provement in soil fertility might occur. Unfortunately, the elements are mostly unavailable. Analysis of the available (and hence biologically significant) nutrients showed the following concentrations (in parts per million): P, 1 to 5; K, 120 to 180; Cu, 3 to 5; Fe, 15 to 40; Zn, 0.5 to 1; Mn, 10 to 20; and S as sulfate, 250 to 450 (*8*). With the possible exception of sulfur, the amount of each element available is insufficient to change current fertilization practices. Moreover, the prospect for release of these unavailable nutrients by weathering and other processes seems poor. Other ash layers in the region deposited thousands of years earlier have changed very little (*30*). In short, as a soil material the ash may prove biologically quite inert.

References and Notes

1. P. E. Hammond. *AEG (Assoc. Eng. Geol.) Newslett.* **23** (No. 3), 15 (1980).
2. W. S. Moen, personal communication.
3. D. R. Crandell and D. R. Mullineaux, *U.S. Geol. Surv. Bull. 1383-C* (1978), p. 26.
4. P. R. Hooper, I. W. Herrick, E. R. Laskowski, C. R. Knowles, *Science* **209**, 1125 (1980).
5. Center for Disease Control, *Mt. St. Helens Tech. Inf. Network Fed. Coord. Office Bull. 13* (1980), p. 4.
6. J. S. Fruchter, D. E. Robertson, J. C. Evans, K. B. Olsen, E. A. Lepel, J. C. Laul, K. H. Abel, R. W. Sanders, P. O. Jackson, N. S. Wogman, R. W. Perkins, H. H. Van Tuyl, R. H. Beauchamp, J. W. Shade, J. L. Daniel, R. L. Erikson, G. A. Sehmel, R. N. Lee, A. V. Robinson, O. R. Moss, J. K. Briant, W. C. Cannon, *Science* **209**, 1116 (1980).
7. R. K. Sorem, paper presented at the Conference on the Aftermath of Mount St. Helens, Washington State University, Pullman, 8-9 July 1980.
8. Data provided by A. Halvorson, Soil Testing Laboratory, Washington State University, Pullman.
9. J. J. Brown, unpublished data; personal communication.
10. R. D. Akre, paper presented at the Conference on the Aftermath of Mount St. Helens, Washington State University, Pullman, 8-9 July 1980.
11. D. M. Powell, unpublished data.
12. D. Kiem, personal communication.
13. E. C. Klostermeyer, personal communication.
14. C. Johansen, *Am. Bee J.* **120**, 500 (1980).
15. G. M. Hyde, *Mt. St. Helens Tech. Inf. Network Fed. Coord. Office Bull. 23* (1980).
16. G. Rubenthaler, unpublished data.
17. R. Kennedy, quoted in the *Goodfruit Grower*, 1 July 1980, p. 5.
18. G. J. Williams, III, J. A. Pottmyer, D. Pyke, J. M. Green, R. O. Littlejohn, R. K. Monson, unpublished data from research conducted on George Hudson Reserve for Biological Research near Pullman, Washington, where alien weed species (*Cirsium arvense*, *Convolvulus arvensis*, *Lactuca serriola*, and *Verbascum thapsus*) were covered by plastic bags in several plots hours before the ashfall on 18 May and have been maintained since that date.
19. R. L. Preston, paper presented at the Conference on the Aftermath of Mount St. Helens, Washington State University, Pullman, 8-9 July 1980.
20. J. McGinnis, *Mt. St. Helens Tech. Inf. Network Fed. Coord. Office Bull. 11* (1980).
21. G. F. Williams, personal communication.
22. G. Barth, personal communication.
23. H. N. Blain, Washington Dry Pea and Lentil Commission, Moscow, Idaho, personal communication.
24. G. W. Bruehl, personal communication.
25. ——, W. L. Nelson, F. Koehler, O. A. Vogel, *Wash. State Univ. Agric. Exp. Stn. Bull. 694* (1968).
26. R. F. Griggs, *Ohio J. Sci.* **19**, 209 (1919); *ibid.*, p. 318.
27. W. A. Eggler, *Ecol. Monogr.* **29**, 267 (1959); *Am. Midl. Nat.* **69**, 38 (1963).
28. G. A. Smathers and D. Mueller-Dombois, *U.S. Natl. Park Serv. Monogr. 5* (1974).
29. M. Molnau, K. Saxton, D. McCool, abstract for presentation at the American Geophysical Union annual winter meeting, San Francisco, September 1980.
30. D. R. Mullineaux, J. H. Hyde, R. Meyer, *J. Res. U.S. Geol. Surv.* **3** (No.3) (1975).
31. Composition of ash from Yakima and Richland was determined by the Soil Testing Laboratory, Washington State University, using estimates from the hygrometer method not corrected for specific gravity (the method is based on a specific gravity of 2.65; the specific gravity of ash is slightly less). Composition of ash from Pullman was determined by the Coulter counter method by the Soil Characterization Laboratory, University of Idaho.
32. Charts A and C in Fig. 1 were redrawn from data provided by M. M. Folsom and R. R. Quinn. Chart B was redrawn from R. Daubenmire, *Wash. Agric. Exp. Stn. Tech. Bull. 62* (1970).

33. We recognize with gratitude the information provided so generously by the research and extension faculty and students of Washington State University, including F. M. Entenmann, Cooperative Extension Service; E. Klostermeyer and other faculty, Department of Entolmology; R. A. Kennedy, Department of Horticulture; R. Preston, Department of Animal Science; G. L. Rubenthaler, Wheat Quality Laboratory, U.S. Department of Agriculture; and R. K. Sorem, Department of Geology. We also thank M. M. Folsom and R. R. Quinn, Eastern Washington University, Cheney; C. Knowles, Idaho Bureau of Mines and Geology, Moscow; and W. Moen, Division of Geology and Earth Resources, Department of Natural Resources, Olympia, Wash., for providing information on the nature and amounts of ash.

The Hawaii to Tahiti Shuttle Experiment

Klaus Wyrtki, Eric Firing, David Halpern, Robert Knox
G. J. McNally, W. C. Patzert, E. D. Stroup, B. A. Taft, R. Williams

The Hawaii to Tahiti Shuttle Experiment has three distinct roots. The first is the work of Bjerknes (*1*), who analyzed ocean-atmosphere interactions associated with the 1957 El Niño event and concluded that large-scale events in the equatorial Pacific Ocean are caused by feedback between ocean and atmosphere and have global consequences. The second root—and the original idea for a shuttle—is Montgomery's 1969 study of the meteorological observations that were made by passenger ships between Hawaii and Tahiti (*2*). He concluded that such simple observations of parameters of the air-sea boundary made by these ships are adequate to detect and describe the low-frequency changes of the ocean-atmosphere system in the central Pacific. He recommended that a transequatorial shuttle program on ships of opportunity be implemented. The third root is an investigation by Wyrtki (*3*) of the relations between flow in the countercurrent, sea level difference across the current, and temperature in the eastern equatorial Pacific, where the countercurrent terminates. He showed that the flow is subject to large interannual variations and that strong flow is concurrent with warming in the eastern equatorial Pacific and El Niño events off Peru.

In the early 1970's the North Pacific experiment (NORPAX) was begun as part of the International Decade of Ocean Exploration. It was based on the ideas of Namias (*4*) and Bjerknes (*1*) concerning the large-scale interactions of ocean and atmosphere and the use of these relations and teleconnections in long-range forecasting. One of the most pronounced climatological events in the Pacific Ocean is, of course, El Niño; and a new theory about its mechanism was developed by Wyrtki (*5*), who analyzed the trade wind field and sea level records. It was shown that, after a period of sustained, strong southeast trade winds, much warm water is accumulated in the western Pacific, and that as soon as the trade winds relax, the water surges back along the equator. This theory was tested and confirmed by analytical and numerical models (*6*) which show that the adjustment of the thermocline is accomplished primarily by an internal Kelvin wave. The changes in ocean structure in the western and eastern Pacific associated with El Niño could be confirmed by

K. Wyrtki, E. D. Stroup, and E. Firing are at the Department of Oceanography and the Hawaii Institute of Geophysics, University of Hawaii, Honolulu 96822; D. Halpern is at the Pacific Marine Environmental Laboratory, National Oceanic and Atmospheric Administration, Seattle, Washington 98105; R. Knox, G. J. McNally, W. C. Patzert, and R. Williams are at Scripps Institution of Oceanography, University of California, San Diego, La Jolla 92093; and B. A. Taft is at the Department of Oceanography, University of Washington, Seattle 98195.

Summary. The Shuttle Experiment conducted between Hawaii and Tahiti from January 1979 to June 1980 was designed to observe the changing equatorial ocean structure and circulation, to study the variations and interactions of the four major equatorial ocean currents, and to develop a scientific basis for their monitoring by simple observations of thermal structure and sea level. Preliminary analyses of the results show that the equatorial thermal structure remains intact during a normal year and that only the positions and intensities of the currents are subject to change. The water transport of the equatorial undercurrent varied from 25 × 10^6 cubic meters per second in January to 51 × 10^6 cubic meters per second in July, but also exhibited strong short-term pulsations. The equatorial surface flow responded strongly to the winds at periods of 1 month and longer. An array of drifter buoys in the equatorial countercurrent was subject to very little dispersion while traveling over 4500 kilometers in 4 months. Low-frequency fluctuations in the North Equatorial Countercurrent can be monitored by means of the difference in sea level between Fanning and Majuro.

past oceanographic observations, but the zonal flow in the central Pacific associated with El Niño is much more difficult to measure.

The NORPAX scientists soon realized the need for an adequate and continuous data base for their studies of the changing ocean-atmosphere system, and the problem of ocean monitoring began to receive more and more attention. They established a program to sample the thermal structure of the North Pacific from ships of opportunity (*7*) and a network of sea level gauges in the equatorial Pacific (*8*). The network of sea level gauges, part of which is shown in Fig. 1, would be capable of monitoring the changing strength of the various equatorial currents by means of the geostrophic relation, but it would be necessary to establish a precise calibration for the procedure.

In the central tropical Pacific the basic hydrographic structure and flow patterns are essentially zonal. The ocean is stratified into a warm upper layer and a cool deep layer, separated by a sharp thermocline. The structure is marked by a sequence of zonal ridges and troughs that are almost permanent but change in intensity and position. If long-period changes have very long zonal scales the system lends itself naturally to systematic monitoring, since observations along a single section would describe much of the variation in the exchange of water between the eastern and western equatorial Pacific. An experiment to explore the relations of the various space and time scales was therefore a prerequisite for a monitoring effort.

In 1975 the time seemed ripe to implement such a program, and the NORPAX equatorial panel was formed under the cochairmanship of W. Patzert and D. Halpern. The then forthcoming Global Weather Experiment of 1979 offered a further incentive: some 40 oceanographic ships were to serve as tropical wind-observing ships in all oceans, and the resulting extensive meteorological coverage of the tropics would greatly benefit the evaluation of concurrently collected oceanographic data, since much of the oceanic variability is forced by the winds.

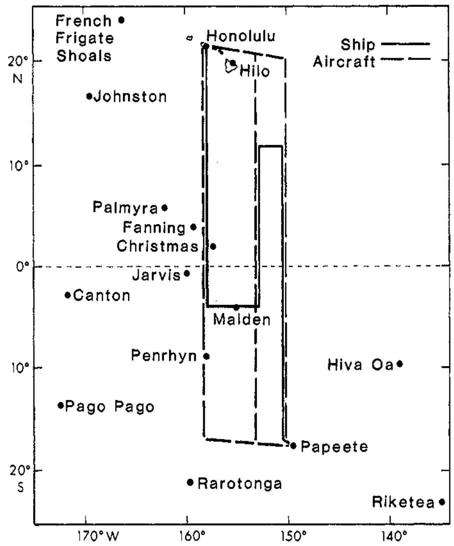

Fig. 1. Location of the Shuttle Experiment showing the ship track, aircraft sections, and sea level stations.

The principal objective of the Shuttle Experiment is to develop the scientific basis for a monitoring system for the tropical Pacific. This requires observation of the low-frequency variations of equatorial temperature, salinity and density structure, and currents and an understanding of the relations between structure and flow, the dynamic interactions between the major currents, and the forcing of their fluctuations by the wind systems. The experiment is also designed to demonstrate how closely the relations between dynamic topography, thermal structure, sea level, geostrophic flow, geostrophic transport, and observed transport can be determined and how these relations can be used to monitor the slow variations of the equatorial circulation by simple observations such as sea level gauges on islands and temperature sections from ships of opportunity.

The central Pacific was chosen as the location for the Shuttle Experiment for several reasons. The hydrographic structure and the currents are of great zonal uniformity, the region can easily be monitored by a north-south section, and the entire exchange of water between the eastern and western equatorial Pacific must pass through such a section. The section from Hawaii to Tahiti was chosen because it was close to a north-south line formed by the stations at which sea level was measured (Fig. 1) but far enough east of the Line Islands that only minor topographic disturbances would be expected. The logistic requirements for the ships and the aircraft did not allow us to place the experiment much farther east. The minimum duration of the experiment was set at 1 year to investigate the low-frequency variations and in particular the strong annual signal. A duration of 16 months was considered appropriate to ensure sufficient overlap at both ends. In 1964 and 1965 a similar but more limited experiment had been conducted which resulted in an understanding of the response of the North Equatorial Current to wind forcing (*9*).

A test Shuttle Experiment was conducted from November 1977 to February 1978 to define the time and space scales of fluctuations in the structure and circulation of the equatorial Pacific and to determine the proper sampling density for the main experiment (*10*). During the test shuttle, weekly air-expendable bathythermograph (AXBT) sections were flown between Hawaii and Tahiti along 150°W (and also, during the last 2 months, along 158°W) to determine zonal differences. The flights were as frequent as every second day. The R.V. *Kana Keoki* made four hydrographic sections along 150°W, three current meter moorings were maintained across the North Equatorial Countercurrent, and satellite-tracked drifter buoys were released. The important findings from the test shuttle were that most of the noise in the temperature data is of high frequency and is largely uncorrelated and that the low-frequency signal emerges clearly above the noise. Coherent variability extended across the equator and across boundaries of major ocean currents and had time scales of the order of months (*11*).

Some surprising differences in ocean structure were observed between 150°W and 158°W, so sampling during the main experiment was extended to three meridians. The time variations of geostrophic transport above 300 meters in the North Equatorial Countercurrent agreed well with variations of transport computed from moored current measurements.

The Experiment

The scientific program of the Shuttle Experiment consisted of 15 monthly cruises between Hawaii and Tahiti along three meridians (Fig. 1). The first five cruises were made by the R.V. *Gyre* of Texas A & M University and the following ten cruises by the R.V. *Wecoma* of Oregon State University. Additional temperature sections were obtained by AXBT along the same three meridians. Thirty of the flights were by Navy P-3 aircraft and five were by National Oceanic and Atmospheric Administration (NOAA) aircraft. The NOAA R.V. *Oceanographer* twice deployed a cluster of current meter moorings at the equator. The *Wecoma* recovered and redeployed them. A diagram showing the operation of the ships and aircraft by time and latitude is given in Fig. 2.

The core program aboard the ships consisted of vertical profiles of temperature, conductivity, and oxygen content to 1000 m at every degree of latitude and longitude along each ship's track. Between the hydrographic stations additional bathythermograph profiles were obtained. These measurements, together with the AXBT sections, document the changing temperature, salinity, and density structure and allow the computation of geostrophic flow. Direct measurements of the flow field to 500 m were also made from the ships by profiling current meter (PCM) at all stations between 10°N and 4°S, and at 0.5° intervals across the equatorial undercurrent. A Doppler speed log was used for continuous profiling of the current structure in the upper 120 m. At the equator a cluster of three moorings, each with five current meters in the upper 250 m, was maintained during the entire experiment to measure the flow in the equatorial undercurrent. To measure the trajectories of the flow, 60 drifter buoys were deployed and their tracks were followed by satellite. During the two special observation periods of the Global Weather Experiment, the *Gyre* and the *Oceanographer* served as two of the 40 tropical wind-observing ships and made upper air soundings with Omega-tracked balloons to determine the atmospheric wind profiles. Routine meteorological observations were also made from the ships. Measurements of

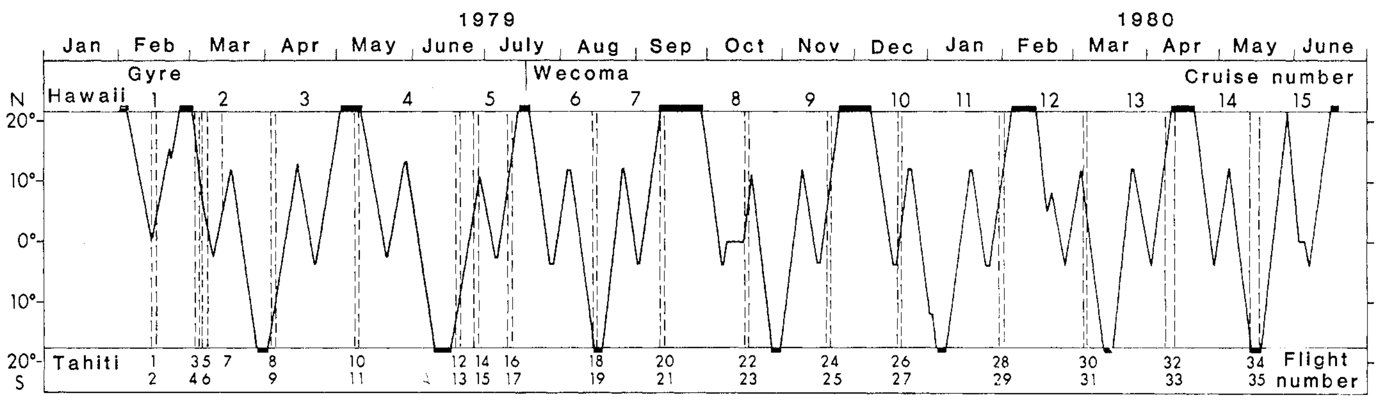

Fig. 2. Diagram of the Shuttle Experiment showing the track of the *Gyre* and *Wecoma* and the flights between Honolulu and Papeete.

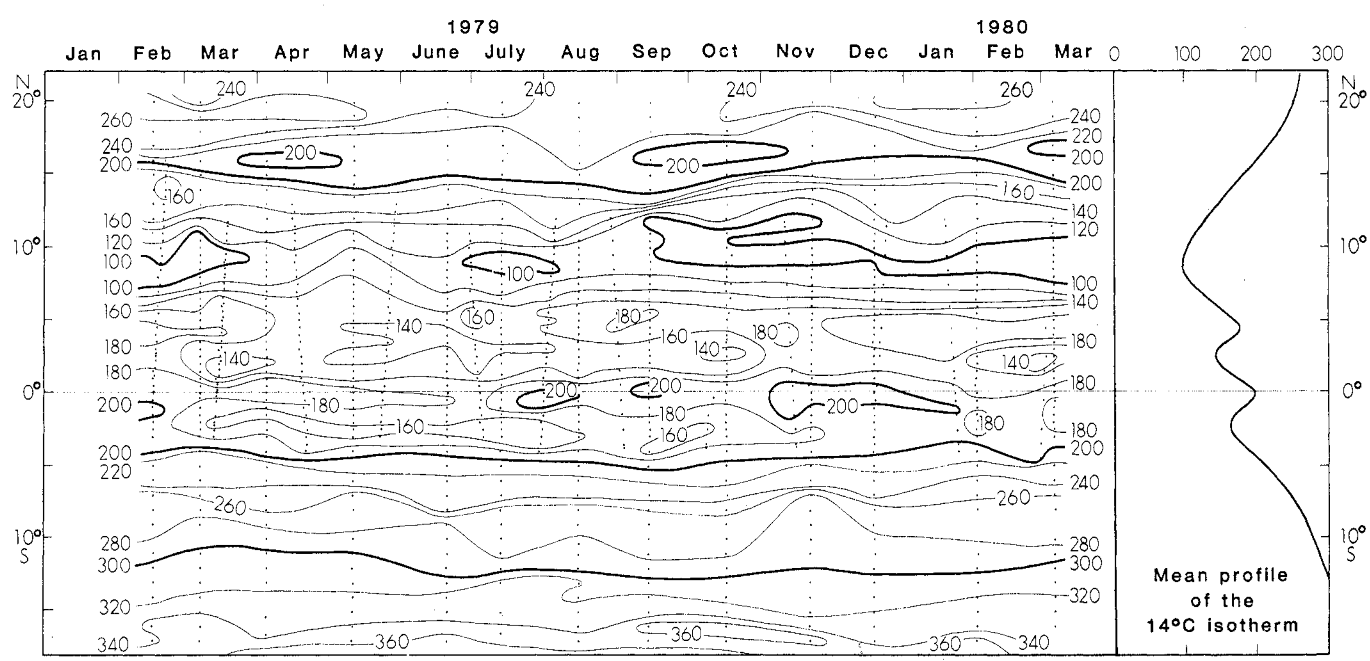

Fig. 3. Topography of the depth (in meters) of the 14°C isotherm along 153°W during the first year of the Shuttle Experiment. The panel on the right gives the mean profile of the 14°C isotherm as a function of latitude, showing the various ridges and troughs.

sea level were made at islands in the general area of the experiment, and the behavior of the wind field over the entire tropical Pacific was inferred from satellite observations of low-level cloud motion. Standard meteorological observations were also made at five of the Line Islands.

The repeated shuttling of a research ship across the equatorial current system provided the opportunity for additional programs. On all northbound cruises, the concentrations of oxygen, phosphate, silicate, nitrate, and nitrite were measured in the upper 400 m. The carbon dioxide content of the air and the surface water was monitored, and tritium, radioactive carbon, and lead concentrations were measured. Biological work included measurements of productivity and chlorophyll and sampling of nekton and neuston on several cruises. Continuous bathymetric soundings were made along the ship track, which was laterally offset 20 nautical miles on each of four cruises.

With the completion of the Shuttle Experiment a unique data set became available for evaluation. It consists of a detailed documentation of the four-dimensional thermal structure of the equatorial Pacific between the sea surface and 1000 m from 20°N to 17°S along three longitudes (150°, 153°, and 158°W) over 16 months. It is complemented by measurements of salinity, oxygen, and nutrients and by direct current measurements. It will be several years before a final scientific analysis of the data is completed, but some results are already apparent.

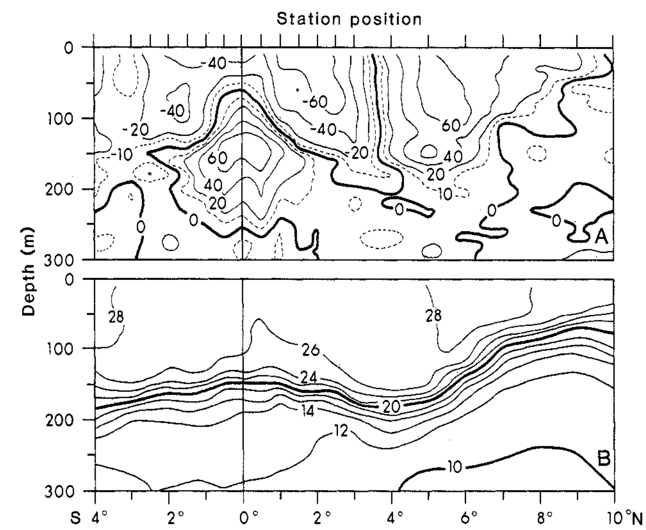

Fig. 4. Profiling current meter measurements at 153°W during January 1980. (A) Zonal component of the current (in centimeters per second) relative to the average current between 300 and 500 m and (B) temperature. Eastward transport is positive.

Changes in the Thermal Structure

The thermal structure between Hawaii and Tahiti is characterized by a sequence of ridges and troughs, and the topography of the thermocline is a good indicator of the zonal geostrophic flow. The thermocline is extremely sharp between about 5°S and 10°N, except at the equator, and becomes deeper and less steep toward the centers of the subtropical gyres. Its changing topography can best be represented by the depth of a selected isothermal surface (Fig. 3). The 14°C isotherm is generally in the lower portions of the thermocline and reflects the geostrophic slope associated with the North Equatorial Current, North Equatorial Countercurrent, and South Equatorial Current. The 14°C isotherm is also in the lower portions of the undercurrent, where downwelling produces an equatorial trough in the isotherms. The equatorial upwelling, indicated by upward deflection of the isotherms, is restricted to shallower depths, usually above 120 m.

During 1979 changes of the thermal structure were slow and systematic; the basic structure of the thermocline was maintained throughout the year. The ridge near 10°N weakened from February to April, shifted slightly south, and intensified again in July and August. The trough near 4°N showed the same pattern: strong in the beginning, weak from April to June, and strong again in the second half of the year. The North Equatorial Countercurrent between the ridge and the trough varied accordingly, as will be discussed in relation to ocean monitoring. The slope associated with the North Equatorial Current is strongest between 11°N and 15°N, where the 14°C isotherm drops from 100 to 200 m. Near 16°N the passage of three eddies is indicated by isolated patches of the 200-m contour in April, September and October, and March. All three eddies are moderately strong and the isotherms rise less than 40 m above the background. Their typical diameter is about 300 kilometers and they take about 1 month to drift across a given meridian. A similar but stronger eddy was noted during the test Shuttle Experiment (*10*). The observations made during the Shuttle Experiment indicate that only a few eddies pass west with the North Equatorial Current during the year.

South of the equator the 14°C isotherm drops from about 180 m near 3°S to more than 340 m near 17°S toward the center of the subtropical gyre, indicating the influence of the South Equatorial Current. The slope is comparatively uniform and changes little during the year. The shallow South Equatorial Countercurrent between 9°S and 13°S is not indicated by the slope of the 14°C isotherm, but only by shallower isotherms. There is little apparent eddy activity associated with the South Equatorial Current. Not a single eddy drifted across 153°W during 1979. A weak eddy was observed at 158°W and 12°S in March 1979.

Faster variability is apparent in the equatorial belt between 5°N and 5°S, but even there the changes are systematic and slow. The trough associated with the equatorial undercurrent is about 180 m deep during the first half of the year and more than 200 m in the second half. On either side, near 3°N and 3°S, is a ridge that varies slowly in intensity. From March to October both ridges are strongly developed and the slope between them and the trough at the equator is steep. This contrast indicates a strong undercurrent, as was measured directly. During the second half of the year the contrast is weaker (although the equatorial trough is deeper), and so is the undercurrent.

This preliminary analysis indicates that the principal thermal structure of the equatorial ocean remains intact throughout a normal year and that only the positions and intensities of the major currents change. These changes are of the order of months, at least outside the equatorial band from 3°N to 3°S, and only a few eddy or wavelike phenomena are superimposed. The higher frequency variability of the order of days, with spatial scales of the order of the station distance, is approximately 6 to 8 m in vertical isotherm displacement and apparently is randomly distributed. Its spectral characteristics require further analysis. The preliminary analysis also indicates that the thermal structure of the central equatorial Pacific in 1979 developed normally, which is advantageous for the further analysis of the data since they are not biased by some large, extraordinary events.

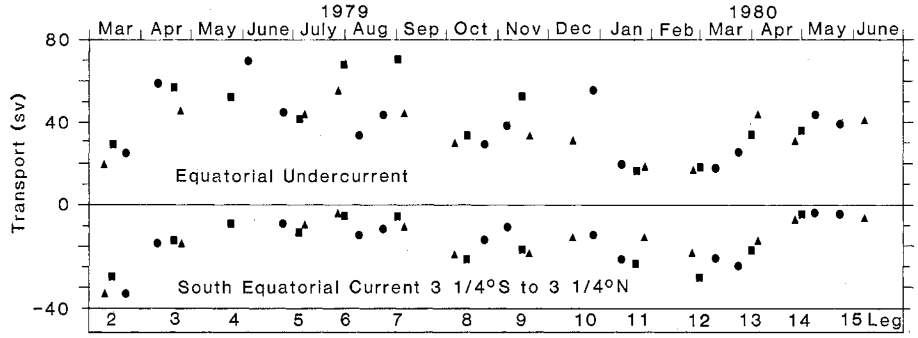

Fig. 5. Transport of undercurrent and the overlying South Equatorial Current relative to the 300- to 500-m layer at (●) 150°W, (■) 153°W, and (▲) 158°W. Eastward transport is positive.

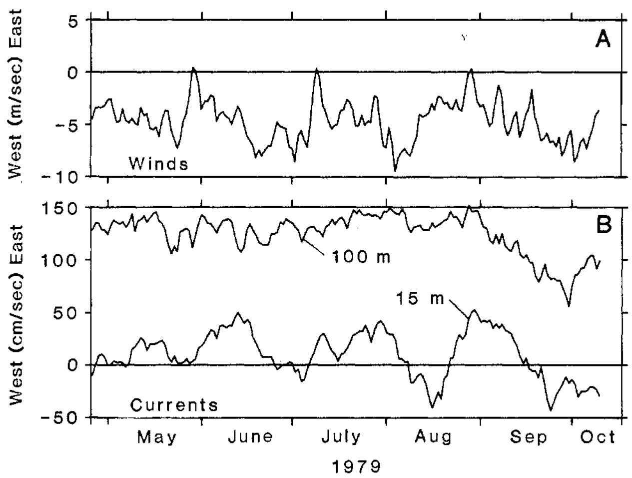

Fig. 6. Low-pass filtered time series of the east-west component of (A) surface winds and (B) currents at 15 and 100 m recorded at the equator near 152°W from May to October 1979.

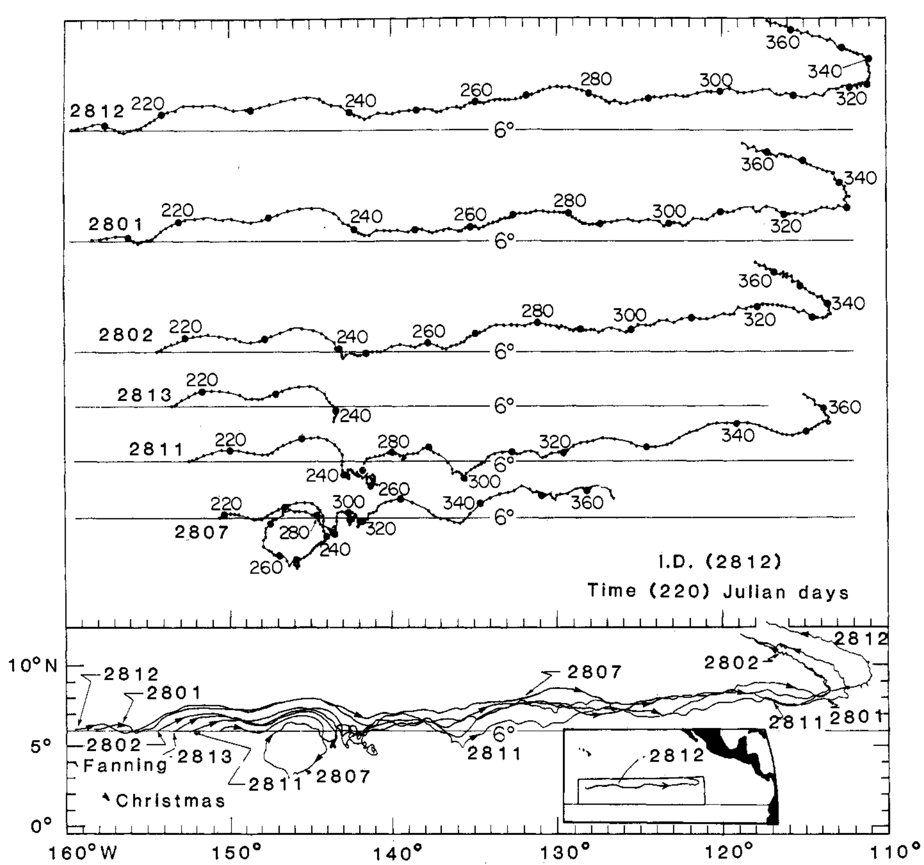

Fig. 7. Paths of six buoys tracked by satellite in the North Equatorial Countercurrent from July to December 1979. All buoys are parachute-drogued at 30 m. In the upper panel the paths of the buoys are offset to allow viewing of individual buoys.

Direct Measurements of Currents

Direct measurements of ocean currents have been made by PCM's from the research vessels, an array of three moored current meter strings near the equator, four deployments of 15 satellite-tracked drifter buoys, and Doppler sonar profiling of the upper 120 m along the ship track.

Current profiles measured with the Duing PCM show the structure of relative currents near the equator. During January 1980 (and representative of northern winter conditions), the North Equatorial Countercurrent flowed in and above the sloping thermocline from 3.5°N to 10°N with subsurface speed maxima greater than 60 centimeters per second (Fig. 4). South of 3.5°N the South Equatorial Current was also strong, with maximum transport per unit width at about 2° on either side of the equator. A very weak undercurrent, with a maximum speed of 80 cm/sec and a transport of about 17 sverdrups (sv; 1 sv = 10^6 m^3/sec) was located in the thermocline exactly on the equator.

Estimated transport for the undercurrent and for the part of the South Equatorial Current within 3.5° of the equator (Fig. 5) ranged from 17 to 70 sv, with a mean of 38.5 sv and a standard deviation of 14.5 sv. There were large fluctuations that were not resolved. In the most extreme example, a transport of 68 sv at 153°W was followed 10 days later by 34 sv at 150°W. Since the velocity profiles on which these transport estimates are based are relative to the average velocity from 300 to 500 m, which typically may be 10 to 20 cm/sec, there is an uncertainty of as much as ± 16 sv, assuming a systematic error of 20 cm/sec in an undercurrent 200 m deep and 400 km wide. Consequently, we cannot be certain how much of the variation seen in Fig. 5 represents true undercurrent fluctuations and how much is due to variations in the flow from 300 to 500 m.

A least-squares fit of the relative undercurrent transports to a mean and an annual harmonic yields a mean of 38 sv and an amplitude of 13 sv, with minimum flow in January and maximum flow in July. This represents part of the low-frequency behavior observed during the Shuttle Experiment. The standard deviation after removal of the annual harmonic is 11.3 sv. Near the equator, the South Equatorial Current was 180° out of phase with the undercurrent. Much of the variation in the undercurrent occurred in the upper 150 m, and near-surface velocity was eastward or only slightly westward during periods of strong undercurrent.

The undercurrent was usually centered no more than 50 km from the equator and showed no sign of systematic meandering as observed in the Atlantic (12). The average position was about 25 km north of the equator.

Continuous recordings of the ocean currents at the equator have revealed a remarkable dependence of the near-surface flow on the winds. From April 1979 to June 1980 an array of three surface buoys was moored near the equator at 152°W. Each mooring contained a wind recorder and five current meters between 15 and 250 m. Figure 6 shows low-frequency time variations of the wind at a height of 3.5 m and of the current at depths of 15 and 100 m from May to October 1979. The vector-mean wind speed and direction were 4.7 m/sec toward 275°, which is typical of the trade winds at this location and time of year. Rarely did the wind blow east. In contrast to the steady westward direction of the wind, the zonal current component at 15 m alternated between eastward and westward, and the predominant direction of the near-surface current was eastward with a mean speed of nearly 10 cm/sec. For periods longer than 1 month the fluctuations of the zonal components of the wind and of the currents at 15 m were similar, indicating a coupling between the local wind and near-surface current fields. At 100 m, the current flowed steadily eastward with an average speed of 125 cm/sec. This strong subsurface current was representative of the equatorial undercurrent, which flows eastward within the thermocline. During September the speed of the current at 100 m decreased from 150 cm/sec to about 50 cm/sec. Measurements by PCM show that this decrease was coincident with a return of the South Equatorial Current to the equator.

Drifters in the Countercurrent

Satellite-tracked drifter buoys, which were drogued at 30 m, gave information about the trajectories of ocean circulation on the large scale. In early August the second array of 15 buoys was deployed in the southern portions of the North Equatorial Countercurrent. Figure 7 shows the tracks of six buoys deployed along 6°N between 160°W and 150°W. Initially the buoys moved east in a somewhat meandering though coherent fashion with an apparent wave length of about 800 km. Near 145°W and around day 240 the southernmost buoys began to slow and move southward. Buoy 2807 became trapped for 45 days in the zone of strong horizontal shear between the eastward flowing countercurrent and the westward flowing South Equatorial Current and followed a nearly circular track. The diameter of the circle was 450 km and it was centered at 5°N. The speed of the buoy was about 35 cm/sec. Buoy 2811, slightly farther north, continued to move east but only at a speed of about 18 to 20 cm/sec. This is in sharp contrast to the motion of buoy 2812, which traveled eastward with an average speed of 54 cm/sec during the first 100 days.

From August through November (days 220 to 340) all buoys except 2807 remained in the countercurrent and moved east at an average speed of 45 to 55 cm/sec, although the speed of the individual buoys varied considerably in time and space. Buoy 2812 drifted eastward at

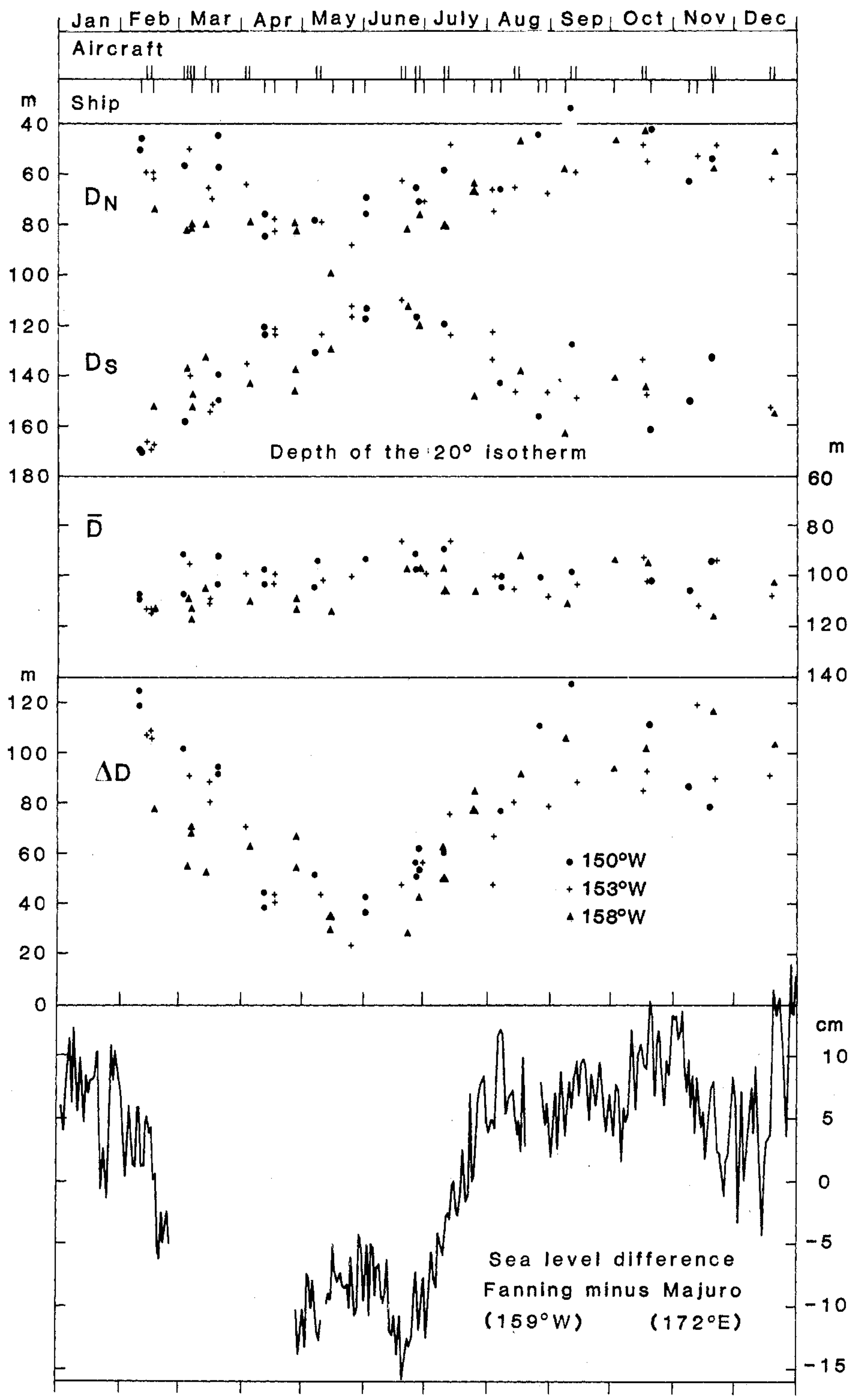

Fig. 8. Development of the slope of the 20°C isotherm across the North Equatorial Countercurrent during 1979 compared with the differance in sea level between Fanning and Majuro. The depths of the 20°C isotherm at the northern and southern flanks of the current are indicated by D_N and D_S, respectively; $\bar{D}$ is the mean depth and ΔD is the difference in meters.

more than 90 cm/sec between days 230 and 240, when the southernmost buoy became trapped in a circular pattern. Buoy 2811 moved much slower than the more northerly buoys before day 300 but much faster during the next 50 days.

At the beginning of December 1979 the buoys arrived at the area near 8°N between 110°W and 115°W, where they slowed and turned north, entering the westward flowing North Equatorial Current. Between days 340 and 360, seven of the buoys (only four are shown in Fig. 7) turned to the northwest between 107°W and 116°W. The deployment of these seven buoys had been spread over 3 degrees of latitude and 9 degrees of longitude during a 15-day period. Thus after more than 4 months in the countercurrent the array had maintained the same areal extent. Considering the narrowness of the current (5°N to 9°N) and the large energetic perturbation in the trajectories, this is remarkable long-term coherence and demonstrates that little dispersion takes place. The paths followed by the buoys confirm previous observations that water enters the countercurrent from the south and leaves it to the north. Whether the northward turning of the current is a seasonal occurrence indicating the eastern terminus of the countercurrent or is a permanent feature of the circulation remains to be determined.

The tracks of the buoys also provide information on smaller time and space scales. A close inspection reveals wavelike or circular patterns with time scales of 2 to 5 days and space scales of 10 to 50 km. Examples of 4-day oscillations are seen in the track of buoy 2811 between days 240 and 260 and of buoy 2807 between days 300 and 320. Shorter 2.5- to 3.5-day oscillations are apparent in the tracks of buoys 2802, 2801, and 2812 between days 320 and 360. The periods decrease with higher latitude in accordance with the expected inertial periods.

These observations of circulation trajectories not only verify the coherent character of a current such as the North Equatorial Countercurrent but form a powerful tool for analyzing and monitoring the large-scale ocean circulation and the movement of water masses.

Monitoring the Countercurrent

An attempt was made to monitor the fluctuations of the North Equatorial Countercurrent, which flows between a ridge in the thermocline topography near 10°N and a trough near 4°N. The fluctuations of its geostrophic flow can be described by the slope of the 20°C isotherm by using a simple two-layer approximation (*13*). With field data from the ship and aircraft temperature sections, the depth of the 20°C isotherm at the ridge identifying the countercurrent was determined as well as the mean depth $\overline{D}$ and the difference ΔD (Fig. 8). In spite of the ambient noise in the data, a low-frequency signal was clearly identifiable. From February to May the ridge deepened while the trough rose, decreasing the slope across the current from about 110 to 30 m and causing very weak flow in the countercurrent in May and June. Thereafter, the slope increased again by uplifting of the ridge and depression in the trough. The slope reached a maximum of about 100 m across the current in September and stayed at about that level during the remainder of 1979. During the entire year the mean depth of the current did not change substantially. The noise of about ± 10 m results from the fact that measurements from a single temperature profile from each temperature section were used to determine the depth of the 20° isotherm at either side of the current, thus entering all the ambient noise of the data into the monitoring scheme.

The change of the slope of the 20° isotherm during 1979 agrees well with the relative sea level difference between Fanning and Majuro. The increase of the sea level difference in July was much faster than the increase in the slope, possibly because of the large east-west separation of the two sea level stations.

This early result indicates that the fluctuations of the North Equatorial Countercurrent can be monitored by either temperature sections or sea level gauges. Similar relations need to be established for other currents.

Conclusions

The large-scale changes in the equatorial Pacific are slow, and systematic patterns, like those exhibited by the thermal structure and the buoys in the countercurrent, prevail. On the smaller scale and, in particular, in and above the undercurrent, the changes are faster. It appears that there is a positive correlation between the time and space scales of the fluctuations. And, while much more analysis is necessary, it is already apparent that the large slow patterns related to ocean-atmosphere interaction can be observed by a monitoring scheme in line with the idea originally advanced by Montgomery (*2*).

References and Notes

1. J. Bjerknes, *Bull. Inter-Am. Trop. Tuna Comm.* **5**, 219 (1961).
2. R. B. Montgomery, *J. Mar. Res.* **26**, 87 (1968).
3. K. Wyrtki, *Science* **180**, 66 (1973).
4. J. Namias, *J. Geophys. Res.* **64**, 631 (1959); *Mon. Weather Rev.* **97**, 173 (1969).
5. K. Wyrtki, *J. Phys. Oceanogr.* **5**, 572 (1975).
6. H. E. Hurlburt, J. C. Kindle, J. J. O'Brien, *ibid.* **6**, 621 (1976); J. McCreary, *ibid.*, p. 632; J. J. O'Brien, A. Busalacchi, J. Kindle, in *El Niño and the Peruvian Fishery: Science, Politics and Economics* (Wiley, New York, 1980).
7. W. B. White and R. L. Bernstein, *J. Phys. Oceanogr.* **9**, 592 (1979).
8. K. Wyrtki, *Eos* **60**, 25 (1979).
9. G. R. Seckel, *Trans. Am. Geophys. Union* **49**, 377 (1968); *Deep-Sea Res.* **22**, 379 (1975); G. Meyers, *J. Phys. Oceanogr.* **5**, 442 (1975).
10. W. C. Patzert, T. P. Barnett, M. H. Sessions, B. Kilonsky, "AXBT observations of tropical Pacific Ocean thermal structures during the NORPAX Hawaii–Tahiti Shuttle Experiment, November 1977 to February 1978" (Ref. 78-24, Scripps Institution of Oceanography, La Jolla, Calif., 1978).
11. T. P. Barnett and W. C. Patzert, *J. Phys. Oceanogr.* **10**, 529 (1980).
12. W. Duing *et al.*, *Nature (London)* **257**, 280 (1975).
13. K. Wyrtki and R. Kendall, *J. Geophys. Res.* **72**, 2073 (1967).

14. We thank the captains and crews of the *Gyre*, *Wecoma*, and *Oceanographer* and of the Navy and NOAA aircraft. The bulk of the project was funded by the National Science Foundation, with additional contributions from the Office of Naval Research and NOAA. Hawaii Institute of Geophysics Contribution No. 1087.