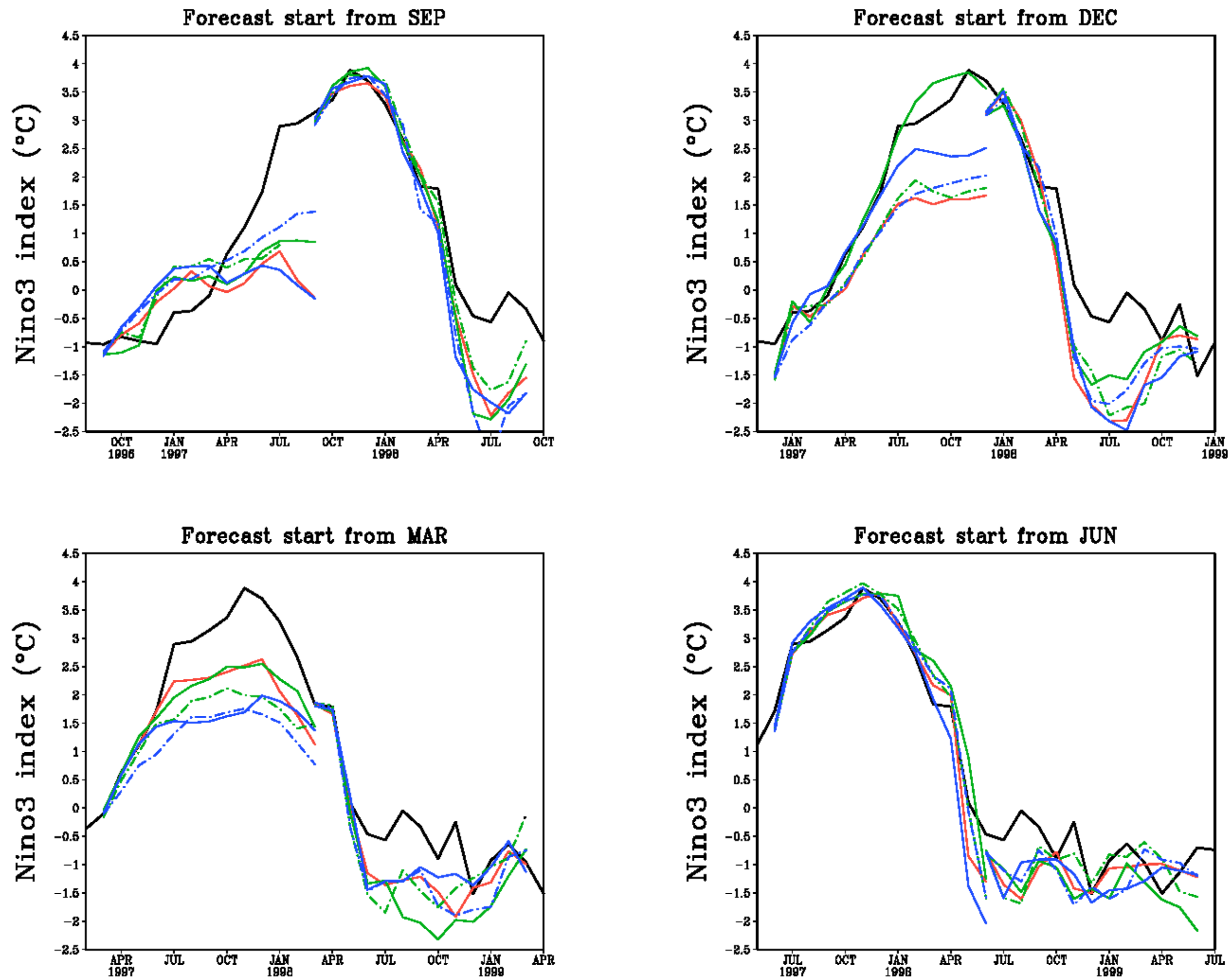
- **Operational perturbations:**
  - Operational ensemble forecasts (**one control** and **5 perturbed runs**)
  - Ocean has analysis initial conditions but atmosphere starts from AMIP runs
- **Dynamic (BV) perturbations :**
  - One pair of bred vector are generated by adding and subtracting to the initial fields
  - Ocean BVs centered at ocean analysis and Atmos BVs centered at AMIP restarts
  - Ocean BVs centered at ocean analysis and Atmos BVs centered at $(BV^{+}+BV^{-})/2$
  - We used constant amplitude for the perturbations

Nino3 index (SST clim drift removed from forecasts)

- Dynamic perturbation (one pair of BV$^+$,BV$^-$)
- Operational perturbation
- Control forecast (no perturbation)



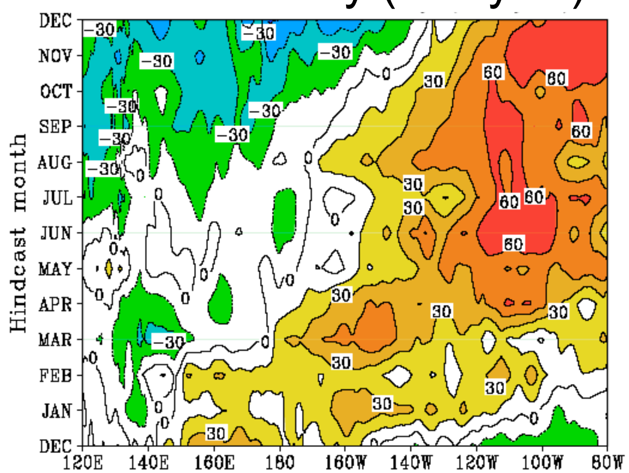
- Ocean BVs centered at ocean analysis and Atmos BVs centered at AMIP restarts
- Ocean BVs centered at ocean analysis and Atmos BVs centered at $(BV^{+}+BV^{-})/2$
- Control forecast



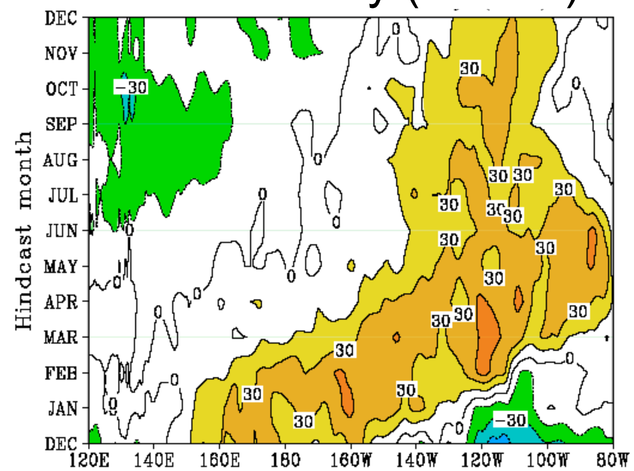
Hovmoller diagram of forecasted thermocline

(Starting from December 1996)

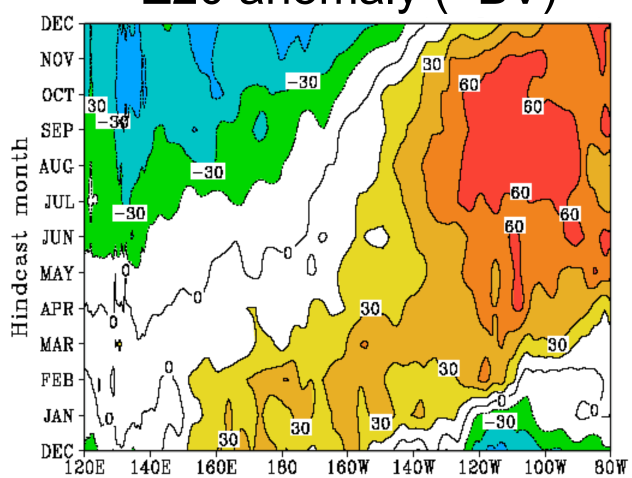
Z20 anomaly (analysis)



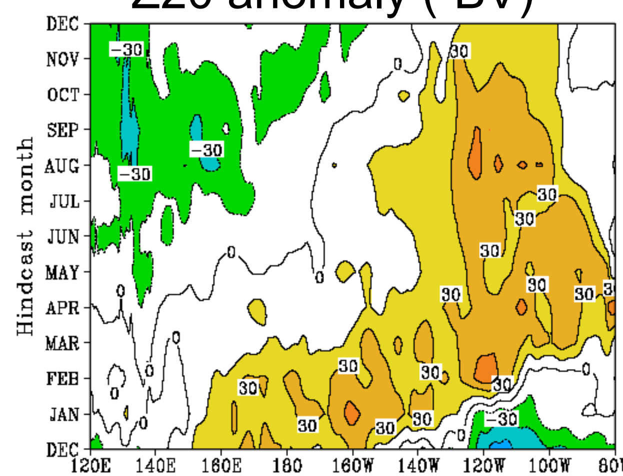
Z20 anomaly (control)



Z20 anomaly (+BV)

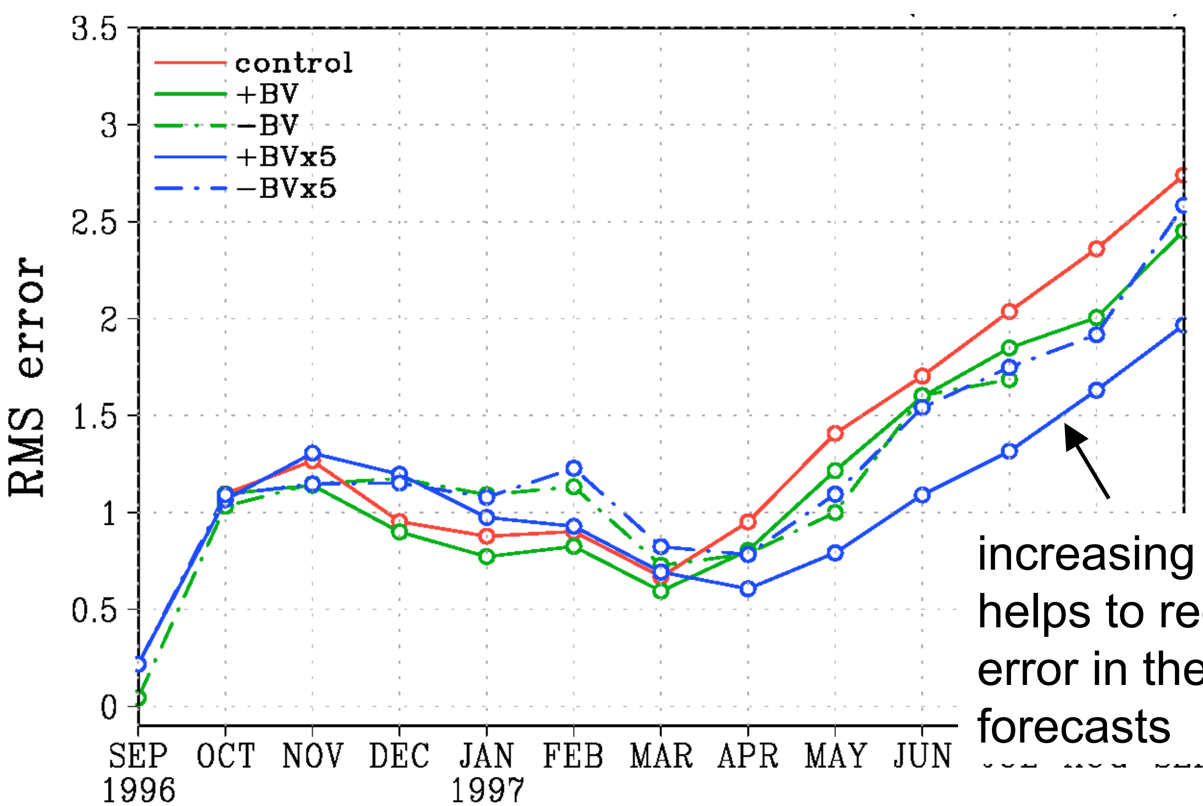


Z20 anomaly (-BV)



The size of ensemble perturbation needs to be adjusted with BV growth rate

Increased the size of the perturbation by a factor of 5 for the case with large growth rate

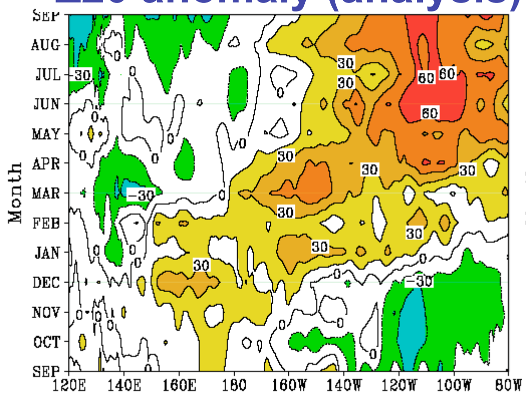


increasing the size helps to reduce the error in the later month forecasts

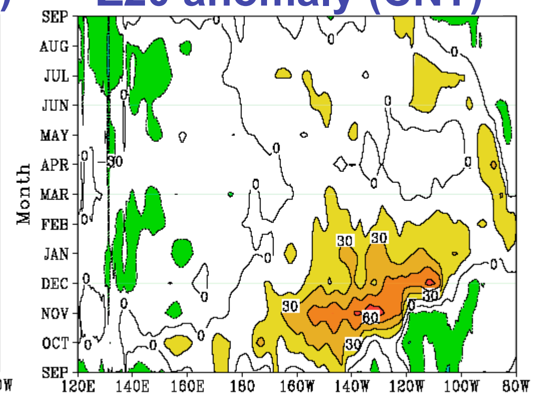
Hovmoller diagram of forecasted thermocline

(Starting from September 1996)

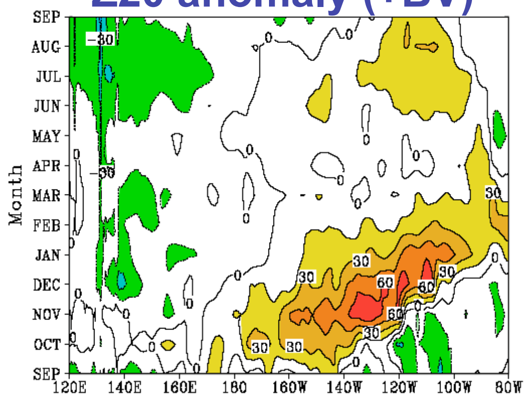
Z20 anomaly (analysis)



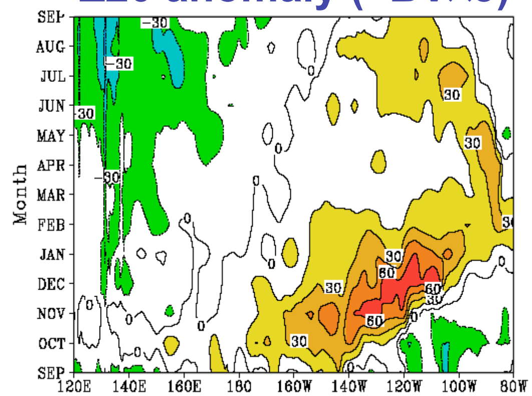
Z20 anomaly (CNT)



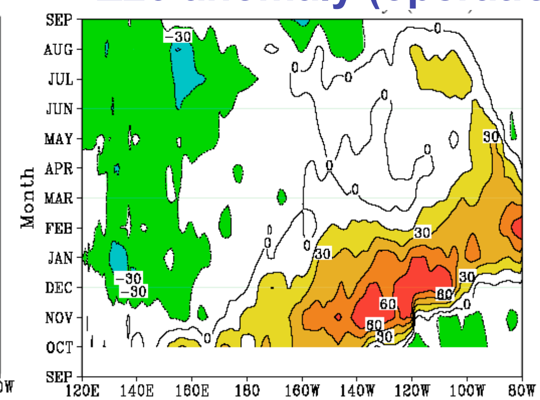
Z20 anomaly (+BV)



Z20 anomaly (+BV×5)



Z20 anomaly (operational)



Summary: NSIPP operational system

- This is a much more complex system (real ocean data, model errors, AMIP atmosphere). Nevertheless, results are encouraging:
- BV growth rate is sensitive to ENSO and is large before and after the event (like in the Cane-Zebiak model)
- The analysis increment in NSIPP CGCM is dominated by dynamical errors whose shape can be captured by bred vectors
- BV captures the eastward movement of the Analysis Incr. along the equatorial Pacific during El Niño evolution
- BV is clearly related to analysis increment for both SST and subsurface temperature, particularly when the BV growth rate is large
- Both the analysis increments and BVs in the subsurface are dominated by structures related to seasonal-to-interannual variability.
- Preliminary results using BV for ensemble forecasting are encouraging, but system needs tuning of amplitude.

Applications

- Bred vectors will be tested as initial coupled perturbations for ensemble ENSO forecasting in the NASA NSIPP operational system.
- Considering their ability to detect the month to month background error variability, bred vectors will also be tested to improve oceanic data assimilation.
- Similar studies are now being done at NCEP

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