NOTES AND CORRESPONDENCE

The Heat Budget of the Tropical Pacific Ocean in a Simulation of the 1982–83 El Niño

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31 August 1987 and 7 December 1987

ABSTRACT

The heat budget of a model that realistically simulates the 1982–83 El Niño indicates that the enormous changes in the winds during that event failed to disrupt the usual seasonal variations in meridional heat transport. Cross-equatorial transport towards the winter hemisphere continued as in a regular seasonal cycle. The key factor was the continued seasonal migrations of the ITCZ during El Niño. In early 1983 the ITCZ strayed farther south than usual and remained near the equator longer than usual thus causing an increase in the northward heat transport. This, together with an increase in the evaporative heat loss because of higher sea surface temperatures, resulted in a large loss of heat from the band of latitudes approximately 12°N–12°S during El Niño.

1. Introduction

Sea level measurements indicate that the average temperature of the upper equatorial Pacific Ocean decreased during the 1982–83 El Niño because of a poleward export of warm surface waters (Wyrtki 1985). Zebiak and Cane (1987) find that the same happens during the warm El Niño phase of the Southern Oscillation in their model: the spatially averaged depth of the thermocline in the equatorial zone decreases. These observational and theoretical studies emphasize that in addition to the zonal redistribution of warm surface waters, which leads to unusually high sea surface temperatures in the eastern tropical Pacific during El Niño, there is a meridional redistribution of warm surface waters. In the model of Zebiak and Cane El Niño occurs only if the spatially averaged value of the depth of the thermocline in the equatorial zone exceeds a certain value. Hence the meridional redistribution of heat determines whether or not necessary conditions for the occurrence of El Niño are satisfied. These results, if valid, are of considerable importance because they imply that we can determine whether El Niño is possible at a certain time by measuring the spatially averaged depth of the thermocline in the equatorial zone. The results also suggest that the conditions that lead to El Niño, an unusually large amount of warm surface waters near the equator, are eliminated by the occurrence of El Niño. In other words, mean conditions that favor unstable ocean–atmosphere interactions and the development of El Niño are altered and stabilized by the interactions.

It appears that variations in the heat budget of the tropical Pacific may be a critical aspect of El Niño. Many questions concerning this heat budget are unanswered. For example, is an increase in evaporation from the ocean surface important during El Nino? The temperature of the tropical troposphere increases significantly during El Niño (Horel and Wallace 1981) and the most probable source of heat is increased evaporation from the ocean surface. Does this loss affect the ocean? During a regular seasonal cycle the flux of heat into the equatorial ocean across its surface compensates exactly for the heat exported poleward in the ocean. Is the poleward heat transport much larger during El Niño than during a regular seasonal cycle? Wyrtki (1974) has observed that during the warm El Niño phase of the Southern Oscillation warm surface waters flow eastward in the equatorial Pacific when the westward surface currents weaken, and sometimes reverse direction, while the eastward North Equatorial Countercurrent intensifies. During the cold phase of the Southern Oscillation the warm surface waters in the east do not simply flow back to the west because the intensified westward surface currents have low temperatures. How does the western equatorial Pacific recover the heat lost during El Niño? This paper addresses some of these questions by analyzing data from a realistic simulation of the 1982–83 El Niño with a General Circulation Model (Philander and Seigel 1985).

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2. The model

For details concerning the high-resolution general circulation model the reader is referred to Philander and Seigel (1985) who simulated the 1982–83 El Niño, and Philander et al. (1987a) who used the model to study the climatological seasonal cycle of the tropical Pacific Ocean. In this study we start by reproducing a climatological seasonal cycle—the model is in equilibrium with the winds described by Hellerman and Rosenstein (1983)—and then, from January 1982 onwards, the model is forced with the "observed" surface wind field provided by the National Meteorological Center. These winds were used in the simulation of the 1982–83 El Niño by Philander and Seigel. No attempt is made to smooth the abrupt transition from climatological to "observed" monthly mean winds so that unrealistic transients are excited. Philander et al. (1987b), in a study of the effect of different initial conditions on simulations with the General Circulation Model find that such transients persist for approximately one year and are most energetic in the eastern equatorial Pacific in the form of Kelvin waves. The change in the winds in January 1982 is relatively modest in comparison with the changes during 1982–83 and the transients are not believed to affect the results significantly. In the figures, the year 1981 is represented as a climatological seasonal cycle. A discontinuous change on 1 January 1982 is evident in Fig. 1 but not in Fig. 5. One important difference between the model as used here and earlier versions is the following: in the formula to calculate the heat flux across the ocean surface the air temperature is specified from observations. The sea surface temperature that the model calculates is realistic, suggesting that the heat flux across the ocean surface in the model is what is needed to simulate the observed sea surface temperature.

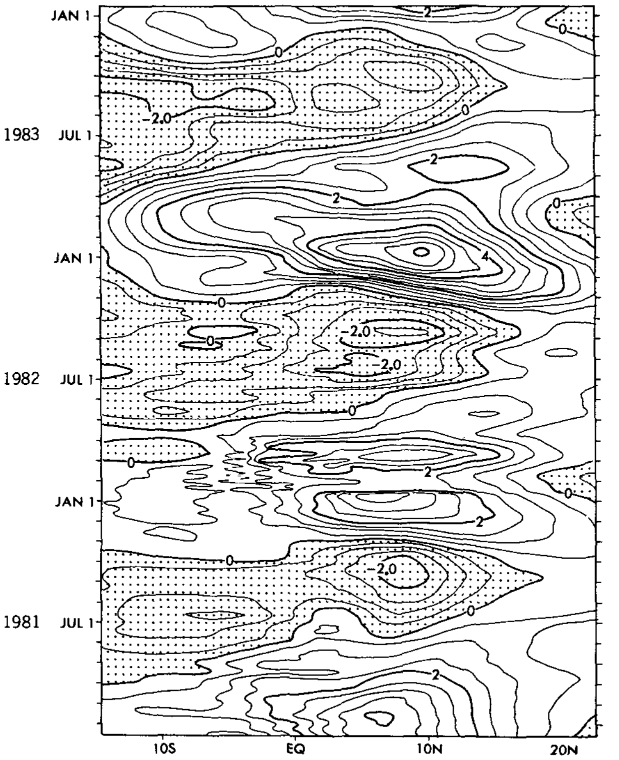

FIG. 1. Vertically and zonally integrated meridional heat transport HT in petawatts. The contour interval is 0.5 petawatts. Transport is southward in shaded areas. The year 1981 in this and subsequent figures is a climatological seasonal cycle.

3. Results

Figure 1 shows the zonally and vertically integrated meridional heat transport HT in the model

$$\mathrm{HT} = \rho c_p \int_{-H}^{0} dz \int_{0}^{L} vT dx$$

(the notation is standard). During a regular seasonal cycle—the year 1981 in Fig. 1—HT is always towards the winter hemisphere: northward from November through May; southward during the other months of the year. The maximum seasonal variation is near 10°N. The northward transport of heat across the latitude results primarily from the northward Ekman drift of warm surface waters and the return of colder water in the thermocline. Hence variations in HT near 10°N depend strongly on variations in the zonal component of the wind near 10°N. The intensity of the winds, in turn, depends on the seasonal migrations of the ITCZ. When the ITCZ is near the equator, early in the year, the northeast trades are intense near 10°N, so that the northward Ekman drift of warm surface waters across that latitude is large. In August and September, when the ITCZ is farthest north, the winds near 10°N are relaxed and the Ekman drift is weak. Although this drift is still northward in August, the heat transport across 10°N at that time is southward in Fig. 1. An inspection of the currents in the model indicate that a relatively steady southward current off the coast of the Philippines transports warm waters southward (Philander et al. 1987a) and contributes to the equatorward transport of heat.

During the early months of the year the heat transport in Fig. 1 is northward in both hemispheres. North of the equator intense northeast trades prevail so that Ekman drift carries warm surface waters northward, but south of the equator the southeast trades are relaxed and drive weak Ekman drift southward across 10°S, for example. A warm equatorward current off New Guinea contributes significantly to the equatorward transport of heat at this time.

In the low latitudes of the Pacific Ocean the equatorward transport of warm water is primarily in western boundary currents and the poleward transport is in the form of Ekman drift across the width of the basin. The zonal equatorial currents link the equatorward and poleward fluxes as explained by Philander et al. (1987a).

The regular seasonal cycle was seriously disrupted during 1982 and 1983. The tradewinds collapsed near the equator where westerly winds prevailed at times. This caused substantial changes in the oceanic circulation: the westward South Equatorial Current weakened and reversed direction in some places; the Equatorial Undercurrent disappeared for a while where there are observations (Firing et al. 1983; Halpern 1987). It is therefore remarkable that in Fig. 1 the variations in meridional heat transport during 1982–83 are strikingly similar to the variations during a regular seasonal cycle. This happened because the movements of the ITCZ determine variations in the meridional heat transport and during El Niño the ITCZ continues its seasonal migrations except that it tends to be equatorward of its usual position (Pazan and Meyers 1982; Ramage and Hori 1981; Rasmusson and Wallace 1983). During the second half of 1982 the ITCZ started its equatorward movement earlier than usual so that the southeast trades were more relaxed than normal, the southward Ekman drift across 10°S for example was weaker than usual and, in Fig. 1 the southward heat transport across that latitude in August was smaller in 1982 than in the preceding and following years. By early 1983 the ITCZ was farther south than usual and remained near the equator longer than usual. The trades near 10°N were exceptionally strong, as shown in Fig. 2, and hence the Ekman drift and the northward heat transport were enhanced, as is evident in Fig. 1. In summary, the phase of the annual change in meridional heat transport was unaltered during the 1982–83 El Niño but the southward transport in the region south of the equator decreased during the southern winter of 1982 and the northward transport increased during the subsequent southern summer. The net result was an increase in the northward transport of heat during that year.

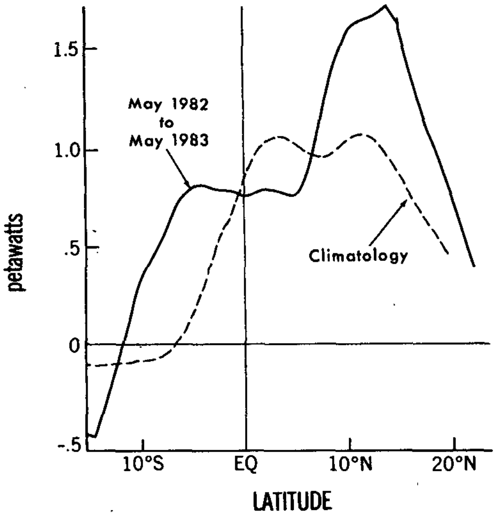

FIG. 3. The time-averaged meridional heat transport for a climatological year and for the year starting in May 1982.

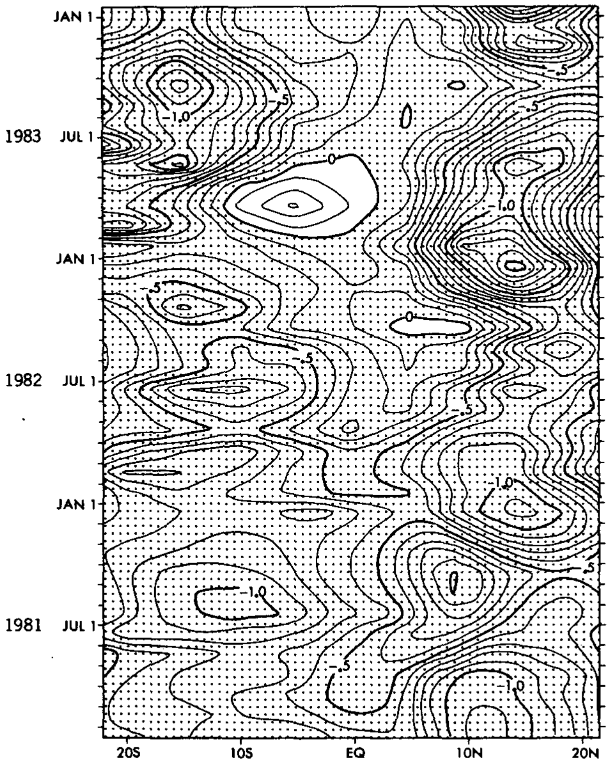

FIG. 2. The zonal component of the surface winds averaged over the longitude band from 150° to 110°W. The contour interval is 0.1 dyn cm^{-2} and winds are westward in shaded areas.

Figure 3 shows the meridional heat transport during a climatological year and during the year that starts in May 1982 when El Niño started to develop. The increase in the northward transport, especially across 10°N, is clearly evident. During the regular seasonal cycle the 10^{15} watts transported out of the zone 5°S–10°N is replenished by the heat flux across the ocean surface. This flux is reduced during El Niño because the higher sea surface temperatures lead to more evaporation. Figure 4 shows that the heat flux across the ocean surface between May 1982 and May 1983 was less than it is during a regular seasonal cycle. In other words, while the ocean exported more heat from the equatorial zone, it gained less across its surface during El Niño of 1982. The result was a decrease in the heat storage, the vertically averaged temperature of the equatorial zone. Figure 5 shows the changes in the zonally averaged heat storage. Towards the end of 1982 there was not merely a zonal redistribution of warm surface waters along the equator, from west to east, but also a meridional redistribution because the neighborhood of the equator gained at the expense of higher latitudes. The equatorward Ekman drift in response to

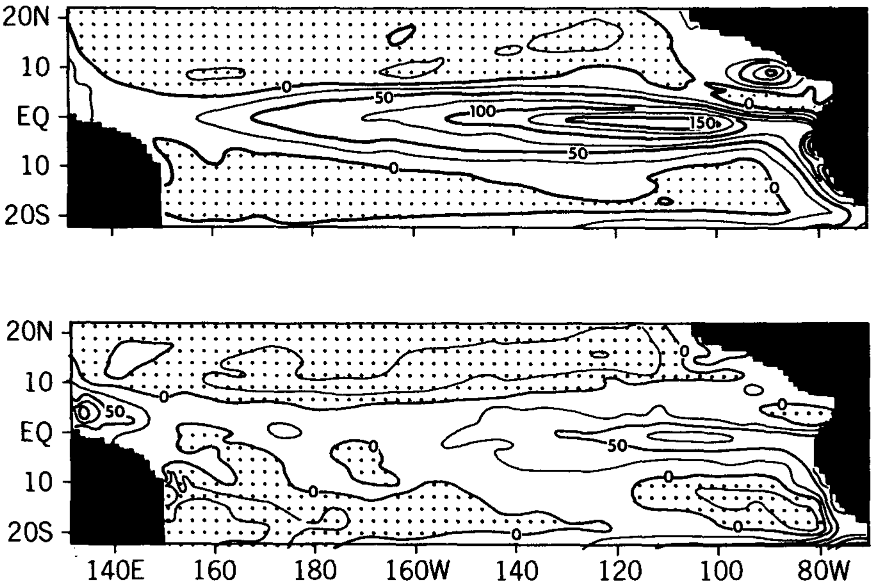

FIG. 4. Heat flux maps for the climatological year (top) and the El Niño period May 82–May 83 (bottom). The contour interval is 25 W m^{-2}, and the ocean loses heat in shaded areas.

the westerly winds that prevailed over the far western Pacific contributed to the equatorial gain. From January 1983 onward the heat storage in a broad band of low latitudes, from approximately 15°S to 12°N, decreased because the flux across the ocean surface was minimal and because the poleward heat transport was large. By July 1983 the heat storage along the equator was essentially normal but adjacent latitudes had a considerable deficit.

During a regular seasonal cycle the annual mean heat transported poleward from the equatorial zone is replenished by the flux of heat across the ocean surface. During El Niño the northward heat transport increases while the flux across the ocean surface decreases so that the heat storage of a wide band of low latitudes, approximately 12°S to 12°N, decreased. The cold phase of the Southern Oscillation, when the ITCZ is displaced poleward from its climatological position, has not yet been simulated with a general circulation model but the results presented here suggest that the following happens during a cold phase: the northward heat transported across 12°N decreases and the flux across the ocean surface in the equatorial zone increases. In Fig. 3 the northward heat transport out the band 12°S to 12°N is approximately 1×10^{15} watts during a regular seasonal cycle and it increased to 1.6×10^{15} watts between May 1982 and May 1983. The flux across the ocean surface replenishes this loss during a regular seasonal cycle but in 1982–83 this did not happen and the heat stored in the band 12°S to 12°N decreased. This change in the heat budget can be summarized as follows:

	Q_t	+	$(\mathrm{HT})_y$	=	Flux across the surface
May 1982–May 1983	−1.6		1.6		0
Seasonal cycle	0.0		1.0		1
Cold phase	1.6		0.4		2

The equation expresses the conservation of heat so that Q_t is the change in heat storage for the basin bounded by 12°S and 12°N, and $(\mathrm{HT})_y$ is the divergence of the heat transported across those boundaries. This equation is averaged over a period of 1 year to obtain the indicated values for which the units are petawatts. If the equation is averaged over a time interval that spans El Niño and the subsequent cold phase, and if we demand that the balance over that complete Southern Oscillation be the same as the balance over a climatological seasonal cycle then it follows that the balance during the cold phase of the Southern Oscillation is roughly as given for the "cold phase" above. In other words, if the heat lost by the equatorial zone during El Niño is restored during the subsequent cold phase of the Southern Oscillation then the northward heat transport across 12°N should decrease and the flux across the ocean surface should increase. The important result here is not the precise numerical value but the significant role that diabatic processes play in the interannual heat budget.

4. Discussion

The results presented here corroborate those of Wyrtki (1985) and Zebiak and Cane (1987) concerning

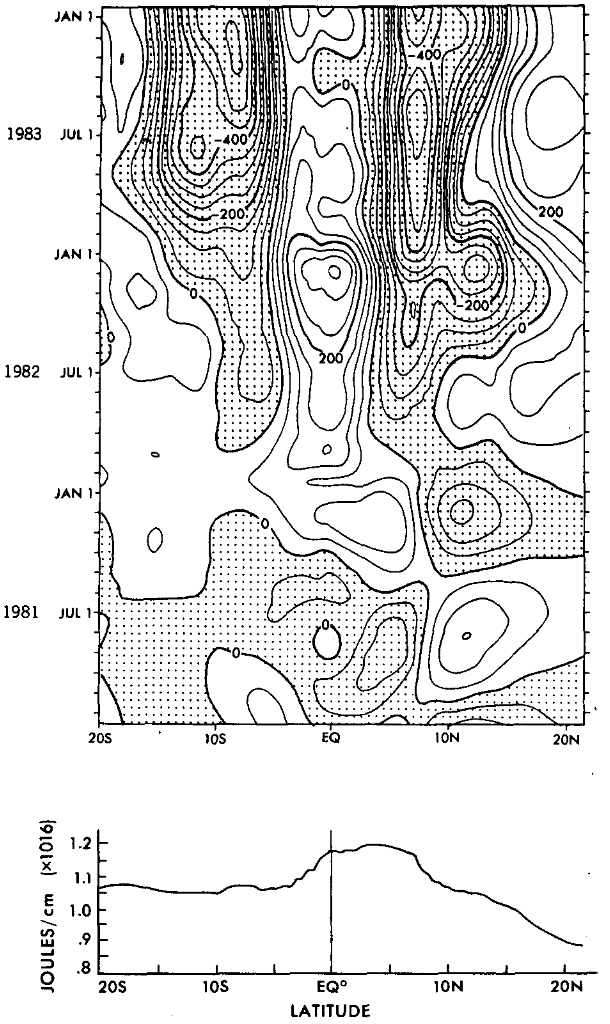

FIG. 5. The vertically and zonally integrated temperature, the heat storage, as a function of latitude and time, after subtraction of the annual mean heat storage for a climatological year, shown in the lower figure. The contour interval is 50×10^{12} J cm^{-1} in the upper figure and heat has been lost in shaded areas.

the decrease in the heat storage of the equatorial zone during El Niño. Heat is lost because of increased evaporation when sea surface temperatures increase, and because of an increase in the northward heat transport when the Ekman drift of warm surface waters, across 10°N especially, increases. The two distinct but related features that characterize the warm El Niño phase of the Southern Oscillation—an eastward displacement of the atmospheric convergence zone over the far western tropical Pacific Ocean, and an equatorward displacement of the ITCZ—both influence the meridional heat transport. The wind variations associated with the eastward movement of the convergence zone are essentially symmetrical about the equator and, in addition to causing a zonal redistribution of warm surface waters in the upper equatorial Pacific, affect the poleward transport of heat in both hemispheres. This does not explain the asymmetrical increase in the northward heat transport which is attributable primarily to the wind variations associated with the ITCZ movements. Furthermore, this result implies that studies of the tropical Atlantic will be of special interest because there the dominant feature of interannual variability is the meridional displacement of the ITCZ (Philander 1986; Horel et al. 1986).

The General Circulation Model that yields the results described here simulates many aspects of the 1982–83 El Niño realistically but it also has flaws because the forcing functions have inaccuracies. Neither the flux of momentum (the windstress) nor the flux of heat across the ocean surface is known accurately. Another factor that could influence the results in an unrealistic manner is the idealized, continuous western wall of the ocean basin which does not permit a loss of warm surface waters to the Indian Ocean; there is evidence that this happens in reality (Gordon 1986). The unrealistic geometry of the western boundary will also distort the currents that advect warm water equatorward in the far western Pacific. Because of these flaws of the model the heat budget presented here may not be an accurate quantitative description of the budget for 1982–83. Rather, the results should be viewed as a realization of what can happen during El Niño and, by inference, what can happen during a cold phase so that averages over the warm and cold phases of the Southern Oscillation describe a normal seasonal cycle. Several cycles of the Southern Oscillation need to be simulated to confirm the results in the table of section 3. (Pares-Sierra et al. 1985 have simulated several cycles with a shallow water model but they entirely neglect diabatic processes.) More accurate estimates of the heat flux across the ocean surface, and its seasonal and interannual variations, will have enormous value. To establish whether interannual changes in the heat storage of the tropical Pacific determine when El Niño can occur requires calculations with realistic coupled models of the ocean and atmosphere.

Acknowledgments. Comments by Dr. D. Hansen on an earlier version of this paper led to considerable improvements. We are indebted to Ms. W. Marshall and Mr. P. Tunison for expert technical assistance in the preparation of this paper.

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