

# The Response of an ENSO Model to Climate Noise, Weather Noise and Intraseasonal Forcing

Mark S. Roulston<sup>1</sup>

Division of Geological and Planetary Sciences, Caltech 150-21, CA 91125

J. David Neelin

Department of Atmospheric Sciences, UCLA, CA 90095-1565

**Abstract.** The response of an intermediate coupled model of the tropical Pacific to different forms of stochastic wind forcing is studied. An estimate of observed Pacific wind variance that is unrelated to Pacific sea surface temperature (SST) has a red spectrum, inconsistent with standard definitions of “weather noise”. The reddening is likely due to SST outside the basin; we propose a definition of “climate noise” for such reddened variance. Effects are compared for (i) red climate noise; (ii) the corresponding white weather noise estimate; (iii) intraseasonal and interannual components of the white noise (to test frequency response); and (iv) a noise product with extra power in the 30-60 day range. Power is not effectively channeled from subannual frequencies to the frequencies associated with ENSO in this model. This suggests that ENSO impacts of the Madden-Julian oscillation are largely restricted to the low-frequency tail rather than the 30-60 day spectral peak. Interannual climate noise originating outside the tropical Pacific appears important.

## Introduction

Now that a basic understanding of the oscillatory nature of ENSO has been obtained (for review see *Neelin et al.* [1998]), more attention is being paid to the effect that stochastic forcing has on the system [*Kleeman and Power*, 1994; *Moore and Kleeman*, 1996; *Kleeman and Moore*, 1997; *Blanke*, 1997]. The role of the Madden-Julian intraseasonal atmospheric oscillation (MJO) on the interannual ENSO system has been of particular interest [*Zebiak*, 1989; *Moore and Kleeman*, 1999]. Stochastic forcing is often used as a model for variability caused by processes excluded from the explicitly modeled dynamics. For instance, the average response of the atmosphere to SST may be approximated by a steady-state atmospheric model while the weather transients due to atmospheric internal variability are approximated as stochastic forcing. Another potential source of noise in regional models is climate variability due to processes outside the model domain. The impacts upon the tropical Pacific of all variability caused by ocean-atmosphere interactions at mid-latitudes and in the tropical Atlantic and Indian oceans would then be represented as a noise process. We use the terms *weather noise* and *climate noise*, respectively,

to distinguish between these two types of stochastic forcing. The term “weather noise” has been used in the ENSO literature to refer to effects of atmospheric internal variability. The term “climate noise” has been used in some earlier literature [*Leith*, 1978] to refer to weather noise, but we propose that it is more usefully reserved for noise effects that include some reddening by oceanic or other slow components of the climate system outside the domain of study.

This paper investigates the impact of these different types of noise on an intermediate coupled model (ICM) of the tropical Pacific.

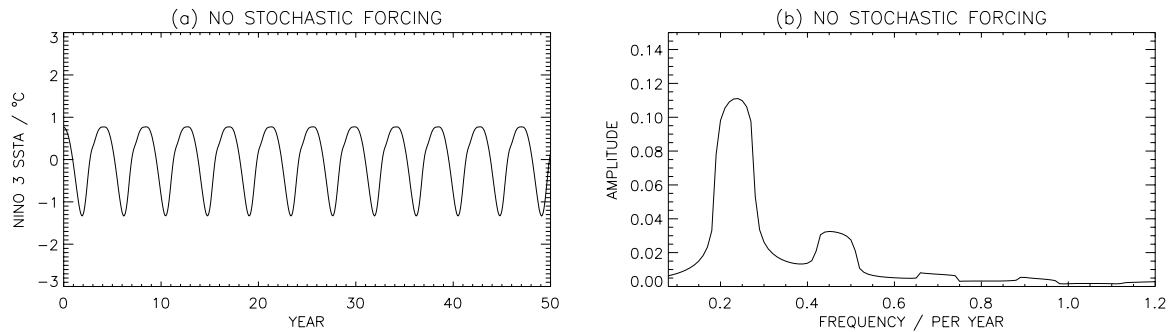
## The Model

The ICM of the tropical Pacific is based on previous ICMs [*Zebiak and Cane*, 1987; *Jim and Neelin*, 1993]. The ocean model is a linearized shallow-water model on a beta-plane with a nonlinear equation for SST. Horizontal advection of SST is included and vertical entrainment into the mixed layer is parameterized. The atmospheric component is a linear, steady-state model [*Gill*, 1980] with heating anomalies proportional to SST. As in other ICMs, as the coupling is increased, the model passes from a stable, *subcritical* regime to a *supercritical* regime where it exhibits interannual oscillations. In the supercritical regime the dominant oscillation has a period of 4.5 years with a second oscillation with a period of 2.1 years. The behavior of the model in the supercritical regime is shown in Fig. 1. All model response amplitude spectra use a smoothing window of  $0.08 \text{ year}^{-1}$  on a Fourier transform of a 200 year series of NINO3 SSTA.

## Climate and Weather Noise

In this context, we wish to approximate as “noise” all the variability in windstress that cannot be modeled using the atmospheric model. Variability in surface heat fluxes is not considered. To estimate the spectrum of the wind noise a linear model relating SST to windstress was constructed empirically using reconstructions of Pacific SST for the period 1961-1994 [*Smith et al.*, 1996] and the Florida State University pseudo-windstress data set for the same period [*Goldenberg and O’Brien*, 1981]. That part of the windstress variance that could be explained by this model was subtracted to leave the residual windstress. Figure 2a is the amplitude spectrum of the residual zonal windstress averaged over the NINO 4 region. The spectrum of this residual is red which is probably due to the ocean acting as a lowpass filter to atmospheric noise. Reddening due to the memory of the ocean within the model domain should have been re-

<sup>1</sup>Now at Pembroke College, Oxford University, U.K.



**Figure 1.** The behavior of the model NINO3 SSTA above the bifurcation with no stochastic forcing. (a) time series of NINO3 SSTA (b) amplitude spectrum of NINO3 SSTA.

moved by the atmospheric model, so the reddening seen in Fig. 2a must be primarily due to the memory of the ocean outside the model domain.

The residual windstress was projected onto its empirical orthogonal functions (EOFs) to produce a set of time series that were modeled as independent stochastic processes. Each of the EOF time series,  $x_t$ , was fitted to a first order autoregressive model (AR1) described by

$$x_{t+1} = ax_t + b\varepsilon_t \quad (1)$$

In Eq. 1,  $a$  is related to the correlation time of the time series,  $\tau$ , by  $\tau \approx 1/(1-a)$  and  $\varepsilon_t$  is gaussian noise with a variance of unity. Since the  $a$  term causes the reddening of the time series, it can be identified with the ocean (outside of the model domain). The gaussian term can be identified with the variability generated by the atmosphere alone. It was found that the value of  $a$  was between  $0.4 \text{ month}^{-1}$  and  $0.65 \text{ month}^{-1}$  for all the EOF time series. This corresponds to an ocean “memory” of about 2 months.

Two cases were of interest. The first will be referred to as the *red noise* case in which  $a$  and  $b$  retain their fitted values. This is an attempt to model all the atmospheric variability not explicitly modeled. This includes variability which would generally be described as climate as well as the variability that would be called weather, and we refer to such processes in general as climate noise. The second case is *white noise* in which  $a = 0$ . This provides a representation of atmospheric transients that are uncorrelated on the time scales of interest, *i.e.*, weather but not climate variability, hence we refer to this in general as weather noise. To investigate the response of the model to stochastic forcing of different frequency ranges, the white noise forcing is divided into two components: (1) the *low frequency noise component*, which has been lowpass filtered to remove all frequency components with periods less than 6 months; (2) the *high frequency noise component*, highpass filtered to remove frequency components with periods greater than 6 months. The filtered noise products do not have a physical interpretation and were constructed to test the frequency response of the model.

The final noise product was to investigate the response to the 30 to 60 day component of the MJO. The MJO is one of the most important sources of intraseasonal variability in the tropical Pacific. The MJO has a spectral peak at periods of 30-60 days [Madden and Julian, 1994]. A noise product was constructed by enhancing the power at these frequencies by

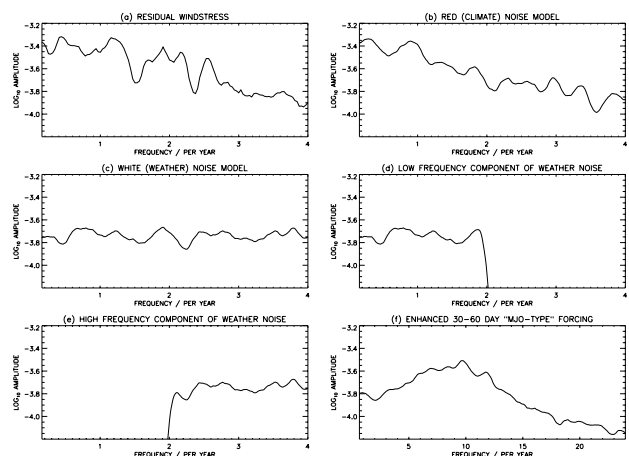
a factor of approximately 5, which is consistent with model studies of the MJO [Waliser *et al.*, 1999].

The amplitude spectra of the zonal NINO 4 windstress for the noise products described above are shown in Fig.2b-f. All amplitude spectra use a smoothing window of  $0.08 \text{ year}^{-1}$  on a Fourier transform of 200 year series (except Fig. 2a, based on a 32 year series.)

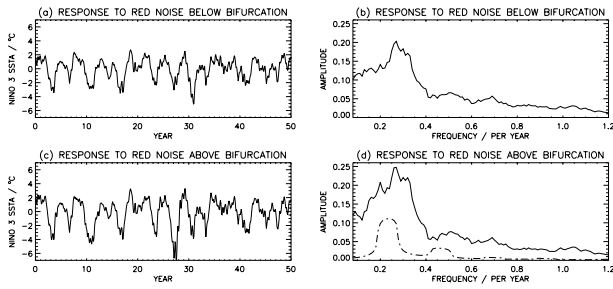
## Results

First the response of the model to the stochastic wind noise based on the complete residual windstress (Fig. 2b) was tested. Figures 3a and 3b show the response of the model in the subcritical regime while Figs. 3c and 3d show the response in the supercritical regime. In the subcritical case the stochastic noise is necessary for interannual variability. This variability, however, has a quite different spectrum to the noise that is driving it. There is a broad peak around 4 years, typical of ENSO. In the supercritical case the model exhibits regular interannual oscillations with a period of 4.5 years in the absence of noise. The addition of the red noise causes the ENSO peak to broaden.

Next the model was forced with the white “weather noise” products (Fig. 2c-e). Figure 4 shows the amplitude response of the model in its subcritical and supercritical regimes. The white noise forcing excites interannual variability in the subcritical regime and broadens the spectral



**Figure 2.** The amplitude spectra of the NINO4 zonal windstress of the different noise products described in the text.



**Figure 3.** The response of the model to the red noise forcing (Fig. 2b). The dashed curve in (d) is the amplitude spectrum for the noise free case.

peak of the pre-existing interannual variability in the supercritical regime. In neither case is the interannual peak as broad or high as when the model is driven by red noise.

The response of the model to the low frequency part of the white noise is similar to its response to the full white noise in both regimes. In the subcritical regime the high frequency noise excites a small interannual response, but the amplitude of this response is less than 20% of its amplitude when the model is forced by the full white noise. In the supercritical regime there is little broadening of the interannual peak but its amplitude is significantly reduced.

The small amount of power at interannual frequencies in the subcritical case is evidence of nonlinear processes. These processes do not seem to be very efficient and only generate a small amplitude response at low frequencies.

To further confirm this finding the model, in its supercritical regime, was forced with the MJO-type forcing. (Fig. 2f.) The result is shown in Fig. 5. As with the high frequency forcing case the amplitude of the primary interannual peak is reduced but again there is little transfer of power to other frequencies.

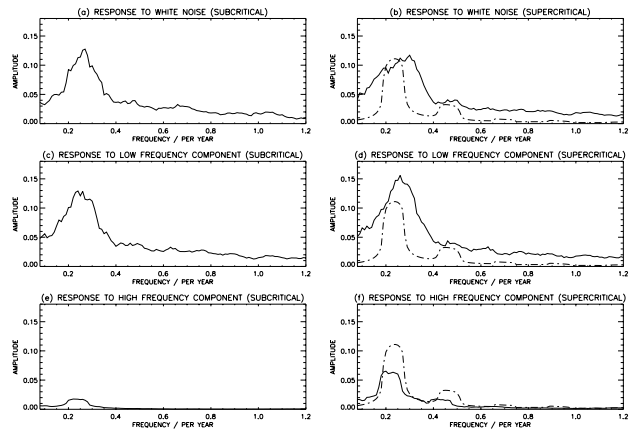
### Discussion and Conclusions

The small response of the subcritical model to the high frequency forcing indicates that nonlinear processes are not very efficient at transporting energy from intraseasonal to interannual frequencies. Even with stronger coupling the effect of stochastic forcing at intraseasonal frequencies on the interannual variability of the model is not great and has a damping effect. The ability of high frequency forcing to reduce the amplitude of the fundamental frequency of a nonlinear limit cycle is a property of systems just above hopf bifurcations. In the model the high frequency wind stress forcing enhances entrainment of cold water into the mixed layer thus damping the interannual oscillation without significantly impacting its phase or frequency. The similarity of the response of the model to the white noise product and the low frequency noise component is consistent with the type of response that would be expected from a largely linear system. We cannot exclude the possibility that mechanisms not included in this model might rectify power from the high frequency noise component into low frequencies [Kessler and Kleeman, 2000], but we can conclude that the primary nonlinearities affecting ENSO—within the upwelling and thermocline feedbacks—are not effective at this.

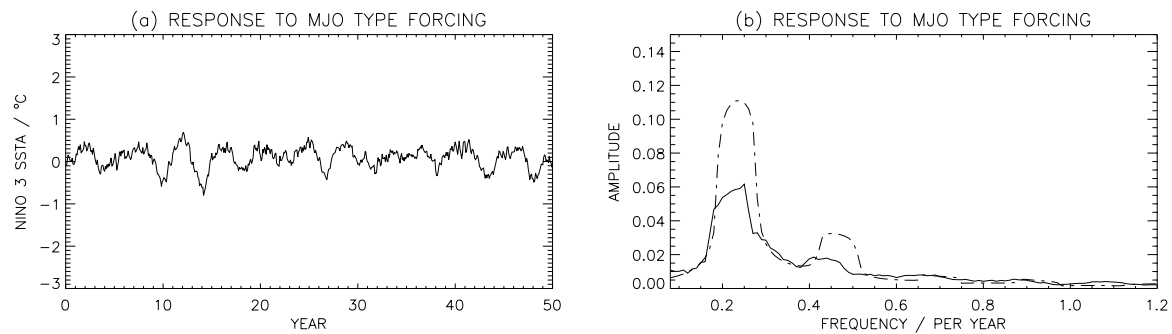
The small impact on the model of extra noise power at periods of 30 to 60 days implies that the variability at intrasea-

sonal frequencies associated with the MJO may not have a significant impact on the interannual variability associated with ENSO. These results are consistent with previous work [Zebiak, 1989] which found that forcing at intraseasonal frequencies had only a marginal effect on the statistics and the predictability of the Cane-Zebiak ICM. We note that this need not imply that the MJO effect on ENSO is small. Because the MJO has irregular temporal variability it has a low-frequency component to its spectral signature. The spatial patterns of variability characteristic of the MJO tend to project onto the modes of the ENSO system that have interannual frequencies [Moore and Kleeman, 1999]. However, it is the *low frequency* component of the MJO variability that may have a significant impact on ENSO, not the variability in the 30-60 day range. Other model experiments have shown that wind bursts can have a significant impact on the evolution of ENSO events [Latif et al., 1988] but it should be remembered that bursts or similar forcings have a low frequency component to their power spectrum. The results in this paper deal with effects on the interannual oscillatory behavior of ENSO *not* individual El Niño events.

In general, the results suggest that interannual forcing has the largest impact on the interannual response of the model, therefore climate noise has an important effect on ENSO variability. In this context, climate noise refers to the residual windstress variability with a red spectrum. The redness of the spectrum is probably the result of the memory of the ocean outside the model domain. Global models should, in principle, simulate this type of variability but if the model has only a regional ocean domain or if a global model fails to reproduce the observed amplitude of climate variability this would lead to an underestimate of the variability at ENSO-type frequencies in the tropical Pacific. The present study does not address the question of how the reddened climate noise is teleconnected from other ocean domains, nor which regions are the most important sources. We would summarize the results as a hypothesis that warrants further study in other models: that red climate noise communicated by the atmosphere from outside the Pacific domain can have substantial influence on ENSO.



**Figure 4.** The response of model NINO3 SSTA to the white noise and the filtered white noise products (Fig. 2c,d,e) in the subcritical and supercritical cases. The amplitude spectrum of the noise free supercritical case is shown (dashed curve) for comparison.



**Figure 5.** The response of the model to the MJO type forcing (Fig. 2f) when the model was *above the bifurcation*. The dashed curve is the amplitude spectrum for the noise free case.

The results and conclusions presented are model dependent. A model with stronger nonlinear processes could be more efficient at channeling power from intraseasonal to interannual frequencies. Some studies of the statistics of ENSO observations have suggested that ENSO can be described as a stable, linear, noise driven system [Penland, 1996; Burgers, 1999], while others conclude it is an unstable cycle perturbed by noise [Grieger and Latif, 1994]. Whether the real system is in the stable or unstable regime, the present results suggest that coupling between high frequencies and low frequencies is weak in both regimes.

**Acknowledgments.** This work was supported by NASA Earth System Science Fellowship NGT5-30068 and by NSF grant ATM-0082529.

## References

- Blanke, B., Neelin, J. D. and Gutzler, D., Estimating the effect of stochastic wind stress forcing on ENSO irregularity, *J. Climate*, *10*, 1473-1486, 1997.
- Burgers, G., The El Niño stochastic oscillator, *Clim. Dyn.*, *15*, 521-531, 1999.
- Gill, A.E., Some simple solutions for heat-induced tropical circulation, *Q.J.R. Meteorol. Soc.*, *106*, 447-462, 1980.
- Goldenberg, S.B. and O'Brien, J.J., Time and space variability of tropical Pacific wind stress, *Mon. Wea. Rev.* *109*, 1190-1207, 1981.
- Grieger, B. and Latif, M., Reconstruction of the El Niño attractor with neural networks. *Climate Dynamics*, *10*, 267-276, 1994.
- Jin, F.-F. and Neelin, J.D., Modes of interannual tropical ocean-atmosphere interaction - a unified view. Part I: Numerical results, *J. Atmos. Sci.*, *50*, 3477-3503, 1993.
- Kessler, W. S., and R. Kleeman, 2000: Rectification of the Madden-Julian oscillation into the ENSO cycle. *J. Climate*, *13*, 3560-3575, 2000.
- Kleeman, R. and Moore, A.M., A theory for the limitation of ENSO predictability due to stochastic atmospheric transients, *J. Atmos. Sci.*, *54*, 753-767, 1997.
- Kleeman, R. and Power, S.B., Limits to predictability in a coupled ocean-atmosphere model due to atmospheric noise, *Tellus A*, *46*, 529-540, 1994.
- Latif, M., Biercamp, J. and von Storch, H., The response of a coupled ocean atmosphere general-circulation model to wind bursts, *J. Atmos. Sci.*, *45*, 964-979, 1988.
- Leith, C.E., Predictability of climate. *Nature*, *276*, 352-355, 1978.
- Madden, R.A. and Julian, P.R., Observations of the 40-50 day tropical oscillation - a review, *Mon. Wea. Rev.*, *122*, 814-837, 1994.
- Moore, A.M. and Kleeman, R., The dynamics of error growth and predictability in a coupled model of ENSO, *Q.J.R. Meteorol. Soc.*, *122*, 1996.
- Moore, A.M. and Kleeman, R., Stochastic forcing of ENSO by the intraseasonal oscillation, *J. Climate*, *12*, 1199-1220, 1999.
- Neelin, J.D., Battisti, D.S., Hirst, A.C., Jin, F.-F., Wakata, Y., Yamagata, T. and Zebiak, S.E., ENSO theory, *J. Geophys. Res.*, *103*, 14,261-14,290, 1998.
- Penland, C., A stochastic model of Indopacific sea surface temperature anomalies, *Physica D*, *98*, 534-558, 1996.
- Smith, T.M., Reynolds, R.W., Livezey, R.E. and Stockes, D.C., Reconstruction of historical sea surface temperatures using empirical orthogonal functions, *J. Climate*, *9*, 1403-1420, 1996.
- Waliser, D.E., Lau, K.M. and Kim, J.H., The influence of coupled sea surface temperatures on the Madden-Julian oscillation: A mode perturbation experiment, *J. Atmos. Sci.*, *56*, 333-358, 1999.
- Zebiak, S.E., On the 30-60 day oscillation and the prediction of El Niño, *J. Climate*, *2*, 1381-1387, 1989.
- Zebiak, S. E. and M. A. Cane, A model El Niño Southern Oscillation. *Mon. Wea. Rev.*, *115*, 2262-2278, 1987.

Corresponding author: M.S. Roulston, Pembroke College, Oxford, OX1 1DW, United Kingdom (e-mail: roulston@maths.ox.ac.uk)

J.D. Neelin, University of California Los Angeles, CA 90095-1565 (e-mail: neelin@atmos.ucla.edu)

(Received June 23, 2000; revised August 15, 2000; accepted September 11, 2000.)