Bred vectors in the NASA NSIPP global coupled model and their application to coupled ensemble prediction and data assimilation

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Outline

- Motivation
- Bred vectors in a perfect model experiment
  - Characteristics of coupled BV, its relationship to ENSO cycle
  - Comparison of coupled BVs obtained from the NASA and the NCEP CGCMs
- Bred vectors in NSIPP operational system
  - The relationship between BV and the one-month forecast error
  - Preliminary ensemble experiment results
- Summary
- Future applications

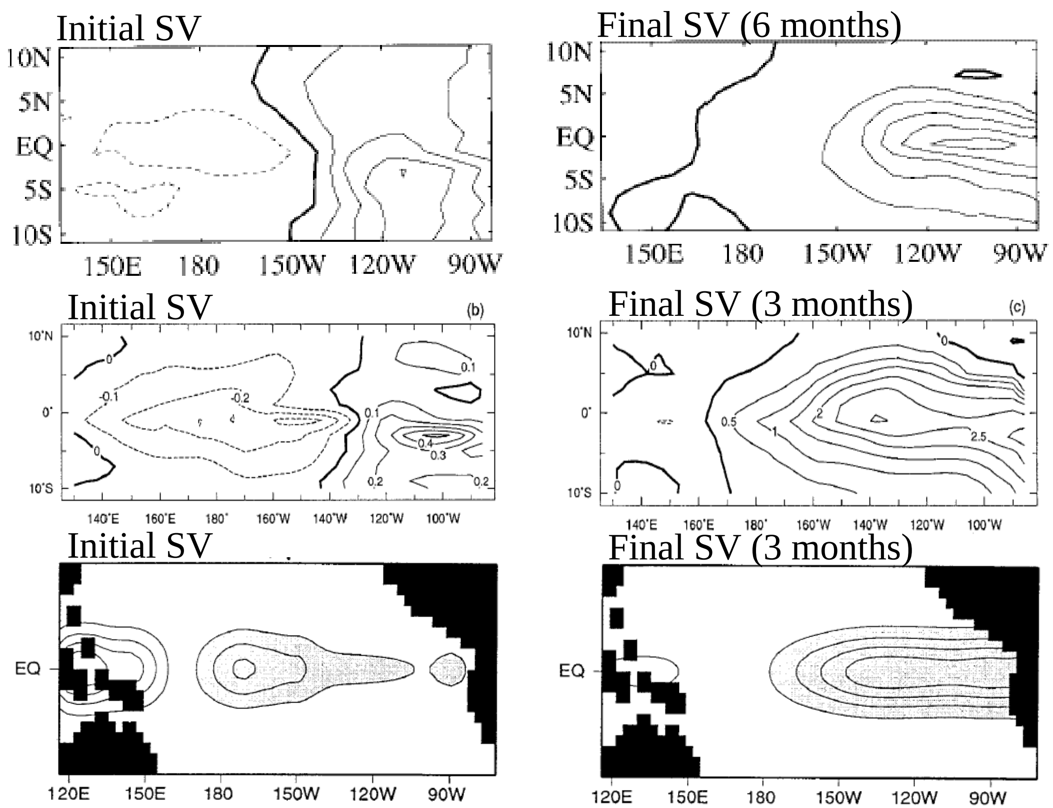
Motivation

- Ensemble forecasting is designed to represent the forecast uncertainties.
- For ENSO prediction, a good forecast is determined by the forecasted SST and ensemble forecast need to represent the SST uncertainties.
- Ensemble perturbations need to have coupled slow perturbations.
- A dynamic coupled GCM includes different types of instabilities.
  - ENSO (interannual)
  - Baroclinic instability (synoptic)
  - Cumulus convection (mesoscale)

How to create slow coupled perturbation for ENSO ensemble forecasting ?

- Methods for ensemble perturbations
  - Linear approaches (Singular Vectors) have to exclude the fastest instability explicitly.
  - Nonlinear model integrations (Bred Vectors) allow fast instabilities to saturate at early time, they can filter fast instabilities !!

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



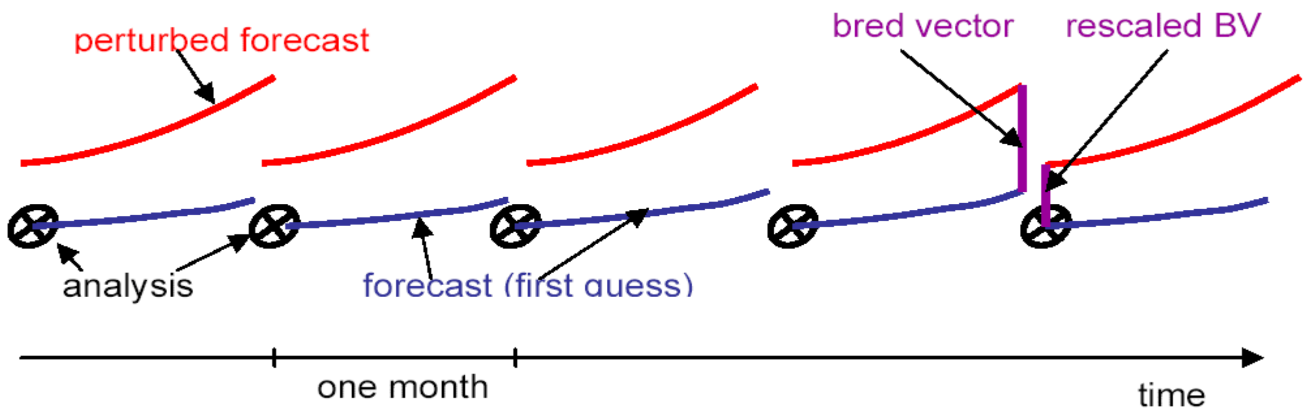
Chen et al. (1997)
Southeast in E. Pacific

Xue et al.(1997)
Equatorial Pacific

Moore and Kleeman (2001)
West-Central Pacific

- **Final SV all show ENSO-related response; but initial SV are very different!**
- **SVs are sensitive to models, perturbations norms….**
- **Need simplifications to construct tangent linear operator for GCM**

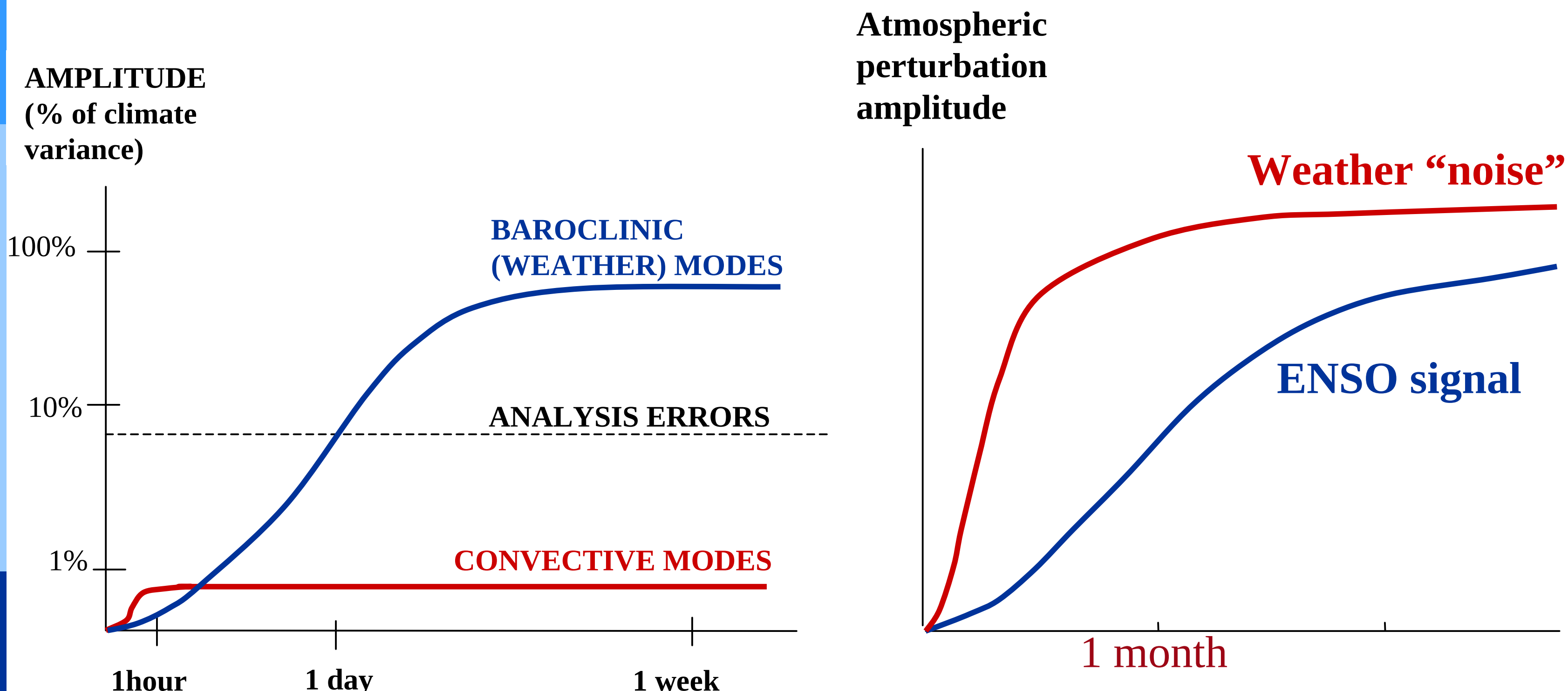
Breeding in a coupled system



- **Bred vectors** :
  Differences between the control forecast and perturbed runs
- **Tuning parameters**
  - Size of perturbation (measured in ocean)
  - Rescaling period (important for coupled system)
- **Rescaling factor is applied to both ocean and atmosphere**
- **Advantages**
  - Low computational cost
  - Easy: essentially running the CGCM twice and rescaling the difference

Breeding parameters

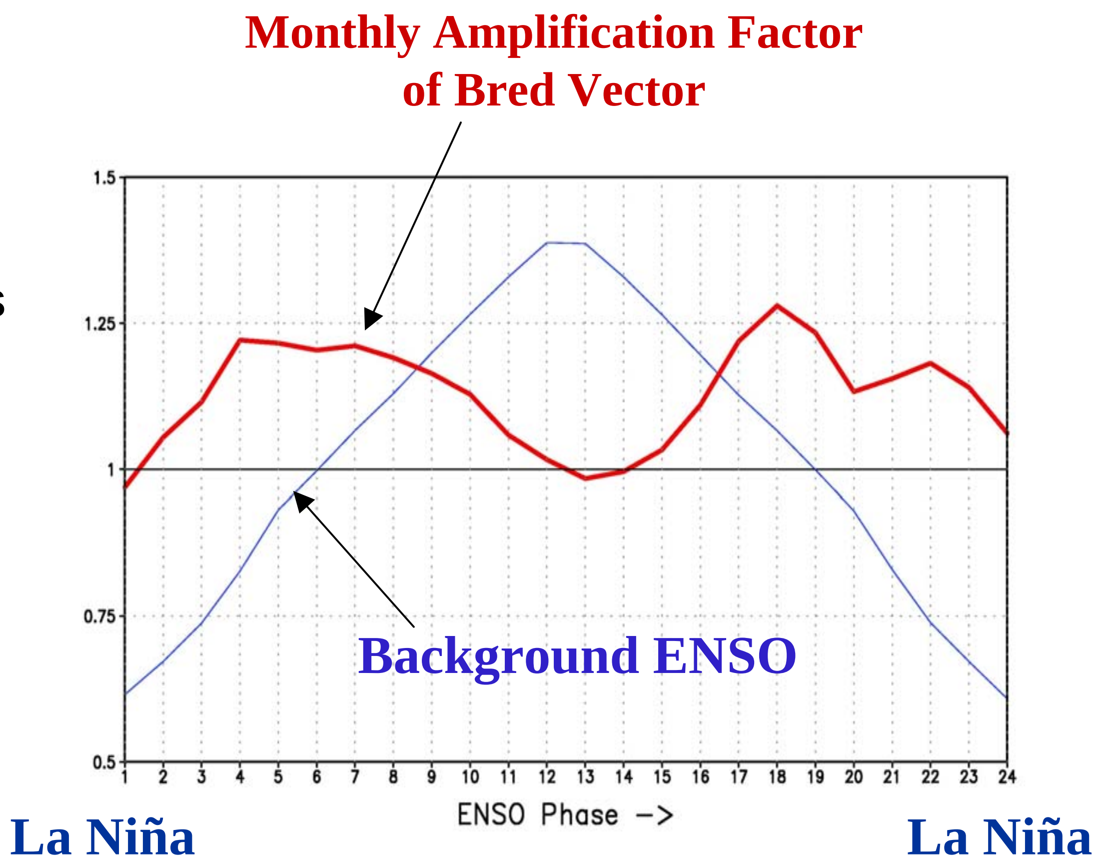
Perturbation size and rescaling period allow choosing the type of instability



- Slowly growing errors need to be measured in the **ocean component**
- Need a long rescaling interval, like 2 weeks or **one month**

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



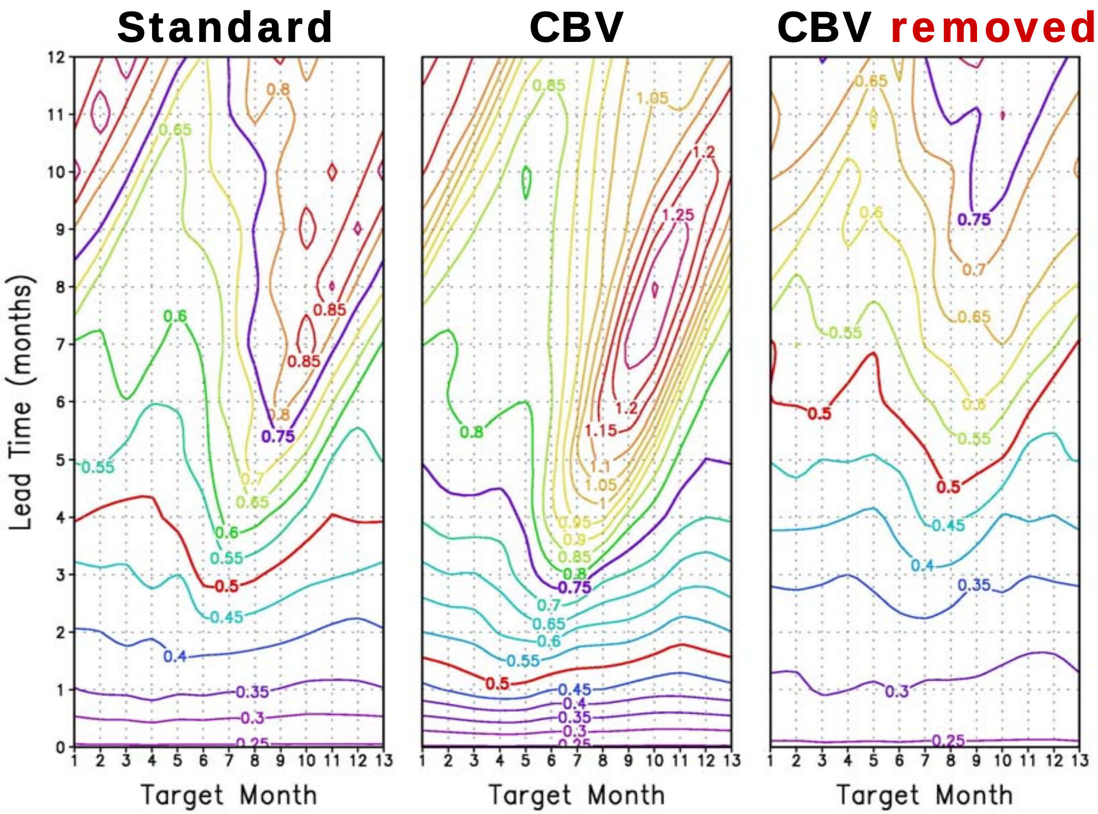
Challenge

- ZC model has only one type of variability (i.e. ENSO)
- The atmospheric component is simply the response to the SST
- What do coupled BV look like when dealing with a much more complex system blending different variabilities (atmospheric weather, etc.)?
- Do we get a similar ENSO-coupled mode?

BV applied on forecast error growth:

- Bred Vectors can be applied to improve the forecast skill and reduce the impact of the “spring-barrier”.
- “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.

Forecast error



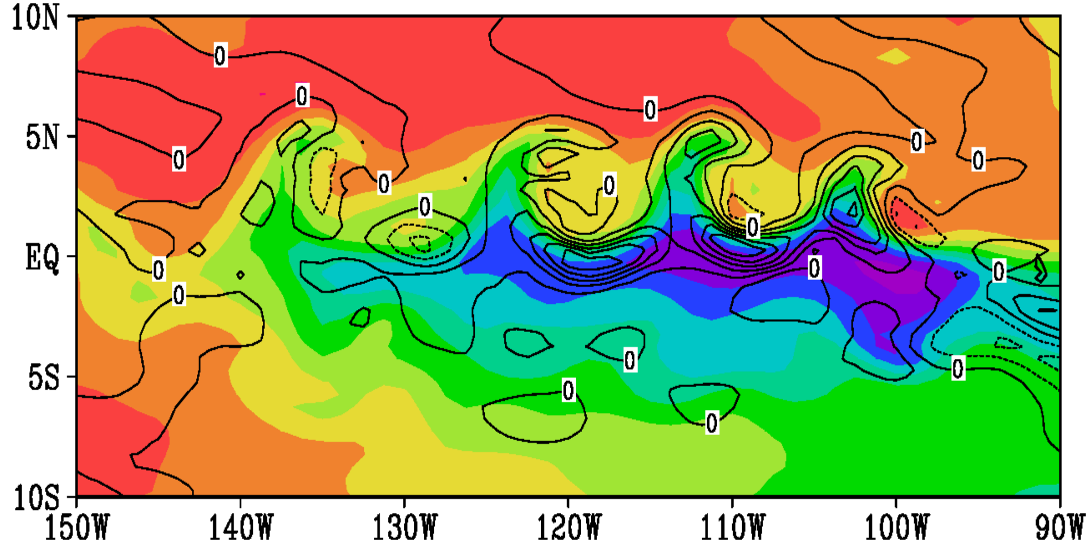
Breeding in perfect model experiments

- Breeding experiments are performed with NASA/NSIPP CGCM
- Results will be compared with BV computed from NCEP/GFS CGCM

NASA Seasonal-to Interannual Prediction (NSIPP) coupled GCM

<table>
<tr><td rowspan="7">Components</td><td>AGCM</td></tr>
<tr><td>▪ Developed by Suarez (1996)</td></tr>
<tr><td>▪ Resolution: 3° X 3.75° X 34</td></tr>
<tr><td>OGCM/Poseidon V4</td></tr>
<tr><td>▪ Developed by Schopf and Loughe (1995), layer models</td></tr>
<tr><td>▪ Resolution: 1/2° X 1.25° X 27</td></tr>
<tr><td>Mosaic LSM</td></tr>
<tr><td colspan="2">▪ Full globally coupled
▪ AGCM and OGCM coupled everyday
▪ Current prediction skill (El Niño hindcasts) is up to 9 months</td></tr>
<tr><td colspan="2">10 years breeding “perfect model” experiment</td></tr>
<tr><td rowspan="2">Breeding</td><td>Size of perturbation: 10% of the RMS of the SSTA (~0.1°C) in tropical Pacific region</td></tr>
<tr><td>Rescaling period: one month</td></tr>
</table>

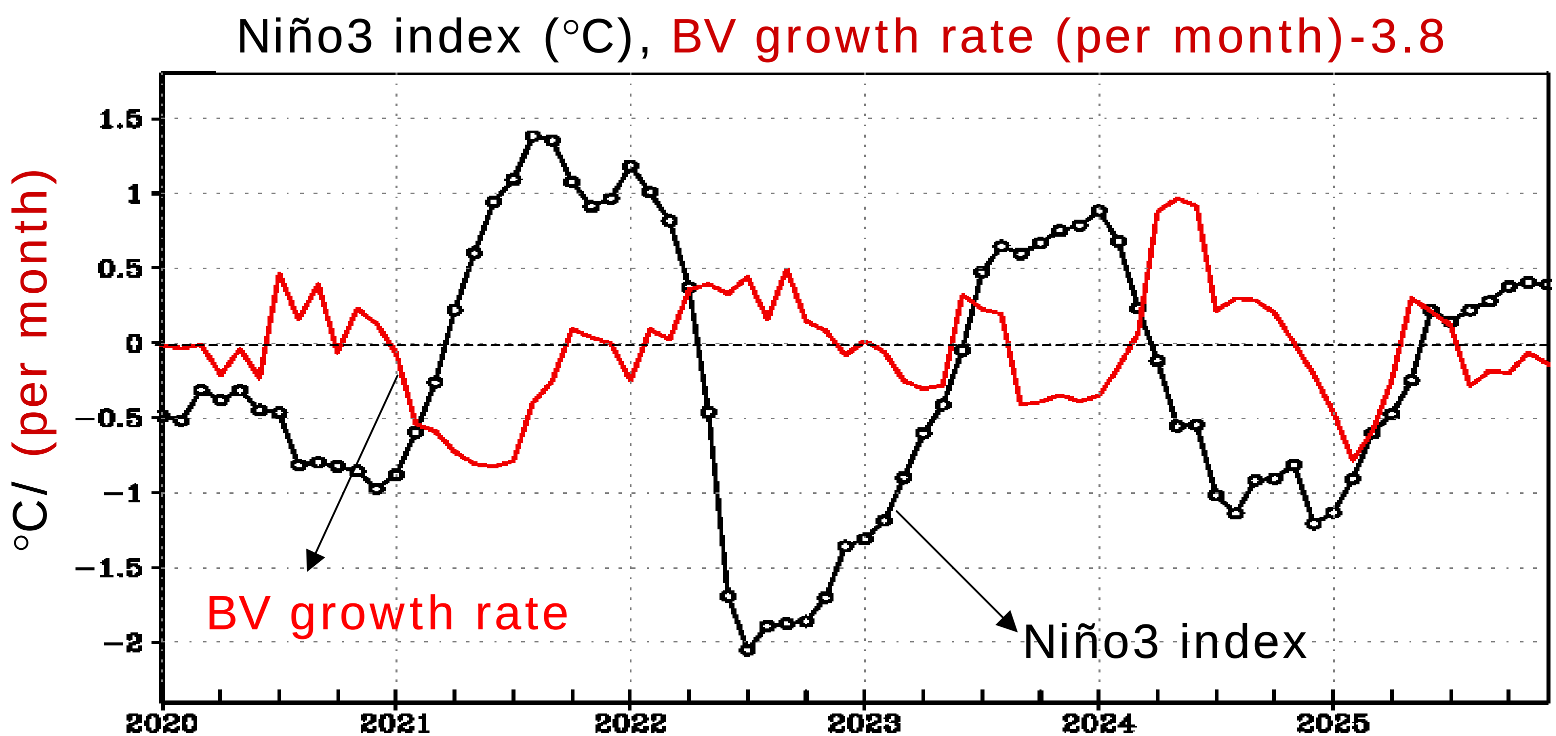
Background SST vs. BV SST



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

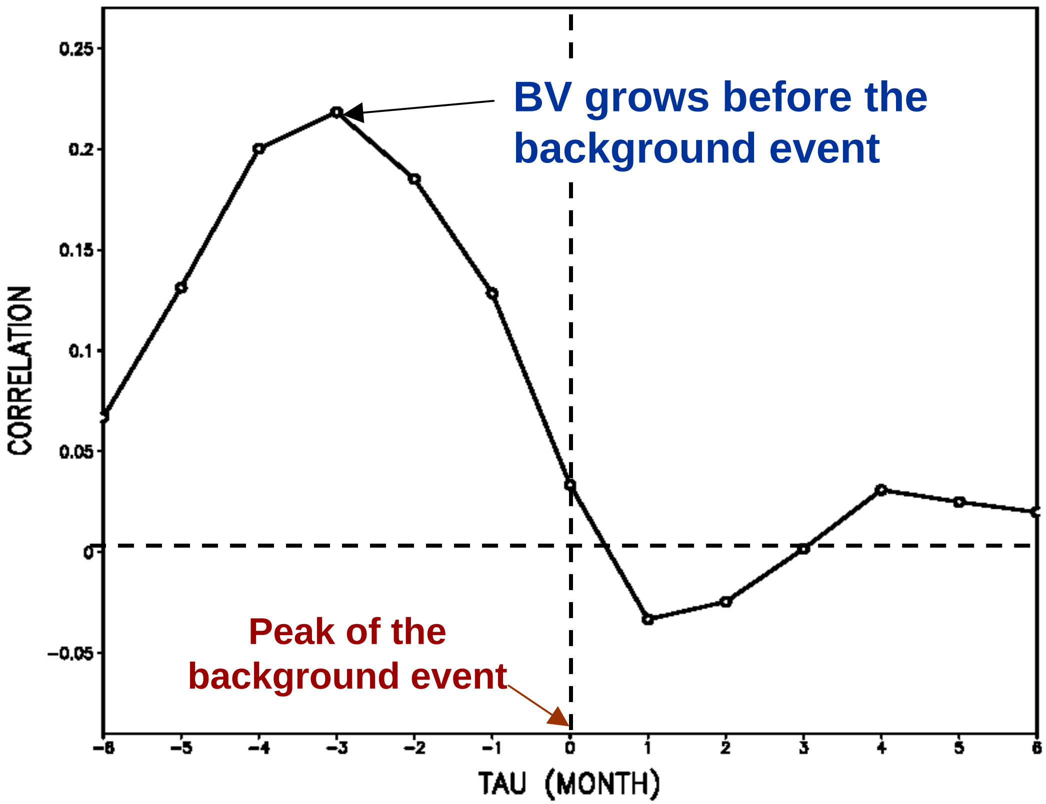
BV growth rate and ENSO cycle

$$\textbf{BV growth rate} = \frac{\sqrt{BV_{SST}(t)}}{\sqrt{BV_{SST}(t-1)}}$$



The BV growth rate vs. the ENSO cycle

Lead/lag correlation between the BV growth rate and background |Nino3 index|



The BV growth rate has a strong dependence on the ENSO phases

- **Detect a precursor of ENSO event**

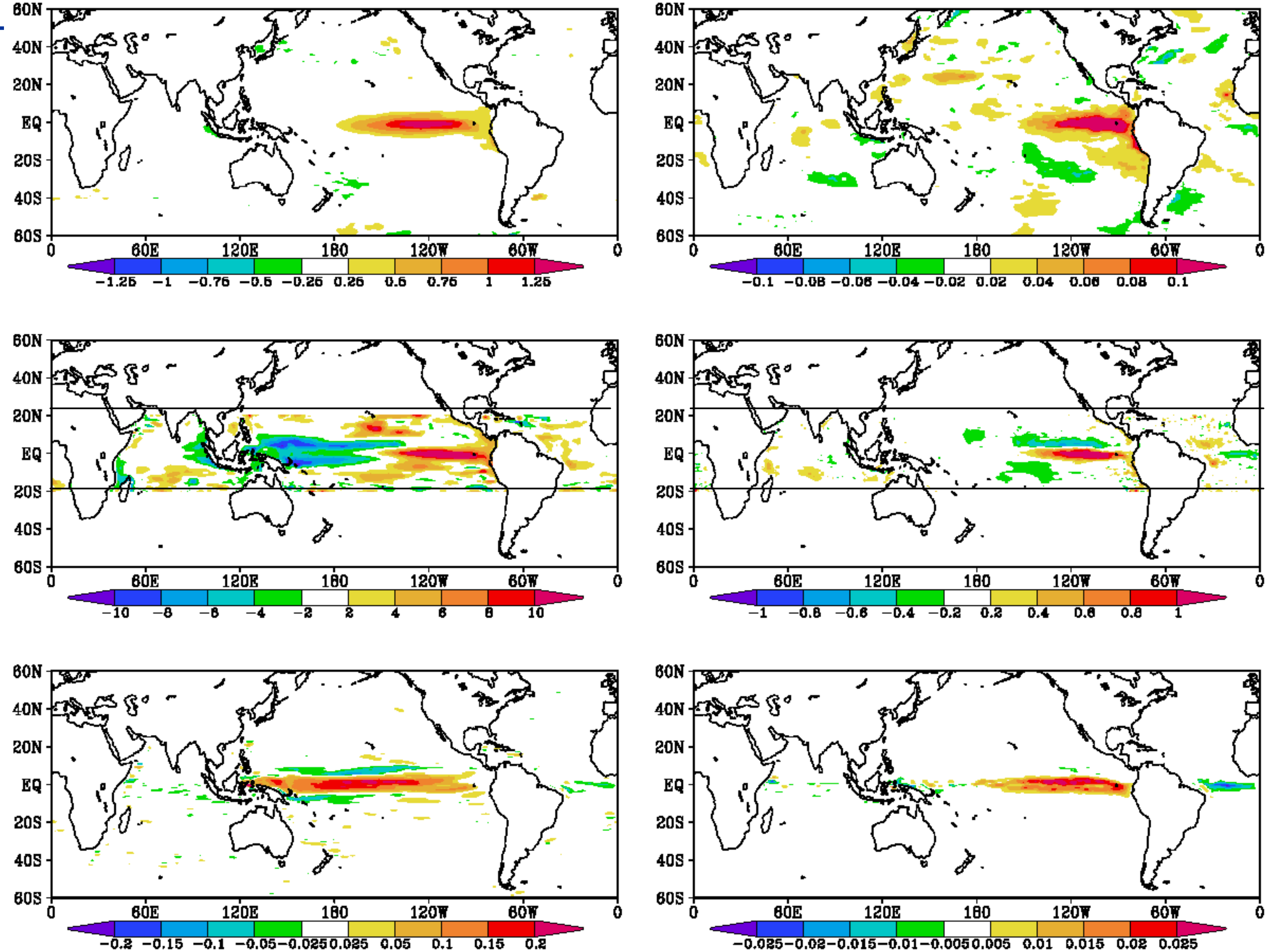
Oceanic maps regressed with NINO3 index

Background | **BV**

SST

Thermocline (Z20)

Surface zonal current



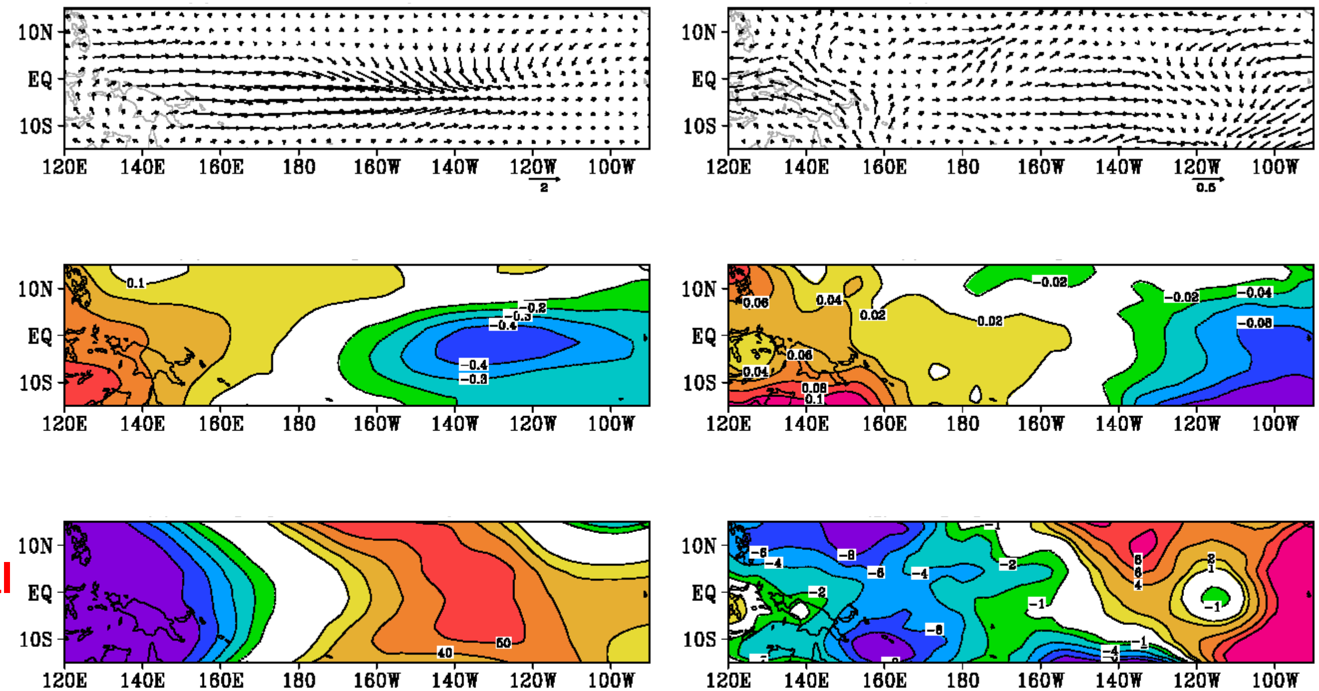
Atmospheric maps regressed with NINO3 index

Background | BV

wind

surface pressure

geopotential at 200mb



The coupled bred vector are able to **perturb the longitudinal circulation in tropical atmosphere**, reflecting the perturbation heating in the eastern Pacific.

NASA and NCEP Coupled GCMs

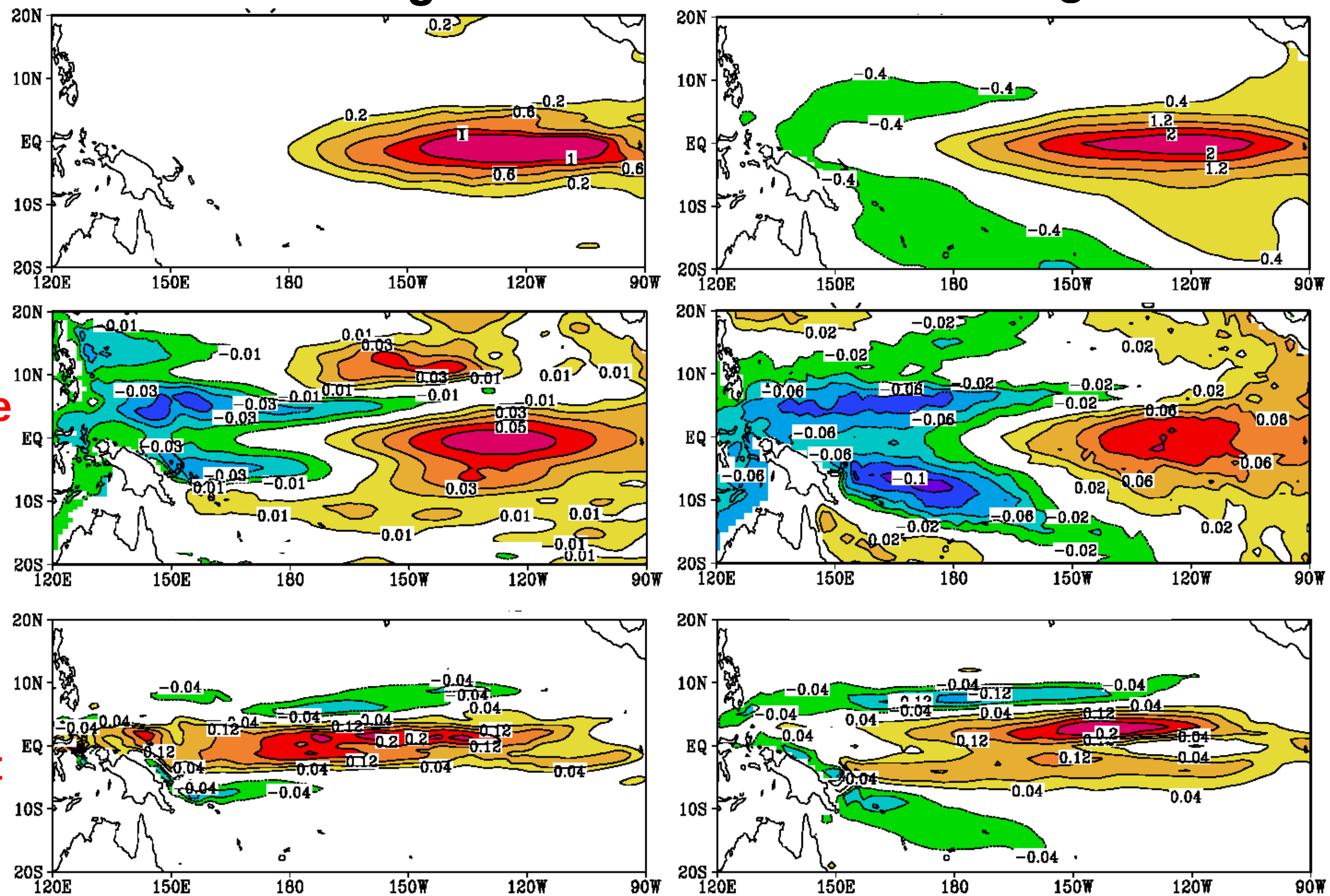
They show a similar ENSO mechanism but differ in the details of the structures.

NASA background | **NCEP background**

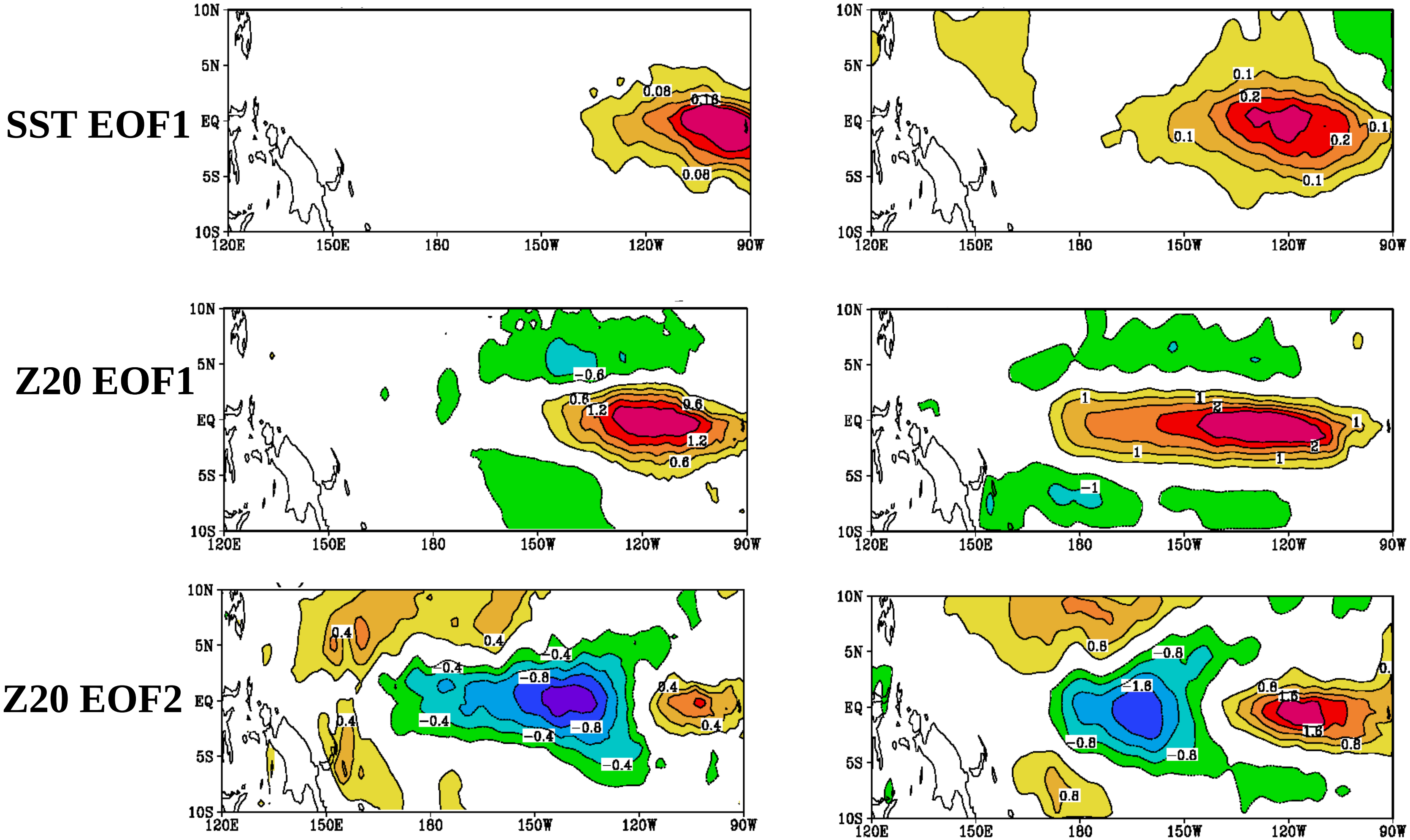
SST

surface height

zonal current



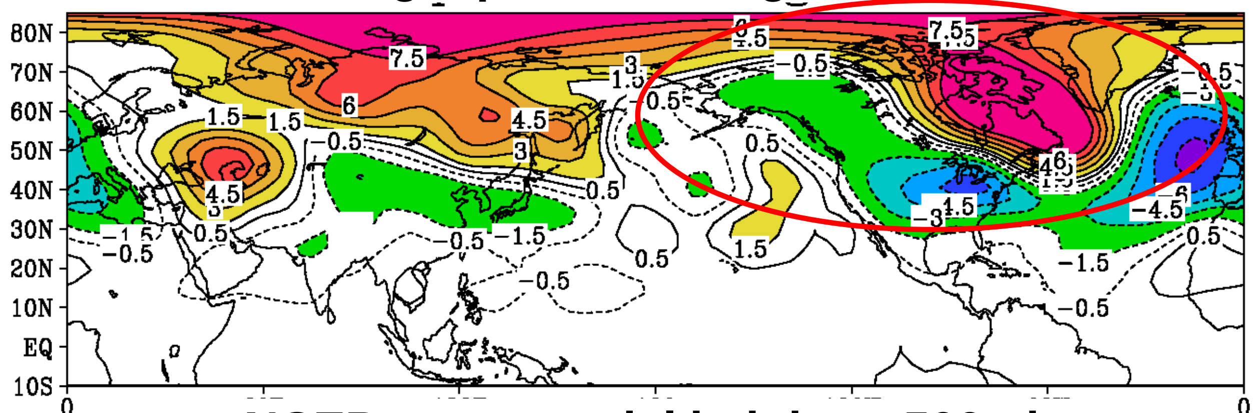
NASA Bred Vector and NCEP Bred Vector



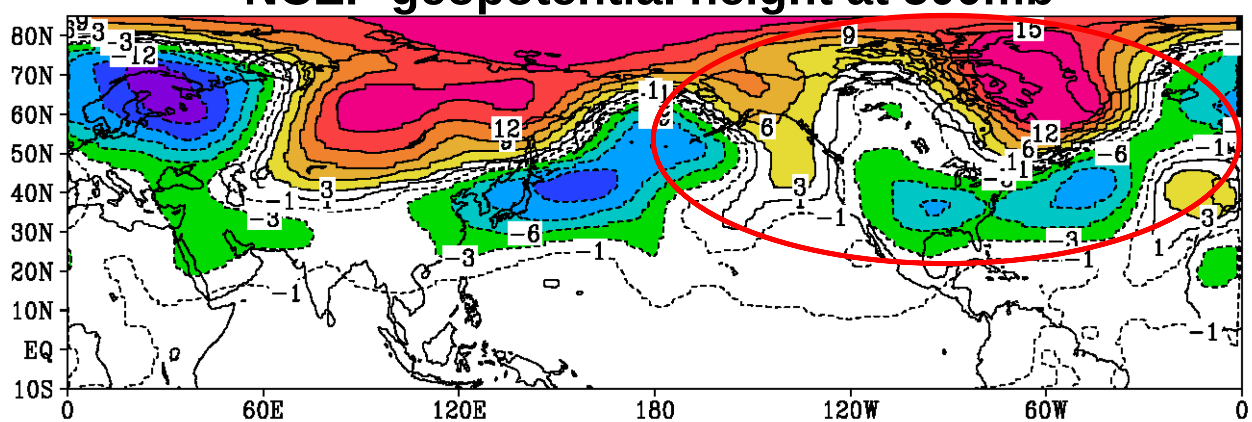
BV obtained with a 4-year NCEP run are extremely similar to BV from NASA's 10 year

NASA BV vs. NCEP BV

NASA geopotential height at 500mb



NCEP geopotential height at 500mb



Both NASA and NCEP coupled BVs have projection on the atmospheric teleconnected region

Summary on perfect model experiments

- Results obtained from this complicated CGCM agree with Cai et al. (2003) in many aspects.
- Coupled breeding can detect a precursor signal associated with ENSO events.
- Bred vectors are characterized by air-sea coupled features and they are very sensitive to ENSO phases.
- Our results suggest coupled BV carries the slowly-varying coupled instability associated with the seasonal-to-interannual variability.
- Bred vectors obtained from both the NASA and NCEP coupled systems exhibit similarities in many fields, even in the atmospheric teleconnected regions.

Breeding in the operational NASA system with data assimilation and forecasts

- **NSIPP operational forecast system**

  OGCM (1/3°× 5/8°× 27 layers)
  - Analysis assimilates temperature observations (univariate optimal interpolation)

  AGCM (2°× 2.5°×34 levels)
  - Initial: AMIP restarts

  The oceanic <u>growing forecast errors</u> is measured by the difference between analysis and forecast

- **Breeding “ imperfect” model experiments**
  - Noisy observations, model error…
  - <u>Bred Vectors</u> are designed to estimate the growing <u>forecast errors</u> (without knowing about the new observations).
  - If BVs are similar to forecast error 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
  1. BVa: **BV SST** in Niño3 region (rescaling size=0.1°C, standard run)
  2. BVb: **BV thermocline (Z20)** in tropical Pacific (size=2m)
  3. 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 (insensitive to the rescaling norm).
- So, we only show results from BVa.

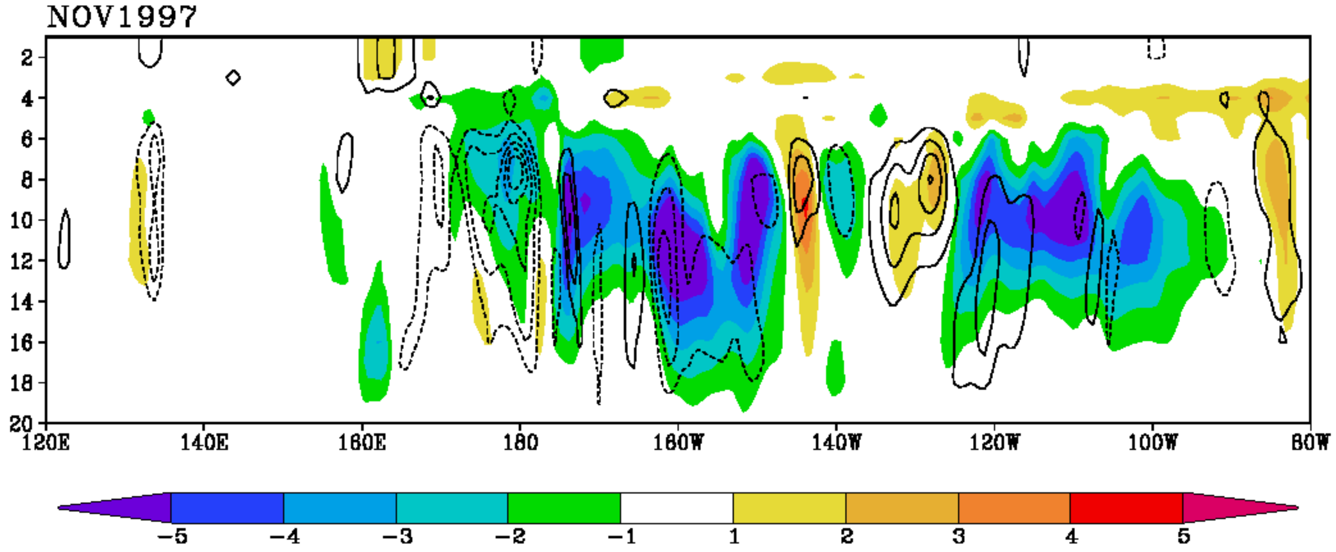
Vertical cross-section at Equator for Bred Vector and Forecast error

Bred vector (contour):

rescaled difference between control forecast and perturbed runs

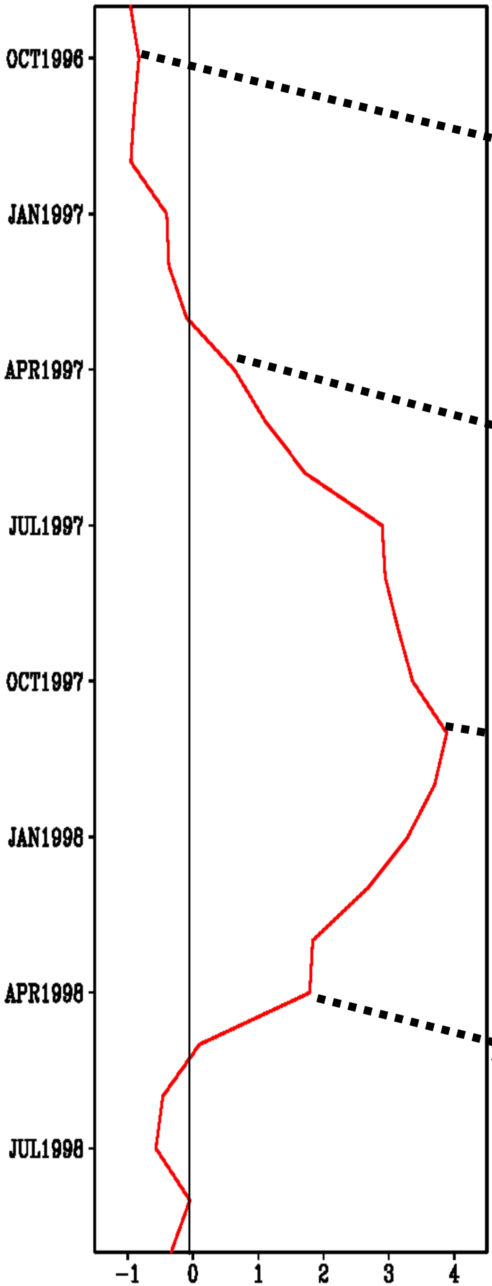
Forecast error (color shading):

Difference between analysis and one-month forecast

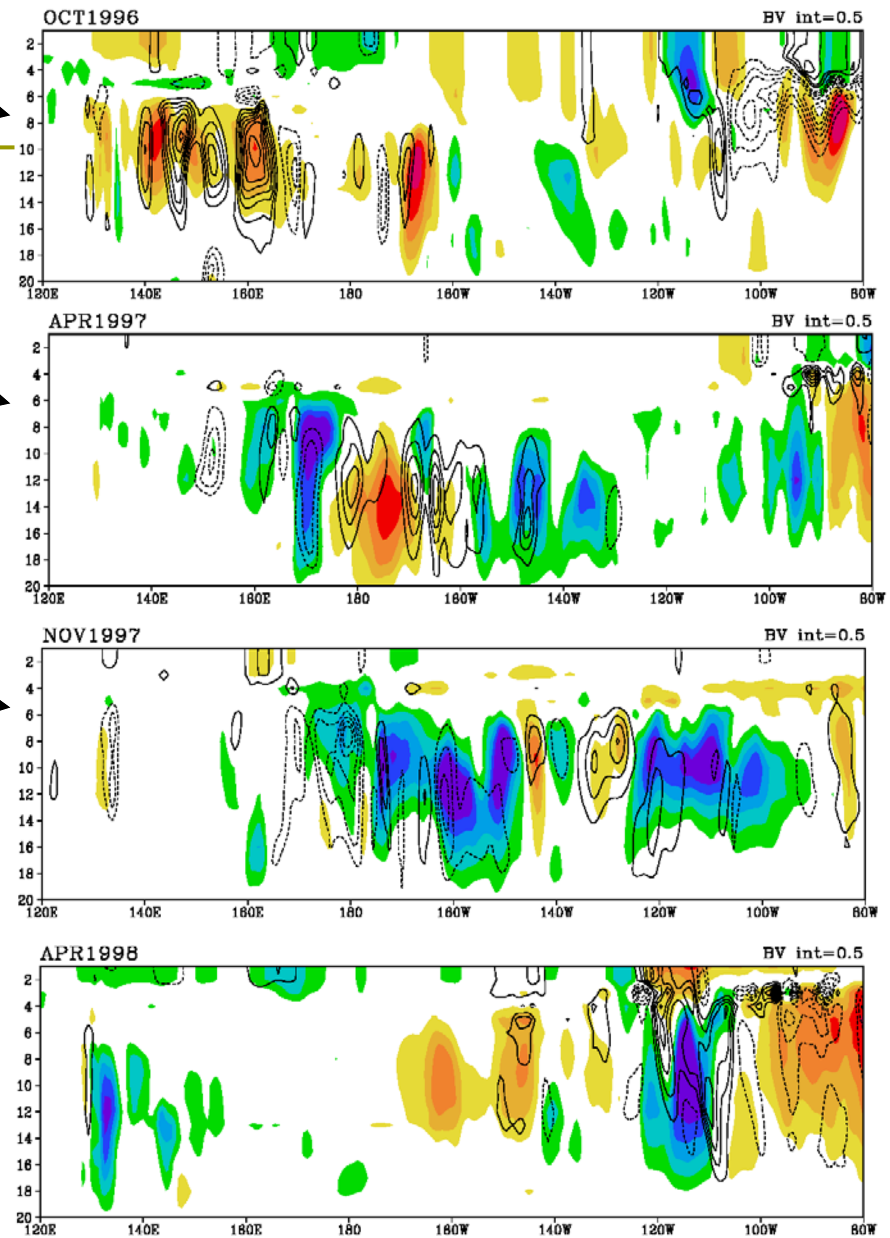


Thermocline (Z20) is located at level 12~15

Niño3 index



Vertical cross-section at Equator for BV (contour) and forecast error (color)



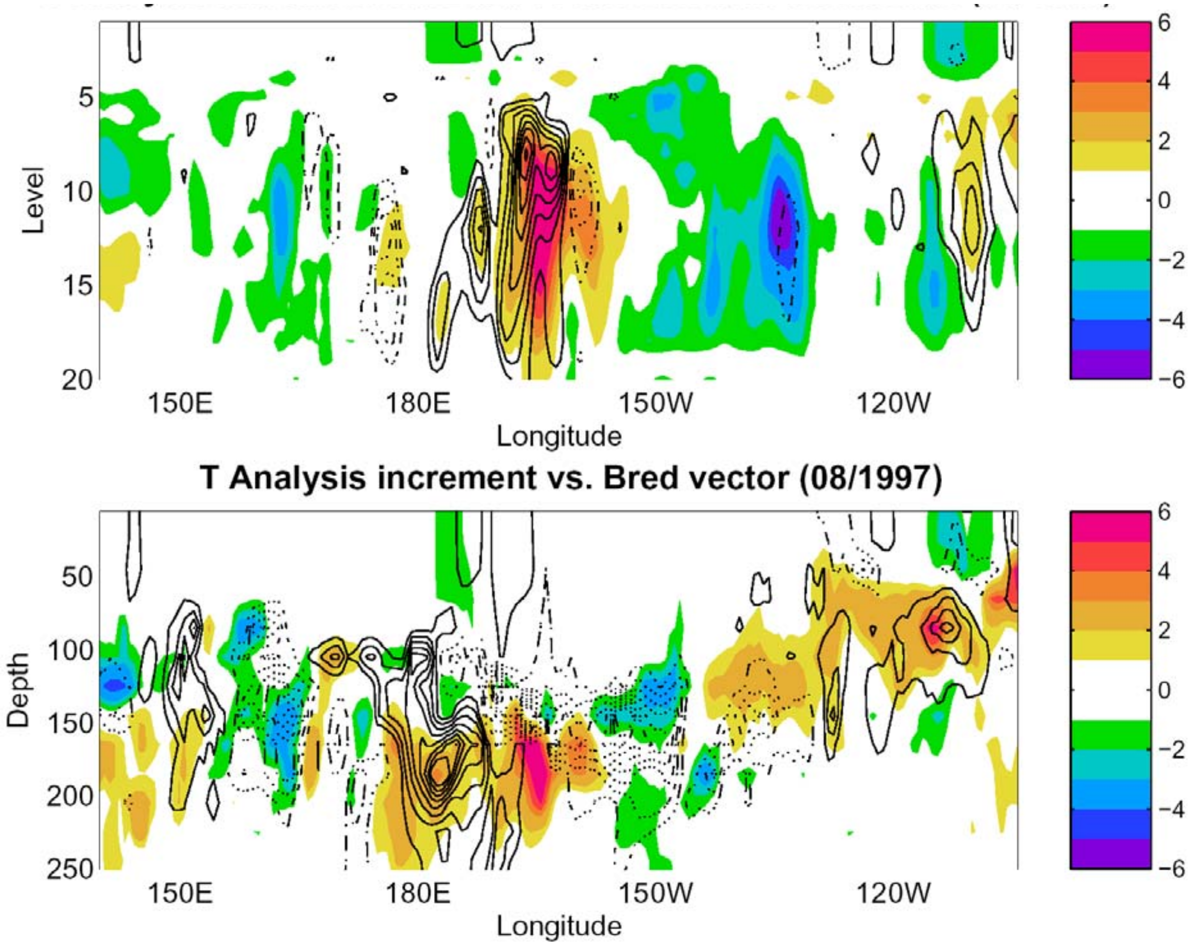
Before 97' El Niño, Fcst. error is located in W. Pacific and near coast region

During development, Fcst. error shifts to lower levels of C. Pacific.

At mature stage, Fcst. error shifts further east and it is smallest near the coast.

After the event, Fcst. error is located mostly in E. Pacific.

Forecast error (color) vs. Bred vector (contour)



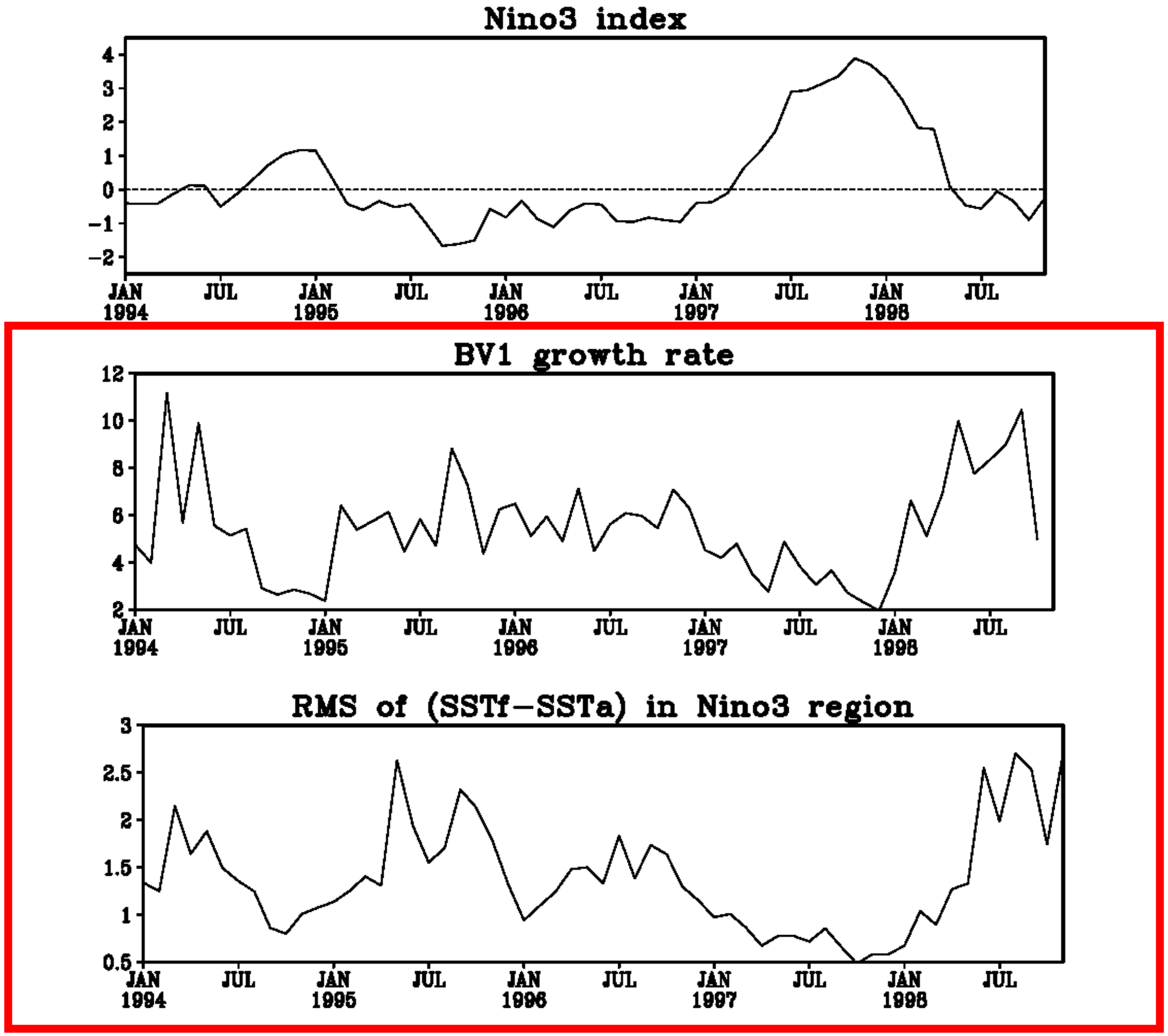
Temperature profile in **model** levels

Temperature profile in **depth** (meters)

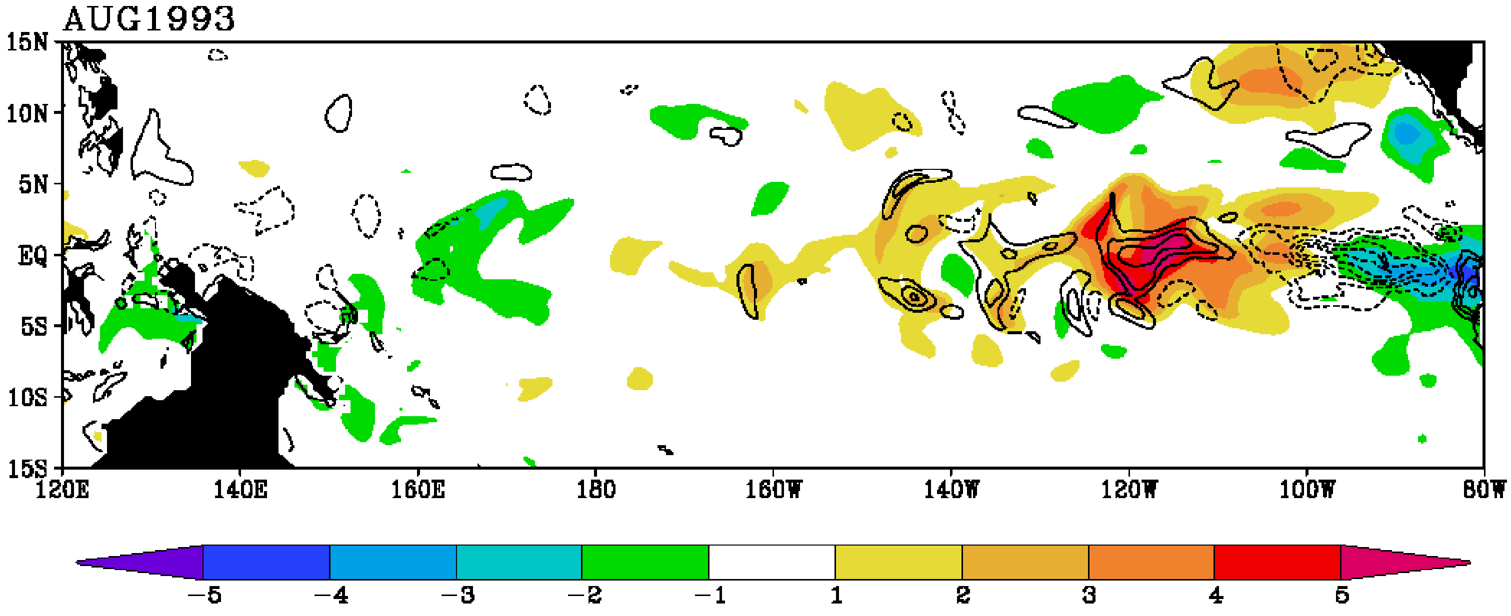
- **Bred vector captures large dynamic errors, located mostly near the thermocline.**
- **Good agreement between BV and Fcst. error on model levels/vertical depth suggests their potential application in DA background error covariance.**

SSTA, BV and Fcst error in Niño3 region

Variations of temperature Fcst error in eastern Pacific are strongly related to BV growth rate

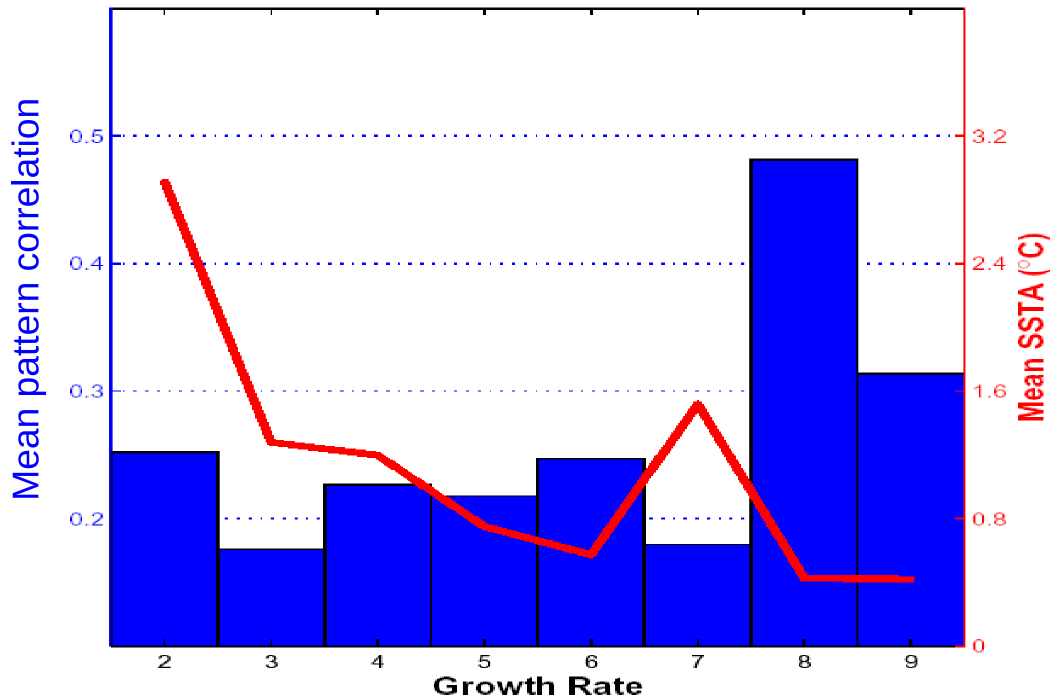


Forecast error (color) vs. BV SST (contour) in tropical Pacific



- For large BV growth, agreement of BV with forecast error is very good.
- Pattern correlation: ***CORR****(BV, Fcst. Error)*

The growing error and background SSTA in the Niño3 region



- Pattern correlation:

  CORR*(BV, Fcst. Error)*
- Data is grouped based on the BV growth rate and mean value is calculated for each group.

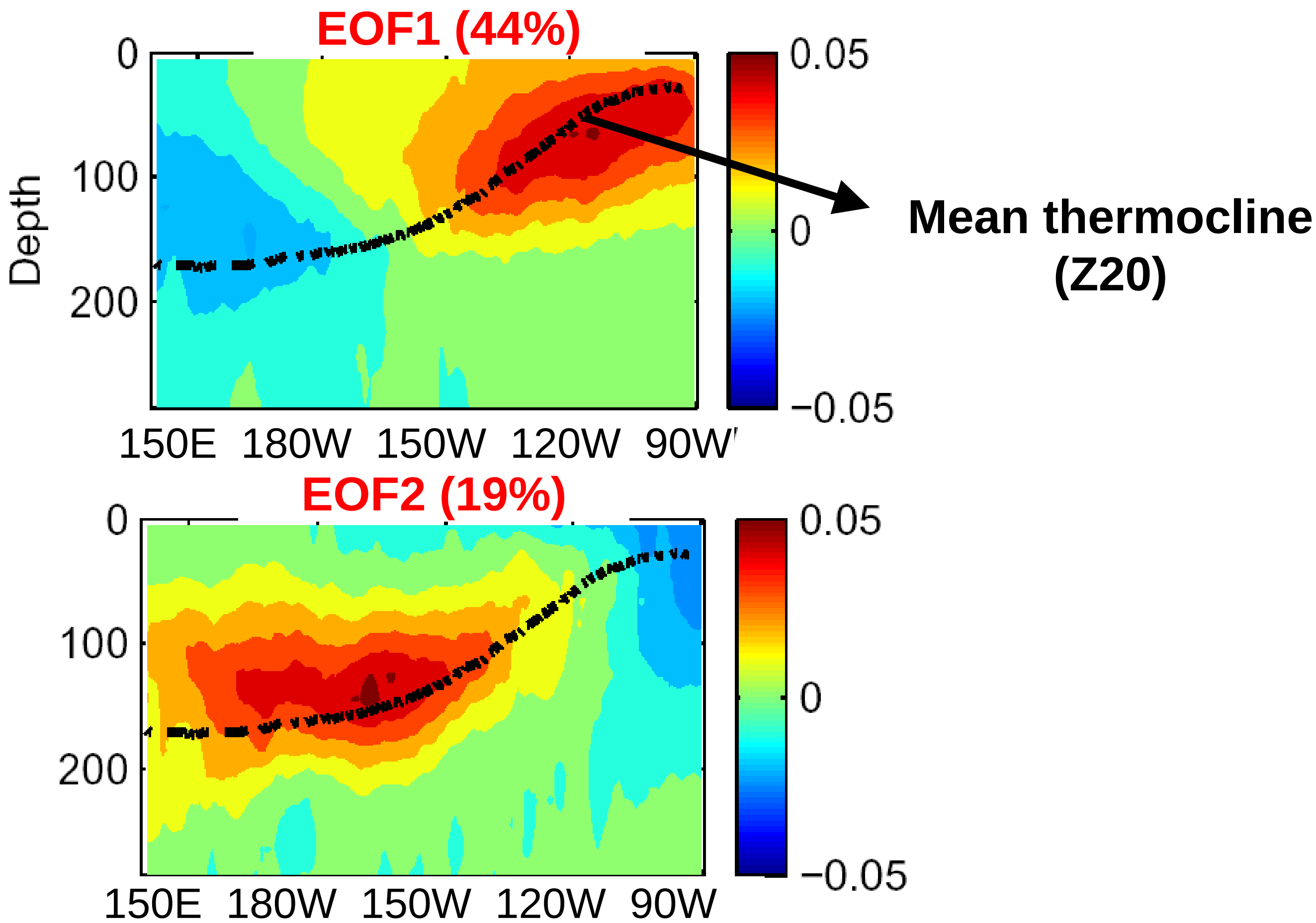
- For large growth rate, the BV has large projection on forecast error (pattern correlation).
- During an ENSO event (large |SSTA|), the growth rate is small.

The equatorial temperature structure: Climate variability vs. Error structure

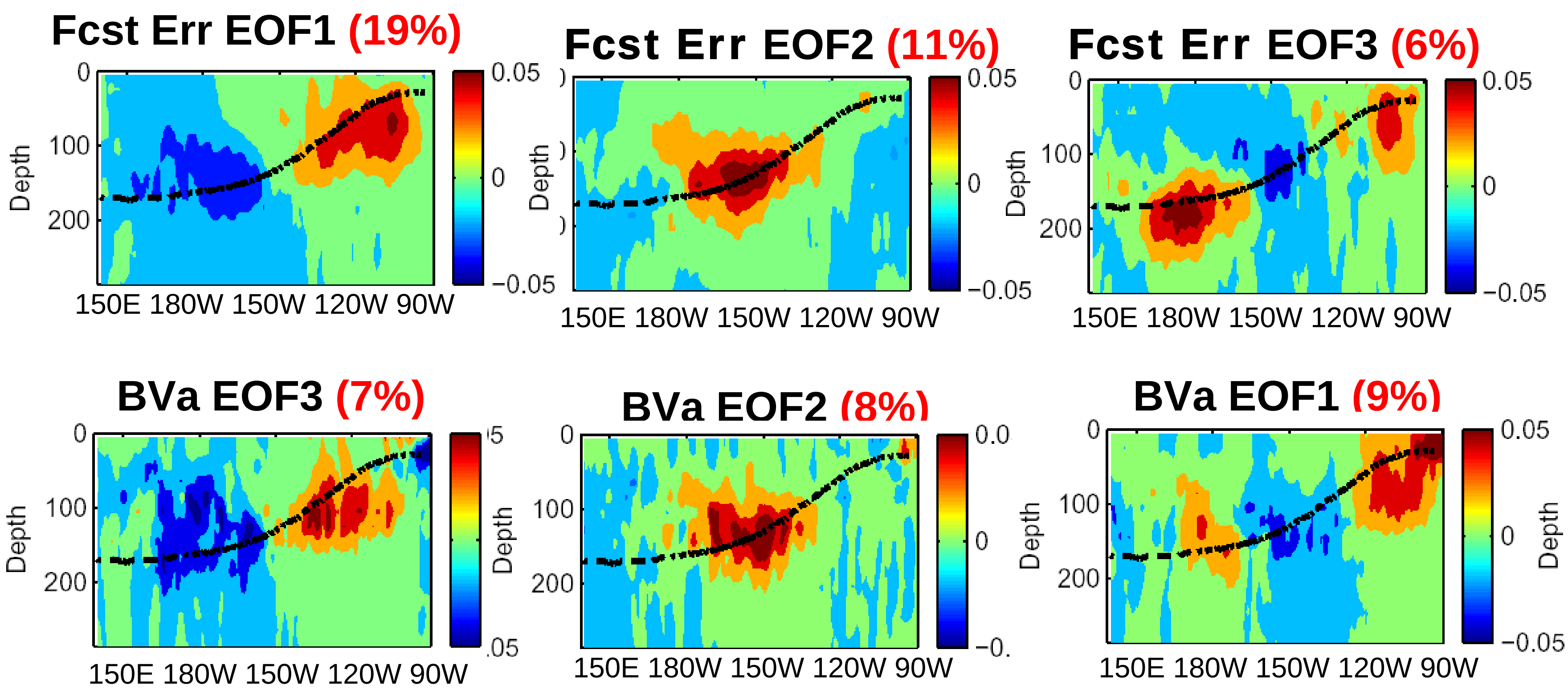
- Climate variability:
  - EOF analysis for temperature anomalies from NSIPP ocean reanalysis
- Dominant error structure in equatorial subsurface
  - EOF analysis for forecast error and bred vector
    - Period (Feb 1993-Nov 1998, 69 months)
    - Time means are removed

Climate variability in subsurface

First two EOF modes relate to ENSO evolution



The equatorial temperature error structure

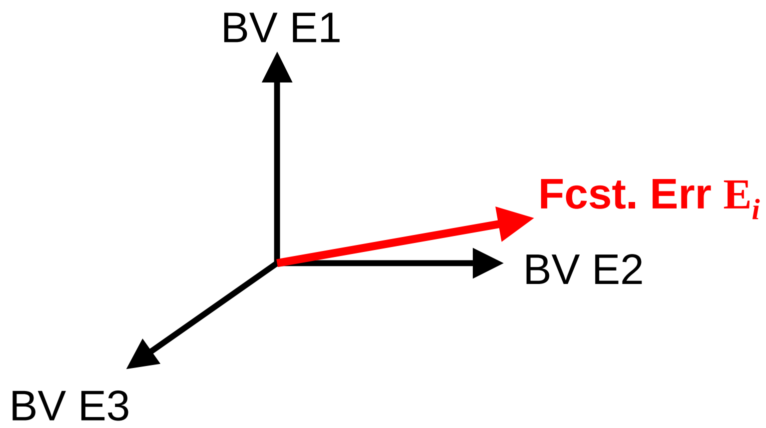


Forecast error and BV have very similar subsurface thermal structure

- In subsurface, large explained variance associated with ENSO constrains the evolution of error structure.

Total correlation between forecast error and bred vectors

Total correlation measures how well the first three BV EOF modes describe the i^{th} Fcst. Err EOF mode.



$$\rho_i = \sqrt{\rho_{i,\mathrm{E1}}^2 + \rho_{i,\mathrm{E2}}^2 + \rho_{i,\mathrm{E3}}^2}$$

	Fcst. Err EOF$_1$	**Fcst. Err EOF$_2$**	**Fcst. Err EOF$_3$**
BV$_a$	0.80	0.84	0.62

Total correlations between forecast error and bred vectors

Total correlation between first three EOF modes

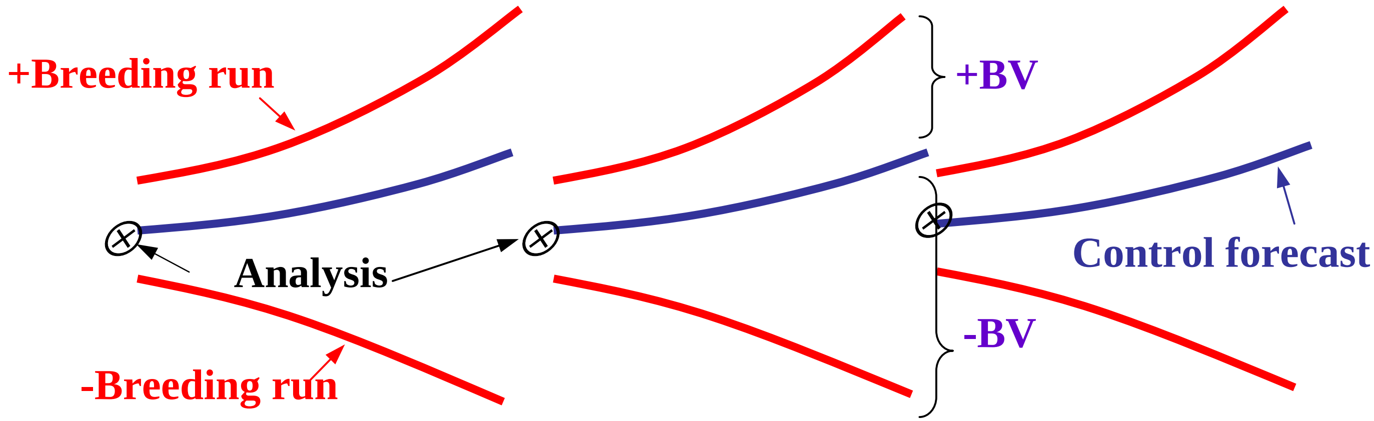
	Fcst. Err EOF_1	Fcst. Err EOF_2	Fcst. Err EOF_3
BV_a	0.80	0.84	0.62
BV_b	0.84	0.75	0.49
BV_c	0.80	0.64	0.50

- The first three EOF modes of forecast error 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.

Ensemble forecasting experiments

- **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**
- **Operational perturbations:**
  - Operational ensemble forecasts (**one control** and **5 perturbed runs**)
  - Ocean has analysis initial conditions but atmosphere starts from AMIP runs

Two-sided breeding cycle

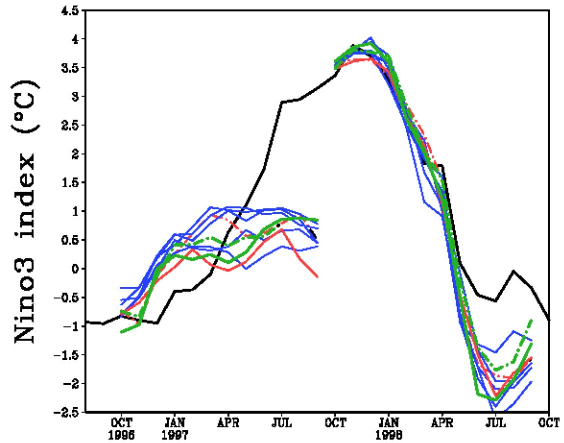


- One pair of BV is adding/subtracting from the initial condition
- Self-generated the bred perturbations

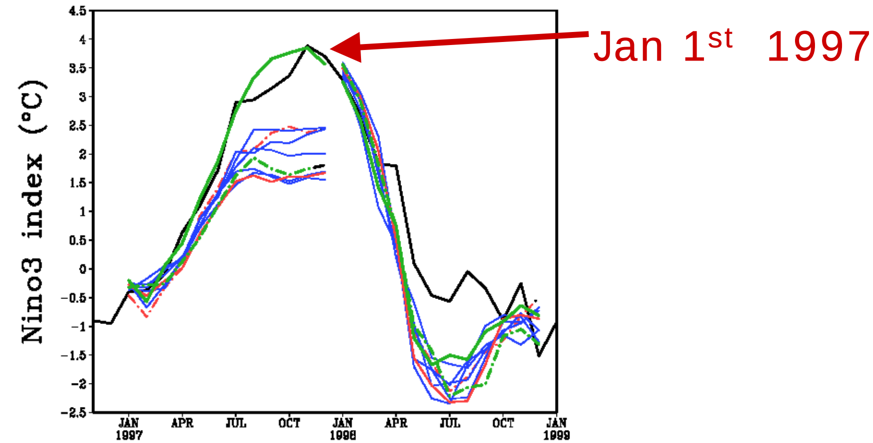
Nino3 index (SST clim. drift removed from forecasts)

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

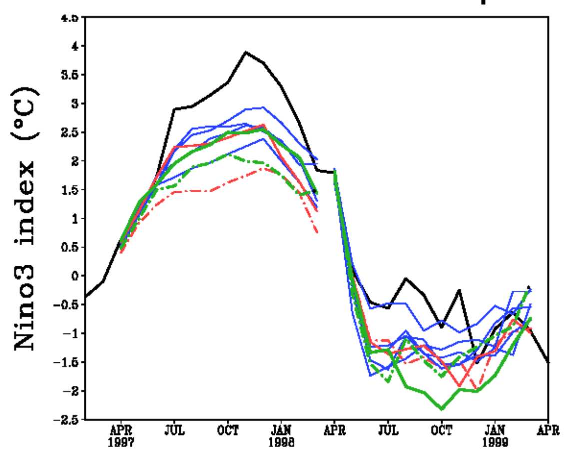
Forecast starts from Oct 1st



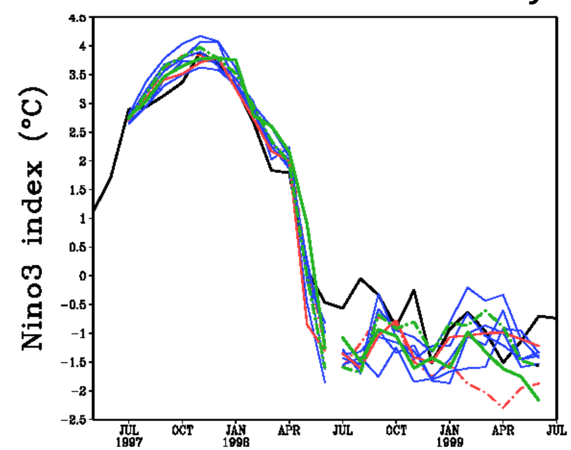
Forecast starts from Jan 1st



Forecast starts from Apr 1st

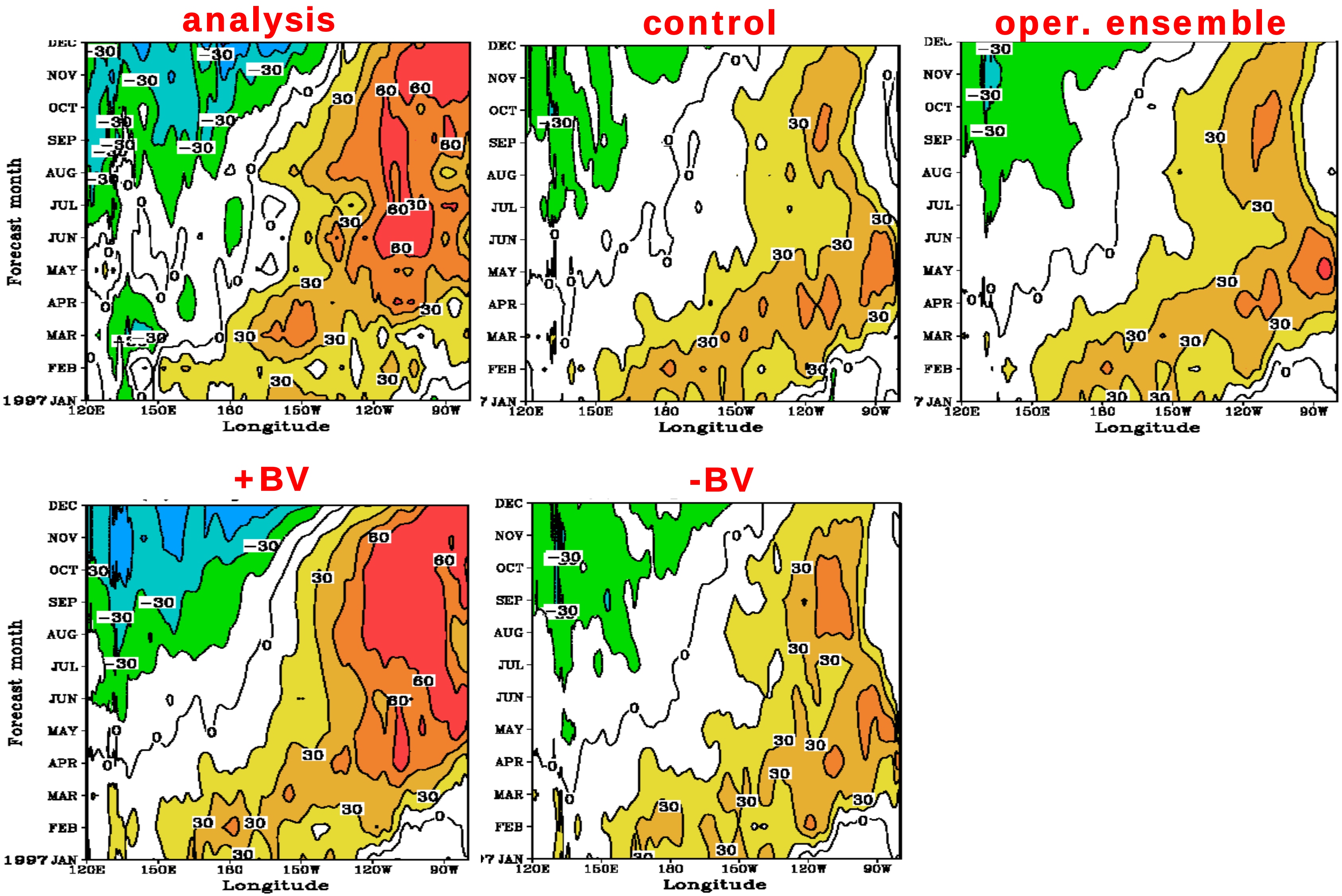


Forecast starts from July 1st



*The amplitudes of BV and operational perturbations in Niño3 region are different.

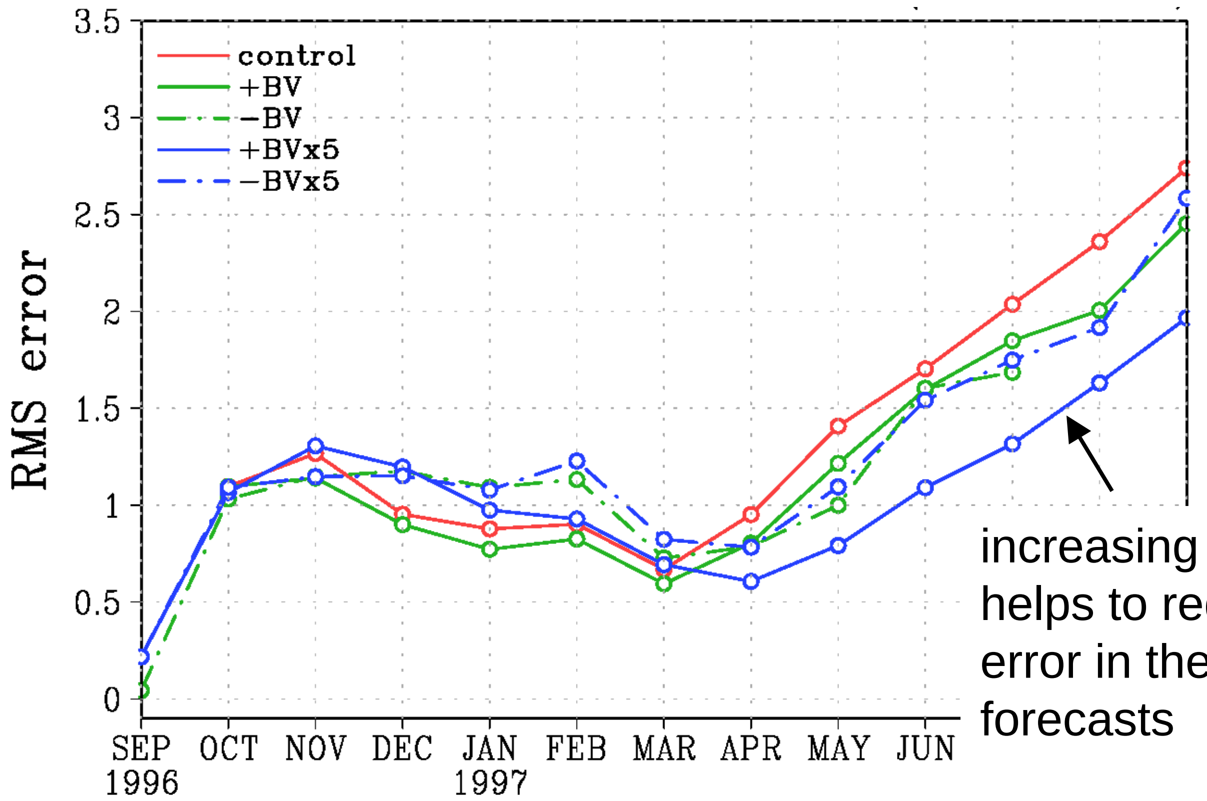
Hovmöller diagram of forecasted thermocline



(Starting from Jan01 1997)

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

Summary on NSIPP operational system

- The one-month forecast errors and the BV growth rate are both sensitive to ENSO, and they are large before and after the event.
- The forecast error in NSIPP CGCM is dominated by dynamical errors whose shape can be captured by bred vectors.
  - BV captures the eastward movement of the forecast error along the equatorial Pacific during El Niño evolution
  - BV is clearly related to forecast errors for both SST and subsurface temperature, particularly when the BV growth rate is large
  - Both the forecast error and the BVs in the subsurface are dominated by large-scale structures related to seasonal-to-interannual variability.

Summary (Cont.)

- Preliminary results using BV for ensemble forecasting are encouraging
  - Our results suggest BV ensemble has larger improvement before the onset of the ’97 El Nino event, providing a stronger vertical displacement of thermocline.
  - BV ensemble has a comparable prediction skill with the operational ensemble when initialing at the mature phase of the event.
  - We suggest that the BV ensemble system needs tuning of the amplitude (proportional to the BV growth rate).

Applications to operational ENSO prediction

- For ensemble forecasting (provide the ENSO coupled perturbations)

  Bred vectors will be tested as initial coupled perturbations for ensemble ENSO forecasting in the NASA NSIPP operational system.

- For ocean data assimilation (better use of the oceanic observations)
  - In univariate OI, background error covariance is time-independent with a Gaussian shape.
  - The ability of bred vectors to detect the month to month forecast error variability should allow to improve oceanic data assimilation by augmenting the background error covariance with features associated with seasonal-to-interannual variability in the subsurface. This can be done at low computational cost.