JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 90, NO. C4, PAGES 7129–7132, JULY 20, 1985

Water Displacements in the Pacific and the Genesis of El Nino Cycles

KLAUS WYRTKI

Department of Oceanography and Hawaii Institute of Geophysics, University of Hawaii, Honolulu

Sea level observations are used to estimate the amounts of warm water exchanged during the 1982–1983 El Nino event, indicating an eastward flux of about 40×10^6 m^3 s^{-1}. At the end of El Nino the equatorial Pacific is depleted of warm water which is lost toward higher latitudes. The duration of a complete El Nino cycle is determined by the time required for the slow accumulation of warm water in the western Pacific. The cycle constitutes an energy relaxation of the ocean-atmosphere system.

INTRODUCTION

Atmospheric forcing by a collapse of the trade winds over the Pacific Ocean has been established as the cause of the ocean's response during El Nino [*Wyrtki,* 1975], and computer models have succeeded in simulating this response in great detail [*Busalacchi and O'Brien,* 1981]. The response of the atmosphere to a redistribution of heat in the ocean has also been studied and modeled by *Gill and Rasmusson* [1983] and by *Philander et al.* [1984], but an understanding of the mechanism leading to a complete El Nino–Southern Oscillation cycle is still lacking [*Rasmusson and Wallace,* 1983]. Recent model computations of meridional heat transport in the equatorial Pacific have shown that anomalous poleward heat transports are associated with El Nino events [*Pares-Sierra et al.,* 1985]. Observations of sea level allow a determination of the volume of warm water in the tropical Pacific, which is large at the beginning and small at the end of El Nino. These changes in ocean heat content are used to develop a theory of a complete El Nino–Southern Oscillation cycle, which is explained as an energy relaxation of the ocean-atmosphere system.

A close relationship exists in the tropical ocean between sea level and the depth of the thermocline as given by the depth of a selected isothermal or density surface. In a two-layer system, changes of sea level height Δh relate to changes of isotherm depth ΔD by the relation $\Delta h = \Delta D \, \Delta\rho/\rho$, where $\Delta\rho/\rho$ is the relative density difference between the two layers. A value $\Delta\rho/\rho = 5 \times 10^{-3}$ has been determined empirically by *Wyrtki and Kendall* [1967] for the North Equatorial Countercurrent. This value has been verified by *Chaen and Wyrtki* [1981] for Truk, and a much more comprehensive study of the relationships between sea level, thermocline depth, and heat content demonstrates that the relation is valid for the entire equatorial Pacific Ocean between about 15°N and 15°S (J. P. Rebert, J. R. Donguy, G. Eldin, and K. Wyrtki, manuscript in preparation, 1985). The relationships between sea level and the depth of the 20°C isotherm for Santa Cruz, Christmas Island, and Truk are shown in Figure 1. The slopes of the relation between changes in sea level and changes in isotherm depth are 6.6×10^{-3}, 5.0×10^{-3}, and 5.5×10^{-3} with correlation coefficients of 0.93, 0.80, and 0.90, respectively.

DATA

Data from a network of sea level stations established in the tropical Pacific Ocean during 1974–1975 have been used to compile monthly maps of sea level anomaly for the period 1975 to 1983, which includes the 1976 and 1982–1983 El Nino events [*Wyrtki and Nakahara,* 1984; *Wyrtki,* 1985*a*]. The sequence of the monthly maps during the nine-year period shows the large scales of the sea level anomalies and the strong coherence of sea level variations in space and time. A sample of such a sea level map for December 1982 (Figure 2) shows the distribution of the stations as well as the sea level anomalies at the peak of the 1982–1983 El Nino.

The sea level maps have been integrated between 15°N and 15°S and from the coast of Asia and Australia to the coast of the Americas to give integrated sea level height. Because of the relation between thermocline depth and sea level height these values can be translated into upper layer volumes

$$H = (\rho/\rho\Delta) \int\int \Delta h \, dx \, dy$$

which represent a measure of the amount of warm water present in the tropical Pacific Ocean. The integration has been carried out separately for positive and negative anomalies H^+ and H^- (Figure 3). The sum $H^+ + H^-$ constitutes the total disturbance of sea level or of upper layer volume; the

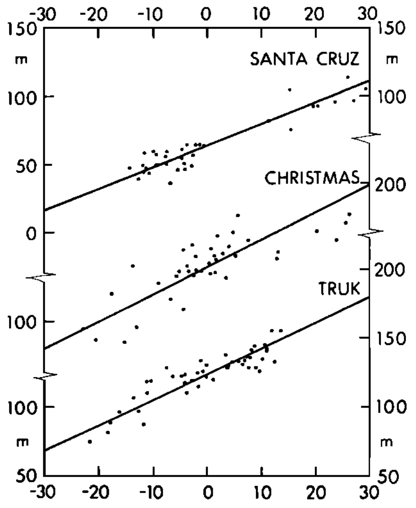

Fig. 1. Relations between monthly means of sea level (centimeters) and the depth of the 20°C isotherm (meters) at Santa Cruz (0°45'S, 90°19'W), Christmas Island (1°59'N, 157°29'W), and Truk (7°27'N, 151°51'E).

Paper number 5C0282.
0148-0227/85/005C-0282$05.00

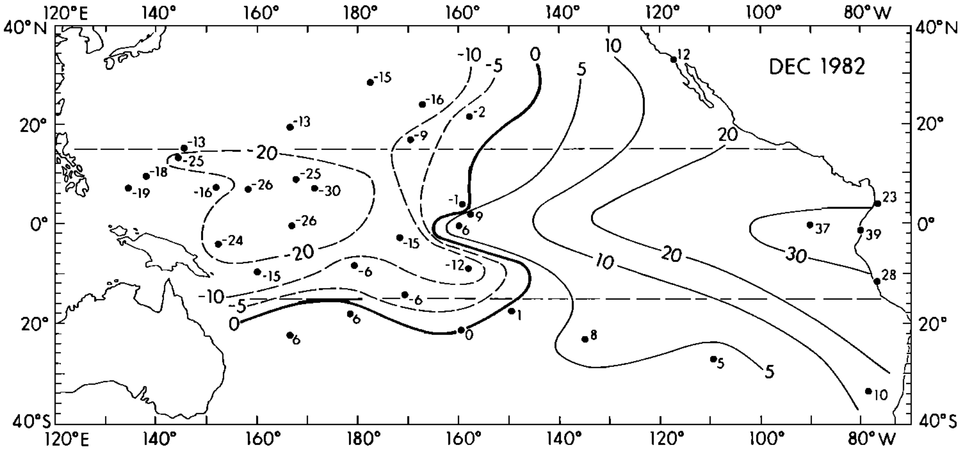

Fig. 2. Sea level anomaly in December 1982 (centimeters). Circles denote sea level stations; values are the deviation of sea level in December 1982 from the seven-year average December sea level 1975 to 1981. The dashed lines at 15°N and 15°S give the area used for the integration of upper layer volumes.

difference $H^+ - H^-$ (Figure 4) is the net disturbance and represents an excess or deficit of warm water. In view of the large scales of the anomaly patterns, the density of observing stations in the western and central Pacific is more than sufficient to allow computation of upper layer volumes. The coherence of sea level variations along the coast of the Americas is also of large horizontal scale. Consequently, a linear interpolation between the central and eastern equatorial Pacific should be sufficient for the determination of the upper layer volumes on monthly time scales. The lack of high-frequency noise in the curves shown in Figure 3 supports this conclusion.

CHANGES IN UPPER LAYER VOLUME

The largest disturbances of sea level and upper layer volume are associated with the 1982–1983 El Nino. From April through October 1982 the positive disturbance of upper layer volume located in the eastern Pacific increases by 6×10^{14} m^3, and from June to December 1982 the negative disturbance in the western Pacific increases by a similar amount. These volume changes of the upper layer imply a flux of water of about 40×10^6 m^3 s^{-1} from the western to the eastern Pacific. This flux is in agreement with direct measurements made by *Firing et al.* [1983] and geostrophic calculations of the flow by *Meyers and Donguy* [1984]. The net result of these water displacements in December 1982 (Figure 2) is a large positive sea level anomaly in the eastern Pacific and an equally large negative anomaly in the western Pacific and a maximal total disturbance ($H^+ + H^-$). The positive anomaly stretches poleward along the coasts of North and South America.

From November 1982 to February 1983 the positive anomaly in the eastern Pacific decreases fast, releasing water toward higher latitudes. From March through May 1983 the positive anomaly increases again, as a negative anomaly forms south of the equator from New Guinea to Tahiti [*Wyrtki,* 1985*b*], resulting in a second peak of sea level in May 1983 in the eastern Pacific. Thereafter the positive anomaly decreases rapidly. The negative anomaly remains almost constant until October 1983, when it starts to decrease. The excess of negative over positive anomalies during the second half of 1983 is about 6×10^{14} m^3 (Figure 4). To put these numbers into perspective, it might be stated that the average volume of warm water above the 20°C isotherm in the Pacific between 15°N and 15°S is about 70×10^{14} m^3; thus the fluctuations during El Nino represent substantial changes of this volume.

A plot of the net disturbance of upper layer volume $H^+ - H^-$ (Figure 4) illustrates best the behavior of the tropical warm water layer throughout an El Nino cycle. From 1977 to 1979 the volume of warm water is below normal; from 1979 to 1982 it increases systematically, reaching a peak in November 1982. This peak is followed by an extremely rapid decline of warm water volume and by a net deficit at the end of El Nino. The loss of warm water from the equatorial Pacific was already noted by *Wyrtki* [1984]; sea level along the entire equator was about 10 cm below normal during the second half of 1983. The 1976 El Nino follows a similar but much weaker pattern with a warm water surplus in early 1976 and a deficit in early 1977.

The poleward escape of the warm water along the coasts of North and South America has been clearly documented by *Enfield and Allen* [1980] and by *Chelton and Davis* [1982]. It can probably be explained by a spindown of the circulation of the subtropical gyres as described by *Godfrey* [1975]. The poleward propagation of a disturbance resulting from the incidence of an equatorial Kelvin wave on a meridional coast has been treated theoretically by *Anderson and Rowlands* [1976]. The draining of warm water has also been determined from model calculations of meridional heat transport by *Pares-Sierra et al.* [1985]. They find that maximum poleward heat transports are associated with El Nino events.

Before the 1982–1983 El Nino a systematic development in the volume of warm water in the tropical Pacific can also be noted. In 1979, negative anomalies exceed positive anomalies; in 1980, both anomalies are about equal; and from 1981 on, positive anomalies dominate (Figure 4). This sequence indicates a systematic increase of the amount of warm water from 1979 to 1982 at a rate of only 3×10^6 m^3 s^{-1} during the three years preceding El Nino.

An estimate of water displacements during the 1976 El Nino [*Wyrtki,* 1979], also based on sea level observations, results in a change of upper layer volume of 8×10^{14} m^3 and in an eastward transport of 27×10^6 m^3 s^{-1}. A somewhat

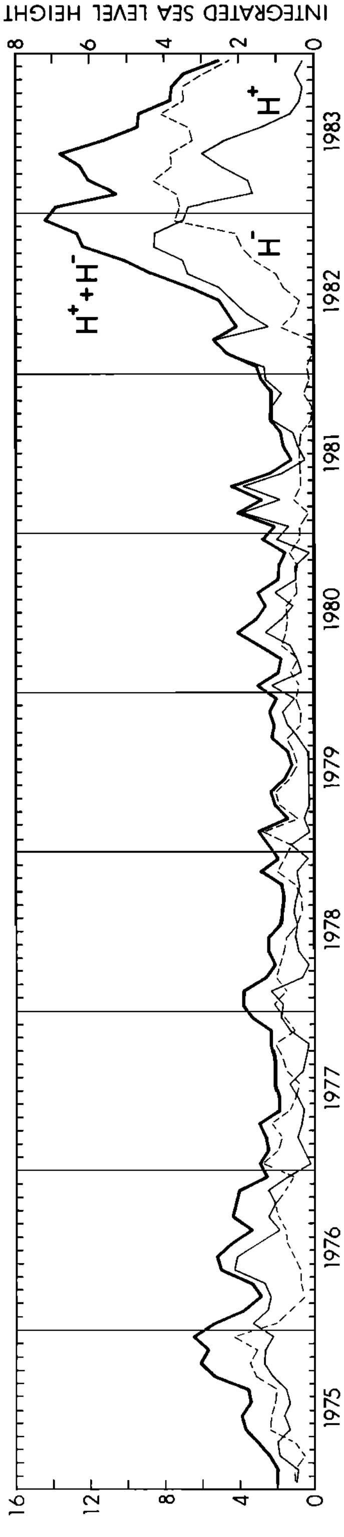

Fig. 3. Integrated sea level height (right scale, 10^{12} m^3) and upper layer volume (left scale, 10^{14} m^3) for the tropical Pacific Ocean from 1975 to 1983. H^+ indicates positive anomalies, H^- negative anomalies, and $H^+ + H^-$ their sum.

similar analysis of heat transports during the 1972–1973 El Nino event has been made by *Gill* [1983] on the basis of relatively few expendable bathythermograph observations. He estimates an eastward transport of 26×10^6 m^3 s^{-1} and finds that about half of this water is lost poleward.

EL NINO CYCLES

The interaction of ocean and atmosphere produces climatic fluctuations. A fast-changing atmosphere with no lateral boundaries acts on the ocean mainly by the transfer of momentum. In contrast, the slow-moving ocean is confined by massive meridional boundaries and acts upon the atmosphere chiefly by the transfer of heat. Consequently, meridional transports of heat in the ocean are predominantly accomplished by meridional flows, whereas in the midlatitude atmosphere they are accomplished by large-scale horizontal turbulence. A recognition of these basic differences between ocean and atmosphere will be used to explain the genesis of El Nino and the Southern Oscillation.

During periods when atmospheric circulation in the tropics is developed with normal strength, the trade winds push warm water toward the west and cause it to accumulate in the western Pacific both north and south of the equator. This process lasts several years until a significant amount of warm water is accumulated by a depression of the thermocline and by an increase of temperature in the mixed layer. There would be no such accumulation if there were no meridional boundaries in the ocean. Small, short fluctuations of the trade winds will have little effect on this long-term accumulation of warm water.

Fluctuations of atmospheric circulation over the tropics will at some time lead to a relaxation of the trade wind field sufficiently widespread and long to allow the triggering of a Kelvin surge, namely a massive eastward displacement of the accumulated warm water along the equator.

The displacement of warm water from the western to the central and eastern Pacific Ocean forces a dislocation of atmospheric circulation, which results in a shift of the area of strongest convection and rainfall from Indonesia to the central Pacific as shown by *Rasmusson and Wallace* [1983]. This displacement of atmospheric circulation assures a continued reduction of the area of trade winds to the east of it and an area of westerly winds to the west of it.

The warm water surging to the east is deflected by the coast of America to both the south and the north and is lost from the tropical ocean. This fact is evident from the sea level observations presented here and from direct observations of heat storage [*White et al.,* 1985].

Thus a complete El Nino cycle results in a net heat discharge from the tropical Pacific toward higher latitudes. At the end of the cycle the tropical Pacific is depleted of heat, which can only be restored by the slow accumulation of warm water in the western Pacific by the normal trade winds. Consequently, the time scale of the Southern Oscillation is given by the time required for the accumulation of warm water in the western Pacific. Its release is triggered by fluctuations of atmospheric circulation in the tropics. An El Nino–Southern Oscillation cycle represents a heat relaxation of the ocean-atmosphere system, in which heat stored in the tropical ocean is discharged toward higher latitudes. The explanation of an El Nino–Southern Oscillation cycle as a combination of atmospheric randomness and a deterministic ocean might be unpleasing to many scientists, but it probably characterizes correctly the interaction between the two media.

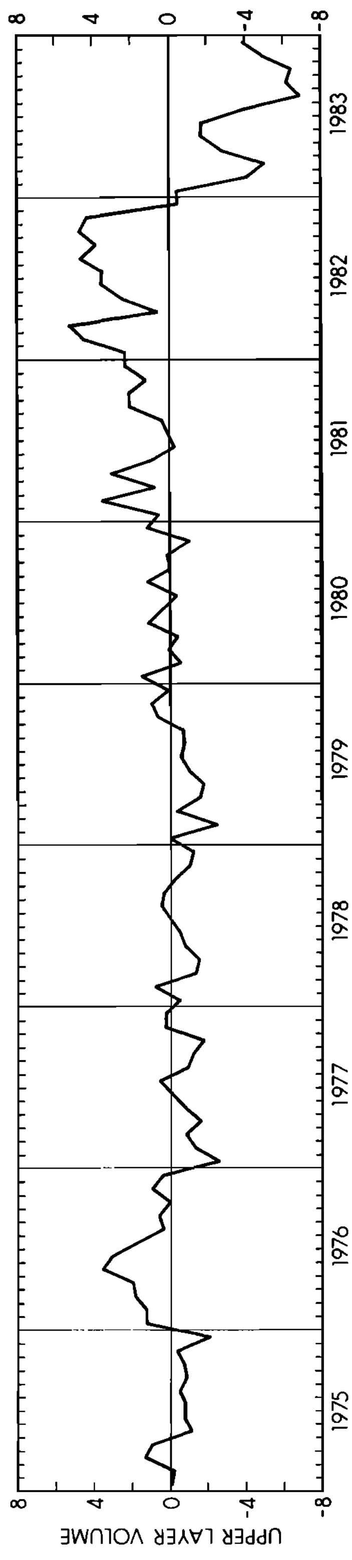

Fig. 4. Upper layer volume of the tropical Pacific (10^{14} m^3) from 1975 to 1983 relative to its mean value of about 70×10^{14} m^3.

Acknowledgments. Support for this research was provided by the National Science Foundation, which is gratefully acknowledged. This is Hawaii Institute of Geophysics contribution 1613.

REFERENCES

Anderson, D. L. T., and P. B. Rowlands, The role of inertia-gravity and planetary waves in the response of a tropical ocean to the incidence of an equatorial Kelvin wave on a meridional boundary, *J. Mar. Res.*, *34*, 295–312, 1976.

Busalacchi, A. J., and J. J. O'Brien, Interannual variability of the equatorial Pacific in the 1960's, *J. Geophys. Res.*, *86*, 10,901–10,907, 1981.

Chaen, M., and K. Wyrtki, The 20°C isotherm depth and sea level in the western equatorial Pacific, *J. Oceanogr. Soc. Jpn.*, *37*, 198–200, 1981.

Chelton, D. B., and R. E. Davis, Monthly mean sea-level variability along the west coast of North America, *J. Phys. Oceanogr.*, *12*, 757–784, 1982.

Enfield, D. B., and J. S. Allen, On the structure and dynamics of monthly mean sea level anomalies along the Pacific coast of North and South America, *J. Phys. Oceanogr.*, *10*, 557–578, 1980.

Firing, E., R. Lukas, J. Sadler, and K. Wyrtki, Equatorial undercurrent disappears during 1982-1983 El Nino, *Science*, *222*, 1121–1123, 1983.

Gill, A. E., An estimation of sea-level and surface-current anomalies during the 1972 El Nino and consequent thermal effects, *J. Phys. Oceanogr.*, *13*, 586–606, 1983.

Gill, A. E., and E. M. Rasmusson, The 1982–83 climate anomaly in the equatorial Pacific, *Nature*, *306*, 229–234, 1983.

Godfrey, J. S., On Ocean Spindown I: A linear experiment, *J. Phys. Oceanogr.*, *5*, 399–409, 1975.

Meyers, G., and J. R. Donguy, The North Equatorial Countercurrent and heat storage in the western Pacific Ocean during 1982–83, *Nature*, *312*, 258–260, 1984.

Pares-Sierra, A. F., M. Inoue, and J. J. O'Brien, Estimates of oceanic horizontal heat transport in the tropical Pacific, *J. Geophys. Res.*, *90*, 3293–3303, 1985.

Philander, S. G. H., T. Yamagata, and R. C. Pacanowski, Unstable air-sea interactions in the tropics, *J. Atmos. Sci.*, *41*, 604–613, 1984.

Rasmusson, E. M., and T. M. Wallace, Meteorological aspects of the El Nino/Southern Oscillation, *Science*, *222*, 1195–1202, 1983.

White, W. B., G. Meyers, J. R. Donguy, and S. Pazan, Short-term climatic variability in the thermal structure of the Pacific Ocean during 1979–1982, *J. Phys. Oceanogr.*, in press, 1985.

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

Wyrtki, K., The response of sea surface topography to the 1976 El Nino, *J. Phys. Oceanogr.*, *9*, 1223–1231, 1979.

Wyrtki, K., The slope of sea level along the equator during the 1982/1983 El Nino, *J. Geophys. Res.*, *89*, 10,419–10,424, 1984.

Wyrtki, K., Monthly maps of sea level in the Pacific during the 1982–83 El Nino, in *Time Series of Ocean Measurements, Tech. Ser.*, vol. 2, Intergovernmental Oceanographic Commission, UNESCO, Paris, in press, 1985*a*.

Wyrtki, K., Sea level fluctuations in the Pacific during the 1982–83 El Nino, *Geophys. Res. Lett.*, *12*, 125–128, 1985*b*.

Wyrtki, K., and R. Kendall, Transports of the Pacific Equatorial Countercurrent, *J. Geophys. Res.*, *72*, 2073–2076, 1967.

Wyrtki, K., and S. Nakahara, Montly maps of sea level anomalies in the Pacific, 1975–1981, *Ref. HIG 84-3*, 8 pp. + maps, Univ. of Hawaii, Honolulu, 1984.

K. Wyrtki, Department of Oceanography, University of Hawaii at Manoa, 1000 Pope Road, Honolulu, HI 96822.

(Received March 5, 1985;
accepted March 6, 1985.)