J13.12 INITIALIZATION OF UNSTABLE COUPLED SYSTEMS BY BREEDING ENSEMBLES

Shu-Chih Yang[1], Ming Cai[2], Malaquías Peña[1], and Eugenia Kalnay[1]*
[1]University of Maryland, College Park, MD and [2]Florida State University, Tallahassee, FL

1. INTRODUCTION

A major challenge in the design of a coupled ocean-atmosphere data assimilation system is the existence of a wide range of growing instabilities. They have doubling time scales that range from about a month or two for ENSO instabilities, a couple of days for baroclinic instabilities, a few hours for mesoscale phenomena, and a few minutes for convection. Methods for ensemble forecasting and data assimilation that rely on the linearization of the model, such as Lyapunov vectors (LVs) and Singular vectors (SVs) will emphasize the fast growing instabilities, even if these instabilities saturate at low amplitudes (Toth and Kalnay, 1993). Effective data assimilation geared towards the longer time scales has to be able to incorporate the slow, coupled instabilities of the ENSO background flow into the background error covariance, since the ENSO forecast errors would have a strong projection on these instabilities. Without a special effort to isolate the slow modes in a coupled data assimilation system, the faster but less relevant instabilities that dominate linear tangent models will wipe out the slower but important coupled processes from the estimated forecast and analysis errors (but not from the real analysis and forecast errors!).

To study whether it is possible to isolate the slow, coupled instabilities in the background flow, we have done experiments with breeding, a simple process that mimics ensemble data assimilation and relies on the use of the nonlinear model. In section 2 we summarize results obtained with breeding using the Zebiak-Cane model. In section 3 we show, using a simple coupled Lorenz model, that it is possible to isolate the slow modes in coupled system by breeding with rescaling intervals and amplitudes based on physical considerations, i.e., long enough to allow for the saturation of faster but irrelevant perturbations. In section 4 we present results of breeding in the NSIPP coupled ocean-atmosphere data assimilation system and in a perfect model coupled simulation. The key condition is that the interval for rescaling the ocean-atmosphere perturbations should be long enough (e.g., one month) to allow atmospheric noise to saturate. The results are encouraging and suggest that coupled data assimilation designed for seasonal and interannual prediction is feasible and could be based on a coupled Ensemble Kalman Filter using similarly long intervals between the coupled assimilation cycles.

2. BREEDING IN THE ZEBIAK-CANE MODEL

Cai et al (2002) performed breeding to estimate the unstable characteristics of the intermediate coupled model of Zebiak and Cane (1987). They used both 1-month and 3-month breeding cycles, and different norms for the renormalization, and the results were found to be insensitive to these choices. They found a single dominant bred vector of the ENSO instability that grew slowly at the peak of El Niño or La Niña episodes, and faster in between episodes. The BV also has seasonal cycle dependence, with maximum growth in early summer. Forecasting experiments (Fig. 1) indicated that the "spring barrier" is associated with the presence of bred vector projections in the initial analysis errors, and that when the projection of the initial errors on the (known) BV structure was eliminated, the forecast errors were substantially reduced and the spring barrier postponed for 4 to 8 months. Although the results were encouraging and served as useful guidance for more complex coupled models, the fact that in the Zebiak-Cane model the atmosphere is diagnosed from the ocean variables eliminates the problem of having both fast and slow instabilities present in the system. As a result these cannot be considered as a proof of usefulness of nonlinear approaches in a coupled system with multiple time scales.

3. **BREEDING IN A COUPLED LORENZ MODEL**

Peña and Kalnay (2003) made experiments with fast and slow coupled Lorenz (1963) models to see if it is possible to isolate slow from fast instabilities by doing breeding. Because breeding is a finite amplitude, finite time generalization of the method to generate Lyapunov vectors (Toth and Kalnay, 1993), it is closely related to the method of Finite Size Lyapunov Exponent (FSLE) proposed by Aurell et al. (1997) and Boffetta et al. (1998), although the bred vectors and their growth rate are easier to compute than the corresponding FSLE values.

Peña and Kalnay (2003) strongly coupled (with a coupling coefficient c=1 in all three variables) a "fast tropical atmosphere" with a "slow ocean", obtaining a solution they denoted "ENSO". They also weakly coupled the tropical atmosphere with a fast "extratropical atmosphere", with a coupling coefficient c_e= 0.08. The equations (1) they used are

---

Corresponding author address, 3431 CSS, College Park, MD. email: ekalnay@atmos.umd.edu

$$\dot{x}_e = \sigma(y_e - x_e) - c_e(Sx_t + k_1)$$
$$\dot{y}_e = rx_e - y_e - x_e z_e + c_e(Sy_t + k_1)$$
$$\dot{z}_e = x_e y_e - bz_e$$

$$\dot{x}_t = \sigma(y_t - x_t) - c(SX + k_2) - c_e(Sx_e + k_1)$$
$$\dot{y}_t = rx_t - y_t - x_t z_t + c(SY + k_2) + c_e(Sy_e + k_1)$$
$$\dot{z}_t = x_t y_t - bz_t + c_z Z$$

$$\dot{X} = \tau\sigma(Y - X) - c(x_t + k)$$
$$\dot{Y} = \tau rX - \tau Y - \tau sXZ + c(y_t + k)$$
$$\dot{Z} = \tau SXY - \tau bZ - c_z z_t$$

with space and time scaling coefficients and uncentering coefficients $\tau = 10, S = 10, k_1 = 10, k_2 = -11$.

The resulting attractor and the evolution of the x-variable in each of the three components is shown in Fig. 2. Fig. 3 shows the growth rate obtained for each of the components of the system as well as the growth rate obtained with nonlinear breeding and for linear Lyapunov and Singular vectors. On the left the intervals are short, and breeding is made with small amplitudes. For small amplitudes ($\delta = 0.05$) and short rescaling intervals ($5\Delta t$), the growth rate of the extratropical atmosphere dominates the total growth rate, as could be expected because these parameters are appropriate for this system. For small amplitudes and frequent rescalings, the BV and the LV growth rate are almost identical to each other and to the growth rate of the extratropical atmosphere, and the growth rate of the SVs is very large and less variable. For an even shorter rescaling interval, the results are similar except for the growth rate of the SVs, which becomes larger and almost constant, suggesting that it cannot discriminate between periods of real growth and decay in the extratropical atmosphere. On the right, we see that for longer rescaling periods ($100\Delta t$) and larger amplitudes ($\delta = 20$), the fast extratropical atmosphere oscillations are essentially completely filtered out from the BVs, and the ocean growth rate dominates the tropical atmosphere, as well as the total growth rate. Unfortunately, the linear approaches of the LV and SV growth, although similar to each other, are still strongly influenced by the extratropical solutions, and don't provide perturbations appropriate for the longer time scales.

These results show that a simple generalization of breeding using amplitudes and rescaling intervals that are chosen based on physical considerations can be used to separate slow and fast solutions in coupled systems. It should be noted that (with the exception of the growth of SVs) the results are not sensitive to small variations of the two parameters as long as they are within the range suggested by the amplitude and time scales of the coupled solution.

4. BREEDING IN THE NASA COUPLED GCM

The experience acquired with the Zebiak-Cane model and with the coupled Lorenz model suggests that it is possible to do breeding in a full coupled atmosphere-ocean model GCM. We have performed simulation experiments using a NASA Seasonal and Interannual Prediction Project (NSIPP) coupled model (described in http://nsipp.gsfc.nasa.gov/research/research_main.html) with a 10 year simulation used as "nature". The breeding was performed using the Niño-3 SST rms amplitude as rescaling variable, and all the atmospheric and oceanic variables were rescaled with the same factor. The amplitude chosen was 0.85% of the natural variability of the Niño-3 variability. The interval for rescaling was one-month, chosen both for theoretical reasons (it is long enough to allow weather noise to saturate, and not so long that the seasonal to interannual ocean variability becomes non-linear), and for practical reasons (we had access only to monthly output). In order to assess whether the results that we obtained with breeding are robust, we performed two independent breeding experiments, with the same configuration but starting with different initial random perturbations. We denote these two experiments as BV1 and BV2.

Fig. 4 illustrates the power of simple breeding in capturing instabilities of the evolving background flow. The coupled NSIPP GCM, like the real ocean-atmosphere system, has instabilities that appear as waves along the equatorial cold tongue. These instabilities were apparent in the coupled system, and the bred vectors (i.e., the instabilities growing upon the evolving basic flow) are also naturally generated. It indicates that with simple breeding it is possible to perform an analysis of the origin of these waves, for example determining whether the bred vectors are associated with barotropic or baroclinic instabilities. This figure corresponds to the BV1 experiment and similar results were obtained from BV2.

Fig. 5 shows the results obtained from both BV1 and BV2, summarized by performing a linear regression of the atmospheric and oceanic fields with the Niño-3 index from each of the two independent breeding runs. It is remarkable that the results are very similar, suggesting a high degree of reliability. Not surprisingly, the strongest signal is apparent in the deep tropics, but the atmospheric fields also show that in the Southern Hemisphere, the basic flow was associated with a slow instability even in the extratropics. G. Yuan and Z. Toth have run a similar experiment with an NCEP coupled model as nature, with very similar results.

We are currently performing a breeding experiment with the NSIPP operational system. In this case we perform breeding as indicated in the schematic Fig. 6: the bred perturbations are defined as the difference between the two nonlinear runs, at the end of the month they are rescaled (with a single rescaling factor obtained from the growth of the perturbation at the Niño-3 region) and added to the new analysis. Fig. 7 presents some preliminary results, suggesting that there was a spurt of growth preceding the two El Niño and La Niña episodes that took place during this experimental period.

5. SUMMARY and PLANS

Our results suggest that breeding with long rescaling intervals can be used to capture the slowly evolving ENSO component of a coupled model. We are currently performing breeding with the operational NSIPP coupled system and plan to use the bred vectors as initial perturbations for ensemble forecasting. If successful, these perturbations could be also used to augment the background error covariance with coupled “errors of the month”.

6. ACKNOWLEDGEMENTS

We are very grateful to Michele Rienecker and Max Suarez for many helpful discussions, and to Sonya Miller for her help. We had also discussions with Zoltan Toth and Guocheng Yuan, Christian Keppenne and we received a version of the coupled Lorenz (1963) model from Jim Hansen. This research has been supported by NASA as part of the NSIPP project.

REFERENCES

Aurell E., Boffetta, G.,Crisanti, A. Paladin G. and Vulpiani A., 1997: Predictability in the large: an extension of the concept of Lyapunov exponent. *J. Phys. A: Math. Gen*. 30, 1-26.

Boffetta G., Crisanti A., Paparella F., Provenzale A. and Vulpiani A.,1998: Slow and fast dynamics in coupled systems: A time series analysis view. *Physica* D 116, 301-312.

Cai, M., E. Kalnay, Z. Toth, 2003: Bred Vectors of the Zebiak-Cane Model and Their Application to ENSO Predictions. *J. Climate*, 16, 40-56.

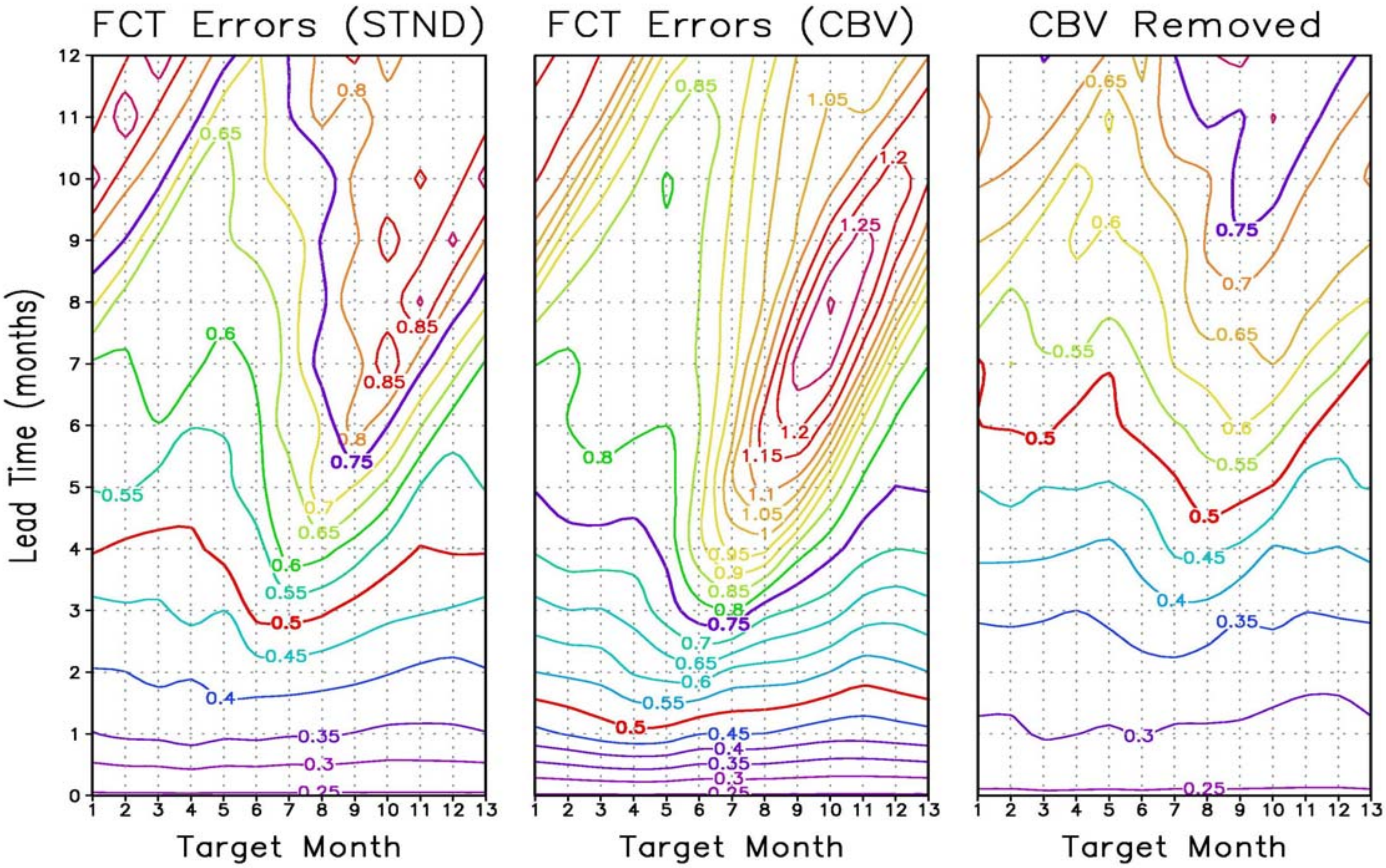
Lorenz, E., 1963:Deterministic non-periodic flow. *J. Atmos. Sci*., 20, 130-141.

Peña, M. and E. Kalnay, 2003: Separating fast and slow modes in chaotic systems. Submitted to the *Non-linear Processes in Geophysics*

Toth Z. and Kalnay E., 1993: Ensemble forecasting at NMC: the generation of perturbations. *Bull. Amer. Meteor. Soc.,*74, 2317-2330.

Yang S-C., Kalnay E. and Cai M., 2003: Bred vectors in the NASA coupled ocean-atmosphere system. Poster presentation. NP8-1WE2P-1657. EGS-EU.

Zebiak, S. and Cane A., 1987: A model for El Niño-Southern Oscillation. Mon. Wea. Rev., 115, 2262-2278.



FCT Errors (STND)

FCT Errors (CBV)

CBV Removed

Fig. 1 Forecast rms error as a function of forecast lead time and target month. Contour interval is 0.05 in a dimensionless unit. Initial errors are simulated (a) random fields, (b) composite bred vectors, and (c) random fields minus composite bred vectors. Note that the presence of the bred vector in the initial error is responsible for the “spring barrier”, and that when it is filtered out, the effect of the spring barrier is postponed for several months.

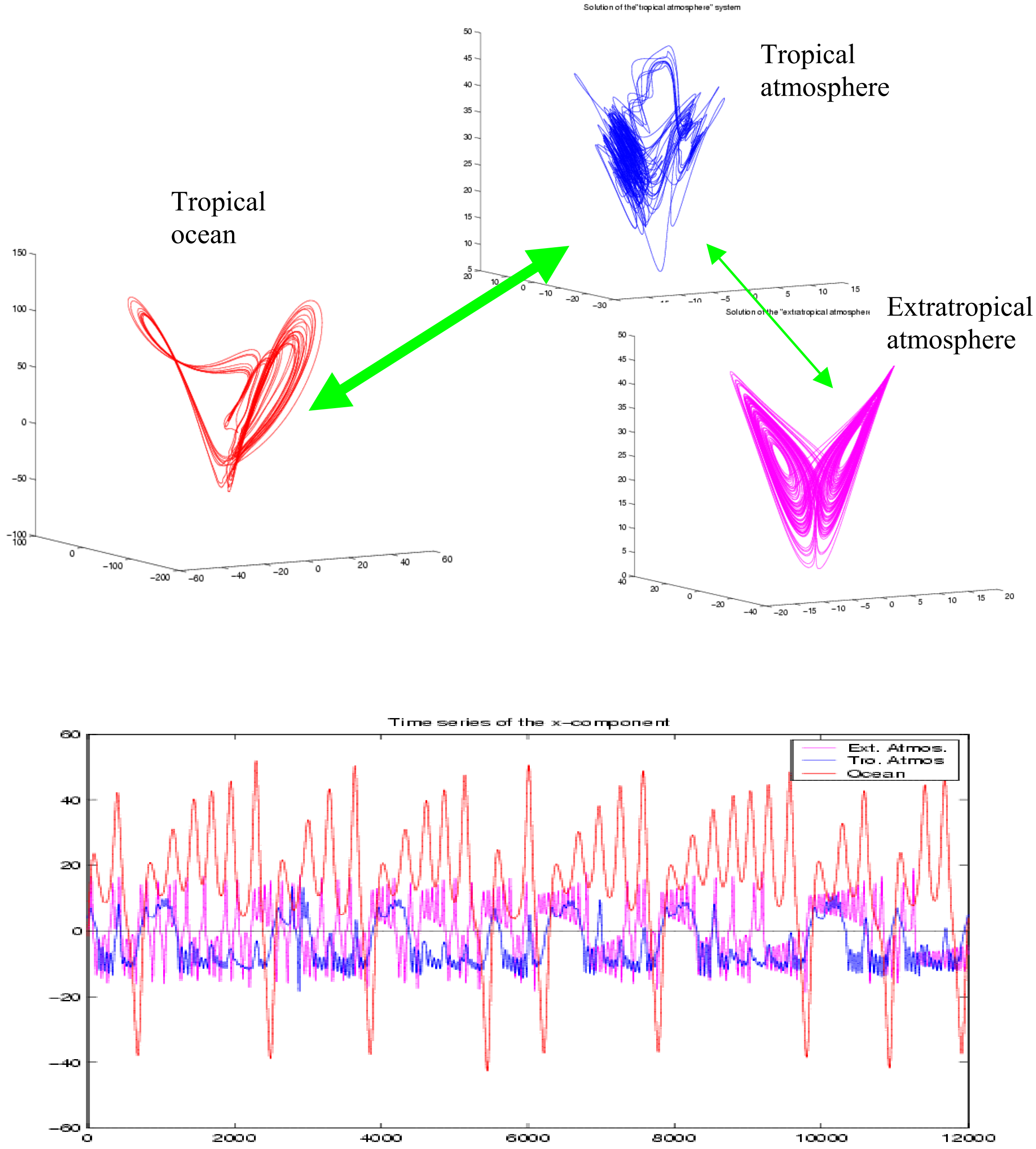
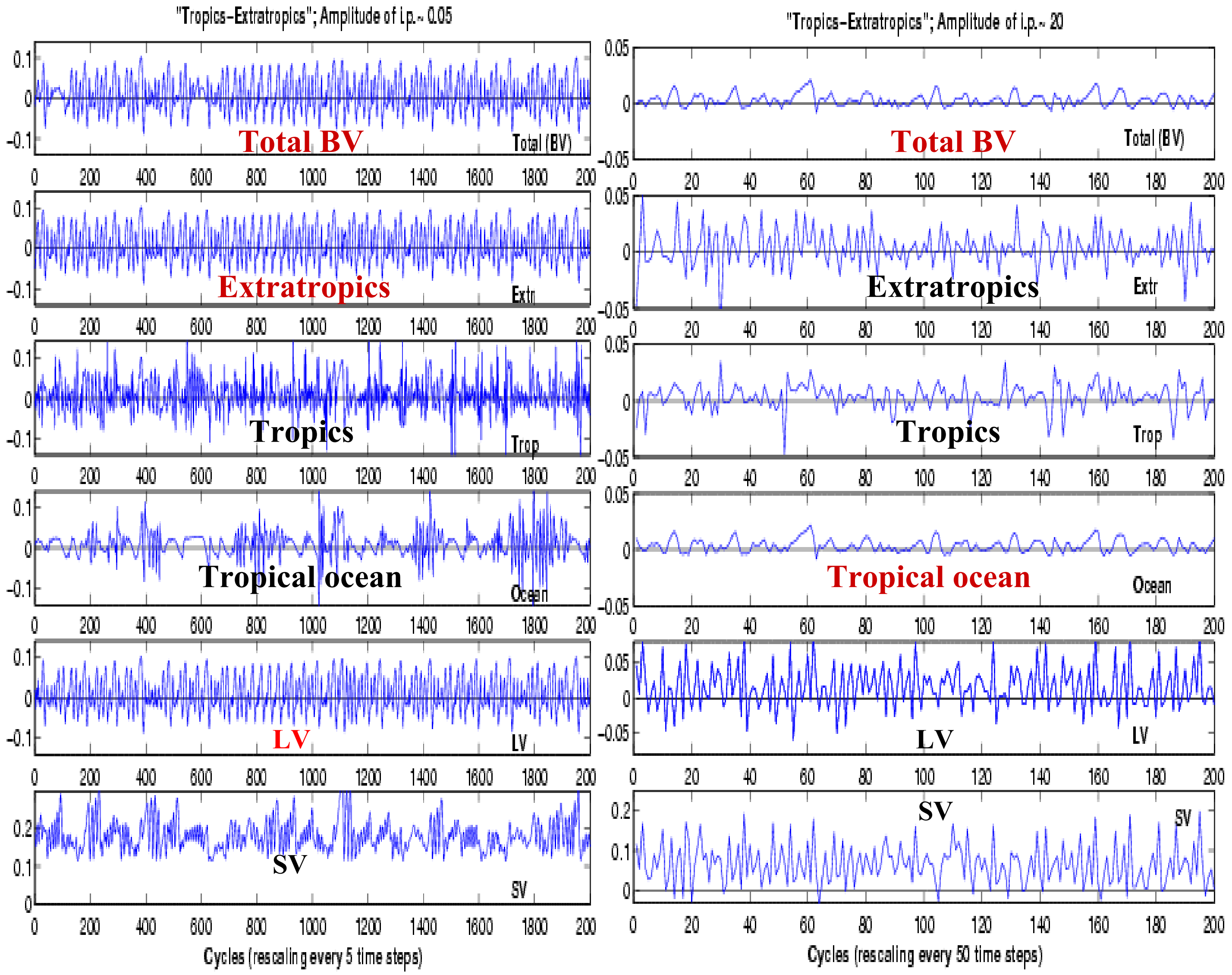


Fig. 2. Top: attractors of the 3-component “tropical-extratropical” coupled system corresponding to equations (1). The “tropical ocean” is strongly coupled to the “tropical atmosphere”, which in turn is weakly coupled to the “extratropical atmosphere”. The thickness of the arrows indicates the strength of the coupling. Bottom: Evolution of the x-component of the systems for the “Extratropical Atmosphere”, “Tropical Atmosphere”, and the “Ocean” sub-systems.



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

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

Fig. 3: From top to bottom: Growth rate of (a) the total BV, (b) the extratropical atmosphere component of the BV, (c) the tropical atmosphere (d) the tropical ocean, (d) growth rate of the leading LV over the same interval, and (e) growth rate of the SV over the same time interval. Red labels indicate results that are essentially identical. Left panel: initial perturbations of 0.05 and rescaling every 5 time steps. Right panel: same as left panel but using initial perturbations of amplitude 20 and rescaling intervals of 50 time steps.

Red colors indicate results that are essentially identical with each other. These results are insensitive to small variations in the amplitude or rescaling interval.

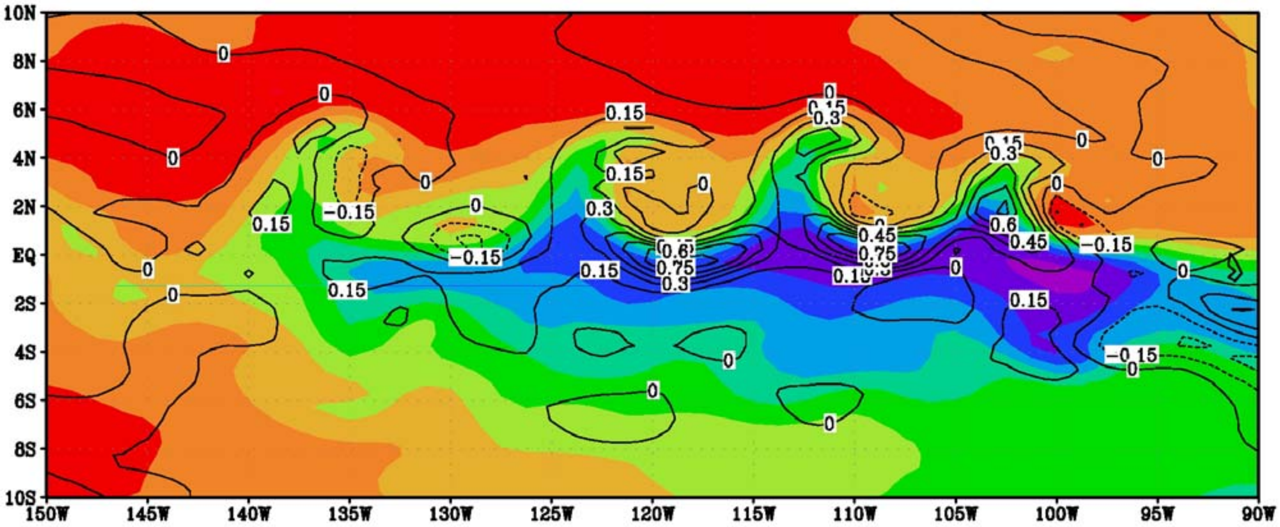


Fig. 4: Example of the evolving background field (SST, colors) and superimposed bred vectors showing how the instabilities associated with the equatorial waves in the NSIPP coupled model are naturally captured by the breeding method. This should allow a simple study of the instability physical mechanisms in such waves.

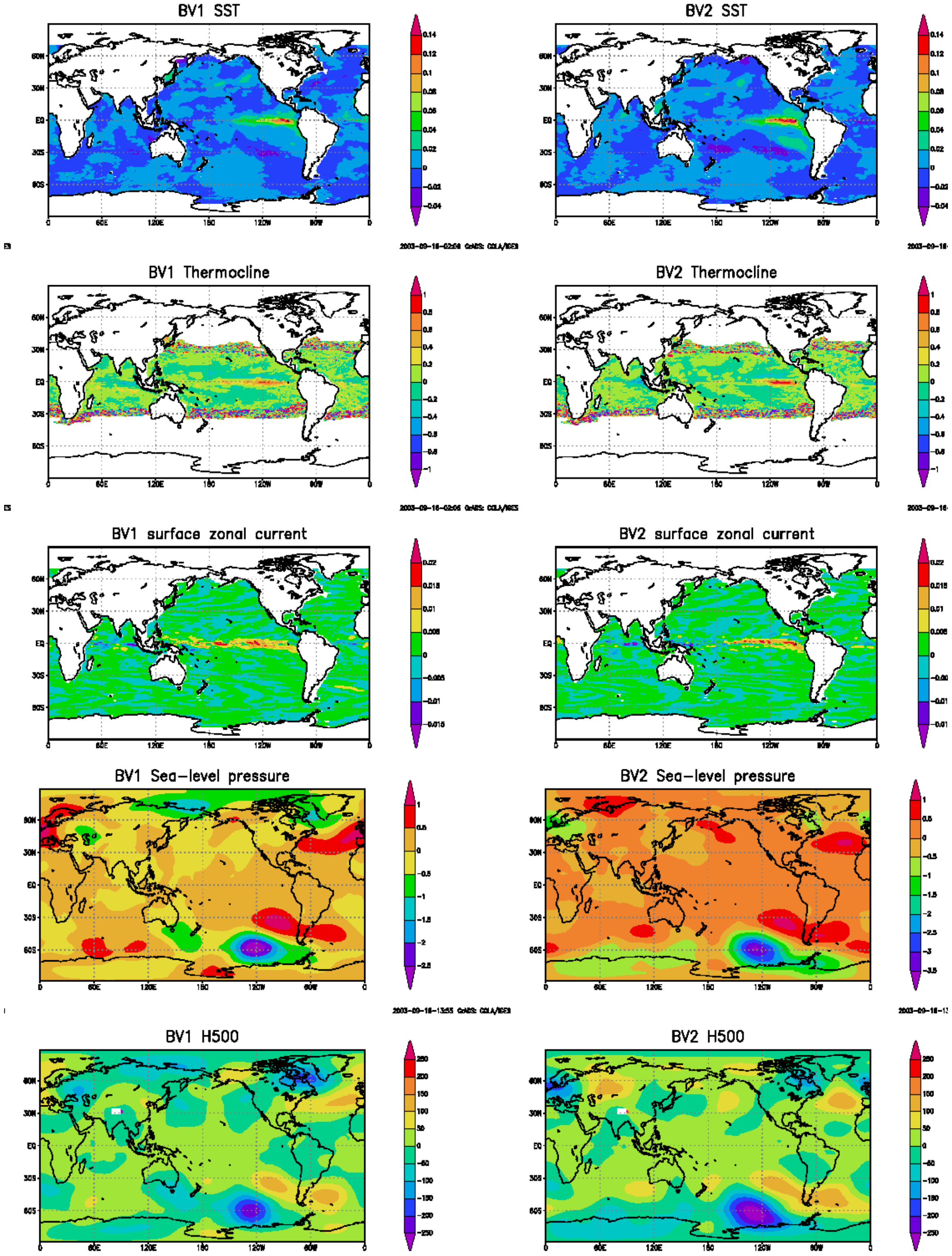


Fig. 5: Oceanic and atmospheric variables regressed with the Niño 3 SST index for two independent breeding runs (BV1 and BV2) made with the NASA NSIPP coupled GCM. The similarity of these results suggest that they are robust.

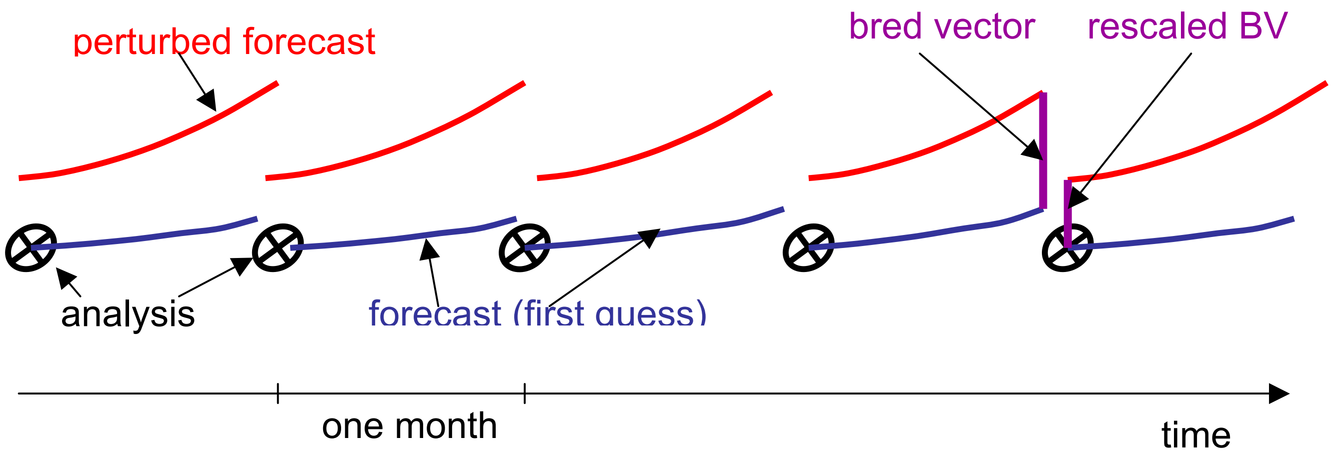


Fig. 6: Schematic of the breeding performed on the operational NSIPP system. The bred vectors are computed as the difference between the nonlinear perturbed forecast and the forecast used as a first guess. They are rescaled using the Niño-3 perturbation size and added to the analysis at the end of the month.

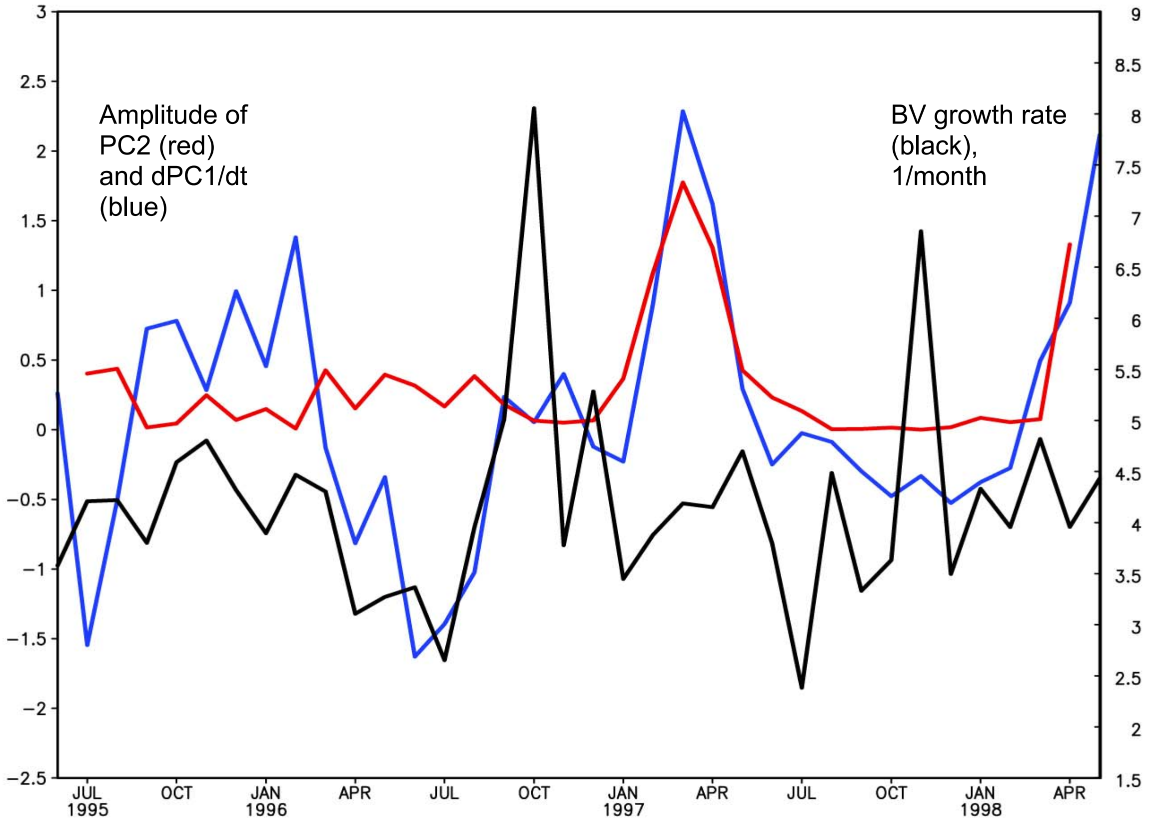


Fig. 7: Preliminary results obtained with breeding using the NASA NSIPP operational system. The black line is the growth of the bred vector (1/month), the blue line is the time change of the first Principal Component (EOF1) and the red line is the amplitude of the second PC2 (EOF2).