# Coupled ocean-atmosphere ENSO bred vector

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# Outline

- Background
- Breeding in operational coupled GCM
  - Relationship between BV and 1-month forecast error
  - BVs with different rescaling norms
- Application on ensemble forecasting with 3 pairs of ±BVs
  - 12-month forecasts starting from coupled BV ensemble
- Summary

# Background

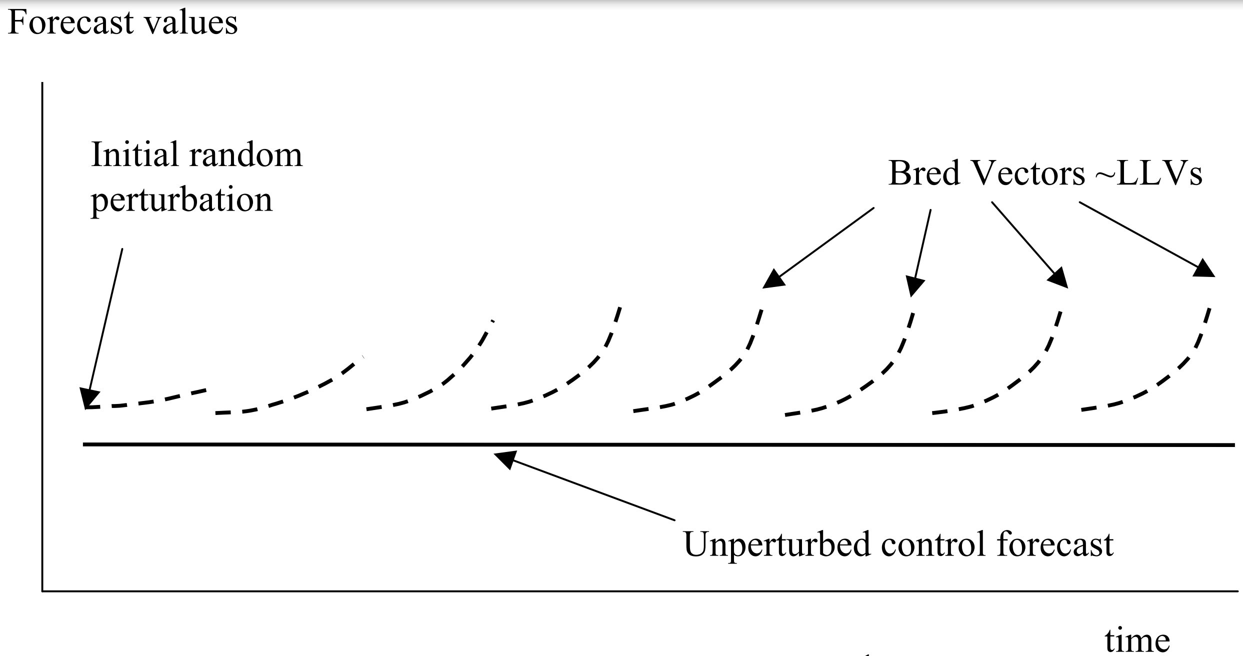
- **A good ensemble should *contain relevant unstable perturbations:***
  - **an ensemble for seasonal-to-interannual prediction should have initial perturbations with coupled instabilities**
- For ENSO prediction, ensemble perturbations need to be generated in a way that carries slow-varying, coupled instabilities.
- A complex coupled model like the coupled GCM, includes instabilities characterized by different time scales (convective, baroclinic,…., and ENSO instabilities)

How to create coupled slow perturbations for ENSO forecasting?

# Methods to generate the initial perturbations

- **Linear approach** (Singular vectors)
  - Need to exclude the fastest (weather) instability explicitly
  - Difficult in a complex dynamical model as CGCM
- **Non-linear integrations** (Bred vectors)
  - Allow fast instabilities to saturate at early time and leave the slow, varying coupled instability
  - Easy to use the full coupled model (full physics)
  - Low computational cost

# Breeding in a coupled system



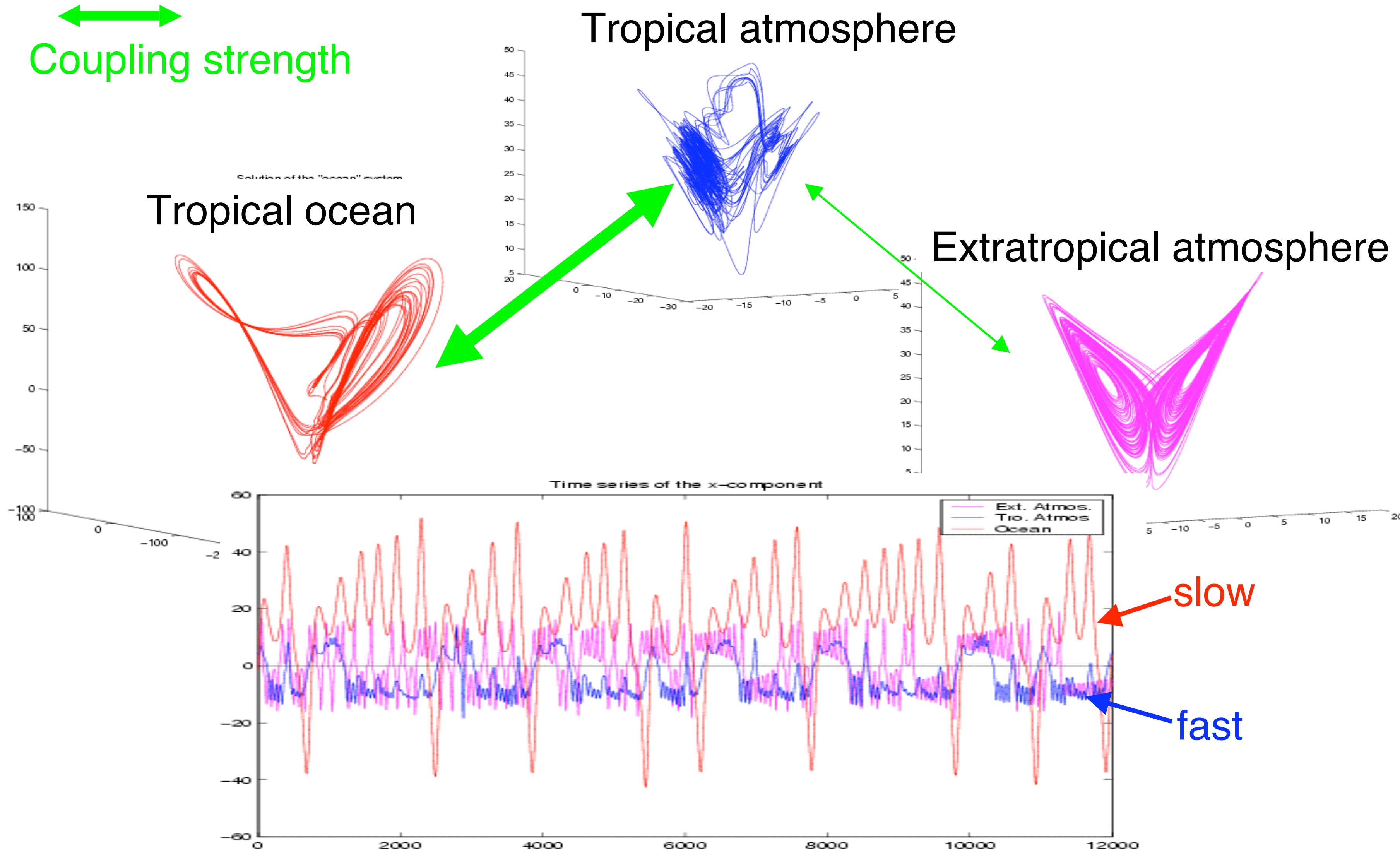

Local breeding growth rate: $g(t) = \frac{1}{n\Delta t} \ln\left( |\delta \mathbf{x}| / |\delta \mathbf{x}_0| \right)$

- Running the coupled model with the perturbed oceanic and atmospheric initial condition
- Fact: instability is characterized with different amplitude and time scale. Only two tuning parameters (rescaling amplitude and time interval)
- Bred perturbations are **naturally coupled**!!

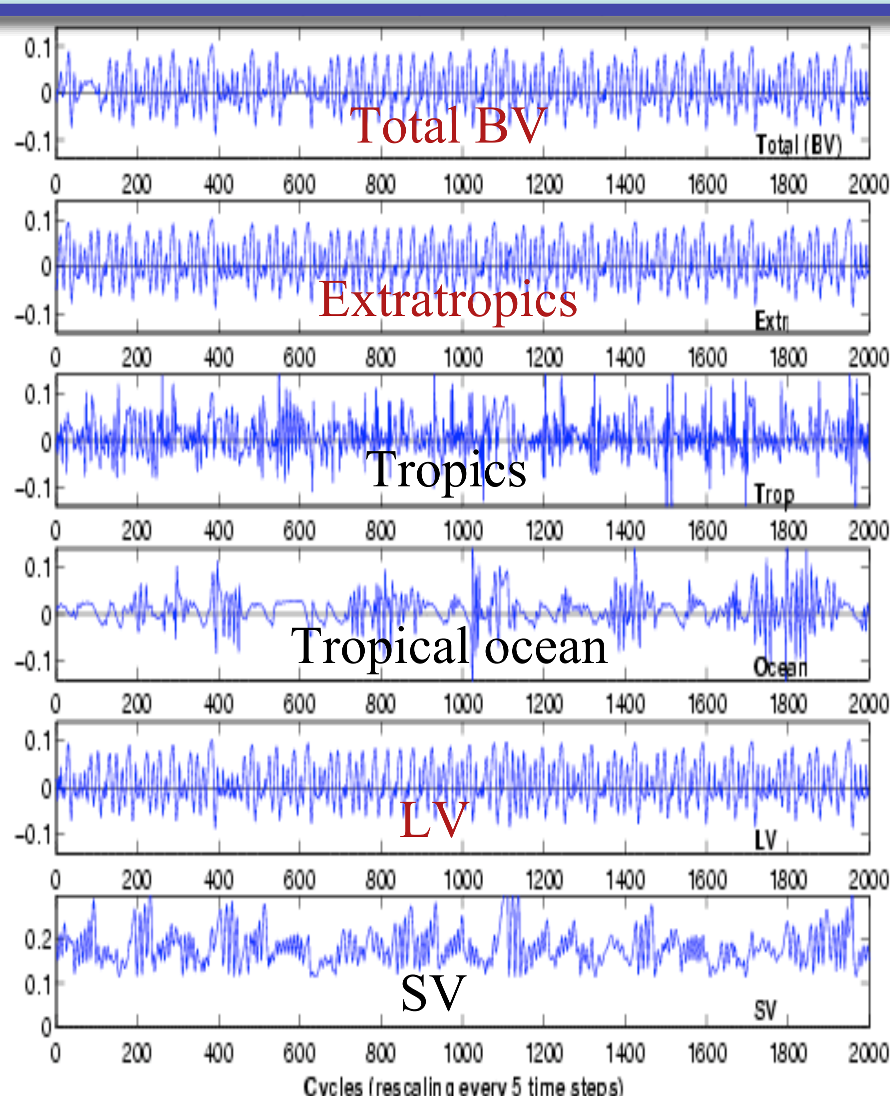
# Isolate slow modes in a fast-slow coupled system

- **Peña and Kalnay (2004):** Coupled Lorenz model experiments show that for slow modes the rescaling in breeding has to be done **using slow variables and long rescaling intervals**
- **Cai et al. (2002): BV growth** in Cane-Zebiak model **depends on season and ENSO phase**, and that they can be used for data assimilation and ensemble forecasting
- **Yang et al. (2006):** Similar dominant coupled ocean/atmosphere bred vector **are found** in NASA NSIPP-1 coupled GCM/NCEP coupled GCM (GFS)
- **Vikhliaev et .al (2006):** Decadal mode in COLA anomaly coupled GCM
- For slow modes, we have to choose a slow variable and a long interval for the rescaling

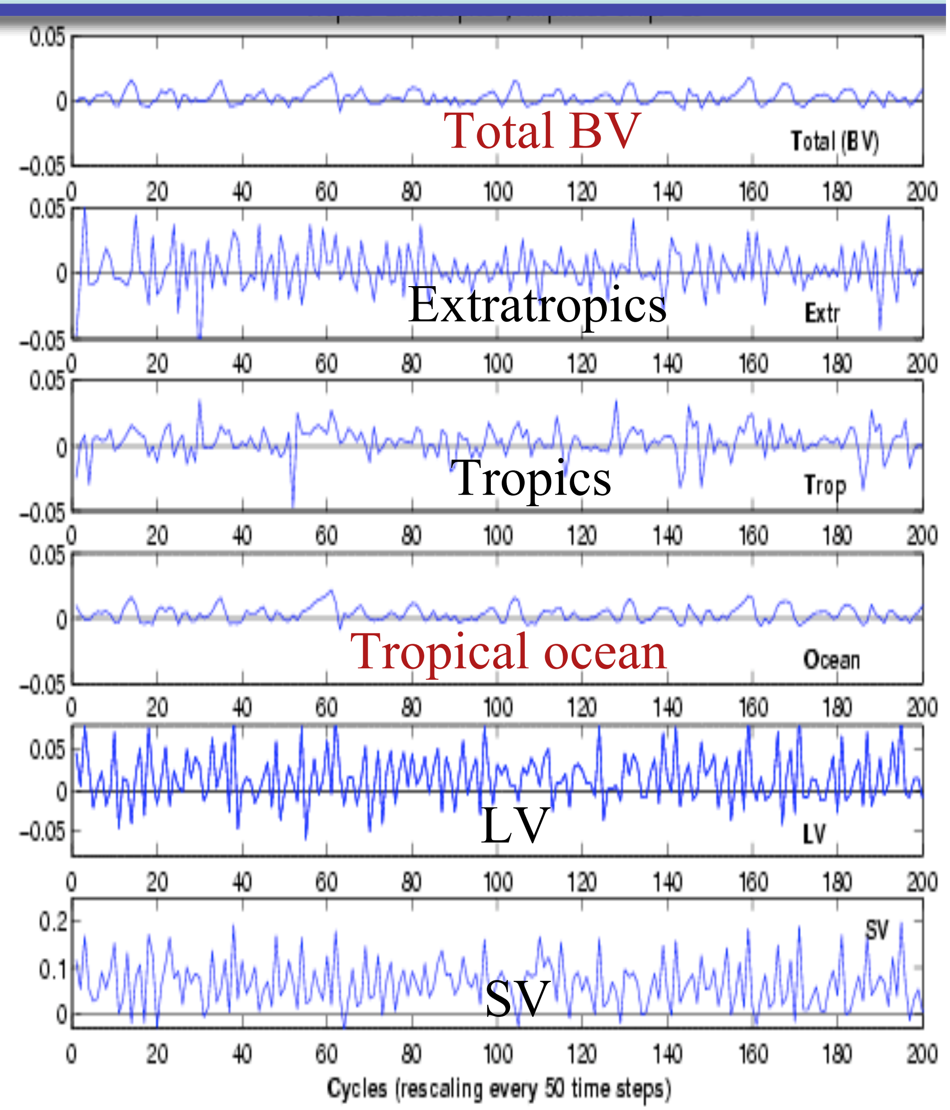
# Coupled fast and slow Lorenz 3-variable models (Peña and Kalnay, 2004)



# WEATHER - ENSO : breeding with different rescaling amplitude ($\delta$) and time interval ($\Delta$)




$$\delta = 0.05, \Delta = 5 \text{ steps}$$




$$\delta = 20, \Delta = 50 \text{ steps}$$

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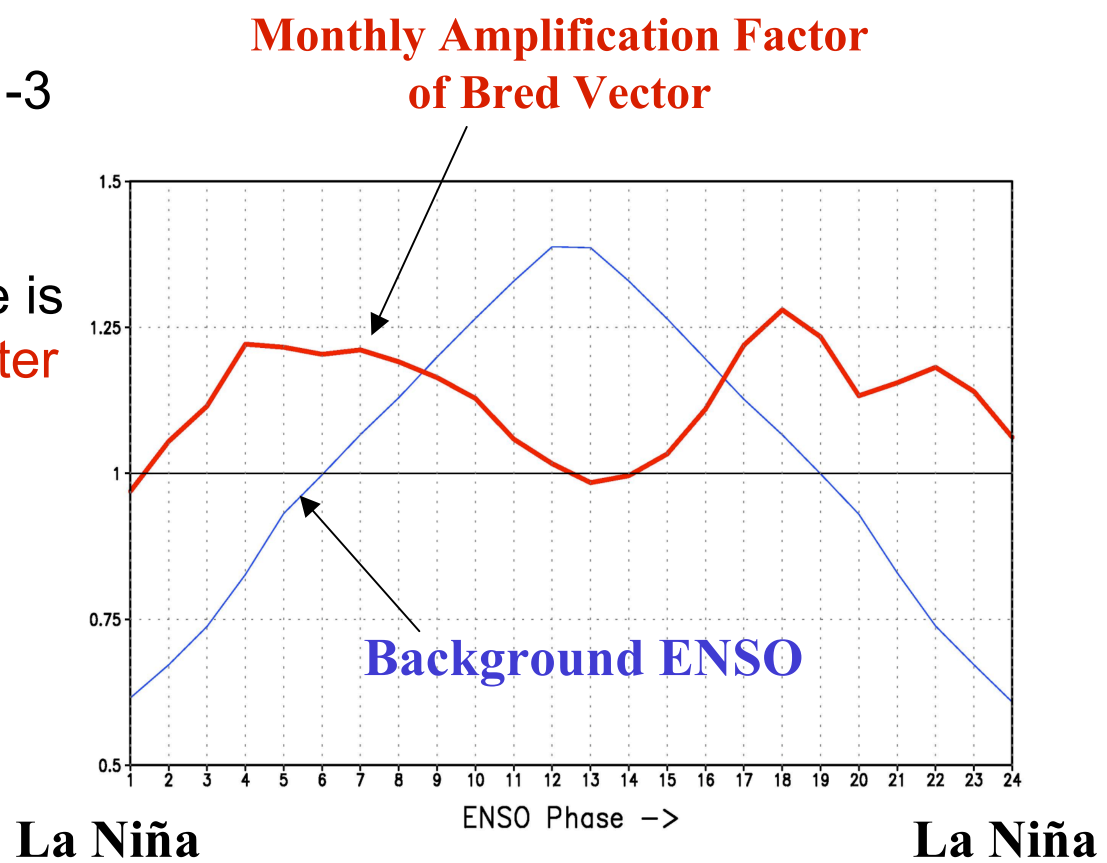
# Cai et al. (2002) results with Zebiak and Cane model:

- Rescaling done every 1-3 months (insensitive to interval and to norm)
- Bred Vector growth rate is strongest before and after ENSO events.



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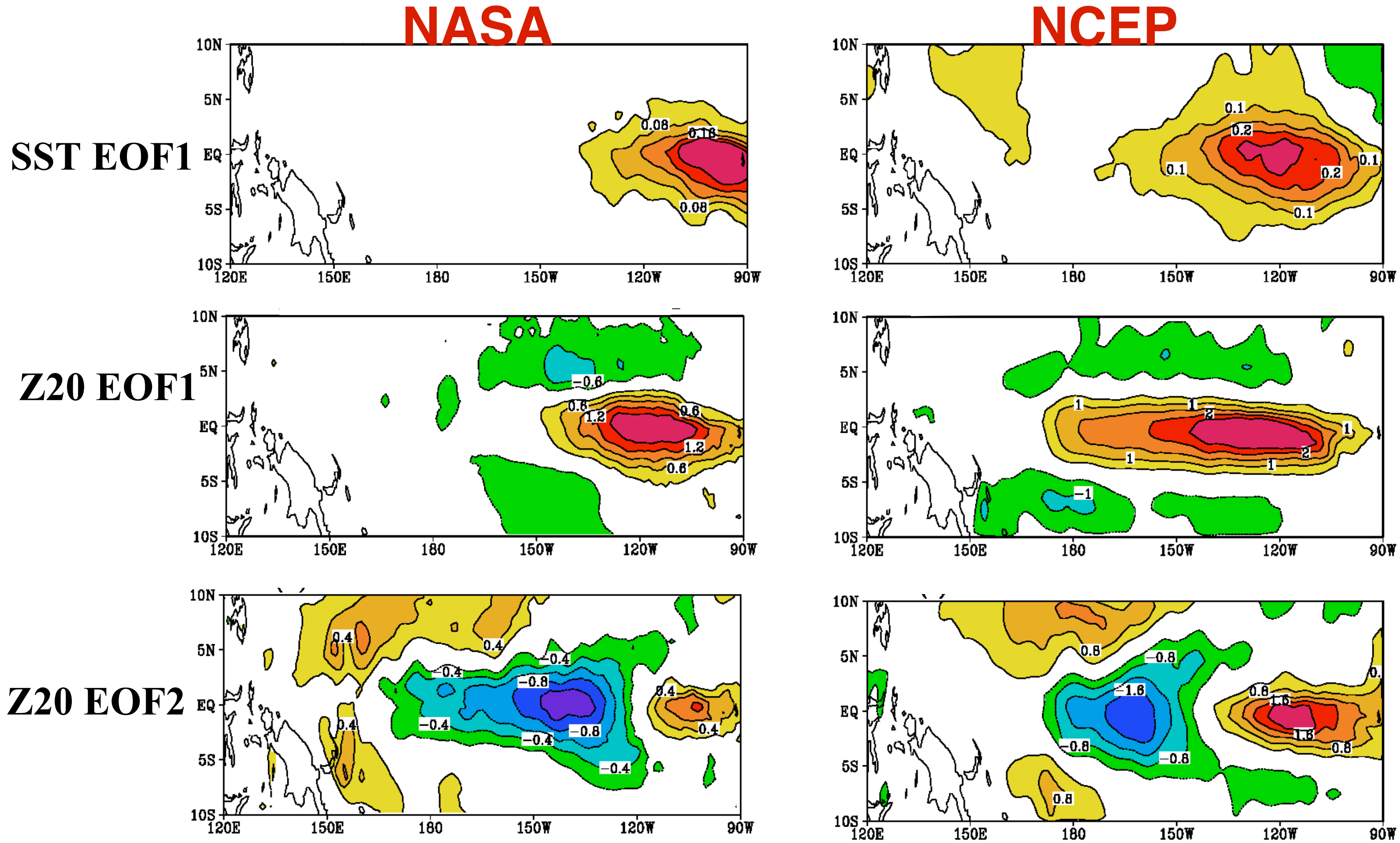
# Bred Vector in NASA and NCEP coupled GCMs: oceanic component (Yang et al., 2006)




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

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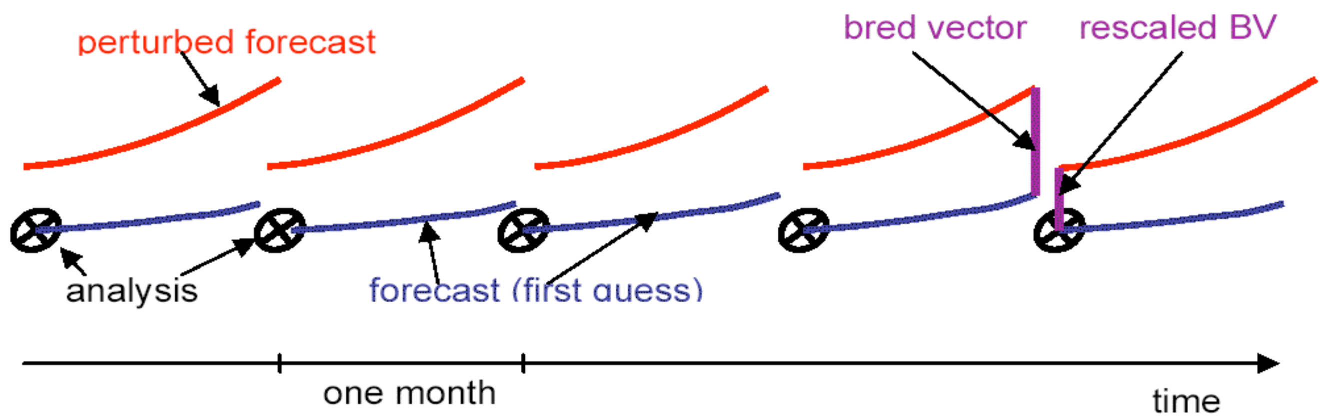
# Challenge

- The complexity of the coupled system is less realistic in perfect model experiments:
  - ZC model has only one type of variability (i.e. ENSO ). The atmospheric component is simply the response to the SST
  - More uncertainties are concerns in imperfect coupled GCM, ex: climate drift, model errors, imperfect initial states…..
- With noisy initial states and imperfect model, can BVs capture the coupled growing errors for the purpose of improving ENSO prediction?
  - If BVs are similar to forecast errors then they have potential for use in ensemble forecasting and data assimilation
  - BVs provide information related to “errors of the month”

## Breeding in the operational NASA coupled system with data assimilation and forecasts

- NASA coupled GCM (Poseidon OCGM+ NSIPP-1 AGCM)
    - The operational system assimilates ocean observations (analysis)
    - Atmospheric initial condition from AMIP
- Bred vector: estimate the growing forecast errors (without knowing about the new observations).
- Ocean component of the coupled growing error: measured by the difference between analysis and $1^{st}$-month forecast

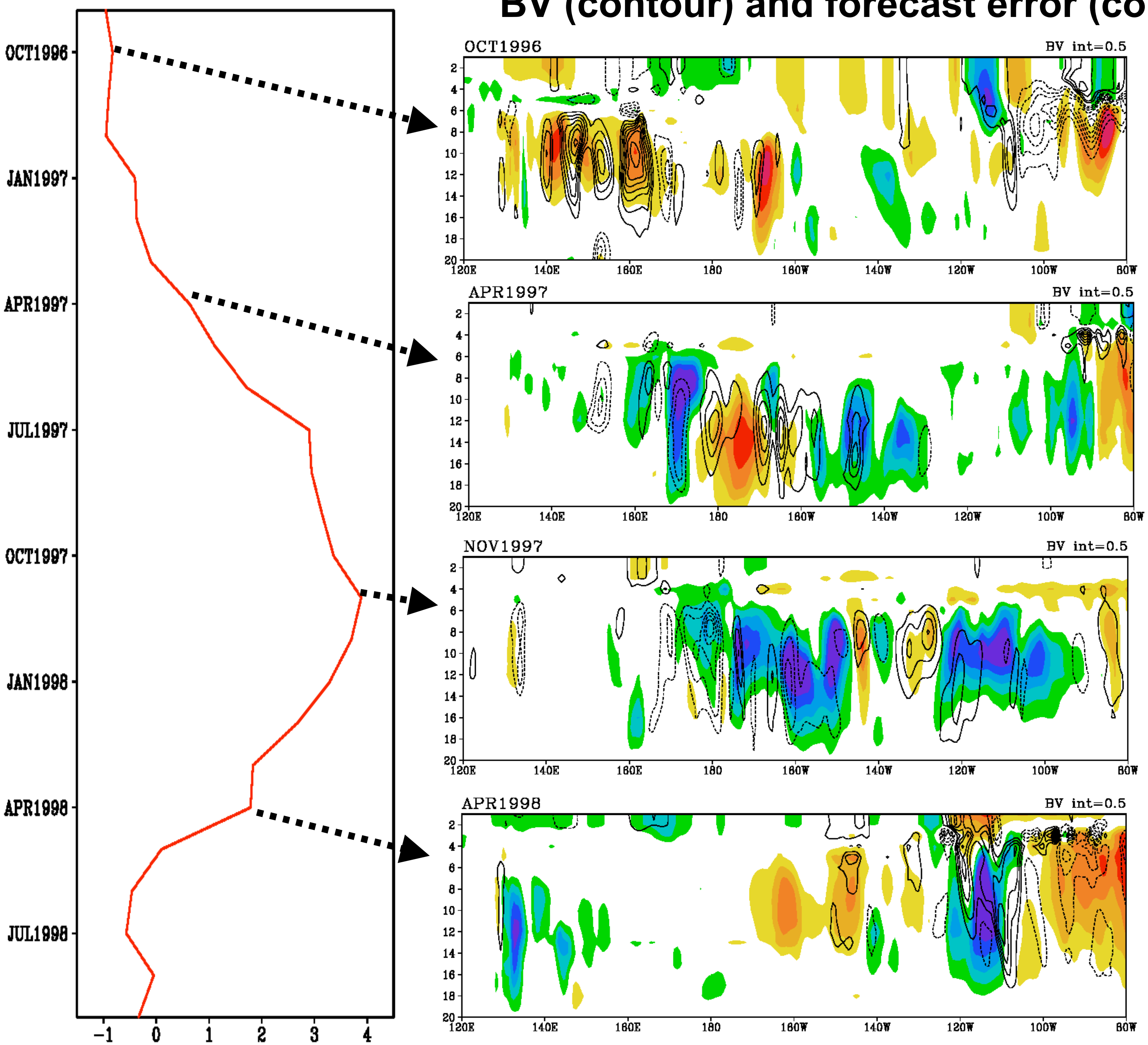
# Breeding in the NASA coupled GCM




- **Bred vectors** : Differences between the control forecast and perturbed run
- Coupled breeding cycle needs to choose physically meaningful breeding parameters in order to choose the type of instability
    - ♦ BV_SST=0.1°C in Nino3 region
    - ♦ Oceanic/atmospheric perturbations are rescaled every month

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

## Niño3 index



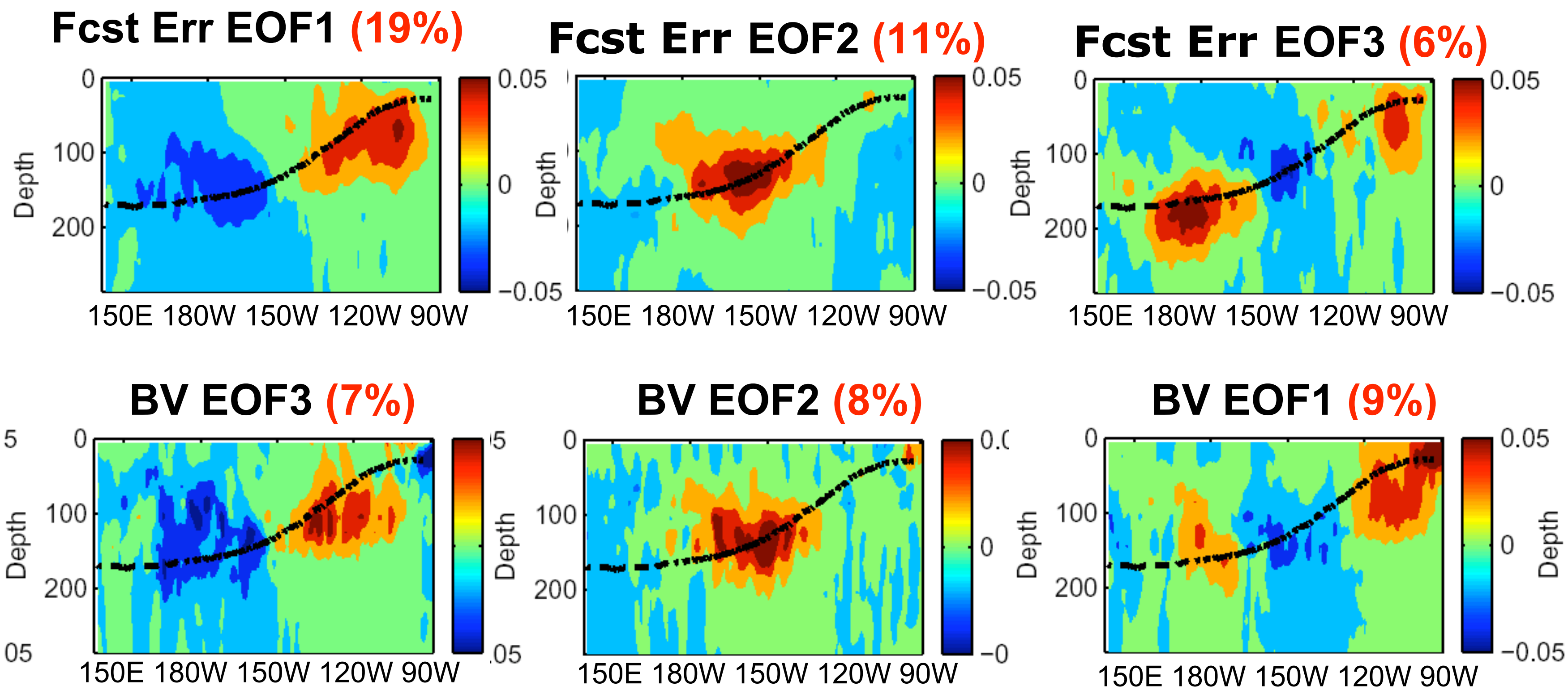

Before 97' El Niño, Fcst. error is located in W. Pacific and near coast region

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.

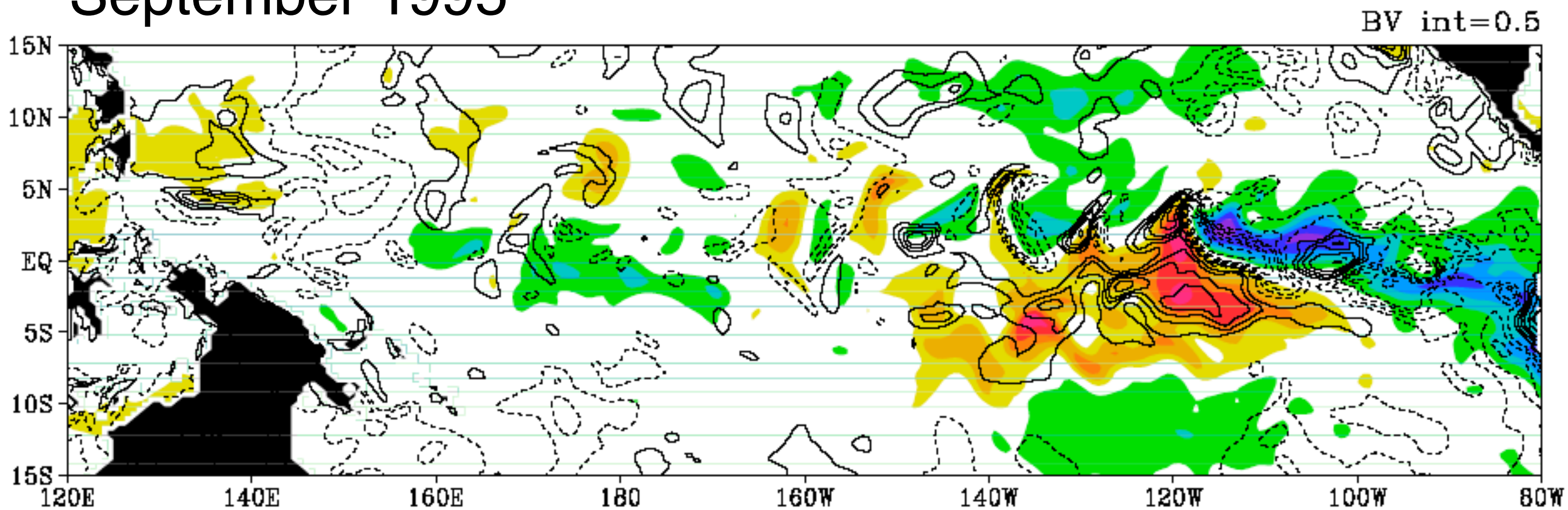
# The equatorial temperature error structure




**Forecast error and BV have very similar subsurface thermal structure**

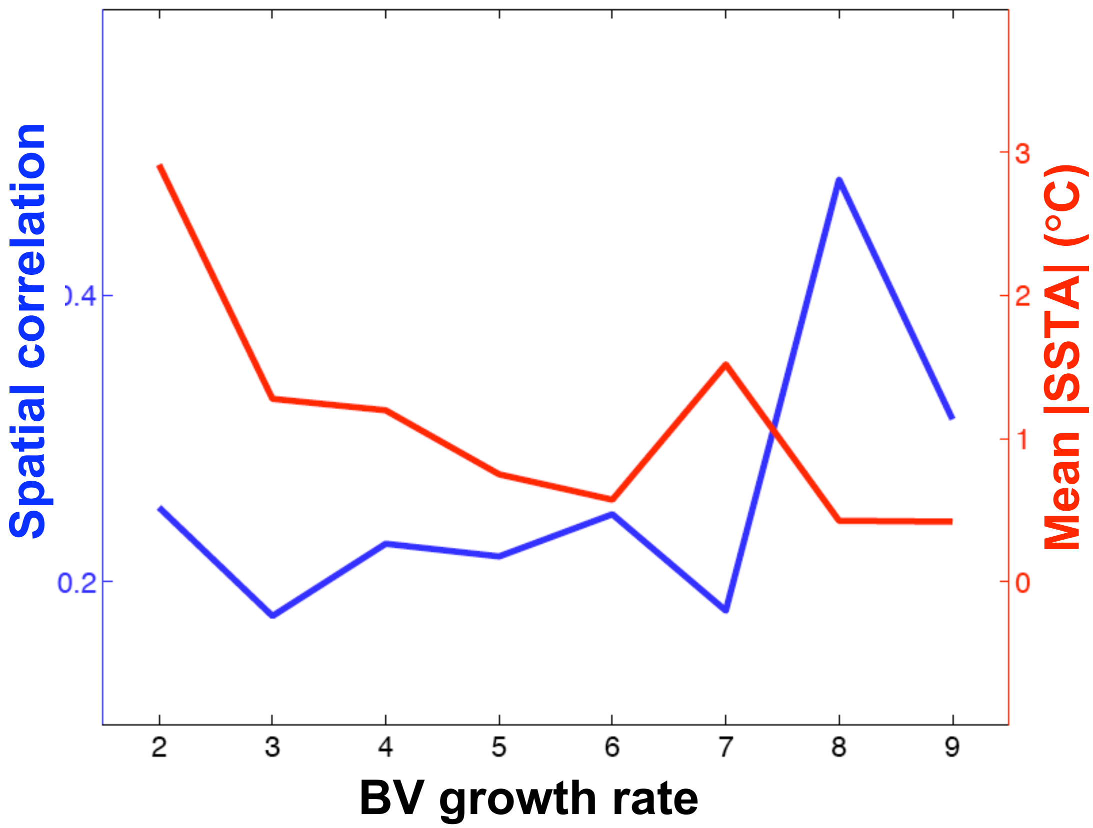
# Forecast error (color) vs. bred vector (contour)

September 1995




•For large BV growth, agreement of BV with forecast error is very good.

# The growing error and background SSTA in the Niño3 region




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

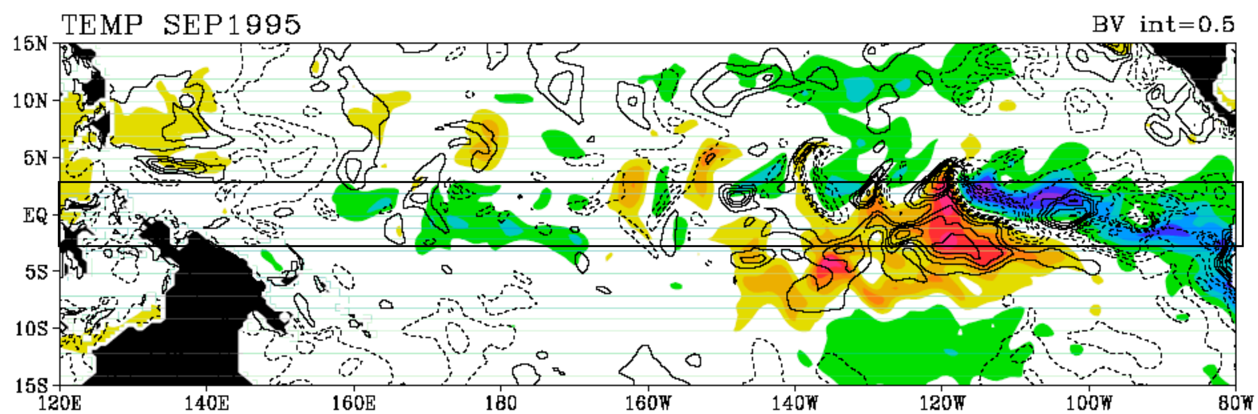
# BV can provide the information related to "error of the month"

- Background error covariance in OI scheme
  - Statistical average error structure: **Flow-independent**
- Bred vector can provide the **flow-dependent information** (errors of the month) at a low cost
- We quantify the agreement between bred vector and forecast error
  - Fit the error structure with an Gaussian function

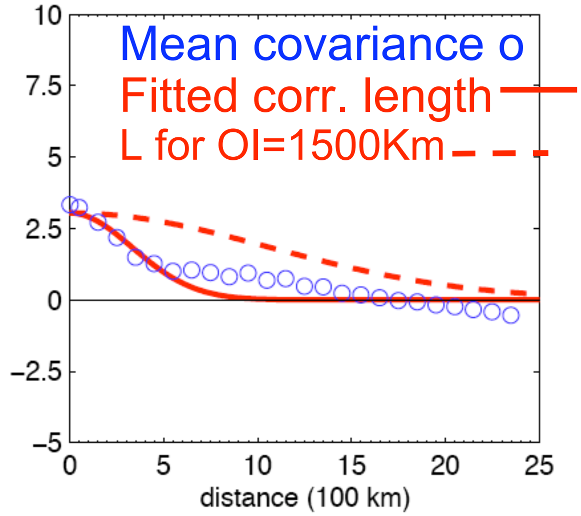
$$f(r) = C_0 \exp[-(r/L)^2] ,$$

$C_0$ fitted variance, $L$: correlation length

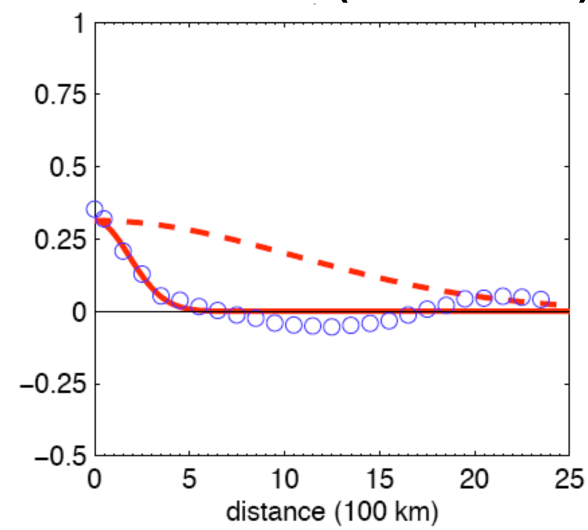
# Structure in forecast error and bred vector: zonal correlation length



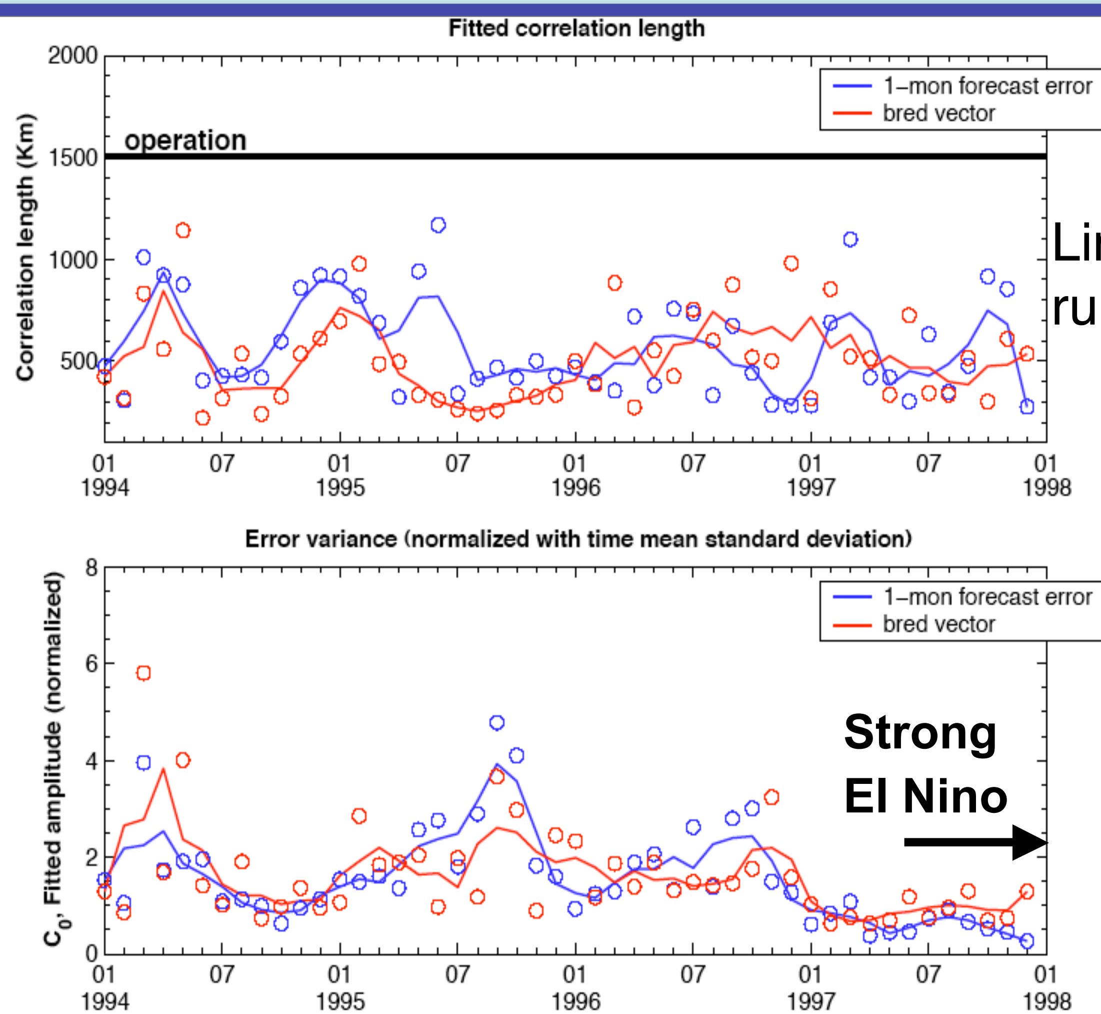

**Forecast error (2.5S~2.5N)**




**Bred vector (2.5S~2.5N)**



# Fitted correlation lengths and variances at equator




Lines are 3 months running mean

- **The fitted corr. lengths of BV show similar ranges as the the month-to-month changing forecast error**
- **The fitted variances from both are consistent**

# Zonal correlation length ($L$) and fitted variance ($C_0$) in tropical Pacific

| | $L$ (Km ) | | STD of $L$ (Km) | | $C_0$ | |
|---|---|---|---|---|---|---|
| | Forecast error | Bred vector | Forecast error | Bred vector | Forecast error | Bred vector |
| 2.5°N~7.5°N | 514 | 540 | 272 | 269 | 0.63 | 0.05 |
| -2.5°~2.5° | 575 | 505 | 251 | 226 | 0.99 | 0.14 |
| 7.5°S~2.5°S | 445 | 416 | 217 | 199 | 0.83 | 0.07 |

- Similar correlation ranges (shorter than $L_{OI}$=1500 Km)
- North show large variances near equator

# BVs with different rescaling norms

- 4 different rescaling norms are chosen to measure the coupled atmosphere-ocean instability (10% of Climate variability, rescale every month)

1. **$|SST_{BV}|=0.1°C$** (in 150°W~90°W, 5°S~5°N)
2. **$|D20_{BV}|=1.5$ m** (in 160°E~140°W, 2.5°S~2.5°N)
3. **$|[u'_{BV},h'_{BV}]|=6.5\times10^{-3}$** (in 130°E-80°W, 5°S~5°N)

   >> the first 4 long wave modes

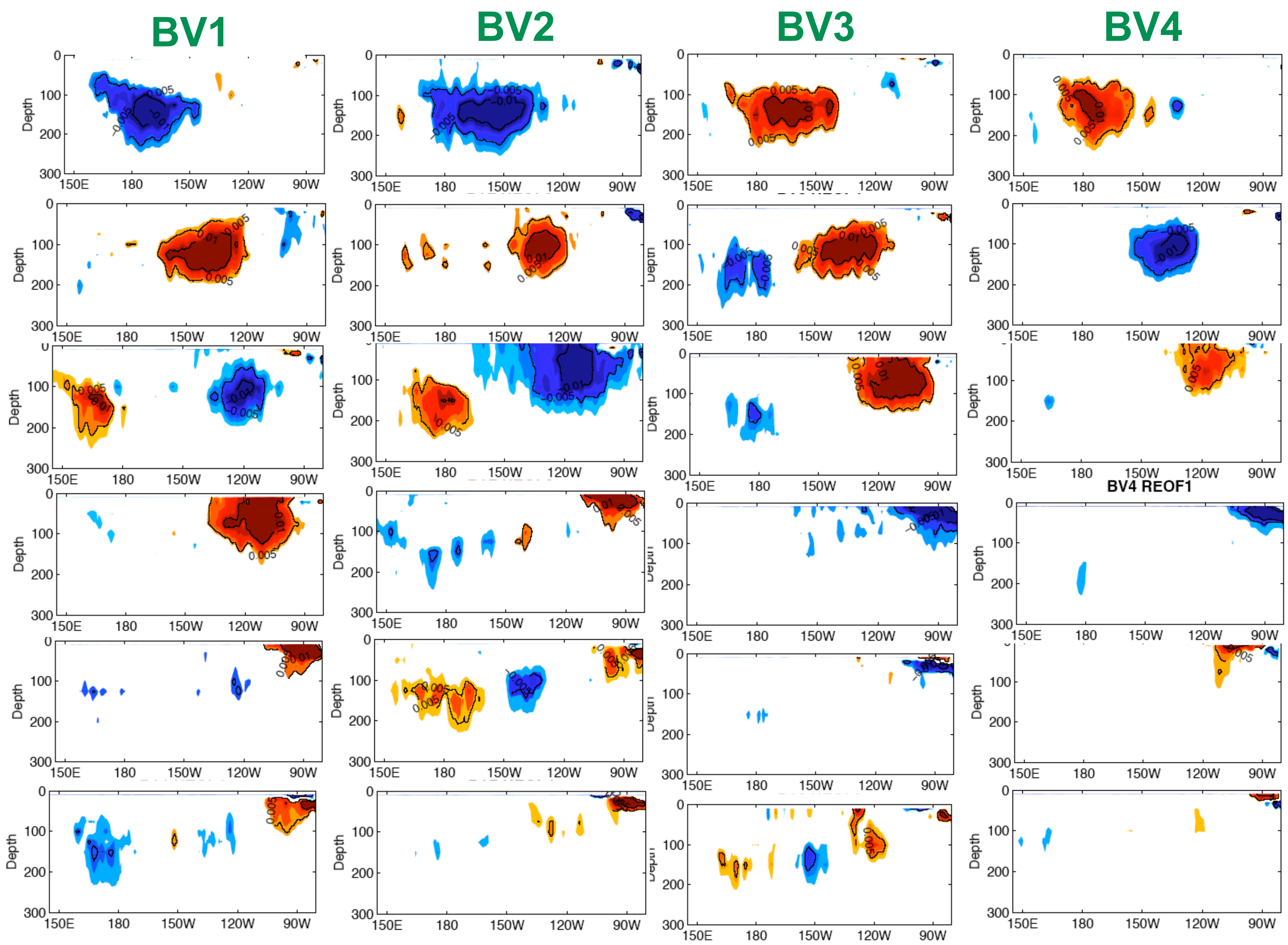
   (Kelvin+3 Rossby waves)

4. **$|[u_{BV}\tau_{xc}+u_c\tau_{xBV}]|=0.1$** (in 130°E-80°W, 5°S~5°N)

   >> work done on the ocean by the atmosphere (Goddard and Philander, 1999)

- Initial condition: Ocean analysis (T, S assimilated) + AMIP start

# BV Rotated EOFs of equatorial subsurface temp.



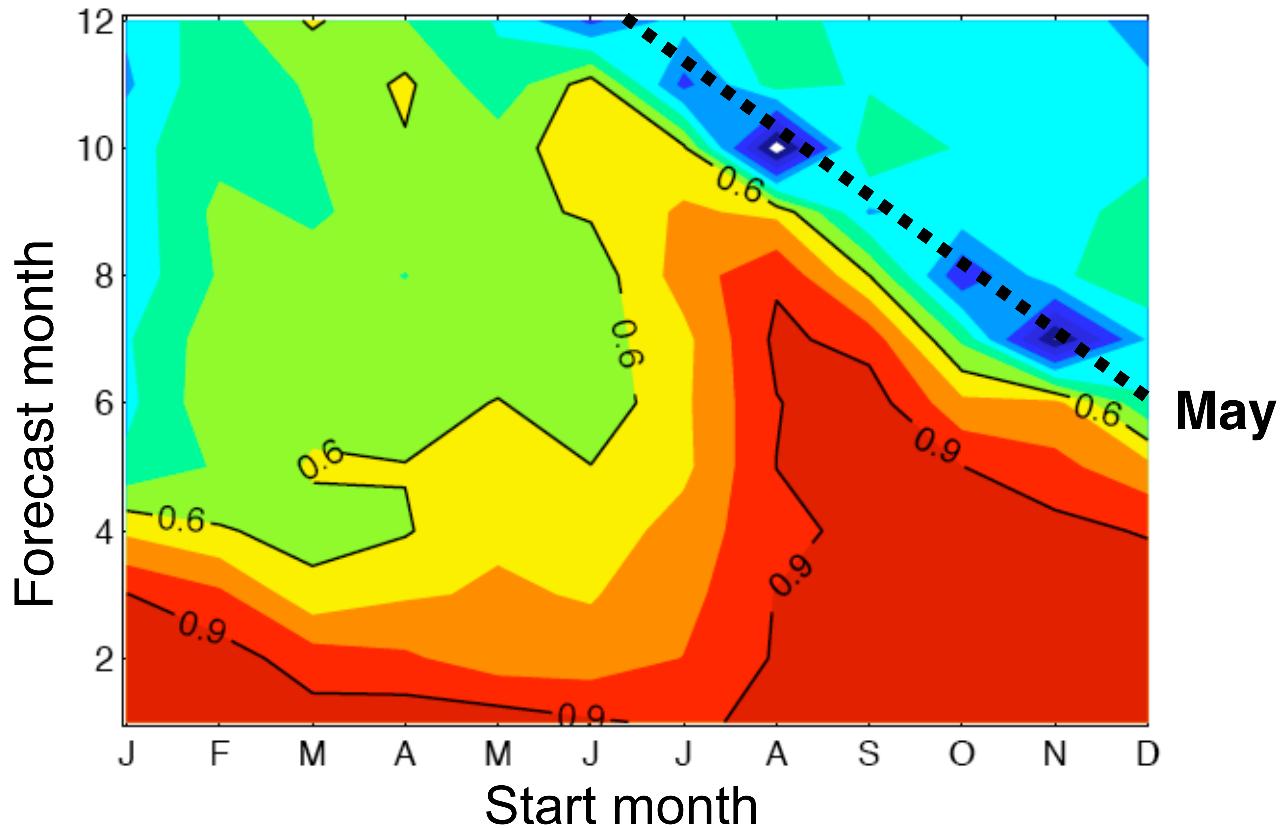
# BV structures

- Equatorial subsurface temperatures of 4 pairs of BVs have similar dominant structures
- Differences can be found with wind-related norm: the dominant zonal-scale structure is shorter

# Applications on ensemble forecasting:

- Control (unperturbed) hindcast
  - **Ocean:** analysis (T and S assimilated with OI scheme)
  - **Atmosphere:** AMIP
- Ensemble hindcasts
  - Initialized with 3 pairs of coupled ±BV
- 12-month hindcast experiments from 1993-2002 for *February, May, August and November start*
  - Compared ensemble with control forecast and observations (Reynolds SST)
  - Impact on equatorial subsurface temperature
  - Results shows large impact when starting from the cold season of the eastern Pacific (**November**)

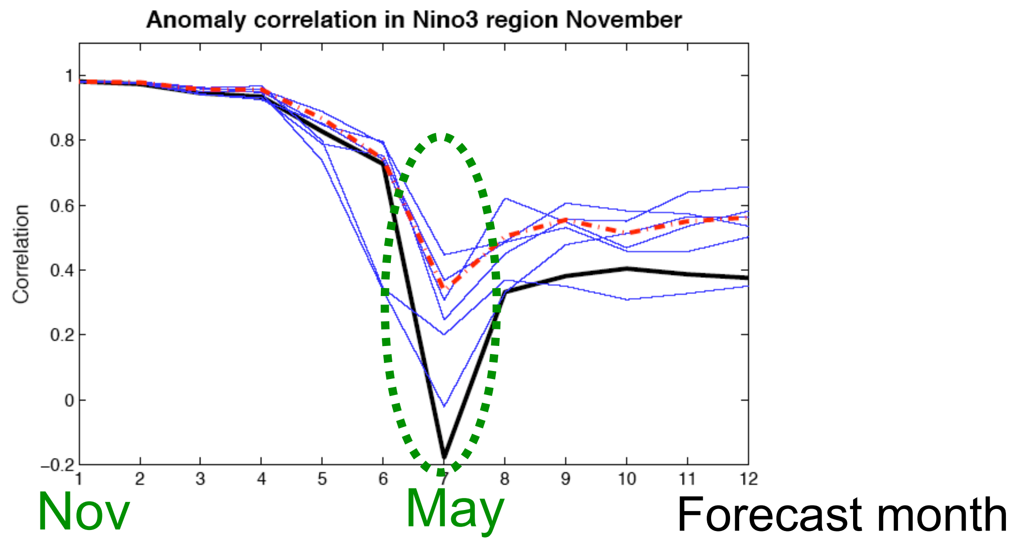
# Anomaly correlation between control hindcast and Reynolds SST in Niño3 region



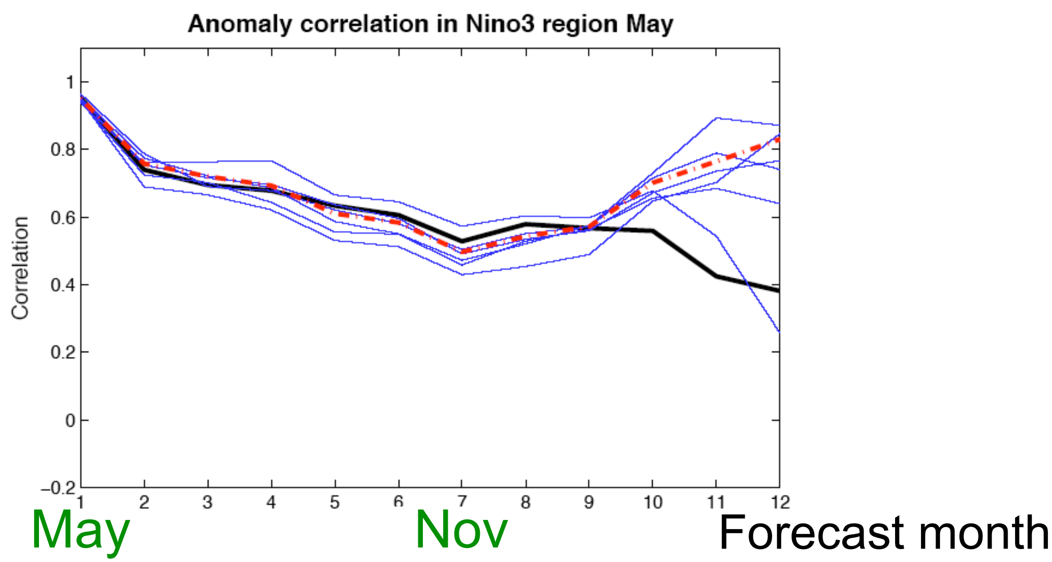

- Starting from the cold season, forecast skill is high for the first 6 months, but they have difficulties to overcome the “spring barrier”.
- When starting from the warm season, forecast skill quickly drops.

# Anomaly correlation with 3 pairs of BVs November and May restarts (1993-2002)

Start from
cold season

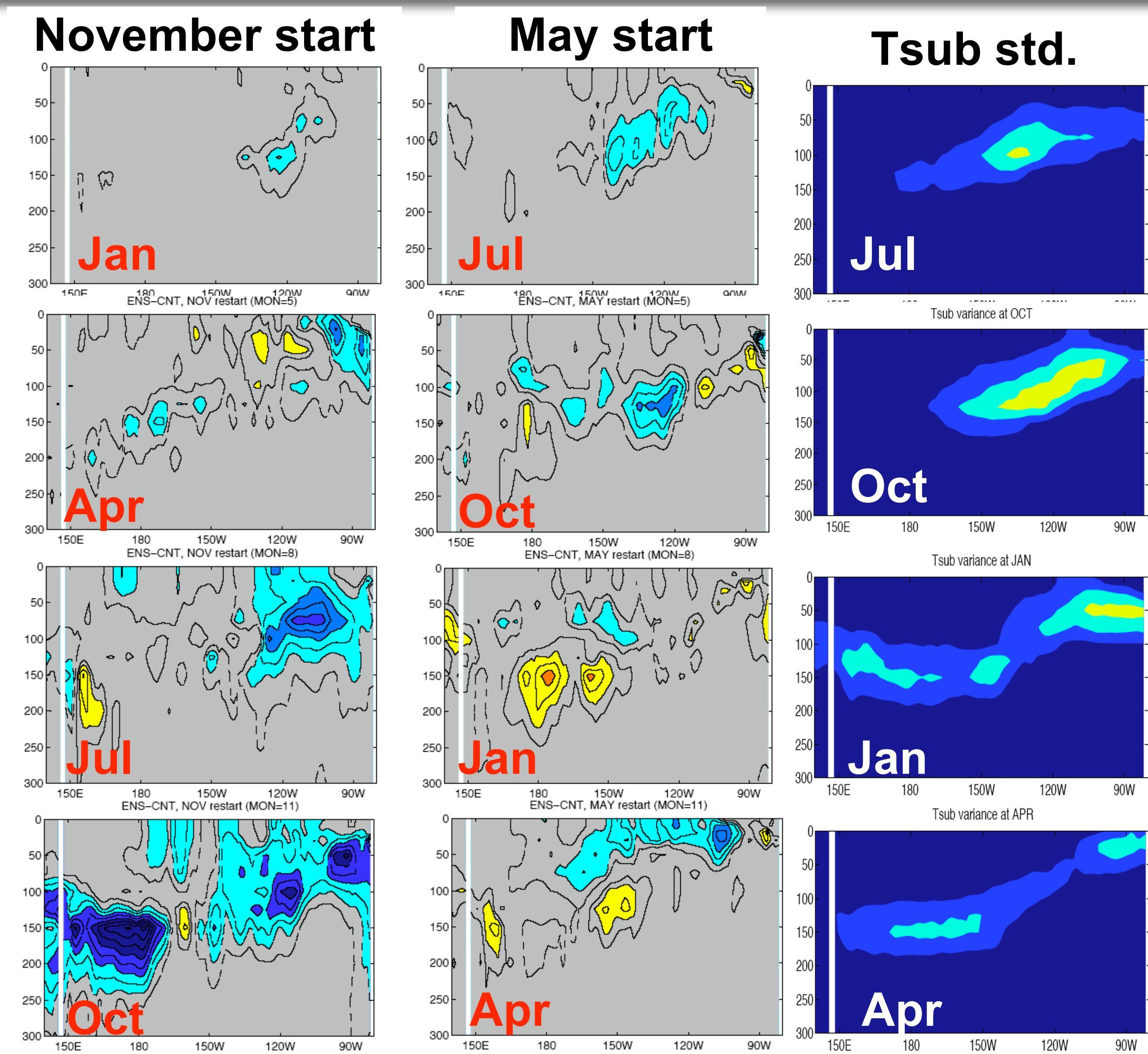



Start from
warm season



# Impact on equatorial subsurface

$(|T_{ens}-T_{ana}|-|T_{cnt}-T_{ana}|)$



# Summary

- **One-month forecast error and BV from NASA CGCM are found to share very similar features:**
  - 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 near the thermocline
- **The forecast error is dominated by dynamical errors whose shapes can be captured by bred vectors.**
  - BV captures the eastward movement of the forecast error along the equatorial Pacific during El Niño evolution
  - The error correlation lengths obtained from BV well represent the structure of forecast error: it is possible to use BV to provide the shapes of month-to-month errors
- **Subsurface temperature of BVs generated with different rescaling norms have similar dominant structures, but some differences are exhibited due to the characteristics of the rescaling norm.**

# Current and future work

- **Ensemble forecasting**, ENSO prediction
  - Use coupled BV as the initial ensemble perturbations for ensemble forecasting so that the ensemble spread is able to reflect the state uncertainties
  - Hindcast experiments initialized from 3 pairs of BVs already showed a large improvement starting from the cold season
  - It helps to alleviate the tendency to overpredict warm/cold events
- **Ocean data assimilation**, better use of the observations
  - use the oceanic component of coupled BV to augment the background error covariance from OI
  - improve the first guess for data assimilation