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MONITORING EQUATORIAL PACIFIC SEA LEVEL WITH GEOSAT

Tide-gauge data from coastal and island stations have revealed intriguing new information about the ocean's role in climate, but observations are lacking for most of the ocean. GEOSAT, in contrast, provides accurate measurements of sea-level variability on a global basis, offering a unique data set for physical oceanographers. Researchers from the National Oceanic and Atmospheric Administration are working with GEOSAT data at APL to search for relationships between sea-level variability in the tropical Pacific Ocean and El Niño.

INTRODUCTION

Changes in the mass distribution of the equatorial oceans (which can be inferred by changes in sea level) are known to play an important role in the development of global weather anomalies on interannual time scales. An example is the El Niño–Southern Oscillation event, which occurs approximately every four years. During El Niño, anomalous eastward transport in the surface layer of the central and western Pacific causes water to pile up in the eastern Pacific, resulting in an increase in sea-surface temperature throughout the eastern Pacific. That change has a dramatic impact on the meteorology of the equatorial oceans (e.g., abnormally heavy rainfall over the central and eastern Pacific) and on the meteorology at higher latitudes.

In 1985, the National Oceanic and Atmospheric Administration (NOAA) and the National Science Foundation began a 10-year research program called TOGA to examine relationships between the tropical ocean and global atmosphere. The ultimate goal of the program is to be able to predict climate anomalies well in advance by observing key oceanic and atmospheric parameters. The GEOSAT altimeter has the potential to make major contributions to this effort. As the only altimeter satellite to be flown in this decade, GEOSAT will provide accurate measurements of sea-level change that can be obtained in no other way.

During its first 18 months, GEOSAT followed a nonrepeating orbit in order to obtain very dense coverage of the marine geoid. The pattern generated an equally dense network of crossover differences (sea-level differences at ground-track intersections) that provide measurements of sea-level change as a function of time. The analysis of large networks of crossover differences enables the construction of sea-level anomaly maps for vast regions of the world's oceans, giving new information that could revolutionize the field of physical oceanography. During the Exact Repeat Mission (which began in November 1986), the satellite has operated in a 17-day, exact repeat orbit approximately collinear with existing Seasat data profiles. Although the two phases of the GEOSAT mission produce different spatial/temporal sampling patterns, the net result will be a continuous, multiyear record of sea-level variability ideally suited for investigating low-frequency sea-level signals.

In this article, we present the results of using GEOSAT crossover data in the equatorial Pacific to study variations of sea level associated with El Niño.[1] The method involves least-squares analyses of crossover differences, first to remove radial orbit error,[2] and then to construct time series of sea-level height.[3,4] This approach provides a common analysis technique applicable to data from both phases of the GEOSAT mission and enables sea-level time series to be constructed over several years.

GEOSAT DATA PROCESSING

The detection of sea-level variability within a few centimeters requires highly accurate altimeter profiles, and NOAA's processing software has been developed to achieve that end. The GEOSAT data are first converted from raw sensor data records to final geophysical data records, which involves the incorporation of the precise ephemeris computed by the Naval Surface Weapons Center, an evaluation of pathlength corrections for the troposphere and ionosphere, and the addition of tide and geoid models. Perhaps the most critical of these steps to sea-level variability analyses is tropospheric water vapor correction. Because GEOSAT lacks an on board radiometer, the water vapor correction must be derived from other sources. The geophysical data records contain two water vapor fields: the first from the Fleet Numerical Oceanographic Center's 12-hour model, and the second from monthly averages derived from three years of Nimbus-7 radiometer data.[5] These records retain the full 10-per-second data rate for altimeter height, while all other parameters (sigma naught (σ^0), wave height, environmental corrections) are 1-second averages.

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The next processing step is the computation of the crossover-difference data set. For large sets of global data, this is a difficult and time-consuming procedure, usually requiring a sizable data storage capacity; e.g., one year of GEOSAT data generates as many crossings as 1-second average altimeter heights (approximately 20 million). The problem becomes manageable if crossovers are needed only in certain regions. In the equatorial Pacific (within 25 degrees of the equator), only 1.5 million crossings were generated during the first year of the mission.

DATA QUALITY CONTROL

Crossover differences give essential information for the evaluation of many parameters critical to altimeter data quality; e.g., Seasat was shown to have a time-tag error (bias) of 79 milliseconds. Crossover differences quickly revealed this bias because the vertical speed of an altimetric satellite reaches values of several tens of meters per second. GEOSAT, with its slightly eccentric orbit, reaches a speed of 50 meters per second, so even a 1-millisecond bias would give a sea-surface height error of 5 centimeters easily observed in crossover height differences. Our analyses of its crossovers do not suggest that GEOSAT's data records possess any timing bias. Time-tag accuracy will be routinely checked in this manner throughout the GEOSAT mission. Similarly, crossovers will be used to compute the proper sea-state bias factor. For Seasat, the factor was 7 percent of significant wave height, an important correction in the presence of typical values of sea state.

Radial orbit accuracy also can be assessed with crossover differences. For that purpose, global crossover sets over periods ranging from 12 to 23 days were generated from first-year GEOSAT data. After removal of tides and environmental effects, the rms crossover-difference values ranged from approximately 75 to 125 centimeters, suggesting a consistent radial precision of less than 1 meter (since each crossover difference contains the error of two independent passes). The precise ephemeris produced for GEOSAT by the Naval Surface Weapons Center is therefore at least as good as the most accurate orbits computed for Seasat.

Once all corrections are applied to the data, regional adjustments can be performed to remove orbit error and to determine final data precision. In regions such as the northeast Pacific, where sea-level variability is small, adjusted crossover differences should have rms values of 10 centimeters or less if the data have been properly processed.[6] Our preliminary results suggest that 4- to 8-centimeter adjustments can be attained with GEOSAT data depending on the arc length chosen.

A similar test of altimeter precision can be made by comparing profiles having the same ground track. Figures 1a and 1b show two collinear GEOSAT profiles across a seamount in the tropical Pacific on days 232 and 327 (1985) for which the cross-track separation is only 3 kilometers. The two passes agree extremely well over the relatively steep geoid gradients associated with the seamount, and even some of the very-small-scale geoid features are repeated accurately. Figure 1c is a Seasat profile located between the two GEOSAT passes (although obtained seven years earlier!). The Seasat data are 1-second averages, while we have plotted the full 10-per-second data for GEOSAT. It is clear from this example that 1-second averages sometimes obliterate real signals. The retention of the full 10-per-second data rate in the GEOSAT geophysical data records will therefore allow analysis at the full resolution of the instrument.

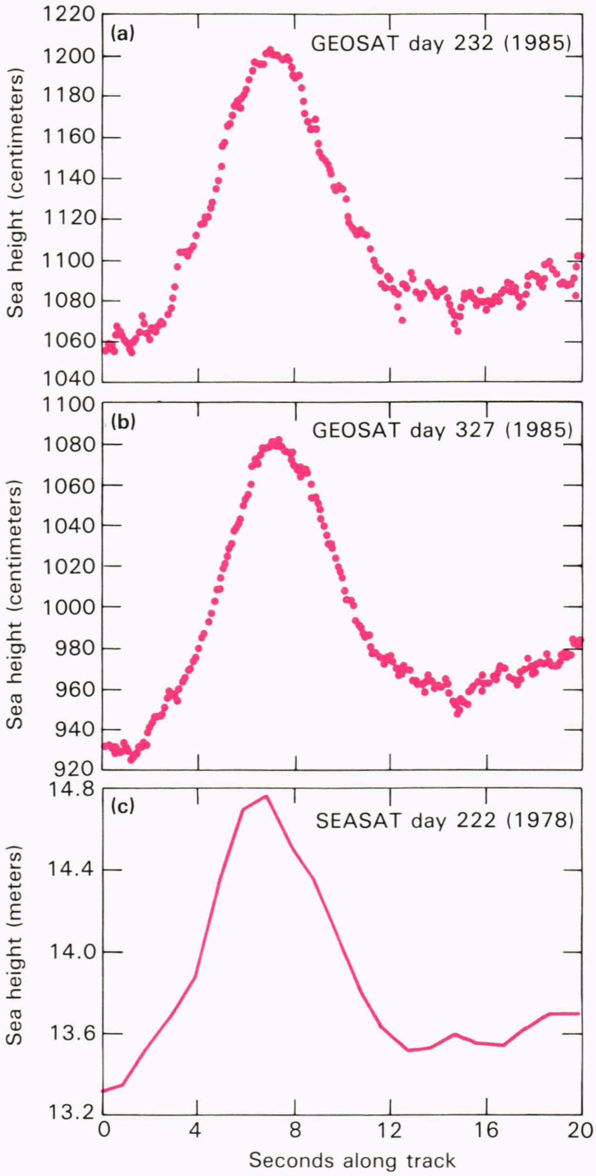

Figure 1—(a and b) Collinear GEOSAT altimeter profiles in the tropical Pacific at 10°N, 192°E, separated by 3 kilometers in the cross-track direction and 95 days in time. Profiles show excellent agreement over the seamount. (c) The corresponding Seasat profile obtained seven years earlier that falls between the two GEOSAT tracks. Seasat data are plotted at 1-second intervals while GEOSAT data are at the full 10-per-second rate.

While most GEOSAT profiles examined appear to be of high quality, obvious anomalies have been found occasionally. Particularly severe spikes have been associated with rain in the altimeter footprint. Shown in Fig. 2 is a typical sea-height profile through a rain cell, plotted

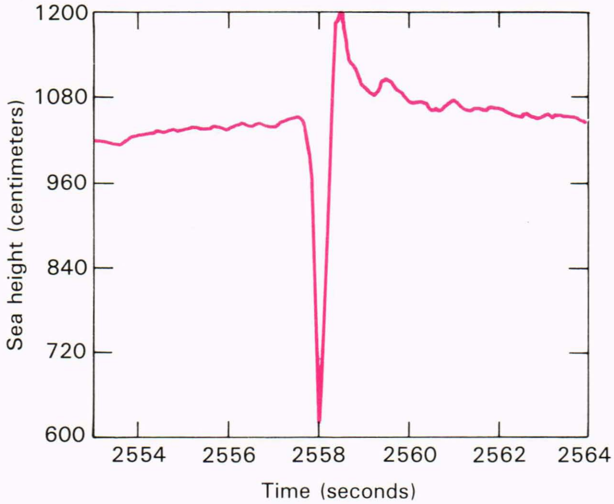

Figure 2—Apparent sea height recorded by GEOSAT during a 10-second period as the satellite passed over a rain cell in the central Pacific. Data are plotted at the full 10-per-second rate. The erroneous measurements (where the spike occurs) span only a 2-second period and can be readily edited based on quality control parameters contained in the GEOSAT geophysical data records. Data are 10-per-second height values for day 329 (1980).

from 10-per-second data. The anomaly begins and ends abruptly, spanning a period of only 2 seconds. The σ^0 parameter along this profile (a parameter proportional to the power of the backscattered radar pulse) shows a loss of nearly 2 decibels at the location of the spike, consistent with the presence of rain.[6] Sea-height anomalies associated with rain cells are easily edited from the data set by checking quality control parameters given in the geophysical data records.

SEA-LEVEL TIME SERIES FROM CROSSOVER DIFFERENCES

Analyses of satellite altimetric sea-level differences at intersections of the satellite's ground track are based on the concept that the geopotential component of sea level is the same on both tracks and thus cancels in the crossover difference. Techniques using crossover differences as input data therefore do not require geoid models. This is of critical importance in the application of altimetry to ocean dynamics because uncertainty in ocean geoid models is larger than the oceanographic signals of interest.

While removing the permanent, gravimetric component of sea-surface topography, crossover differences retain information on radial orbit error and time-variable oceanographic phenomena, principally tides and the variable geostrophic ocean circulation (expressed in terms of dynamic height variability). Tides can be removed adequately with existing models.[7] Orbit error and variability of dynamic height can then be separated because of differences in their spatial scales. Orbit error has a dominant frequency of one cycle per revolution, corresponding to a wavelength equal to the earth's circumference (40,000 kilometers), while most low-frequency dynamic height signals in the tropics have length scales of fewer than 5000 kilometers. Thus, satellite orbit error can be eliminated by a standard least-squares technique that minimizes crossover differences in simultaneous solutions for all altimeter profiles in a given region. Relative orbit error can be reduced to the level of a few centimeters that way.[8] Networks of adjusted crossover differences thus reveal information on dynamic height variability as a function of time because the shorter scale sea-level variation signals are not removed in the adjustment. That information can be expressed in terms of group statistics[9] or sea-level time series.[3]

The generation of time series from crossovers involves a separate processing step to convert from height differences (at many combinations of times) to a time-ordered sequence of heights, referred to as an arbitrary zero point. After first removing radial orbit error, crossover data must be grouped into areas that are small compared with the horizontal variability scale of interest (typically a few hundred kilometers). Altimeter data obtained anywhere in the defined area can then be considered representative of the area as a whole. Each crossover difference within the area provides a measure of sea-level change between two discrete times (the times of the two intersecting passes). Given a network of crossovers, the problem is to solve for a series of individual heights consistent with the height differences. Least-squares techniques give a straightforward solution for computing the heights, yielding a time series of sea-level change from the first altimeter pass to the last.

The ability to recover accurate sea-level time series from crossover differences was recently demonstrated[4] using Seasat altimeter data in the equatorial Pacific where results could be compared with island tide-gauge records. Unfortunately, Seasat lasted only about 100 days, not long enough to provide a very useful sea-level record. GEOSAT, by contrast, has performed flawlessly for 2 years and is expected to continue to do so for several more years.

Figure 3a shows an example of a sea-level time series computed for an area centered on the equator at 202°E, just south of Christmas Island (1.9°N, 202.5°E), where tide-gauge data are available. The altimetric record spans the 14-month period from April 24, 1985, to June 30, 1986, during which approximately 275 altimeter profiles were obtained in the 2- × 8-degree sample area. Plotted in Fig. 3a are the 275 individual heights determined by least squares, together with a curve fitted to the data by objective analysis. The rms scatter of the observations about the fitted line is approximately 4 centimeters. Much of this residual variability may be due to real sea-level signals on time scales shorter than 15 days (the decorrelation time chosen for the objective analysis) or an incomplete correction of environmental errors.

Figure 3b shows a comparison of the altimeter time series with low-pass-filtered Christmas Island tide-gauge data. Although there are occasions when the records differ by as much as 5 to 10 centimeters, the two generally agree within a few centimeters. The second half of the altimetric record is remarkably consistent with tide-gauge

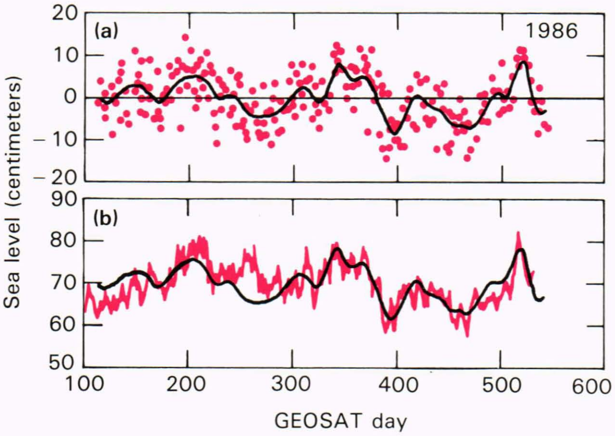

Figure 3—(a) Sea-level time series derived from 14 months of GEOSAT altimeter data near Christmas Island in the central equatorial Pacific. Colored circles represent individual altimeter observations as determined by a least-squares adjustment of crossover differences. The smooth curve shows objective analysis results for the same measurements (15-day decorrelation time). (b) A comparison between GEOSAT altimeter-derived sea level with tide-gauge time series for Christmas Island. A Gaussian, low-pass filter (2-day half width) has been applied to the tide-gauge data. Agreement of these two independent data sets is approximately 3 centimeters rms. Note in particular the close correspondence at the sharp, 12-centimeter peak centered on day 515. This feature is a well-documented Kelvin wave that traveled across the Pacific during May through June 1986. It is these waves that are associated with the El Niño phenomenon. This comparison verified the accuracy of the altimetric results and paves the way for systematic mapping of sea-level change for the entire tropical Pacific.

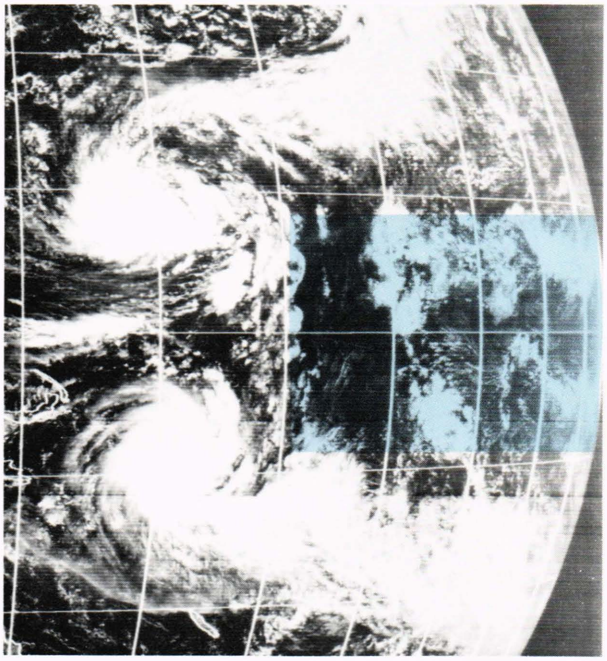

Figure 4—Satellite photograph of cloud cover over the western Pacific on May 18, 1986. The cross-equatorial cyclone pair (Lola—Northern Hemisphere, Namu—Southern Hemisphere) is visible northeast of Australia along 160°E. The cyclones first appeared on May 16 to 17 approximately at the positions shown and then rapidly diverged northward and southward. Maps of sea-level anomaly at 10-day intervals determined from GEOSAT altimeter data (see Fig. 5) show the sea-level response to this massive burst of westerly winds along the equator. The tinted rectangle indicates the approximate area of sea-level analysis.

observations. We know of no reason for the instances of disagreement during the first 200 days; the discrepancies may be attributable to real differences between open-ocean sea-level observations and those obtained by an island tide gauge. In fact, time series generated from independent altimeter passes in adjacent regions agree with the altimetric record in Fig. 3a. Based on this comparison, we conclude that GEOSAT altimeter data are adequate for monitoring sea-level variations in the tropics with an accuracy of a few centimeters.

Both the altimeter and the tide-gauge records in Figs. 3a and 3b display 10- to 50-day fluctuations indicative of wind-driven equatorial Kelvin waves. Miller and Cheney[10] showed a good correlation between the sea-level and zonal-wind fluctuations in the western tropical Pacific. Sea-level peaks in Figs. 3a and 3b on days 419 (February 23, 1986) and 520 (June 4, 1986) were found to coincide with westerly wind bursts 23 days earlier (January 31, 1986, and May 12, 1986) in the region 4000 kilometers west of Christmas Island. The May 1986 burst was actually part of a larger, more intense atmospheric disturbance. A satellite infrared image of the western Pacific on May 18, 1986 (Fig. 4 and front cover), reveals a pair of tropical cyclones arranged symmetrically north and south of the equator along 160°E. The effect of this massive westerly burst was to produce a downwelling Kelvin wave at the equator in the western Pacific. This pulse was clearly detected in the GEOSAT altimeter data, appearing as a 10- to 15-centimeter positive sea-level anomaly (Fig. 5) that traveled eastward across the Pacific at a speed of approximately 3 meters per second.

Recently, it has been suggested that the onset of sea-surface warming in the eastern tropical Pacific during an El Niño–Southern Oscillation event may be triggered by short, intense bursts of westerly winds in the western Pacific such as those associated with cyclone pairs. According to that scenario, anomalous westerlies generate downwelling Kelvin waves in the ocean, which then propagate eastward along the equator. Since the waves produce eastward zonal current anomalies and the mean zonal sea-surface temperature gradient is negative (colder eastward), surface temperatures in the eastern Pacific increase due to advection of warm water zonally along the equator.

In late 1986, an El Niño was triggered by those conditions. Strong westerly bursts persisted throughout the west during the fall, sending a series of Kelvin waves eastward across the Pacific. Although this most recent El Niño was not particularly severe, it was the first such event observed by a satellite altimeter. Shown in Fig. 6 are sea-level time series for November 1986 to February 1987 derived from GEOSAT crossover differences. Ten time series are shown, extending along an 8000-kilometer stretch of the equator from 174 to 246°E at intervals of 8 degrees longitude. Each time series in the figure is

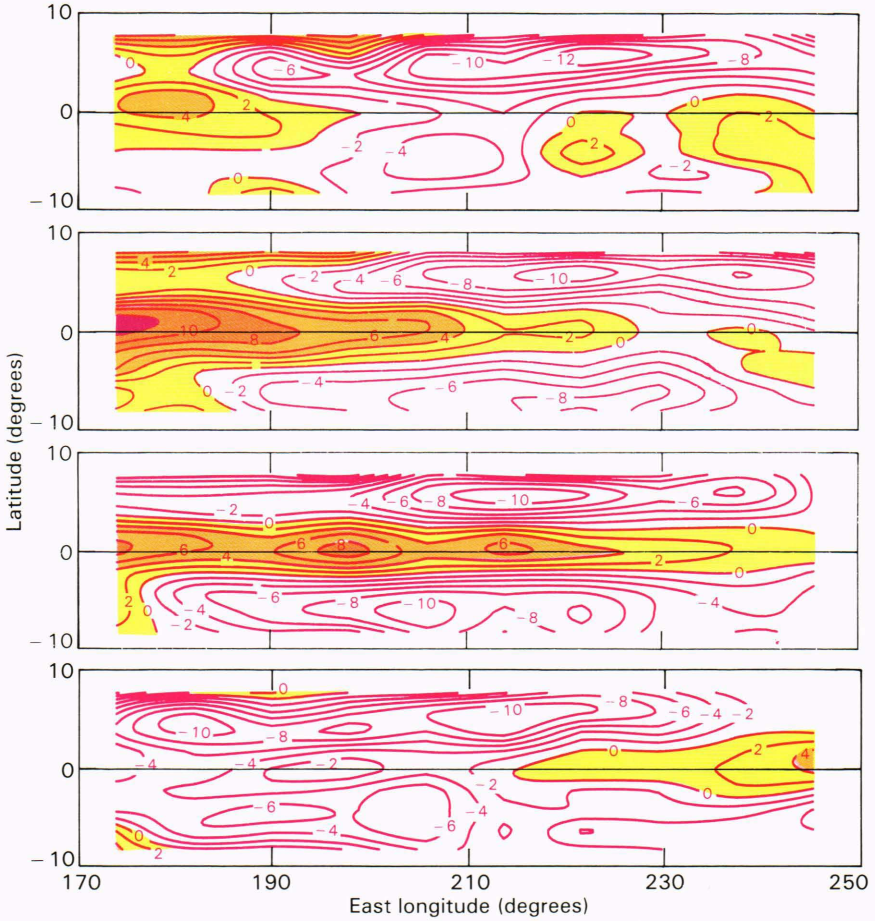

Figure 5—Maps of sea-level anomaly at 10-day intervals between May 18 (top) and June 17, 1986 (bottom). Each was constructed from 90 GEOSAT time series at intervals of 8 degrees longitude by 2 degrees latitude. Contours are at 2-centimeter intervals and represent anomalies relative to mean sea level during the 14-month period, April 1985 to June 1986. Positive sea-level anomalies along the equator show a Kelvin wave that propagated eastward through this area at a speed of approximately 3 meters per second. The wave was a response to bursts of strong westerly winds associated with a cyclone pair in the western Pacific on May 18 (Fig. 4 and cover). Negative sea-level anomalies north and south of the equator are believed to be Rossby waves, also generated by wind, that propagated westward on opposite sides of the Kelvin wave.

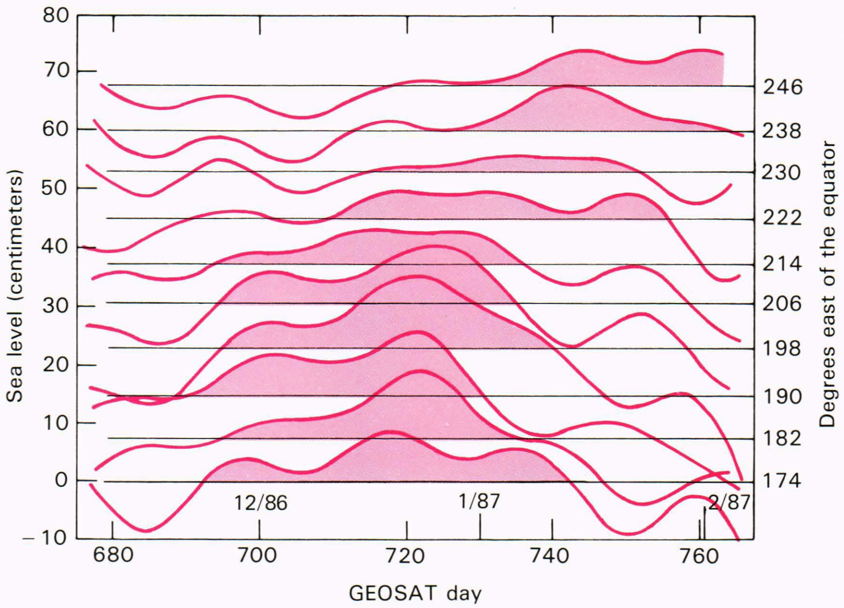

Figure 6—Sea-level time series derived from three months of GEOSAT altimeter data along an 8000-kilometer section of the equatorial Pacific. Westernmost profiles are at the bottom of the figure, and subsequent profiles are at intervals of 8 degrees longitude. Time series have been separated 7.5 centimeters relative to one another. This time period corresponds to the 1986-87 El Niño when bursts of westerly wind generated downwelling Kelvin waves in the western Pacific. These pulses, manifested as positive sea-level anomalies in the GEOSAT time series, travel eastward across the Pacific at approximately 3 meters per second.

offset vertically 7.5 centimeters relative to its neighbor. In the west, sea level rose 15 to 20 centimeters during November and December, then fell to November levels by the end of January. This positive sea-level pulse can be seen to arrive progessively later toward the east as the Kelvin wave slowly crossed the Pacific.

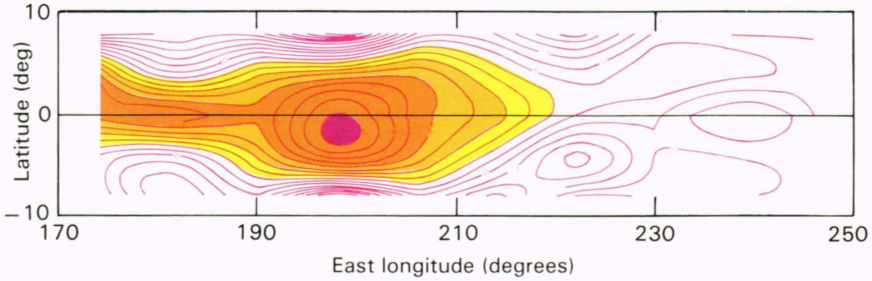

Figure 7—A map of sea-level anomaly on December 15, 1986, constructed from 50 GEOSAT time series at intervals of 8 degrees longitude by 4 degrees latitude. Contours are at 2-centimeter intervals and represent anomalies relative to mean sea level during the 4-month period, November 1986 to February 1987. The Kelvin wave associated with the 1986-87 El Niño can be seen to extend along a narrow band at the equator. Peak-to-peak amplitude is 20 centimeters, and the zonal wavelength is at least 15,000 kilometers.

Time series at 40 other locations between 8°N and 8°S were computed to construct sea-level maps and thereby to examine the spatial structure of the equatorial Kelvin wave. Figure 7 shows one such coinciding with maximum sea level in the west. The Kelvin wave is the long, narrow feature oriented along the equator. Its amplitude is approximately 20 centimeters peak-to-peak, and its zonal wavelength is at least 15,000 kilometers. The amplitude of the wave falls off rapidly to the north and south, consistent with the theory of equatorially trapped waves. Such maps provide resolution never before achievable and represent an important new way of observing the global ocean.

SUMMARY

Observations of sea level and its change with time provide unique information about the ocean and its dynamic interaction with the atmosphere. We have shown that GEOSAT altimeter data can be used to construct time series of sea level at discrete locations with an accuracy of a few centimeters for time scales of 10 days and longer. For that purpose, GEOSAT data are equivalent to having island tide gauges every few degrees throughout the ocean. Considering the scarcity of gauges in most open-ocean regions, it is clear that GEOSAT and satellites in general have a revolutionary potential for oceanography.

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ACKNOWLEDGMENTS—We are grateful to the Navy for granting us access to GEOSAT data and to APL for their generous support and hospitality in providing us a place to work. In particular, we thank C. Kilgus, GEOSAT project manager at APL, and Commanders D. McConathy and F. Wooldridge, GEOSAT project managers for the Navy. Credit is also due to Rear Admiral J. Bossler and W. Kaula of NOAA who generously supported our project, and to P. Wolff, Associate Administrator for the National Ocean Service, which provided funding for the GEOSAT processing facility. Thanks are also due to Rear Admiral J. Seesholtz, Oceanographer of the Navy, who strongly supported GEOSAT's oceanographic mission. Tide-gauge records were kindly supplied by K. Wyrtki, University of Hawaii.