Some Thoughts about the West Pacific Warm Pool

Klaus WYRTKI

University of Hawaii, Honolulu
Hawaii, 96822 - U.S.A.

ABSTRACT

Large scale aspects of the West Pacific warm pool will be discussed on the basis of existing data and information. A definition of the warm pool in terms of an isothermal layer is simple and definitive in the vertical, but difficult with regard to its horizontal extent. Even if narrowly defined by the 28°C isotherm, the pool undergoes large annual variations in its horizontal extent. The region of overlap is only about one half of the size of the pool. The pool is persistent only between 10°N and 10°S with its center at 170°E. An inspection of the circulation of upper layer water indicates that the pool gains water from the two anticyclonic gyres, and discharges warm water by means of the countercurrent and the Indonesian throughflow. The residence time of water in the pool is only 1.3 years and makes the pool sensitive to interannual variations of heat advection and heat input. There seems to be little interhemispheric exchange of water through the pool.

The role of the countercurrent as a boundary current between the two gyres will be described, and its response to variations in the intensity of the two subtropical gyres. A strong South Pacific gyre will lead to a weak countercurrent and to an accumulation of warm water in the warm pool. This situation persists during the build-up phase before El Nino. In contrast, a strong North Pacific gyre will lead to a strong countercurrent and a drain of warm water from the warm pool as is occurring during El Nino. As a consequence, the variations of the volume of warm water in the warm pool and the occurrence of El Nino may well be linked to pulsations of the subtropical gyres in the two hemispheres.

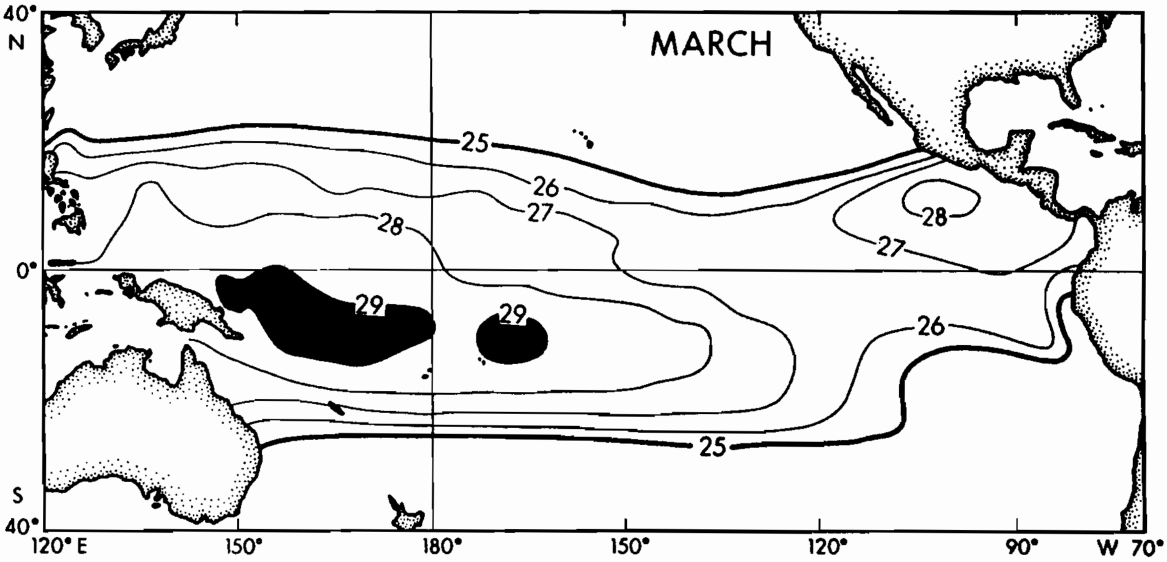
1. Introduction.

The West Pacific Warm Pool has been the subject of much scientific interest in recent years because of its relation to the development of El Nino, and an entire large scientific experiment (TOGA COARE, 1988) devoted to it is in the final planning stages. It seems therefore appropriate to spend some time analyzing a few aspects of the warm pool based on existing data and information. In this brief study I would like to point out how difficult it is to generate a definition of the pool, discuss the circulation of water through the pool and its residence time, and to relate fluctuations of the water volume in the pool with fluctuations of the two subtropical gyres. Analysis of these fluctuations will result in some important insights into the role of the equatorial countercurrent in the dynamics of the warm pool.

2. Definition, size and depth of the warm pool.

The warm pool contains tropical surface water, which by definition is warm and of relatively low salinity due to excessive evaporation. Because of its low density it forms a lens of light water which floats on the denser waters below, which are of subtropical origin and therefore cooler and of higher salinity.

Such a warm pool exists in the eastern tropical Pacific off the coast of Central America. It is shallow, warm and of very low salinity, but most important it is contained by convergent movements of the two subtropical gyres. These horizontal flows form the



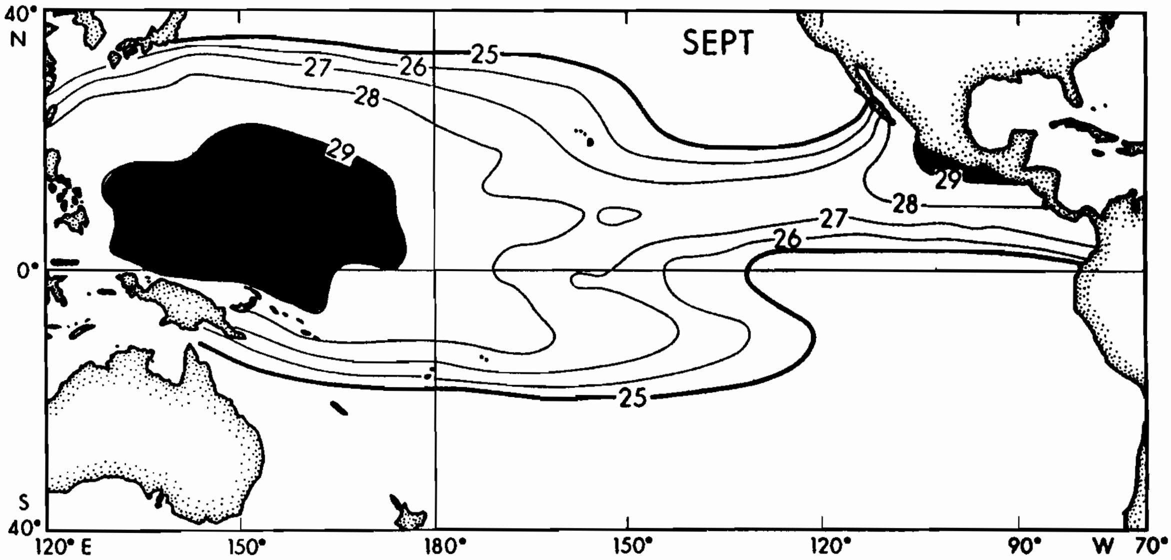


FIG.1. Average sea surface temperature in the tropical Pacific Ocean in March and September. Only isotherms warmer than 25°C are shown to define the warm pool.

Galapagos Front and the Cabo San Lucas Front and force the tropical surface water into a rather restricted area, from which it can escape only to the west, chiefly with the North Equatorial Current.

In the western tropical Pacific a similar pool is formed, but the warm layer is much deeper and can be stratified with respect to salinity as has recently been uncovered by Lukas and Lindstrom (1987). The water movements in the region are divergent and move water polewards into the western boundary currents. Therefore the pool is poorly defined horizontally.

A definition of the warm pool is relatively easy in the vertical through the use of a selected isothermal layer. In fact any isotherm above about 22°C would be useful, because the upper thermocline is very steep. A definition is much more difficult with regard to the pools horizontal extend. If one would use the 25°C isotherm, there would be only one large warm pool in the Pacific, and it would seasonally extend as far north as Japan and as far south as Brisbane, Australia (Fig. 1). Such a definition would clearly be undesirable. In contrast, the selection of the 29°C isotherm would define a pool that is too small and that might occasionally disappear. For these reasons the 28°C isotherm has been used by many scientists as a practical compromise for the definition of the west Pacific warm pool.

Accepting such a definition one is immediately confronted with large annual variations of the boundaries of the pool (Fig. 2). The extreme northerly position is reached in September, when the pool stretches far into the northern subtropical gyre. In March the pool barely reaches to 10°N. The annual fluctuations in the southern hemisphere are less pronounced, but the size of the pool doubles from September to March. The area covered permanently by the pool is relatively small, from about 10°N to 10°S and from Indonesia to 170°W, and represents only about half of the average area of the pool. The pool is slightly larger in the northern than in the southern summer. These large annual fluctuation of the boundaries of the pool make a definition of its size and volume rather difficult and somewhat uncertain. One also has to keep in mind that the annual heating and cooling cycles along the boundaries will add to or remove water from the pool.

The depth of the pool as given by the 28°C isotherm has been charted from XBT observations for each season, but only the maps for the July-August-September and the January-February-March periods are shown (Fig. 3). The maximum depth of the pool is just over 100 m, and the deepest area is near the equator and the date line, and not further west, where surface temperatures is warmest (Fig. 1). Where the pool is a permanent feature it is between 60 and 100 m deep. The distribution of depth changes little with the season, in contrast to its horizontal extend. Along the fringes, especially in the summer hemisphere, the pool is shallower and the boundary is not well defined.

In view of the poorly defined horizontal boundaries of the warm pool it is rather difficult to estimate its volume. Taking the average depth as 80 m and the area as 25×10^{12} m^2, the volume of the pool is about 20×10^{14} m^3. It should be noted that the area is about 15% larger in northern summer and 15% smaller in southern summer. The western boundary of the pool is arbitrarily assumed to be the line from the Philippines to New Guinea, not counting the warm water in the Indonesian Archipelago.

3. Circulation through the warm pool.

Waters of the subtropical gyres of the northern and southern hemisphere circulate through the warm pool and warm water leaves the pool in the North Equatorial Countercurrent and through the Indonesian Archipelago. It would be interesting to estimate the flows in and out of the pool in order to determine the pathways of water through the pool and to arrive at an estimate of the residence time of water in the warm pool. This is not an easy undertaking because of the poorly defined boundaries of the pool, and estimates will off course be rather crude. Toole, Zou and Millard (1988) have tried to establish a mass budget for waters warmer than 12°C for a smaller area in the western Pacific, and they point to the difficulties inherent in such studies.

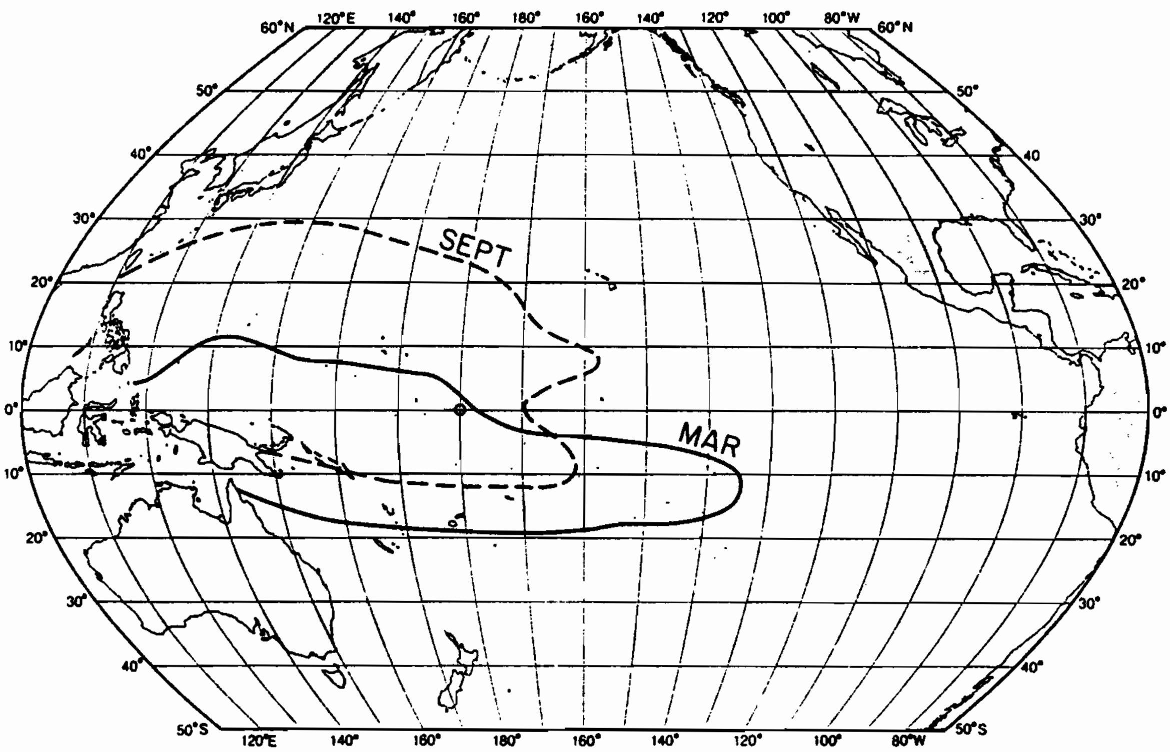


FIG.2. The warm pool in March and September as given by the 28°C isotherm. Note the small overlap.

All inflow into the warm pool occurs between Hawaii and Tahiti (Fig. 4). The Hawaii to Tahiti Shuttle Experiment has resulted in a rather solid determination of the geostrophic flows that enter and leave the warm pool in the east (Wyrtki and Kilonsky, 1984). Transports in the upper 400 m have been computed and they give 24 Sv (Sverdrup) for the North Equatorial Current, 20 Sv for the Countercurrent and 15 and 26 Sv for the two branches of the South Equatorial Current flowing north and south of the equator, respectively. Not all this water is warm enough to enter the warm pool, because these currents extend into the thermocline and even transport water below the thermocline. An inspection of the sections shown by Wyrtki and Kilonsky (1984) allows to estimate the flows of water in the mixed layer that enter or leave the warm pool between Hawaii and Tahiti.

The North Equatorial Current is deep reaching and only about half of its transport is in the mixed layer. As this water flows west the temperature of the surface water slowly increases to more than 28°C and it enters the warm pool, accounting for a contribution of about 12 Sv. The Countercurrent flow is much more concentrated in a shallow surface layer than the Northern Equatorial Current. Most of its water is warmer than 27°C and represents a loss of warm water from the pool. This flow can be estimated as about 15 Sv. The South Equatorial Current flows both north and south of the equator.

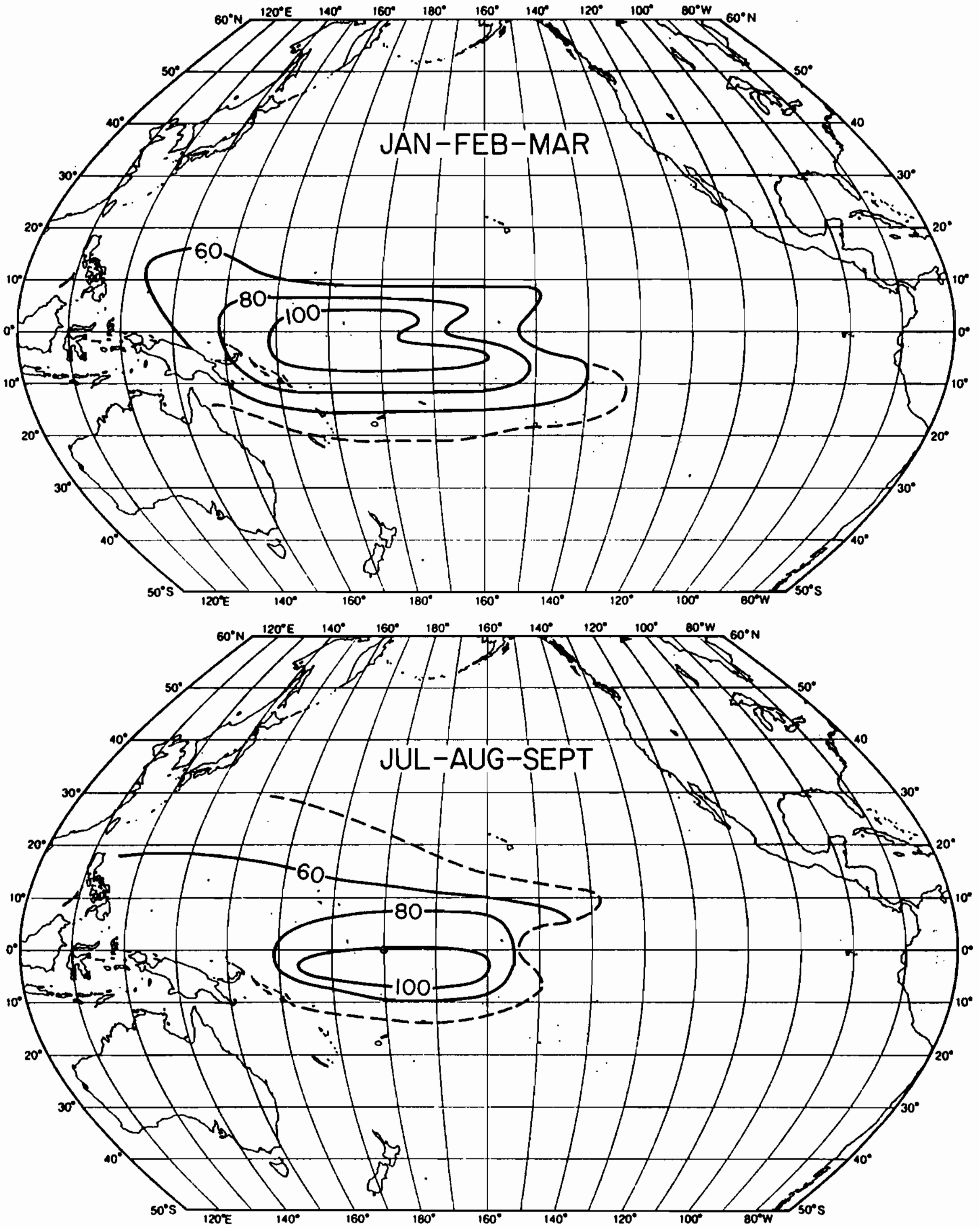


FIG.3. The average depth (in meters) of the 28°C isotherm as derived from XBT observations for the season January-February-March (top) and the season July-August-September (bottom).

Its northern part is very shallow and most of the flow consists of warm water. A reasonable estimate for this flow is 12 Sv. The southern part of the South Equatorial Current penetrates deeper into the thermocline and its westward flow of warm water may be estimated as 20 Sv between the equator and 8°S. South of this latitude flow is variable and weak, and westward flow is intertwined with the South Equatorial Countercurrent.

The warm pool looses water through the Indonesian Archipelago. Estimates of this throughflow vary between 5 and 14 Sv (Gordon, 1986), and some of the throughflow may involve water in and below the thermocline. Assuming a loss of warm water at a rate of 8 Sv appears reasonable.

So far we have estimated losses of water from the warm pool as 15 Sv in the Countercurrent and 8 Sv in the throughflow, and gains of 44 Sv in the North and South Equatorial Currents. The balance of 21 Sv must consequently leave the warm pool polewards with the western boundary currents. A schematic sketch of the pathways of warm water through the warm poll is given in Figure 4. It may be emphasized that most of the water entering the pool with the North Equatorial Current leaves again with the subtropical gyre circulation after only a short residence in the pool. The South Equatorial Current provides most of the water of the pool, which leaves as very warm water either with the Countercurrent or with the throughflow. About half of the water of the southern part of the South Equatorial Current participates in the circulation of the southern subtropical gyre. The pathways of water inside the gyre are off course speculative and simplified, but it seems rather clear that there is little interhemispheric exchange of water. The Indonesian throughflow is chiefly supplied from warm water of the southern hemisphere as assumed by Gordon (1986).

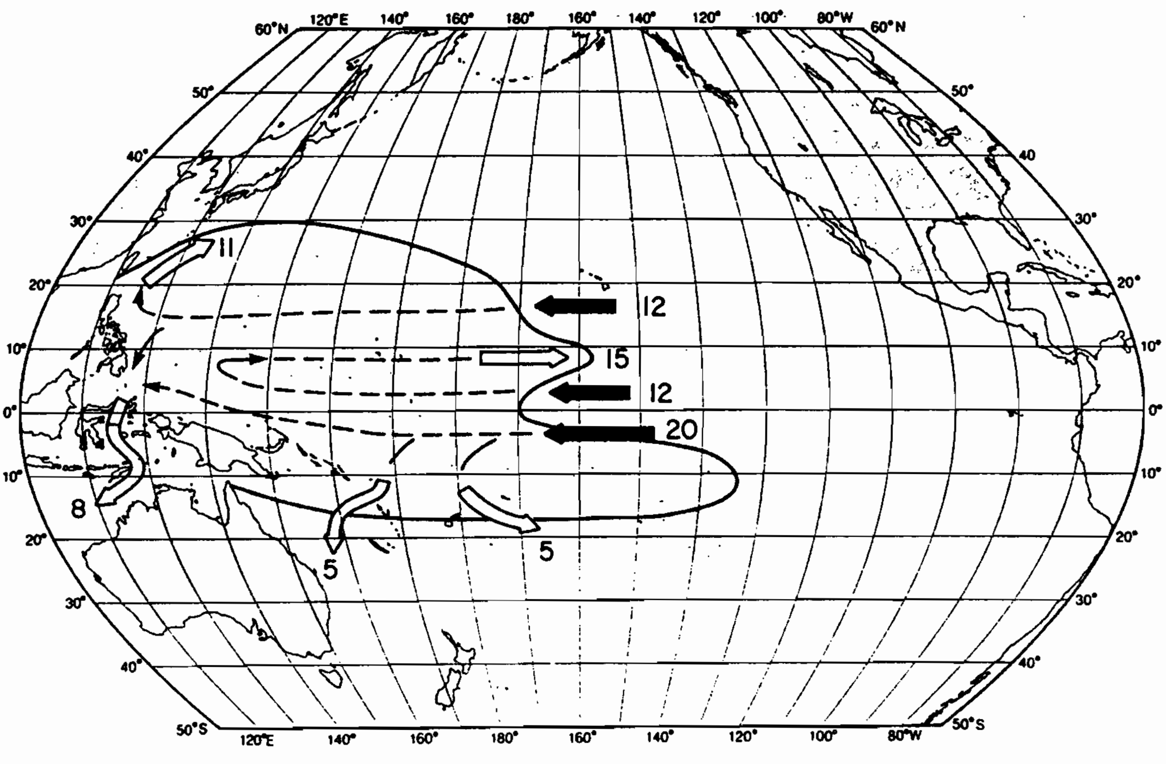


FIG.4. Estimates of water flowing into (solid arrows) and out of the warm pool (open arrows) in Sverdrups (10^6 m^3 s^{-1}).

Inside the warm pool water exchange between the various currents may be much more intense than sketched in this schematic diagram. The circulation to the north of New Guinea is subject to strong changes with the season, as shown by Schott (1939). Current measurements by Firing and Jiang (1989) have shown enormous fluctuations from year to year, and drifting buoy trajectories indicate strong water transfers between the various zonal currents (Hacker, Firing and Lukas, 1989).

Along the fringes of the pool, the water participating in the anticyclonic circulation of the subtropical gyres will be subject to the seasonal heating and cooling cycle. It will therefore become part of the pool when warmed, and disappear from the pool when cooled, an effect that results in the large annual variation of the poleward boundaries of the pool.

The above estimates of the water transports in and out of the warm pool allow to estimate the residence time of warm water in the pool. All inflow into the pool is from the east between Hawaii and Tahiti and it amounts to about 44×10^6 m^3 s^{-1}. The total volume of the pool is 20×10^{14} m^3. Dividing volume by circulation rate gives a residence time of only 1.3 years. This short residence time of warm water in the pool implies that the water in the pool is exchanged rather frequently and that the pool may be very sensitive to interannual variations of its volume. This residence time is short compared to the interval between El Nino events. It should also be noted that the warm pool gains its water from the two subtropical gyres and looses water with the Countercurrent and the Indonesian throughflow. The water lost with the Countercurrent will partially reach the warm pool in the eastern tropical Pacific and partially be re-circulated into the NEC, thus remaining in the tropical ocean. The water lost with the throughflow, on the other hand will be lost to the Pacific Ocean and represents an export of heat from the Pacific to the Indian Ocean.

The warm pool will also be very sensitive to interannual variations of its temperature and heat content. The average depth of the permanent, central portion of the pool is about 80 m. A slow change of its mean temperature by 1°C over a period of 2 years can certainly be detected by observations. Such a change can be produced by a small change of surface heat input of only 5 W m^{-2} , which is clearly below the threshold of detection.

4. The warm pool and the subtropical gyres.

Fluctuations of the volume of water in the warm pool are probably related to fluctuations of the circulation of the subtropical gyres. These gyres represent large masses of warm water that rotate in an anticyclonic direction. The warm upper layer of these gyres has a very characteristic shape, as shown by Shaw and Wyrtki (1972), especially when viewed as a two layer system. A schematic north-south section through the two subtropical gyres of the Pacific Ocean is shown in Figure 5. The mean depth of the upper layer in each gyre is given by the volume of warm water present in the gyre, which is probably very stationary because it is formed by the mean climatic conditions over a long period. The slope of the upper layer thickness from the center of each gyre toward the equator or toward the poles is a function of the strength of circulation in each gyre. A strong circulation will cause a larger slope than a weak circulation, and consequently a shallower position of the thermocline at the periphery and a deeper position in the center of the gyre, if the water volume remains constant. There is little doubt that changes in gyre circulation happen at much faster time scales than changes in their volume. The subtropical gyres are largely wind-driven, and consequently their circulation will vary with the wind forcing.

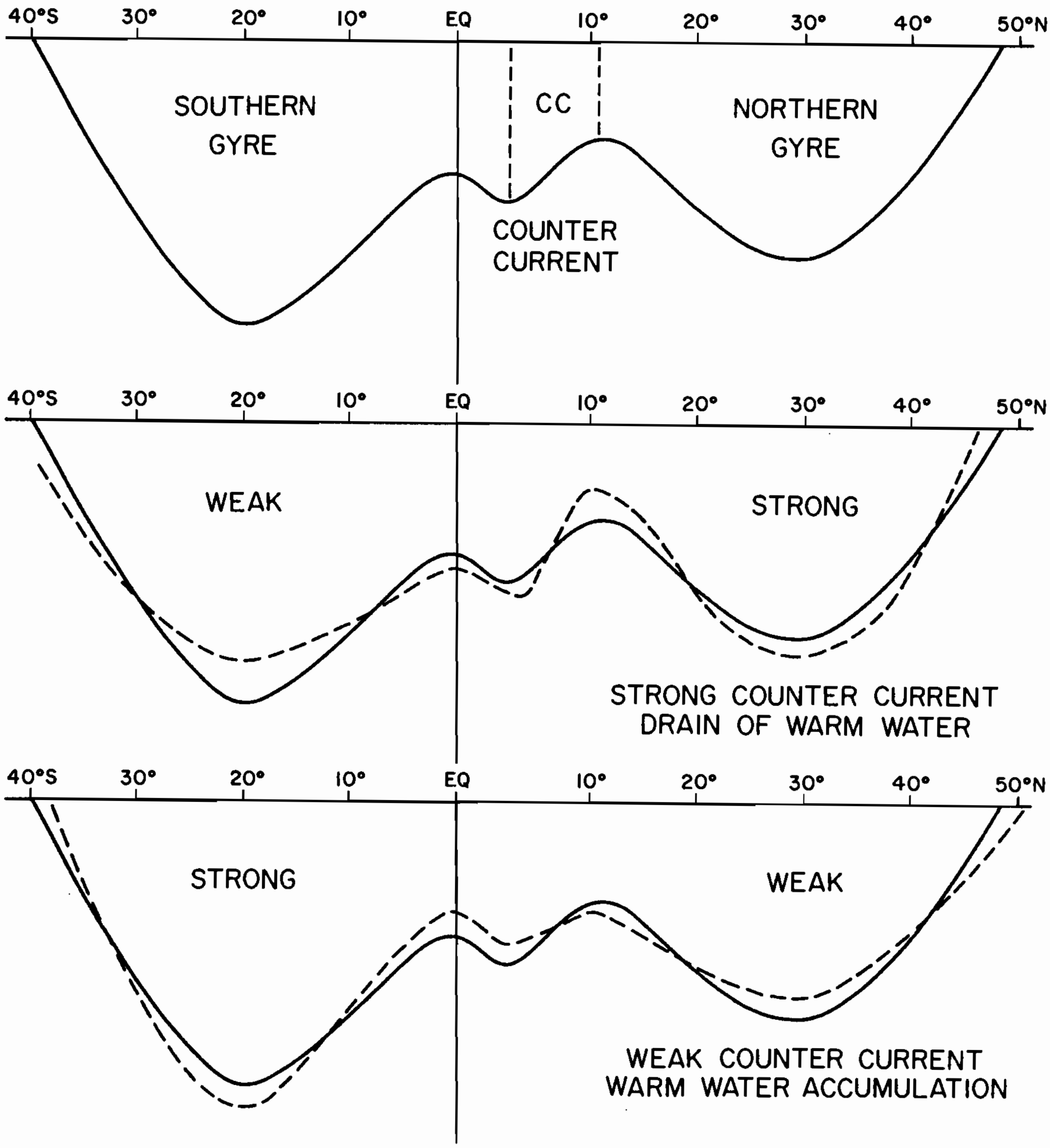


FIG.5. A schematic north-south profile of the shape of the thermocline across the two subtropical gyres in the Pacific (solid line) and possible patterns of oscillation (dashed lines) in relation to the strength of the countercurrent.

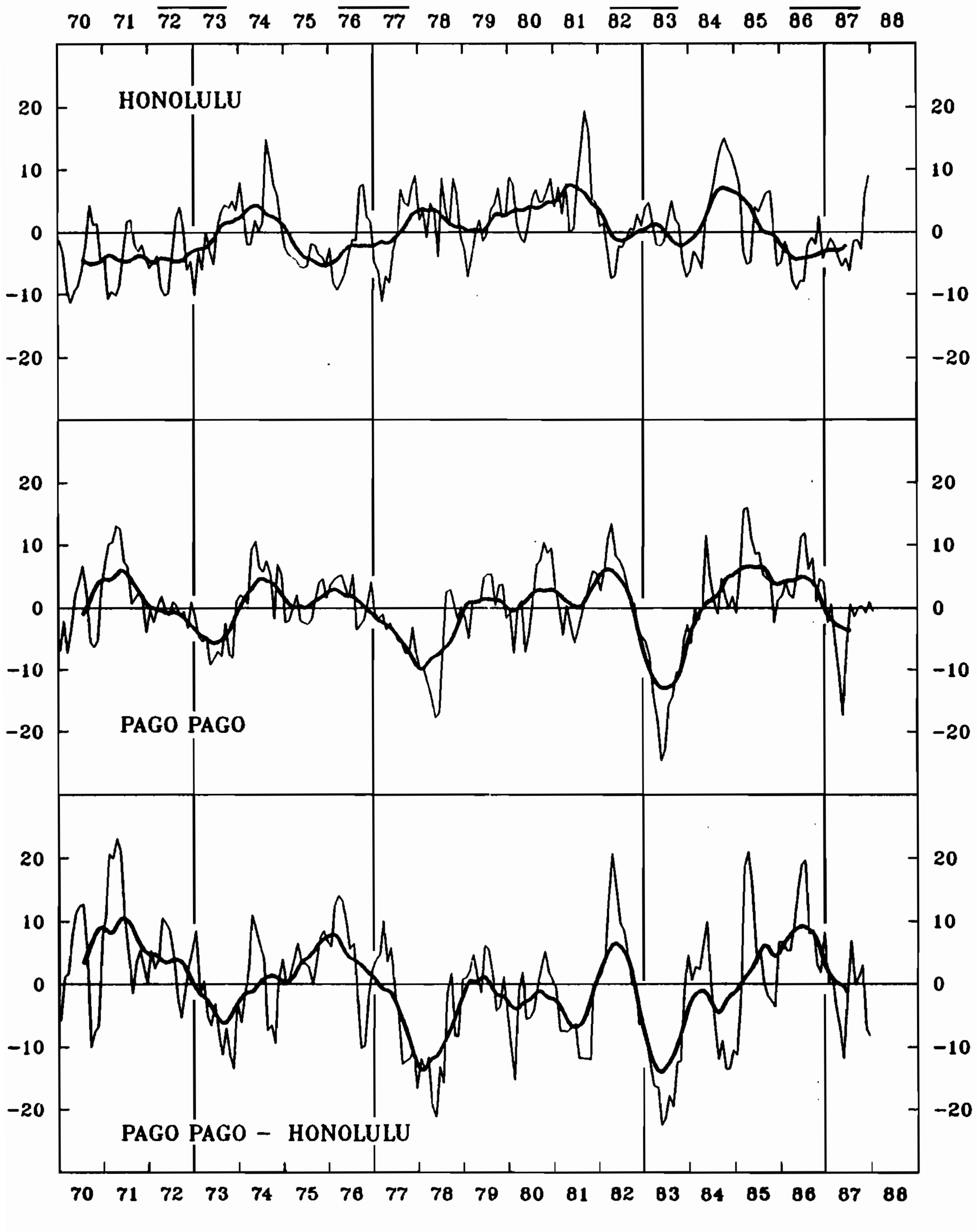


FIG.6. Monthly mean sea level at Honolulu and Pago Pago and their difference (in cm) from 1970 to 1988. The thick curves give the 12-month running means. The major El Nino events of 1972-73, 1976, 1982-83 and 1987 are marked by vertical lines.

Because the subtropical gyre of the southern hemisphere penetrates across the equator into the northern hemisphere, the slope of the thermocline reverses north of the equator. It is very unlikely that the volume of the two gyres and the intensity of their circulation match in such a way that the thermocline would have the same depth where the two gyres meet. In fact the thermocline of the northern gyre at its southern boundary is usually higher than the thermocline of the southern gyre at its northern boundary. This difference of thermocline depth causes a geostrophic current to develop between the two subtropical gyres, which is called the North Equatorial Countercurrent. It is therefore appropriate to consider the Countercurrent as a boundary current between the two subtropical gyres. Fluctuations in the intensity of circulation in the two gyres will cause fluctuations in the depth of the thermocline at their periphery and will change the slope of the thermocline across the Countercurrent. Consequently the Countercurrent will be subject to strong fluctuations caused by the fluctuations of the two gyres.

Fluctuations of the two subtropical gyres have been documented by Wyrtki and Wenzel (1984) by means of sea level observations. They have shown that the gyres oscillate out of phase with a period near 4 years, and that these oscillations are related to El Nino events. Fluctuations of the baroclinic structure of the subtropical gyre in the western North Pacific have been documented by White and Hasunuma (1980) and also show a periodicity related to El Nino events. It is useful to consider the reaction of the Countercurrent to oscillations of the gyres, and this is sketched schematically in Figure 5. If the northern gyre is strong, and the southern gyre weak, the difference of the thermocline across the Countercurrent will be large and the Countercurrent strong. This situation implies a strong drain of warm water from the warm pool, and is typical for El Nino conditions, when the warm pool looses mass. In contrast, when the southern gyre is strong, and the northern gyre is weak, the difference of the thermocline across the Countercurrent will be small, and the Countercurrent will be weak. This situation will lead to a small drain of water from the warm pool, but to a strong accumulation of warm water in the pool by an intensified South Equatorial Current. During this period the warm pool will grow, and that typically happens between El Nino events.

It remains now to relate the fluctuations of the subtropical gyres as observed by sea level at Honolulu and Pago Pago to the occurrence of El Nino. Wyrtki and Wenzel (1984) have used data from 1948 to 1982 to show that the sea level difference between Pago Pago and Honolulu increases between El Nino events, indicating an acceleration of the southern gyre. During these periods the South Equatorial Current is strong, adding warm water to the pool, and the Countercurrent is weak, draining less water from the pool. Both effects allow the warm pool to grow. During El Nino the sea level difference between Pago Pago and Honolulu decreases, the southern gyre becomes weaker, the Countercurrent stronger, and water is being drained from the warm pool. Six more years of sea level data have been added to the time series of Wyrtki and Wenzel (1984) covering the 1982-83 and the 1986-87 El Nino events (Fig. 6). During both events the same pattern is apparent: between El Nino events the sea level difference between the two gyres increases, and drops rapidly during these events. This confirms the contention that El Nino events involve an aperiodic discharge of warm water from the western equatorial Pacific as stated by Wyrtki (1985).

5. Conclusions.

The west Pacific warm pool gains water from the two subtropical gyres, but chiefly from the South Pacific gyre with the South Equatorial Current. The pool looses water with the Countercurrent, with the Indonesian throughflow and polewards with the subtropical gyres. Water in the pool has a short residence time and consequently the pool is sensitive to interannual variations of volume and heat content caused by fluctuations of advection and surface heat flux. To understand fluctuations of the warm pool, the interactions with the two gyres must be taken into account. Fluctuations of the circulation in the two subtropical gyres are systematically linked to fluctuations of the Countercurrent and changes in the volume of the warm pool. The gyres are wind-driven and fluctuations of their circulation are due to fluctuations of the winds. Wind fluctuations in turn, in particular of the southeast trade winds in the Pacific, are linked to El Nino events, which only demonstrates how strongly fluctuations in the ocean and in the atmosphere are coupled.

It will be very difficult to measure the volume fluctuations of the warm pool and more difficult to measure the transports of the currents flowing in and out, so that a mass budget can be derived, and the contributions of the subtropical gyres to the pool can be determined. On the other hand there seems to be little doubt that the interaction of the two subtropical gyres is intimately involved in the fluctuations of the warm pool and in the creation of El Nino events. It may be a challenge to theoreticians to model these gyre-gyre oscillations.

Acknowledgements. Support for this research was provided by National Science Foundation, grant OCE8515404, with contributions from NASA, and National Oceanographic and Atmospheric Administration grant NA85ABH00032.

REFERENCES

Firing, E., and S. Jiang, 1989: Variable currents in the western Pacific measured during the USA-PRC bilateral TOGA project. Abstracts: Western Pacific International Meeting and Workshop on TOGA-COARE. ORSTOM. Centre de Nouméa, p. 19.

Gordon, A., 1986: Interocean exchange of thermocline water. *J. Geophys. Res.*, **91**, 5037-5046.

Hacker, P., E. Firing, R. Lukas, 1989: Observations of the low-latitude western boundary circulation in the Pacific during WEPOCS III. Abstracts: Western Pacific International Meeting and Workshop on TOGA-COARE. ORSTOM. Centre de Nouméa, p. 35.

Lukas, R., and E. Lindstrom, 1987: The mixed layer of the western equatorial Pacific Ocean. Proceedings of the 'Aha Huliko'a Hawaiian Winter Workshop on The Dynamics of the Oceanic Surface Mixed Layer. Honolulu, January 1987, P. Muller and D. Henderson, eds. 67-94.

Schott, G., 1939: Die aquatorialen Stromungen des westlichen Stillen Ozeans. *Annalen der Hydrographie und Maritimen Meteorologie*, **67**, 247-257.

Shaw, R., and K. Wyrtki, 1972: The shape of the warm surface layer in a subtropical gyre. In: Studies in Phys. Oceanogr. A. L. Gordon, ed., New York, p. 179-194.

TOGA COARE, 1988: A Coupled Ocean-Atmosphere Response Experiment for the Warm Pool Regions of the Western Pacific: Science Plan. U.S. TOGA COARE Science Working Group.

Toole, J. M., E. Zou, and R. C. Millard, 1988: On the circulation of the upper waters in the western equatorial Pacific Ocean. *Deep-Sea Res.*, **35**, 1451-1482.

White, W. B., and K. Hasunuma, 1980: Interannual variability in the baroclinic gyre. *J. Mar. Sci.*, **38**, 651-672.

Wyrtki, K., 1985: Water displacements in the Pacific and the genesis of El Nino cycles. *J. Geophys. Res.*, **90**, 7129-7132.

Wyrtki, K., and J. Wenzel, 1984: Possible gyre-gyre interaction in the Pacific Ocean. *Nature*, **309**, 538-540.

Wyrtki, K., and B. Kilonsky, 1984: Mean water and current structure during the Hawaii to Tahiti Shuttle Experiment. *J. Phys. Oceanogr.*, **14**, 242-254.

WESTERN PACIFIC INTERNATIONAL MEETING AND WORKSHOP ON TOGA COARE

Nouméa, New Caledonia
May 24-30, 1989

PROCEEDINGS

edited by

Joël Picaut *
Roger Lukas **
Thierry Delcroix *

* ORSTOM, Nouméa, New Caledonia
** JIMAR, University of Hawaii, U.S.A.

INSTITUT FRANÇAIS DE RECHERCHE SCIENTIFIQUE
POUR LE DÉVELOPPEMENT EN COOPÉRATION

ORSTOM

Centre de Nouméa

TABLE OF CONTENTS

MEETING COLLECTED PAPERS

WATER MASSES, SEA SURFACE TOPOGRAPHY, AND CIRCULATION

EL NINO/SOUTHERN OSCILLATION 1986-87

MOMENTUM, HEAT, AND MOISTURE FLUXES BETWEEN ATMOSPHERE AND OCEAN

EMPIRICAL STUDIES OF ENSO AND SHORT-TERM CLIMATE VARIABILITY