NOTES AND CORRESPONDENCE

Local and Remote Forcing of ENSO Ocean Waveguide Response

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22 July 1988 and 6 October 1988

ABSTRACT

Several experiments using an ocean general circulation model have been carried out in order to explore the degree to which the oceanic waveguide response during the 1982–83 ENSO event was locally and remotely forced. Experiments in which the chosen monthly mean surface stress field was imposed only within three degrees of the equator (3°N/S) and within seven degrees of the equator (7°N/S) reveal that the 7°N/S winds reproduce the equatorial results of the full winds case to within differences small compared to the variability of interest. The 3°N/S winds case reproduces equatorial dynamic height acceptably, but introduces errors in SST and upper-ocean currents that approach the ENSO signal. A 7°N-S experiment in which the meridional stress is set to zero (NOYST) shows that meridional stress plays a nontrivial, but not dominant role, in the 1982–83 model behavior; errors generally are comparable to those of the 3°N/S case. A final experiment, in which the 1982–83 winds were imposed west of the dateline and climatological winds were imposed east of 170°W (WPAC), illustrates the extent to which the central and eastern Pacific were forced by winds in the western Pacific. While there is nontrivial remote forcing, the locally forced variability is roughly twice as great.

Implications for coupled ocean–atmosphere modeling and for design of future surface wind stress monitoring arrays for ENSO prediction are considered.

1. Introduction

Owing to the past decade of measurements and data analysis in the tropical Pacific, it is now clear that oceanic variability occurs widely during ENSO events. In order to plan for future observational efforts directed to increasing our ability to predict ENSO events with coupled ocean–atmosphere models, it is necessary to try to identify the essential elements of the variability that determine the behavior of the coupled ocean–atmosphere system. Sea surface temperature (SST) variations appear to be the primary physical variable as far as the atmosphere is concerned. The essential elements for the ocean are not so clear at present, because the ocean not only responds to both wind stress and surface heat flux changes, it also permits propagation and evolution of anomalous density field features over periods that can be as long as the duration of a typical ENSO event. In this Note some ocean model results are presented that bear on determining the essential oceanic elements.

Most atmospheric model studies of ENSO have used large space scale SST anomaly fields for model boundary conditions. The largest relative SST anomalies (SST anomaly normalized by the standard deviation of SST) occur within the equatorial waveguide and along the northwestern South American coast. The processes that determine the meridional extent of the SST anomaly have not been described, but Ekman transport out of the waveguide is plausibly responsible for a substantial part of the spread. If this is correct, then understanding waveguide SST change processes is a central part of the problem.

Some recent progress has been made concerning the importance of extrawaveguide thermal anomalies in the oceanic ENSO cycle. Observations suggest that anomalous conditions existed north of the waveguide in the central and western tropical Pacific in 1981, well before the 1982–83 ENSO event (e.g., White et al. 1985) and some simple model studies indicate that similar anomalies can be generated by wind forcing (Inouye et al. 1987). But were these anomalies important to the subsequent equatorial waveguide thermal variability? Recent hindcasts of the 1982–83 event, using climatological model January initial conditions, and different analyses of the surface wind fields found excellent equatorial upper-ocean dynamic height skill was possible (Harrison et al. 1989), suggesting that the free evolution of the 1981 extra-equatorial anomalies was not a central part of the subsequent near-equatorial dynamic height behavior. In other words, even if the baroclinic anomaly north of the waveguide in 1981 propagated westward and reflected off the western Pacific coastline, ultimately sending an equatorial Kelvin pulse eastward in 1982, this Kelvin pulse did not have enough amplitude in dynamic height to produce a significant discrepancy between the model wind-forced

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equatorial dynamic height variability and observations during the ENSO period.

The relative importance of local and remote forcing within the waveguide itself has been of interest since the work of Wyrtki (1975) and McCreary (1976). Also, it has been suggested that zonal wind stress changes cause the primary waveguide response (Cane 1985), based on low-frequency linear long-wave dynamics. During the 1982–83 ENSO event every available surface wind field indicates that there were substantial departures from climatological conditions in the central and eastern central Pacific, and that meridional wind anomalies were a prominant part of the ENSO wind changes (e.g., Harrison et al. 1989).

The purpose of this work is to explore which aspects of the tropical surface wind stress field are important in determining the model upper ocean thermal field within the waveguide during 1982–83. In particular, the extent to which response is forced locally or remotely will be examined, using a series of ocean general circulation model experiments.

A series of ocean model experiments have been carried out to explore these questions; the results of five experiments are reported here. Each experiment makes use of some form of the surface wind pseudostress fields produced by Jim Sadler's group at the University of Hawaii and uses exactly the same primitive equation ocean model as described in Harrison et al. (1989) and Philander and Seigel (1985). The reference experiment (henceforth REF) used the complete SADLER fields, and is the experiment labeled "SADLER" in Harrison et al. (1989): the second experiment here (henceforth called "3N/S") used the SADLER fields within 3°N and S of the equator and were then held at their 3° values further poleward; the third experiment used SADLER stresses within 7°N and S latitude ("7N/S") and more poleward values were held at their 7° value. The radius of deformation of the first baroclinic mode is about 3 deg so the 3N/S experiment involves accurate winds roughly spanning the waveguide, while the 7N/S experiment includes accurate forcing out to a bit past two radii of deformation for the first mode. Neither experiment includes accurate forcing in the North Equatorial Counter Current (NECC) latitudes. These experiments will address the issue of waveguide response forced by extrawaveguide wind stress changes.

The fourth experiment (NOYST) used the 7N/S zonal wind stress only; the meridional wind stress was set to zero. The fifth experiment (WPAC) used the full SADLER wind stress field west of the dateline, the monthly mean climatological stresses of Hellerman and Rosenstein (1983) east of 170°W, and bilinear interpolation between the fields spanning 170°W and 180°. These experiments will address questions of forcing within the waveguide.

The SADLER stresses are used because they produced very good equatorial dynamic height comparisons with observations, because they had the best extrawaveguide dynamic height comparisons, and because they produce the most dramatic changes in surface currents and SST within the waveguide of all the hindcasts (see Harrison et al. 1989 for detailed comparisons). Thus it seems reasonable to expect that these results would be the most difficult to reproduce of those in that study.

It should be noted that the model parameterizes the surface heat flux at every grid point in terms of only the wind speed and the SST values at that point (see Philander and Siegel 1985, for details of the surface heat flux parameterization). Thus, wherever the wind is imposed and the SST has remained at its value from the reference experiment the net surface heat flux will be identical to that of the reference case. Until SST values depart significantly from their reference experiment values, they can be altered only by ocean current changes.

The inevitable limitations of idealized studies such as these will not be belabored here; the results reported clearly depend upon the wind field used, and it is not possible to establish their generality. Other limitations of this modeling approach are discussed in the last section. Whether of general applicability or not, the results presented here offer a useful framework for further studies with coupled ocean–atmosphere models.

2. Results

Table 1 presents rms differences, for upper ocean quantities of interest, between the REF experiment and each of the other experiments. Note that the values presented for WPAC-REF differences are for maximum values east of the dateline. Note also that there tends to be significant variation of RMS difference as a function of longitude, so ranges of values typically are quoted. Clearly the 7N/S experiment has quite

TABLE 1. Equatorial rms differences from REF experiment.

		T (°C)		U (cm s^{-1})	
Experiment:	SST	Thermocline	0–250 m	Surface	Thermocline
3N/S	0.8 → 1.2	~1.5	~1.2	10 → 60	10 → 15
7N/S	0.3 → 0.7	~0.6	~0.5	7 → 12	5 → 8
NOYST	0.7 → 1.2	~0.5	~0.7	20 → 30	10 → 30
WPAC	up to 6	up to 4	up to 5	30 → 60	~30

small differences; it produces differences significantly smaller than the ENSO variability in REF, for every comparison done. The 3N/S experiment is substantially less successful than 7N/S; in several of the comparisons the differences found are nearly comparable to the ENSO signal in REF. The NOYST experiment produces differences comparable to the 3N/S experiment, except that it does better on thermocline temperature. The WPAC experiment produces the largest differences, and differences that are unacceptably large in all variables. It is useful to consider a few specific timeseries comparisons to show the character of the differences found.

First consider equatorial upper ocean heat content comparisons for the REF, 3N/S, and 7N/S experiments (Fig. 1). Upper ocean heat content is tantamount to upper ocean dynamic height calculations in these experiments, because salinity effects are here of secondary importance in dynamic height changes. Figure 1 shows 0–250 m average temperature timeseries at 100°, 160°W, and 165°E on the equator. Note that the qualitative behavior is very much the same for all three experiments at each location, and these results are typical of other longitudes across the basin. Evidently it is adequate to provide only 3N/S winds to reproduce this most widely studied aspect of the ENSO waveguide signal, which has been modeled mostly with very simple physics (e.g., Busalacchi and Cane 1985).

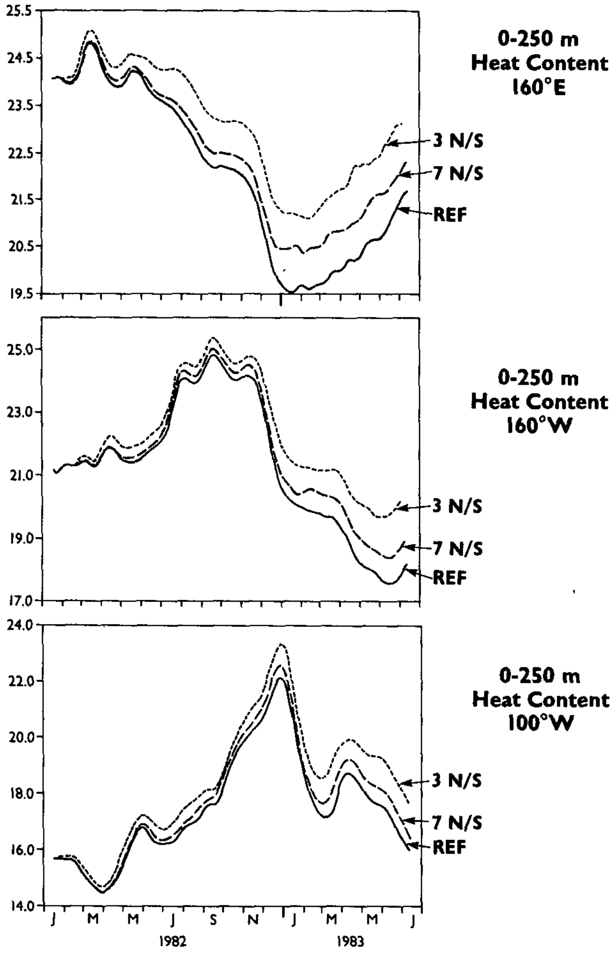

FIG. 1. Equatorial 0–250 m. average temperature (heat content) vs. time at 160°E, 160°, and 100°W for the REF, 3N/S, and 7N/S experiments. See text.

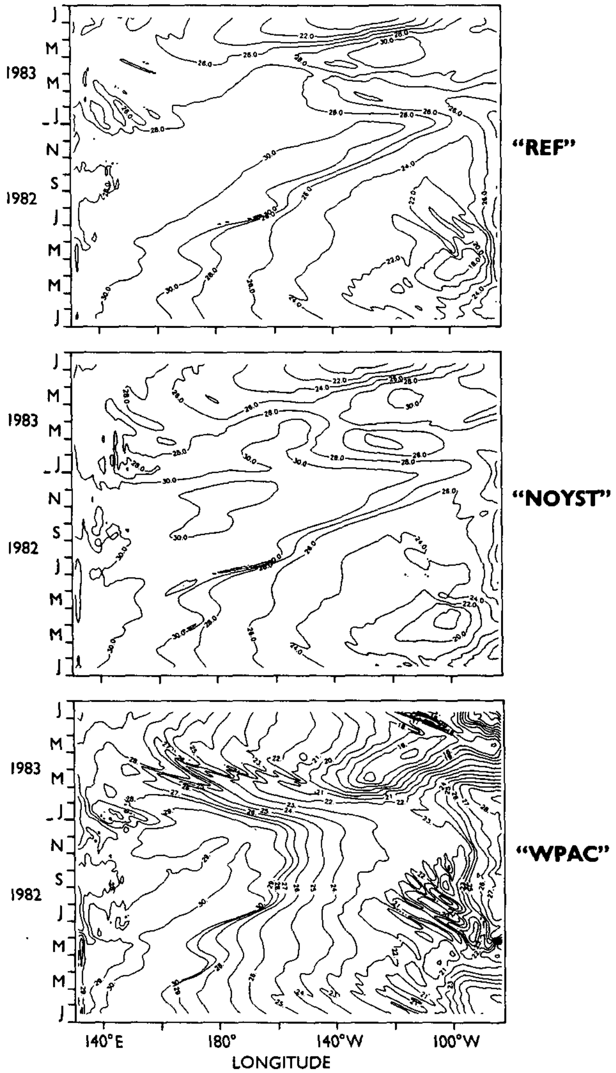

FIG. 2. Equatorial SST across the basin vs time for the REF, NOYST, and WPAC experiments. See text.

The Table 1 data indicate that the rms differences between REF and 3N/S are about 1°C across the basin; between REF and 7N/S about 0.5°C across the basin. Given the typical error estimate of about 0.2°C for an XBT profile, the 7N/S rms difference is only about twice the observational uncertainty that would result from a single cast. Note that the rms vertically averaged temperature signal in REF is about 3°C in the eastern central Pacific and about 1.7°C in the western Pacific; as noted above, the 7N/S errors are small compared with the model ENSO heat content signal.

Although dynamic height changes are of interest, changes in upper-ocean temperatures and currents are of more concern to ENSO modelers, because they are variables intrinsically involved in ocean dynamics and ocean–atmosphere coupled processes. Figure 2 presents time series of equatorial SST across the basin for the REF, NOYST, and WPAC experiments. (The 3N/S and 7N/S experiments are so similar in pattern to the REF experiment that it is not interesting to compare their results in this fashion.) Note that the NOYST experiment reproduces the qualitative behavior of REF very well—the movement of water warmer than 28°C from the dateline in May 1982 to the eastern Pacific in December 1982, a period of quite warm conditions in early 1983 and then rapid cooling in mid-1983 that begins first in the central Pacific and spreads eastward. However, the quantitative differences are typically about 1°C or somewhat greater. The WPAC experiment also shows warming penetrating into the eastern Pacific, so that it is perhaps 2°C warmer than it was in early 1982, but it is much cooler than REF. Clearly the eastern Pacific warming forced by wind changes in the western Pacific was only part of the model ENSO signal; locally forced warming is very significant even with the SADLER wind field.

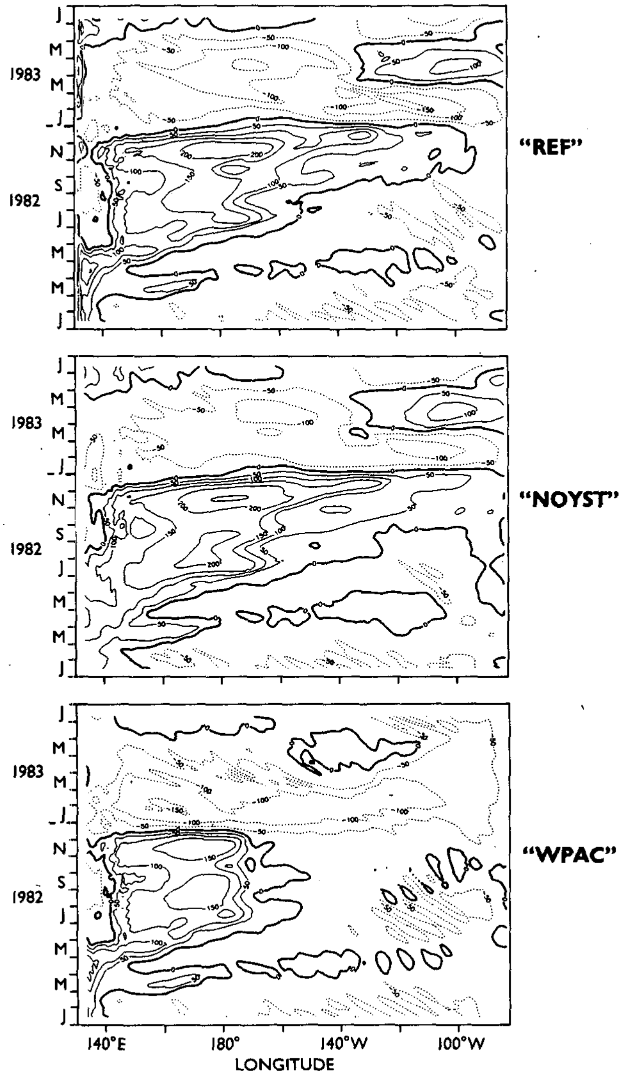

FIG. 3. Equatorial surface zonal velocity across the basin vs time for the REF, NOYST, and WPAC experiments. See text.

Examination of the equatorial surface zonal velocity fields illustrates the effects (Fig. 3). Surface eastward flow extends across the basin in late 1982 in both the REF and NOYST experiments, but is not found systemmatically east of about 150°W in the WPAC experiment. Note that in the WPAC experiment the normal eastern and central Pacific surface westward flow is greatly reduced, and that the instability waves (which are normally prominent late in the calendar year) are gone late in 1982; substantial remotely forced changes have taken place, but these changes are only part of the response.

3. Summary and discussion

It has been shown that imposing the 1982–83 SADLER monthly mean windstress only within 7° of the equator leads to model equatorial upper-ocean current and temperature behavior very similar to that produced when the winds are imposed within 30° of the equator. Relative to the ENSO changes produced by the 30N/S winds, the 7N/S differences are small. When a more extreme truncation of the winds is imposed, to within 3° of the equator, upper-ocean dynamic height is still acceptably hindcast, but other differences begin to approach the ENSO signal magnitude.

When the meridional wind stress is omitted, but the zonal wind stress is retained within 7° of the equator, the magnitude of the differences becomes similar to that produced by the 3N/S experiment. Evidently the meridional wind contributed nontrivially to model near equatorial behavior during the 1982–83 ENSO event. Because the meridional wind has considerable power in the 3- to about 7-day band near the equator (e.g., Luther and Harrison 1984), it is difficult to obtain accurate low frequency information about it from conventional merchant marine observations. This work suggests that accurate ocean modeling of the waveguide requires that we find ways to observe the meridional wind accurately.

When only the western Pacific wind stress is imposed, and climatological forcing is maintained east of the dateline, very large differences are found in the central and eastern Pacific. There is clear evidence of remote forcing of the eastern and central Pacific waveguide, but the locally forced response is at least as important as the remotely forced response.

Thus accurate representation of the zonal and meridional stress within 7° of the equator appears adequate for acceptable waveguide studies of the 1982–83 period. Interestingly, it also appears unnecessary to have ocean information outside the waveguide for these studies; recall that Harrison et al. (1989) obtained very satisfactory waveguide dynamic height hindcasts for this event, while explicitly excluding the possibility of propagation of energy from outside the waveguide in 1981 into the waveguide during 1982. From the forced-ocean model perspective adopted here, one would infer that ocean waveguide behavior during the 1982–83 ENSO period was controlled by waveguide and near-waveguide forcing and data alone. Additional work will be needed to determine if similar coverage would suffice for studies of the annual cycle or of other two-year periods.

Of course the ENSO phenomenon is fundamentally a coupled ocean–atmosphere process. Adopting the single fluid perspective of the ocean, as has been done here, limits the inferences about ENSO mechanisms that can be drawn from this study. The ideal experiments would be done with a coupled ocean–atmosphere model that was able to reproduce the 1982–83 ENSO event from some set of initial data. One could then restrict the spatial extent of ocean–atmosphere interaction permitted, and see if the event could be reproduced satisfactorily. One might imagine some experiments in which SST variation was restricted, and others in which wind variation was restricted. To the author's knowledge no such experiments have been done. A very interesting result using a simple coupled ocean–atmosphere model has been reported by Battisti (1988), which tends to support the ocean model result; he filtered his model winds to zero poleward of 5° latitude, and yet obtained no significant equatorial waveguide differences. To date, only equatorial waveguide coupled processes have been invoked to rationalize the available coupled model ENSO cycles (Suarez and Schopf 1988; Schopf et al. 1989; Battisti 1988); the claim by Graham and White (1988) that extrawaveguide variability must be incorporated into an ENSO scenario in order to rationalize the behavior of these models is not correct.

The need to explore these questions more fully, with a physically realistic coupled ocean–atmosphere model that reproduces observed ENSO events is clear. Until such studies have been done, we can only speculate on the basis of the behavior of simpler systems.

The atmosphere and ocean are full of low frequency variability in and near the tropics. The disruptions associated with each ENSO event force oceanic motions that are expected to persist for years subsequent to each event. Determining which aspects of the variability are fundamental elements to the coupled system's future behavior, and which are energetic but relatively unimportant, is a challenge at present. In a quasi-periodic system it can be very difficult to distinguish between the two; many realizations, encompassing a considerable range of event separations in time will need to be examined. Similar comments can be made for atmospheric variability associated with ENSO.

REFERENCES

Battisti, D. S., 1988: The dynamics and thermodynamics of a warm event in a coupled atmosphere/ocean model. *J. Atmos. Sci.*, **45**, 2889–2919.

Busalacchi, A. J., and M. A. Cane, 1985: Hindcasts of sea level variations during the 1982–83 El Nino. *J. Phys. Oceanogr.*, **15**, 212–221.

Cane, M. A., 1984: Modeling sea level during El Nino. *J. Phys. Oceanogr.*, **14**, 1864–1874.

Graham, N. E., and W. B. White, 1988: The El Nino cycle: A natural oscillator of the Pacific ocean-atmosphere system. *Science*, **240**, 1293–1302.

Harrison, D. E., W. S. Kessler and B. S. Giese, 1989: Ocean circulation model hind casts of the 1982–83 El Niño: Thermal variability along the ship of opportunity tracks. *J. Phys. Oceanogr.*, **19**, 397–418.

Hellerman, S., and M. Rosenstein, 1983: Normal monthly wind stress over the world ocean with error estimates. *J. Phys. Oceanogr.*, **13**, 1093–1104.

Inoue, M., J. J. O'Brien, W. B. White and S. E. Pazan, 1987: Interannual variability in the tropical Pacific Ocean for the period 1979–1982. *J. Geophys. Res.*

McCreary, J. P., 1976: Eastern tropical ocean response to changing wind systems: With application to El Nino. *J. Phys. Oceanogr.*, **6**, 632–645.

McCreary, J., and D. L. T. Anderson, 1984: A simple model of El Nino and the Southern Oscillation. *Mon. Wea. Rev.*, **112**, 934–946.

Philander, S. G. H., and A. D. Seigel, 1985: Simulation of El Nino of 1982–83. *Coupled Ocean-Atmosphere Models*, J. Nihoul. Ed., Elsevier, 517–541.

Schopf, P. S., M. J. Suarez and S. K. Kim, 1989: An alternative formulation of the delayed-action oscillation for ENSO. *J. Atmos. Sci.*, in press.

Suarez, M. J., and P. S. Schopf, 1988: A delayed action oscillator for ENSO. *J. Atmos. Sci.*, **45**, 3283–3287.

White, W. B., G. A. Meyers, J. R. Donguy and S. E. Pazan, 1985: Short-term climatic variability in the thermal structure of the Pacific Ocean during 1979–1983. *J. Phys. Oceanogr.*, **15**, 917–935.

Wyrtki, K., 1975: El Nino—the dynamic response of the equatorial Pacific Ocean to atmospheric forcing. *J. Phys. Oceanogr.*, **5**, 572–584.