El Niño–Southern Oscillation Displacements of the Western Equatorial Pacific Warm Pool

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The western equatorial Pacific warm pool (sea-surface temperatures >29°C) was observed to migrate eastward across the date line during the 1986–1987 El Niño–Southern Oscillation event. Direct velocity measurements made in the upper ocean from 1986 to 1988 indicate that this migration was associated with a prolonged reversal in the South Equatorial Current forced by a large-scale relaxation of the trade winds. The data suggest that wind-forced zonal advection plays an important role in the thermodynamics of the western Pacific warm pool on interannual time scales.

The Southern Oscillation is a large-scale seesaw in atmospheric pressure between the eastern subtropical Pacific and the maritime land masses of Australia and Indonesia (*1, 2*). Pressure differences between these two regions drive easterly trade winds, which are the principal forcing function of tropical ocean circulation. The trade winds converge in the western Pacific in regions of deep atmospheric convection and high rainfall rates. A drier air mass then returns eastward aloft before descending in the subtropical high region of the eastern Pacific. Periods when the pressure is unusually high in the west and low in the east are associated with El Niño, an oceanic phenomenon characterized by weakened trade winds in the central and western Pacific and sea-surface temperatures (SSTs) that are warmer than usual from the coast of South America to west of the date line (*3*). El Niño–Southern Oscillation (ENSO) episodes occur on an irregular cycle of about 2 to 10 years, the most recent of which occurred in 1986 to 1987 (*4, 5*). Although the origins of ENSO may be traced to the tropics, its manifestations are felt worldwide through disruptions in the atmospheric general circulation and associated weather patterns (*1, 6*).

The western Pacific warm pool, defined by SSTs > 29°C, has recently taken on a special significance in ENSO studies (*7, 8*). The SSTs in the western equatorial Pacific are the highest in the world ocean. Such high temperatures lead to tremendous variability in deep convection because the ability of the atmosphere to hold water vapor increases nonlinearly with temperature (*9*). During ENSO, the warm pool and deep convection associated with converging easterlies are observed to migrate eastward across the date line. This migration of the warm pool has generally been attributed to wind-driven zonal current advection, on the basis of model studies (*7, 10, 11*) and empirical mass-balance studies (*12–14*). However, until recently there have been no direct current measurements west of the date line suitable for testing this hypothesis. In this report, we present moored and shipboard velocity measurements for 1986 to 1988 and show that the western Pacific warm pool is responding to current variations in a manner consistent with inferences drawn from models, theory, and earlier empirical studies.

To place these measurements in perspective, we review the broad outlines of air-sea interaction on ENSO time scales as discussed in the context of several simple coupled ocean-atmosphere models (*15*). In these models, warm tropical SST anomalies generate anomalous deep atmospheric convection fed by convergence of surface winds. This surface convergence leads to a significant weakening of the trade winds west of the warm SST anomalies. The ocean responds rapidly to this weakening: surface currents locally accelerate eastward, and

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large-scale equatorial Kelvin and Rossby waves radiate out from the directly forced region to reinforce and spread the warm SST anomaly across the basin (*16*). This couples the ocean to the atmosphere in a positive feedback loop, wherein westerly wind anomalies reinforce the eastward currents, and this process in turn leads to further warming. As this feedback continues, the thermocline rises in the west and descends in the east to compensate for the mass of water drained from the western Pacific. Warm SST anomalies continue to grow and persist for 12 to 18 months, until easterly trade winds return to their full strength and the event terminates.

In 1986, maximum SSTs (>29.5°C) were centered near 165°E (Fig. 1) during boreal summer (June, July, and August), and the winds within about 10° of the equator were near normal. One year later, during the height of the 1986–1987 ENSO, the warmest waters in the equatorial Pacific were found between 160°W and 180°W, and over this warm-water pool there was a strong anomalous convergence of surface winds. This convergence was associated with anomalous deep atmospheric convection over the same range of longitudes (*4*) and weakened trade winds between 160°E and 160°W within 5° of the equator (*17*). In boreal summer 1988, the warmest surface waters were west of 160°E between the equator and 10°N, and a well-developed cold tongue with minimum temperatures on the equator formed all the way west to 165°E. The cold tongue is usually confined to east of about 160°W (*18*), and its presence in the western Pacific in 1988 is consistent with the occurrence of stronger than normal easterly trade winds west of 160°W.

The zonal migration of the warmest surface waters can be related to the direction and magnitude of flow across 165°E, as determined from shipboard and moored velocity measurements made during 1986 to 1988 (*19, 20*). In particular, meridional sections of zonal velocity between 10°N and 10°S (Fig. 2) show a dramatic interannual reversal of flow in the upper 100 m of the water column. Before the ENSO, in June 1986, flow was westward between 8°S and 3°N in the South Equatorial Current at speeds up to 0.6 m s^{-1} and eastward between 3°N and 7°N in the North Equatorial Countercurrent at speeds up to 0.6 m s^{-1} (*21*). However, 1 year later, flow was eastward between about 7°S and 6°N at speeds up to 0.8 m s^{-1}. The volume transport associated with currents in the upper 100 m between 5°N and 5°S was 11 Sv to the west in 1986 and 47 Sv to the east in 1987 (1 Sv = 10^6 m^3 s^{-1}). This is a difference of 58 Sv, which is larger than the annual mean transports of all the major zonal currents in the western and central equatorial Pacific (*20, 22*). The large anomalous eastward mass flux in 1987 drained the warm surface layer in the western Pacific and thus elevated the upper thermocline by 20 to 40 m (Fig. 2, D and E) and depressed sea level by 20 to 30 cm (*4, 5*). After the ENSO, in boreal summer 1988, the westward South Equatorial Current returned to its pre-ENSO strength and displaced the warm surface layer to the west across 165°E at a rate of 7 Sv. A depression of the upper thermocline and an increase in the volume of water having a temperature >29°C relative to 1987 values was associated with this westward volume transport (Fig. 2, E and F).

These transport estimates are based on only three meridional sections, each separated by approximately 1 year. The high variability of the near-surface equatorial ocean on time scales shorter than this could affect the interpretation of our measurements in terms of interannual variability. However, our transport estimates are the same magnitude as indirect estimates of yearly averaged volume transports from the western to the eastern Pacific inferred from island sea-level data during the 1976 ENSO [27 Sv (*13*)] and the 1982 to 1983 ENSO [40 Sv (*14, 23*)]. The equatorial velocity profiles are also consistent with averaged time-series

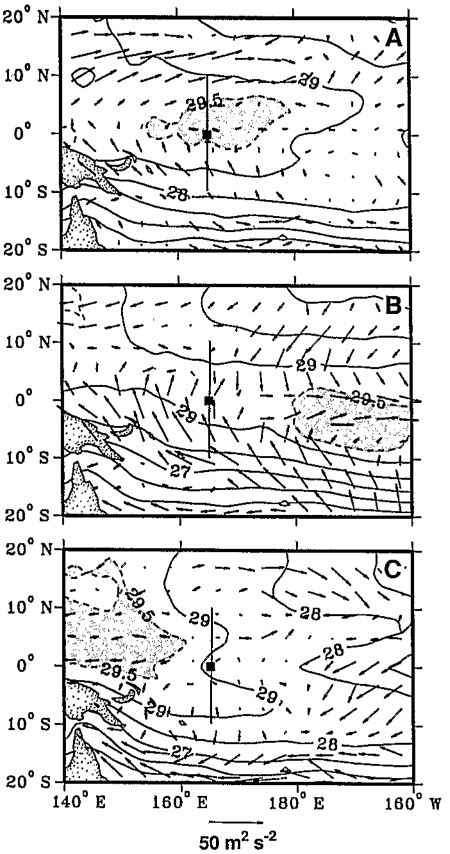

Fig. 1. Contours of SST for (**A**) June to August 1986, (**B**) June to August 1987, and (**C**) June to August 1988. Contour interval is 1°C for temperatures ≤29°C. The 29.5°C isotherm is dashed and water warmer than 29.5°C is shaded. Also plotted are wind pseudostress anomaly vectors (defined as |U|U, where U is vector wind speed) for each period. The SST analyses are from the Climate Analysis Center of the National Meteorological Center; pseudostress data are from (*28*). The square indicates the location of a current meter mooring at 0°, 165°E; the vertical line between 10°N and 10°S, 165°E indicates the section along which measurements shown in Fig. 2 were made.

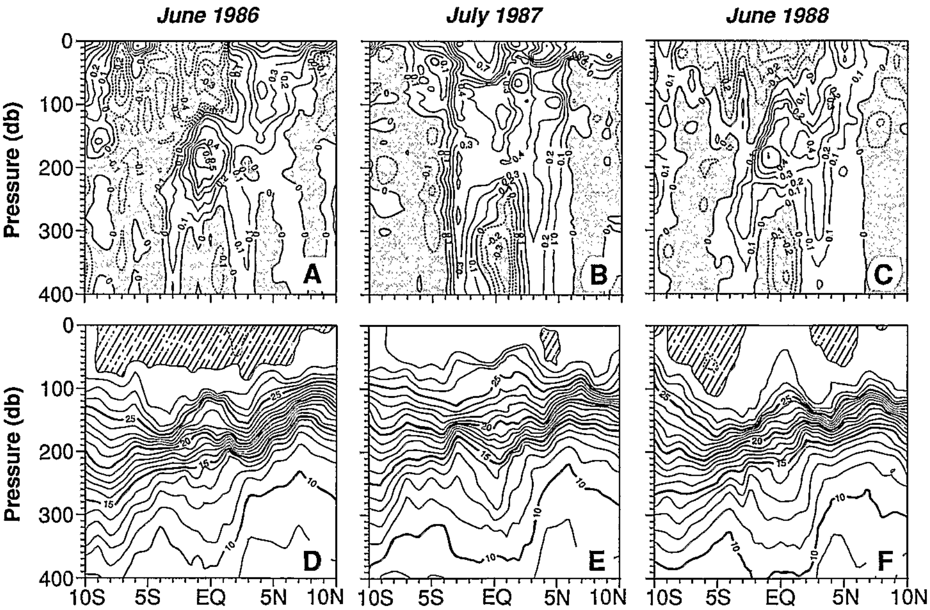

Fig. 2. Meridional sections of zonal velocity (**A**, **B**, and **C**) and temperature (**D**, **E**, and **F**) for June 1986, July 1987, and June 1988 along 165°E. Westward flow and temperatures >29°C are shaded.

measurements collected from a current meter mooring at 0°, 165°E during boreal summers from 1986 to 1988. The mooring data (Fig. 3A) have the same character as the shipboard velocity profiles at the equator and show that flow was eastward in the surface layer during 1987 but westward before and after the ENSO event. The differences are largest in the upper 100 m (for example, 0.6 m s^{-1} between 1987 and 1988 at 50 m) and diminish into the thermocline (*24*). The mooring data, like the shipboard data, indicate that the thermocline shoaled in 1987 (Fig. 3C), as is consistent with the notion that a large eastward volume flux drained the western Pacific of its warm surface layer.

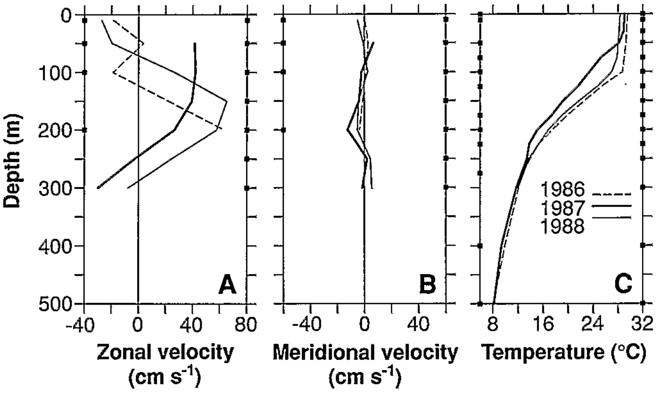

Fig. 3. Profiles of (**A**) zonal velocity; (**B**) meridional velocity; and (**C**) temperature averaged during 1 June to 2 July 1986, 1 June to 31 August 1987, and 1 June to 31 August 1988. Instrument depths are indicated on the left axes for 1986 and on the right axes for 1987 and 1988.

Further evidence supporting this advective hypothesis is given by estimates of the horizontal distance over which water parcels would be displaced. These estimates were obtained by integrating the velocity measurements from the 165°E mooring in time. The resultant time series of positions differs from actual fluid-parcel trajectories because of inhomogeneities in the horizontal flow field and because of the neglect of vertical velocities. However, the method provides a useful indicator of lateral displacements of water mass in lieu of true Lagrangian measurements. The longest continuous moored velocity record available for this purpose at this station is from 13 December 1986 to 31 December 1988 at a depth of 50 m. Meridional velocities are relatively small (Fig. 3B) so that the largest displacements are in the zonal direction. These displacements, superimposed on contours of SST in Fig. 4, are comparable in magnitude and duration to displacements derived from a model of the ENSO (*10*) and indicate that water parcels could reach the central Pacific by October 1987 before returning westward.

The 29°C isotherm at the eastern edge of the warm pool was displaced to 150°W during July and August 1987 before retreating to near 160°E in mid-1988 (Fig. 4). Displacements of this isotherm and those inferred from the mooring data would closely correspond to one another if (i) zonal advection were the primary determinant in the surface heat balance; and (ii) the velocity field were uniform over distances separating the 29°C isotherm from the mooring at 165°E. In support of the zonal-advection hypothesis, excursions of the 29°C isotherm resemble those inferred from the mooring velocity data collected when the 29°C isotherm was near 165°E in 1988. Conversely, when the 29°C isotherm was located east of the date line in 1987, its excursions tended to be smaller in amplitude than those inferred from the mooring data, and they tended to lead excursions inferred from the mooring data by about 2 months. The lead-lag relation, if interpreted in terms of water-mass displacements, implies a westward phase propagation of about 0.8 m s^{-1}, comparable to that expected for large-scale equatorial Rossby waves. The smaller zonal displacements of the 29°C isotherm relative to those inferred from the mooring data can be interpreted as a damping of SST anomalies by loss of latent heat to the atmosphere (*25*). In addition, one would expect that zonal displacements on the equator (as computed from the mooring data) would have been larger than the average displacement between 5°N and 5°S (the interval over which SST was averaged in Fig. 4) because of the tendency for zonal currents off the equator to be deflected meridionally by Coriolis forces.

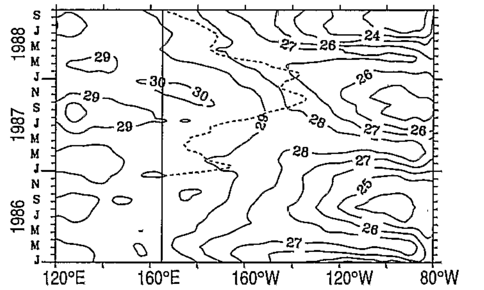

Fig. 4. Averaged SST from 5°N to 5°S as a function of longitude in the Pacific from 1986 to 1988. Superimposed as a dashed line are estimated water-mass displacements from the current meter mooring at 0°, 165°E.

Earlier analyses have shown that the zonal-velocity variations at 0°, 165°E are significantly correlated with local wind variations (*5*). Variations in local winds do not account for all of the observed zonal velocity variance, however, and the foregoing discussion suggests that velocities associated with remotely generated Rossby waves may also be important. Direct evidence for equatorial Rossby waves has been obtained from basin-wide satellite sea-level measurements in the Pacific during 1986 and 1987 (*26*). Moreover, wind-forced westward-propagating Rossby waves are an important dynamical component in nearly all ocean models of ENSO (*27*). In these models, westerly wind anomalies (like those shown in Fig. 1b) generate Rossby waves that advect the surface layer eastward and elevate the thermocline in the western Pacific in a manner consistent with our moored and shipboard velocity and temperature data.

In summary, we attribute zonal displacements of the western equatorial Pacific warm pool observed from 1986 to 1988 to wind-forced variations in current velocity and transport in the upper ocean. In addition, our data can be interpreted to imply that remotely forced equatorial Rossby waves contribute to these current variations, consistent with our present understanding of ocean dynamics. However, inferences about the role of Rossby waves must be considered tentative on the basis of the data used in this study, because our velocity measurements derive from only a single meridian (165°E). More complete oceanic data sets than are currently available are needed to understand fully the dynamics of current variations like those we have observed.

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