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A BASELINE STATISTICAL MODEL FOR TROPICAL PACIFIC WIND STRESS ANOMALIES

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1 INTRODUCTION

ENSO simulation and prediction remain a challenge, due in part to uncertainty about how tropical Pacific wind stresses respond to SST anomalies (SSTAs). In this study, we posit a simple statistical model for monthly-mean stress anomalies, namely a linear response to SSTAs plus noise, and then apply this model to two widely-used observational stress analyses. We find that (1) the response and noise characteristics of the two analyses are quite different, and (2) more than 75% of the observed stress anomaly variance is not linearly related to large-scale SSTAs. Coupling the stress model to an intermediate-complexity ocean model produces a transient ENSO mode which is sustained by noise. Experiments with this model suggest that ENSO predictability may be limited more by future atmospheric "weather" than by errors in ocean initial conditions—motivating a stochastic ensemble approach to ENSO prediction.

2 DATA

We consider monthly-mean wind stresses from two observational analyses: the NCEP/NCAR Reanalysis-1 (NCEP, Kalnay et al. 1996) and the Florida State University pseudostress (FSU, Stricherz et al. 1997). The FSU pseudostress $\|\mathbf{u}_a\|\mathbf{u}_a$ is converted to wind stress $\boldsymbol{\tau}$ using

$$\boldsymbol{\tau} = \rho_a c_d \|\mathbf{u}_a\|\mathbf{u}_a \quad (1)$$

with $\rho_a = 1.2$ kg m^{-3} and $c_d = 1.3 \times 10^{-3}$. Monthly-mean SSTs are from the Smith et al. (1996) reconstruction.

The data are averaged onto a 5.625° lon by 2° lat grid covering the tropical Pacific ocean (129.375°E–84.375°W, 20°S–20°N). A 12-month climatology is computed separately for 1961–79 and 1980–99, and then subtracted from the total fields to give monthly-mean SSTAs and stress anomalies ($\boldsymbol{\tau}'$) for each dataset and period.

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3 STATISTICAL STRESS MODEL

A simple statistical model for the stress anomalies is

$$\mathbf{Y} = \mathbf{X}\mathbf{W} + \mathbf{E} \quad (2)$$

where $\mathbf{Y}_{n\times q}$ is a matrix consisting of the n observed monthly-means of the q-element stress anomaly field, $\mathbf{X}_{n\times p}$ is the corresponding matrix for the p-element SSTA field, $\mathbf{W}_{p\times q}$ are time-independent weights multiplying the SSTAs, and $\mathbf{E}_{n\times q}$ are stochastic shocks. We assume *a priori* that the stress shocks are normally and independently distributed in time, with zero mean and a variance that is stationary in time.

Singular value decomposition of the SSTA/$\boldsymbol{\tau}'$ covariance matrix gives

$$\mathbf{C} = \frac{\mathbf{X}'\mathbf{Y}}{n-1} = \widetilde{\mathbf{A}}\mathbf{D}\widetilde{\mathbf{B}}' \quad (3)$$

where tildes denote nondimensional matrices. $\mathbf{D}_{r\times r}$ is a diagonal matrix, $r \equiv \min(p,q)$, whose diagonal elements are the singular values of $\mathbf{C}$. $\widetilde{\mathbf{A}}_{p\times r}$ and $\widetilde{\mathbf{B}}_{q\times r}$ are unitary matrices whose columns are the left (SST) and right (stress) singular vectors of $\mathbf{C}$.

The SSTA weights are estimated by regressing the observed stress anomalies onto a set of predictors—here taken to be the SSTA singular vector expansion coefficients that explain the greatest fraction of squared covariance between the observed $\boldsymbol{\tau}'$ and SSTA:

$$\widehat{\mathbf{Y}}_N = \mathbf{X}\widehat{\mathbf{W}}_N \quad (4)$$

$$\widehat{\mathbf{W}}_N = \widetilde{\mathbf{A}}_N \left(\widetilde{\mathbf{A}}'_N \mathbf{X}'\mathbf{X}\widetilde{\mathbf{A}}_N\right)^{-1} \widetilde{\mathbf{A}}'_N \mathbf{X}'\mathbf{Y} \quad (5)$$

$$\widehat{\mathbf{E}}_N = \mathbf{Y} - \widehat{\mathbf{Y}}_N \quad (6)$$

where $\widehat{\mathbf{Y}}_N$ and $\widehat{\mathbf{E}}_N$ are the deterministic and residual stresses estimated from N predictors. A predictor is included only if it is an essential part of a group of 3 or fewer predictors that, together, significantly improve the model at more than half the gridpoints. Improvement at a gridpoint is deemed significant if a two-tailed F-test on the change in residual sum of squares indicates less than 1% probability of that change occurring by chance.

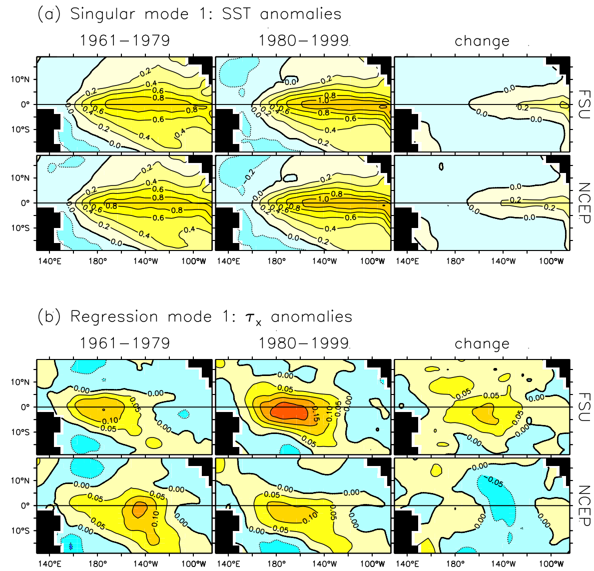

Figure 1: Mode 1 of the deterministic wind stress model. Projection onto the SSTA singular vector (°C) in panel (a) produces the corresponding zonal stress anomaly (dPa) in panel (b). (τ_y anomalies are not shown.)

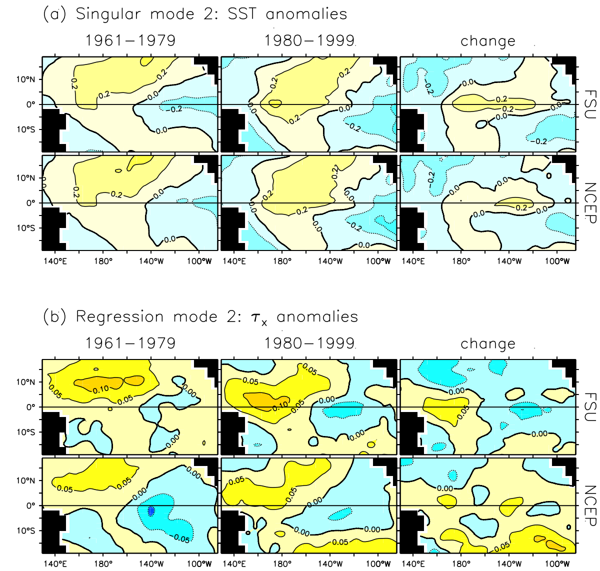

Figure 2: Mode 2 of the deterministic model.

Fig. 1 shows the leading regression mode for each dataset and time period. This mode accounts for about 87% of the SSTA/$\boldsymbol{\tau}'$ square covariance, and resembles the mature phase of an El Niño event: warm SSTAs in the equatorial eastern Pacific give rise to equatorial westerlies and off-equatorial easterlies in the west/central basin, and weak easterlies near the eastern boundary. Yet the details of the stress responses clearly differ between the analyses. At the equator, the NCEP response is weaker than FSU in the west Pacific, and shows a prominent peak near 145°W during 1961–79 that is not evident in FSU. And while FSU indicates a strengthening of the response since 1961–79, with increased convergence in the equatorial eastern Pacific, NCEP shows more of a weakening and a westward shift, with little change in the convergence in the east but instead increased convergence in the western and central Pacific.

Fig. 2 shows the second regression mode, which captures the onset/termination phases of ENSO and accounts for about 8% of the SSTA/$\boldsymbol{\tau}'$ square covariance. The $\boldsymbol{\tau}'$ response consists of westerlies in the northwest, and easterlies on and south of the equator in the east. The response is generally stronger in FSU, except during 1961–79 when NCEP shows strong easterlies near 140°W. And from 1961–79 to 1980–99, FSU indicates a strengthening of the westerly response in the western equatorial Pacific and a weakening in the east, while NCEP shows smaller and less coherent changes.

Table 1 indicates that the singular vectors included in the deterministic model account for most of the SSTA variance and SSTA/$\boldsymbol{\tau}'$ covariance in the observations, regardless of dataset or time period. But that the regression accounts for less than a quarter of the $\boldsymbol{\tau}'$ variance indicates that the bulk of the stress anomaly is *not* linearly related to simultaneous large-scale SSTAs. This residual variance is largely intraseasonal, and grows stronger away from the equator (not shown). The intraseasonal variance is more active in FSU than in NCEP, especially near the dateline and on the equator; this is why the regression models based on FSU admit fewer SSTA predictors than do those based on NCEP.

Fig. 3 indicates that the residual stresses in the western equatorial Pacific are linked to subsequent changes in the large-scale zonal SST gradient at the equator. The correlations are weak but statistically significant; for both periods and datasets, a westerly residual stress tends to be preceded 6–12 months earlier by central Pacific cooling, and followed 6–10 months later by warming. The correlations are stronger for FSU than NCEP, and stronger for 1980–99 than 1961–79. There is some evidence that the residual stress in the west is related to local changes in the zonal SST gradient at zero lag: all cases show warm simultaneous SSTAs slightly east of the reference point, and cold SSTAs slightly west.

The correlation of the residual stress with SSTA at positive lags may partly indicate the transient ocean/atmosphere response to stochastic stresses: i.e., westerly wind bursts initially warm the east Pacific (by flattening the thermocline and advecting the warm pool eastward) and cool the west Pacific (through increased evaporation and vertical mixing). Such changes would presumably be amplified by large-scale coupled feedbacks at long timescales.

On the other hand, the lag correlations in Fig. 3 also

Table 1: Number of modes retained in each statistical stress model, with the percent squared covariance, SSTA variance, and $\boldsymbol{\tau}'$ variance that project onto the singular vectors, and the percent $\boldsymbol{\tau}'$ variance captured by the regression model.

	1961–1979		1980–1999	
	FSU	NCEP	FSU	NCEP
number of modes	4	5	3	5
% square covariance	98	99	98	98
% SSTA variance	81	85	76	81
% $\boldsymbol{\tau}'$ variance				
singular vectors	23	44	25	39
regression	13	23	14	20

suggest that the stress is not simply a linear function of SSTA. In particular, the significant residual correlations at negative lags show that the residual cannot simply be stationary, independent Gaussian noise, as was assumed *a priori* in Section 3. Besides the tendency for westerly residuals during cold-to-warm transitions, the residual is unusually active during boreal winter and spring, and in some locations is not normally distributed and is significantly autocorrelated beyond one month lag (Wittenberg 2002). Clearly, the statistical model (2) is only a partial description of the wind stresses. A more complex version (including nonlinearity, seasonality, and nonstationary noise) is certainly warranted, but the available data record is rather short and uncertain to adequately constrain the additional parameters this would entail (Wittenberg 2003).

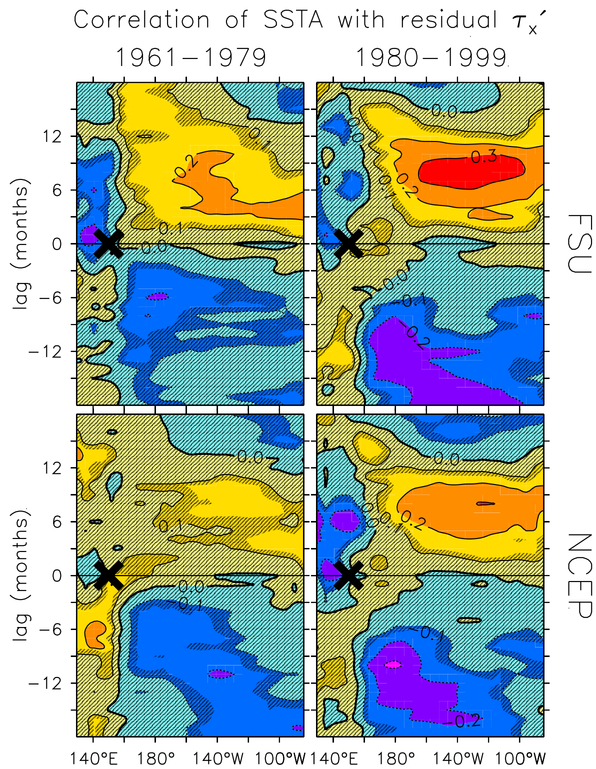

Figure 3: Correlation of the lagged observed equatorial SSTA with the residual zonal stress anomaly at a point (marked) on the equator at 150°E. Hatching masks values exceeded by more than 5% of correlations between white noise and the observed SSTAs.

4 IMPLICATIONS FOR ENSO FORECASTS

To examine the behavior of the coupled ocean/atmosphere under the assumption (2), we couple the statistical stress model to the intermediate-complexity ocean model of Wittenberg (2002). We shall present results only from the stress model based on the FSU 1980-1999 data—noting that other products may behave differently (Harrison et al. 2002). The residual stress is simulated by decomposing it into principal components, and then fitting a red noise timeseries model to each component.

In the absence of noise, the hybrid coupled model produces a damped ENSO with a period of 3.1 years and an e-folding decay time of about 10 years. Turning on the wind stress noise gives rise to a sustained, irregular ENSO, with a broad spectral peak around 3.3 years and a NINO3 SSTA standard deviation of about 1°C; both the amplitude and period are decadally modulated. This statistically stationary hybrid coupled model thus appears to mimic many of the properties of the observed ENSO.

To the extent that this hybrid model represents reality, it may help explain the failure of ENSO forecast models to anticipate the severity and sudden termination of the 1997–98 El Niño event (Landsea and Knaff 2000; Fedorov et al. 2003). Interestingly, both the FSU and NCEP products show sustained residual westerlies in the central Pacific during the onset of the event, and residual easterlies during its decay (Fig. 4). If these residual stresses were truly random, then it is perhaps not surprising that deterministic models (which as yet do not accurately simulate the full spectrum of tropical Pacific intraseasonal variability) failed to produce good forecasts.

To illustrate, Fig. 5 shows a particular run of the stochastically forced hybrid coupled model, which here serves as the "truth" to be predicted. At the beginning of year 20, following a mild cold event, the truth is used to initialize two types of forecasts. The first is a deterministic forecast without noise (solid line). This forecast does head into an El Niño, indicating that the excessive heat content which had accumulated in the west/central Pacific during the preceding La Niña had predisposed the system toward a warming. Yet this forecast underestimates the severity and rapid decay of the true event, since the truth happened to receive a sustained series of random westerly wind bursts during its onset and a series of easterly bursts during its decay. This may well have been the case for the 1997–98 El Niño.

The specific wind bursts that occurred for the "truth" in Fig. 5 could never have been predicted. However, as

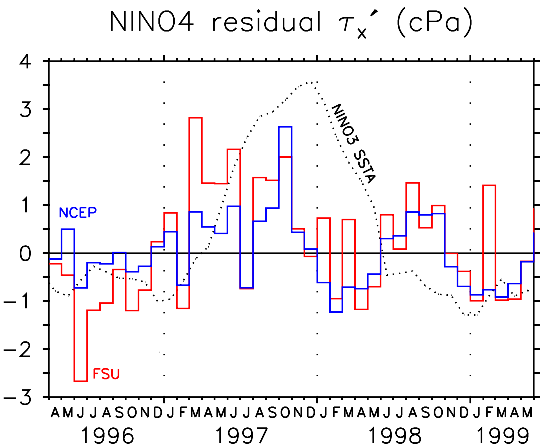

Figure 4: Residual zonal wind stress (cPa) averaged over the NINO4 region (160°E–150°W, 5°S–5°N) for FSU (solid) and NCEP (dashed). Also shown are the SST anomalies (°C) averaged over the NINO3 region (150°W–90°W, 5°S–5°N, dotted).

their *statistics* were known, it would have been possible to forecast the *risk* of a severe El Niño. To illustrate, the contours in Fig. 5 show the quantiles of an ensemble of 200 independent forecasts initialized from the truth at the beginning of year 20. Though they start from identical initial conditions, each ensemble member subsequently receives a different realization of the stochastic stress, which eventually causes the ensemble to disperse. From the forecast quantiles it is clear that the "truth" was quite an unusual case: fewer than one percent of the forecasts exceeded its peak amplitude in August of year 20 and in December of year 21.

The point is that this stochastic ensemble forecast *could not have been improved*, since the initial conditions, forecast model, and noise statistics were all perfect. Further experiments with perturbed initial conditions and no noise show very little dispersion and grossly underestimate the risk of strong events— it appears atmospheric "weather" trumps data assimilation errors for limiting predictability in this model.

5 CONCLUSION

The surface wind stress over the tropical Pacific ocean is crucial for understanding and forecasting El Niño— yet simulating the observed stress remains a challenge for atmospheric GCMs. We have described a statistical stress model that can serve as both a realistic feedback for ocean simulations, and a tool for evaluation and intercomparison of atmospheric models. The model consists of deterministic and stochastic parts. Both parts are sensitive to the particular time period and observational dataset used to fit the model, underscoring both the importance of decadal changes in ENSO and the need for

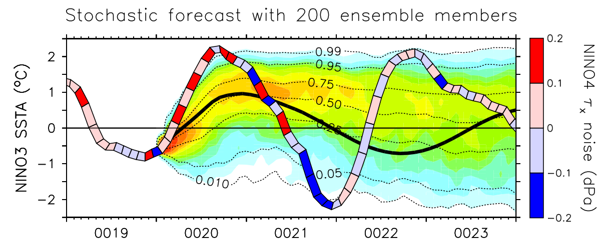

Figure 5: Stochastic probability forecast of NINO3 SST anomalies. The stochastic control run is illustrated as a banded tube, where the colors indicate the NINO4 amplitude of zonal stress noise in that run. The control run provides the initial conditions, beginning in year 20, for 200 stochastic forecasts forced by different realizations of the noise. The contours give the fraction of forecasts colder than a given temperature. Solid line shows the evolution of a forecast without noise.

improved stress reanalyses.

Coupling an ocean model to the statistical stress yields a reasonable ENSO simulation, supporting the view that the phenomenon may represent a damped oscillator driven by noise. With this perspective, "surprises" like the very strong 1997–98 El Niño are no longer so surprising and should be expected from time to time. Society could better manage the risk of these events if provided with reliable probability forecasts, which will require an improved understanding of the structure of the stochastic forcing and its interaction with ENSO.

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