GEOPHYSICAL RESEARCH LETTERS, VOL. 28, NO. 10, PAGES 2061-2064, MAY 15, 2001

Changes Of ENSO Stability Due To Greenhouse Warming

Axel Timmermann

International Pacific Research Center, Honolulu, HI 96822, USA

Abstract. Based on a Coupled General Circulation Model (CGCM) simulation we study the influence of anthropogenic greenhouse warming on the stability of the El Niño -Southern Oscillation phenomenon(ENSO). The linear stability of such a complex model cannot be assessed directly, hence we will derive empirical low order models for ENSO from the CGCM simulation under consideration. These models capture essential features of ENSO and are sensitive also to temporal changes in ENSO statistics. An eigenvalue analysis of these reduced models reveals that as greenhouse warming progresses a transition takes place from a stable oscillatory behavior to an unstable oscillation. This transition coincides with an abrupt change in simulated ENSO activity and can be explained in terms of changing ocean dynamics.

1. Introduction

One of the very important questions of climate research is that of the stability of our present climate with respect to anthropogenic changes of the atmospheric composition. It is not only the climate mean state which might be subjected to changes and instabilities as the greenhouse gas concentrations in the atmosphere increase but also its variability which could be influenced strongly by anticipated climate changes (Knutson et al., 1997, Timmermann et al., 1999). The focus of this paper is the sensitivity of ENSO with respect to anthropogenic warming. In contrast to earlier studies by the same author (Timmermann et al., 1999) and (Timmermann, 1999) the study presented here shall focus on the stability of ENSO rather than on the statistical description of ENSO changes. On account of the fact that all CGCM simulations show a different ENSO response to a CO_2 doubling (Collins 2000a, Collins 2000b) our results here could be strongly model dependent. However, what we would like to do here is to explain how in a state-of-the-art CGCM simulation ENSO stability properties change as a result of anthropogenic greenhouse warming.

2. Data

In order to study the influence of greenhouse warming on the dynamical stability of ENSO we analyze a transient climate change experiment performed with the CGCM ECHAM4/OPYC3 (Roeckner et al., 1996, Bacher et al., 1997, Timmermann et al., 1999). The atmosphere model ECHAM4 is coupled to the isopycnal ocean model OPYC3, adopting an annual mean flux correction method (Bacher et al., 1998). The climate change simulation follows the prescribed greenhouse gas emission scenario IS92a (see e.g. IPCC 1992). In two recent papers by Roeckner et al., (1996) and Bacher et al., (1998) the ENSO physics of the control integration without an increase of greenhouse concentrations are validated.

In Timmermann et al., (1999) it was found that during a transient greenhouse warming experiment conducted with this CGCM abrupt changes of ENSO variability can occur which are superimposed on an overall trend towards stronger ENSO activity. These changes are reminiscent of abrupt regime transitions and might be associated with different stability properties of ENSO.

Since the CGCM is far too complex to carry out a linear stability analysis of ENSO we derive a surrogate ENSO model from the two leading EOF modes of tropical SSTA and the two leading modes of tropical Pacific sea level height anomalies (see Fig.1). The two leading EOFs of SSTA and sea level height anomalies capture about 60-70% of the variance of their respective data fields.

The EOF analysis is based on a 40 year chunk of data taken from the beginning of the greenhouse warming simulation (corresponding to atmospheric greenhouse gas concentrations of the years 1860-1900). The first SSTA mode corresponds to the mature ENSO phase (El Niño or La Niña), whereas the second EOF mode is characterized by a dipole-like structure. It is associated with a zonal displacement of the ENSO-related SSTA. When the second SSTA EOF mode has a positive principal component, the El Niño center will be shifted eastward, whereas a La Niña situation will be focussed on the equator more westward to its normal position. The opposite holds for negative values of the second principal component. This structure is similar to the optimal variability fingerprint of the ECHAM4/OPYC3 model (Timmermann, 1999), i.e. the pattern which is associated with the strongest increase of variability in a greenhouse warming simulation. The first EOF mode of sea level variability describes an east-west thermocline see-saw mode, consisting of off-equatorial signals in the warm pool region and equatorial anomalies in the central and eastern equatorial Pacific. The second sea level EOF can be interpreted in terms of a Kelvin wave traveling along the equator and an off equatorial Rossby wave[1]

[1] It should be noted here that these patterns are rather stable during the greenhouse warming simulation. The corresponding EOF patterns for the last 40 years of this simulation look very similar to the first 40 years, except for a slight eastward shift by 5^0 of the second EOF pattern of SST anomalies. This pattern explains 12% of the variance in the former and 9% in the latter case. This robustness justifies our approach to project the dynamics onto a standard set of EOFs extracted from the first 40 years of the integration.

Paper number 2001GL012879
0094-8276/01/2001GL012879$05.00

Eventually, SST and sea level anomalies taken from different (overlapping) 40 year-long windows of the greenhouse warming simulation are projected onto these standard EOF patterns from the early stage of the integration. The resulting (detrended) principal components and their time derivatives (using a 4th order accuracy scheme) are used in order to derive empirically a 4 dimensional ordinary differential equation (ODE) system, which optimally fits the data and which can be subjected to a linear stability analysis. This is done in the following manner.

3. Methodology

We derive an empirical low order model ENSO from the data under consideration (in our case the leading principal components of SSTA x_1, x_2 and those of sea level anomalies x_3, x_4 or the projections of the anomalies extracted from the sliding windows onto the standard EOF pattern) by making the following nonlinear ansatz

$$\dot{x}_j = \sum_{i=1} \Phi_i^j(x_i) + \sigma^j \xi_j, \qquad (1)$$

Equation (1) defines a nonlinear multiple regression problem. The last term represents Gaussian white noise of variance $(\sigma^j)^2$. Equation (1) is solved nonparametrically using the ACE (Alternating Conditional Expectation) algorithm of Breiman & Friedman (1985)[2]. For details on the numerical implementation of the ACE algorithm see ref. (Voss 2000, Voss and Kurths 1997). Using the ACE algorithm, the estimators $\tilde{\Phi}_i^j(x_i)$ are determined as lookup tables which is an important advantage of nonparametric regression methods because no a priori assumptions are made on the degree of nonlinearity of the problem. However, since we are interested in the linear stability properties of the reduced system we linearize $\tilde{\Phi}_i^j(x_i)$ around the stationary state. The dynamics of the linearized system is then determined by the matrix (a_{ij}) which connects $\dot{x}_i = \Sigma_j a_{ij} x_j$. It has been shown (Timmermann et al., 2000) that this methodology works very efficiently in order to reduce complex spatio-temporal ENSO dynamics. For the linearized 4 dimensional principal component model which we believe to mimic crudely the sensitivity of the simulated ENSO an eigenvalue analysis $\lambda_n x_{i,n} = \Sigma_j a_{ij} x_{j,n}$ is performed. The real and imaginary parts of λ_n (n denoting the nth eigenvalue) characterize the growing and oscillatory components of the linearized dynamical system, respectively.

4. Results

Figure 2 displays the imaginary part (associated with the ENSO period) of the two complex conjugated eigenvalues as a function of time. It is obtained by computing the linear stability of separate low order EOF models which are derived from the detrended principal components (x_1, x_2, x_3, x_4) for overlapping 40 year windows.

One observes an interannual ENSO component with a period which varies around 2.3 (Im$\sim$ 0.22) and 3.4 (Im$\sim$ 0.15) years and a low frequency ENSO component characterized by periods of 6 years and longer. The 2.3 year period captured by the linearized 4 EOF model is consistent with the main ENSO periodicity of 2.3 years in the CGCM simulation (see Bacher et al., 1998).

As can be seen from Figure 2 there is no significant trend in ENSO frequency, unlike the one observed in the HadCM2 greenhouse warming simulation (Collins 2000b) for a CO_2 quadrupeling experiment. Fedorov and Philander (2000) argue that this particular robustness of the ECHAM4/OPYC3 model might be due to deficiences in the mean state simulation, namely a too shallow thermocline. The changes of the quasi-biannual ENSO period correspond roughly to the timescale changes quantified by a wavelet analysis (not shown) of the simulated Niño 3 SST anomalies. In contrast to the interannual ENSO mode, the low frequency oscillatory ENSO mode does not exists for the whole simulation time. The origin of its sporadic emergence and disappearance is not clear.

In Figure 3 (lower panel) one observes that the growth rate (associated with the real part of the eigenvalues) of the linearzied low order ENSO models is characterized by a strong trend from negative to positive values, and hence from a stable oscillatory regime to an unstable one.

This change of the linear stability is accompanied by an increase of ENSO activity (upper panel, Figure 3), as measured by the running standard deviation of Niño3 SST anomalies. In particular the abrupt change of ENSO variance during the 80's[3] is marked by a strong change of the growth rate from almost vanishing values to positive values, i.e. from stable to unstable conditions.

In a recent paper by An and Jin (2000) the linear stability of ENSO is analyzed using observations and an intermediate coupled-atmosphere ocean model. Forcing the reduced physical ENSO model with decadal wind patterns the authors find a shift from a stable to an unstable oscillatory regime which occurred between the 70s and 80s. It is also argued in their paper that this qualitative change of ENSO stability is accompanied by a decadal shift in the amplitude, structure and frequency of ENSO. These results are confirmed in a companion study (An and Wang 2000) using a different intermediate ENSO model. The results presented here follow along the same line.

In Figure 4 the relative changes of (a_{ij}) between an early greenhouse warming stage (1860-1900) and a late stage (2060-2100) are shown, i.e. $(a_{ij}^{CO_2} - a_{ij}^{CTR})/a_{ij}^{CTR}$. They are fanned out with respect to the time derivatives $(\dot{x}_1, \dot{x}_2, \dot{x}_3, \dot{x}_4)$ they contribute to. Apparently the relations between $\dot{x}_4$ and x_1, $\dot{x}_4(x_4)$, $\dot{x}_3(x_2)$ change substantially. These changes can be attributed to significant changes in ocean dynamics. The largest change can be interpreted as a change in the relation between Kelvin waves, off equatorial Rossby wave initiation and the ENSO related SSTA pattern (EOF2 SSHA, and EOF1 SSTA). Furthermore, one observes a strong influence of the second SSTA EOF mode on thermocline dynamics, as represented by the first EOF mode of sea level height anomalies. In the late greenhouse warming stage there is a tendency for El Niño events to occur more to the east. This is most likely the reason for the changes in the interactions among the EOF modes, shown in Figure 4. As noted earlier the second EOF mode of SST anomalies is sim-

[2]which we modified slightly as compared to the original paper by Breiman & Friedman (1985) in that the l.h.s of eq.(1) is kept fixed

[3]The time 1980 corresponds to the observed greenhouse gas concentrations of 1980.

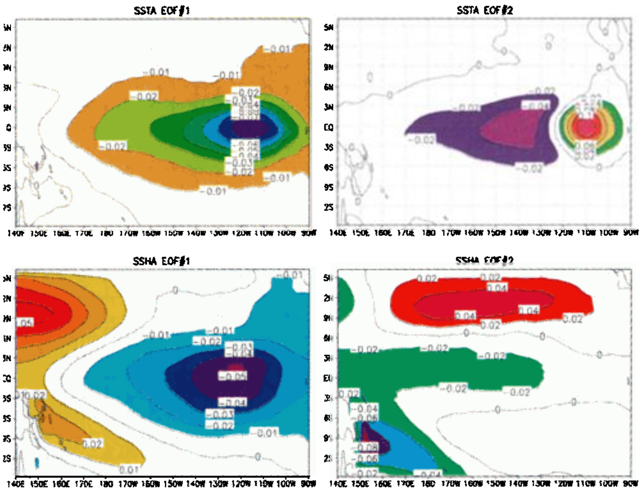

Figure 1. Dominant EOF patterns of sea surface temperature anomalies (upper panel) and sea level anomalies (lower panel). Data are obtained from the first 40 years of a greenhouse warming simulation performed with the CGCM ECHAM4/OPYC. Patterns are dimensionless.

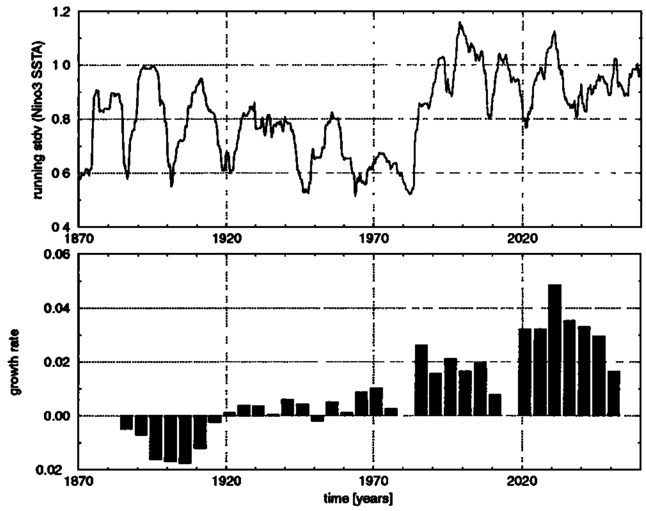

Figure 3. Upper panel: Running standard deviation of Niño 3 SSTA using a 10 year window. Lower panel: Dominant Real Eigenvalue of the reduced 4-EOF ENSO model (based on the two leading principal components of SSTA and Sea level anomalies). For each 40 year window an optimal set of linear ODE's is determined and subjected to an eigenvalue analysis.

ilar to a pattern which accompanies the strongest increase in ENSO variability in the ECHAM4/OPYC3 greenhouse warming simulation (Timmermann, 1999).

5. Summary

Overall the empirical dynamical analysis of a greenhouse warming simulation presented here suggests that changes of ENSO activity might be linked to changes in the stability properties of ENSO. Instead of fitting parameters of an intermediate physical model to the observations and studying the stability of this reduced ENSO model (An and Jin 2000, An and Wang 2000) we derive dynamical models empirically from the data under consideration and subject these reduced models to a stability analysis. The empirical models capture the dynamics of a truncated EOF subspace which characterizes ENSO dynamics in terms of SST and sea level anomalies. Both methodologies are complementary to each other. On account of the fact that different climate models show a different ENSO sensitivity in response to greenhouse warming (Collins 2000a) our results should be regarded as one possible scenario. Nevertheless, the method used here might prove powerful in understanding the dynamics also of other CGCM simulations.

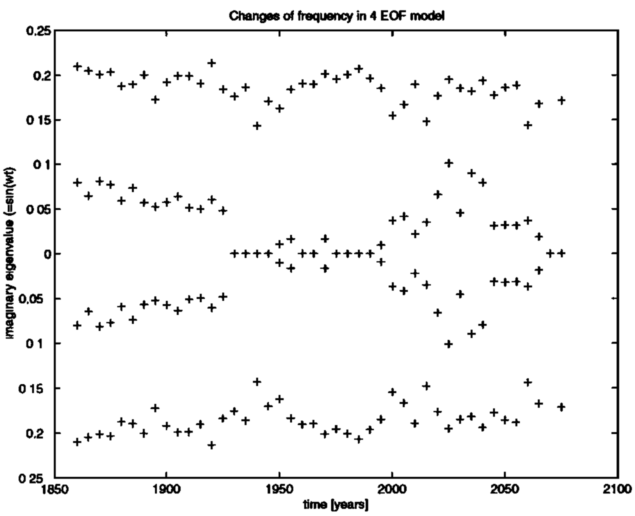

Figure 2. Imaginary Eigenvalue of the reduced 4-EOF ENSO model (based on the two leading principal components of SSTA and Sea level anomalies). The four stars at each time step represent the positive and negative values of the imaginary part of the complex conjugated eigenmodes. For each 40 year-long window an optimal set of linear ODE's is determined and subjected to an eigenvalue analysis.

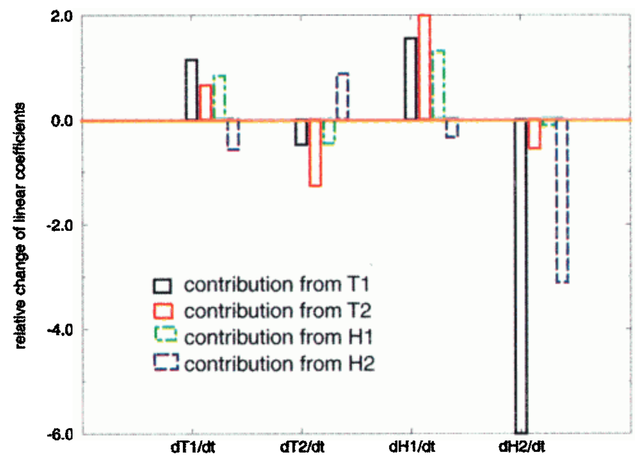

Figure 4. Relative changes of the linear coefficients a_{ij} in $\dot{x}_i = \sum_j a_{ij} x^j$ between an era close to CO_2 doubling and a 40 year window which is representative of natural climate variability alone. $x_1 = T_1$, $x_2 = T_2$ correspond to the principal components of the two leading SSTA EOF modes and $x_3 = H_1$, $x_4 = H_2$ to the principal components of the two leading sea level EOF modes.

Acknowledgments. The author is grateful to H. Voss for providing the ACE algorithm. The IPRC is supported in part by the Frontier Research System for Global Change. This manuscript is SOEST contribution number 5358 and IPRC contribution number 81.

References

An, S.-I, and F.-F.- Jin, An eigen analysis of the interdecadal changes in the structure and frequency of ENSO mode. *Geophys. Res. Lett.*, **27**, 2573-2576, 2000.

An, S.-I., and B. Wang, Interdecadal change of the structure of the ENSO mode and its impact on the ENSO frequency. *J. Climate*, **13**, 2044-2055, 2000.

Bacher, A., Oberhuber, J. M. and Roeckner, E., ENSO dynamics and seasonal cycle in the tropical Pacific as simulated by the ECHAM4/OPYC3 coupled general circulation model. *Clim. Dyn.*, **14**, 431-450, 1998

Breiman, L. and J. H. Friedman, Estimating optimal transformations for multiple regression and correlation. *J. Americ. Statist. Assoc.*, **80**, 580-598, 1985.

Collins, M., Understanding Uncertainties in the response of ENSO to Greenhouse Warming. *Geophys. Res. Lett.*, **27**, 3509-3513 , 2000a.

Collins, M., The El-Niño Southern Oscillation in the second Hadley Centre coupled model and its response to greenhouse warming, *J. Clim.*,**13** 1299-1312, 2000b.

Fedorov, A.V. and S.G.H. Philander, Is El Niño Changing?, *Science*, **288**, 1997-2002, 2000.

IPCC, Climate Change 1992. The Supplementary Report to the IPCC Scientific Assessment. Edited by J. T. Houghton, B. A. Callander and S. K. V. Varney. Cambridge University Press, 200 pp ,1992.

Knutson, T.R., S. Manabe and D. Gu Simulated ENSO in a Global Coupled Ocean Model: Multidecadal Amplitude Modulation and CO_2 Sensitivity. *J. Clim.*, **10**, 138-161, 1997.

Roeckner, E., Oberhuber, J. M.,Bacher, A., Christoph, M. and Kirchner, I., ENSO variability and atmospheric response in a global atmosphere-ocean GCM. *Clim. Dyn.* **12**, 737-754, 1996.

Timmermann, A., Detecting the Nonstationary Response of ENSO to Greenhouse Warming, *J. Atmosph. Scien.*, **56**, 2313-2325, 1999.

Timmermann, A., M. Latif, A. Bacher, J. Oberhuber, E. Roeckner Increased El Nino frequency in a climate model forced by future greenhouse warming,*Nature*, **398**, 694-696, 1999.

Timmermann, A., H.U. Voss, R. Pasmanter, Empirical Dynamical System Modeling of ENSO using Nonlinear Inverse Techniques, *J. Phys. Oceanography*, in press.

Voss, H., J. Kurths, Reconstruction of nonlinear time delay models from data by the use of optimal transformations. *Phys. Lett. A*, **234**, 336-344, 1997.

Voss, H.U., *Analysing Nonlinear Dynamical Systems with Nonparametric Regression*, To appear in: A. Mees (ed.), *Nonlinear Dynamics and Statistics* (Birkhäuser, Boston, 2000).

Axel Timmermann, International Pacific Research Center 2525 Correa Road Honolulu, HI 96822 USA. email: timmera@soest.hawaii.edu

(Received January 18, 2001; accepted February 27, 2001.)