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MONITORING TROPICAL SEA LEVEL IN NEAR-REAL TIME WITH GEOSAT ALTIMETRY

Geosat is the first altimeter satellite used for long-term, continuous monitoring of sea level. Since its launch in 1985, we have been using the data to study connections between the ocean and atmosphere in the tropical Pacific. In early 1987, shortly after the onset of the 1986–87 El Niño, we began processing these data in near-real time (1 to 2 weeks after acquisition) to monitor sea level during this interesting climatic event. An operational NOAA program of monthly sea-level monitoring has evolved that encompasses all three tropical oceans.

INTRODUCTION

After Geosat's first 18 months in orbit, we described the Navy's altimeter mission as a "milestone in satellite oceanography."[1] Built and operated by APL, Geosat had gathered 270 million measurements of global sea level with a precision of approximately 3 cm. In a field historically limited by a lack of observations, it was already the most extensive oceanographic data set ever collected.

Now in its fifth year of operation, Geosat continues to observe the global oceans. The unclassified data sets prepared and distributed by NOAA[2] are the focus of oceanographic and geophysical research at more than 40 institutions worldwide. It is anticipated that the mission will last through the decade, and that it will link up with other altimeter missions in the 1990s.

Our interest is in the determination, over periods ranging from months to years, of sea-level change in the tropical oceans, particularly as it relates to the El Niño phenomenon—a warming event that occurs every three to seven years in the eastern tropical Pacific and is frequently associated with worldwide climatic variations.

The Geosat mission is divided into two parts: the classified geodetic mission (GM), which extended over 18 months from April 1985 to October 1986, and the unclassified exact repeat mission (ERM), which began in November 1986 and is still continuing. To work with the entire Geosat data set, we maintain a secure computing facility at APL and have analyzed more than four years of these data to derive continuous time series of sea level throughout the tropical oceans. The four-year period is particularly valuable for the Pacific Ocean because it includes the recently completed 1986–87 El Niño. The Geosat data have provided the first complete picture of sea-level variability during an El Niño event, and relationships have been established between changes in sea level and fluctuations in the large-scale wind field.

Part of our research goal is to develop the means for near-real-time monitoring of sea-level variations with satellite altimeter data, which is essential if altimetry is to be assimilated by operational numerical models and other oceanographic observations. We hope that such models will lead ultimately to improved forecasting of weather and climate. In this article, we describe the technique used during the last two years to produce sea-level time series and maps for the tropical Pacific using Geosat data in near-real time. The method is based on both crossover and collinear differences, that is, differences of sea-level height observed at the intersections of crossing ground tracks and along repeating ground tracks. Thus, data can be accepted from multiple satellites regardless of their orbital inclination or ground track. This technique may have direct application to sea-level monitoring in the 1990s when simultaneous operation of several altimeters is envisioned.

NEAR-REAL-TIME DATA FLOW

The system for Geosat data collection and processing at NOAA is designed to produce monthly sea-level updates, which are usually adequate because changes evolve relatively slowly in the tropical oceans. Other groups involved with Geosat, such as the Naval Ocean R&D Activity and APL, process the data in a more real-time mode, often in one day or less.

Geosat transmits its data to the APL ground station approximately twice each day. Sensor data records are produced within one day of acquisition, delivered to us weekly, and transported to NOAA's Geodetic R&D Laboratory in Rockville, Md., for processing. An ephemeris for Geosat, computed each day by the Naval Astronautics Group from Doppler tracking, is also provided to us weekly. The sensor data records are combined with the ephemerides, solid and fluid tide models, and ionosphere corrections to produce interim geophysical data records; this part of the processing normally runs one to two weeks behind real time. Corrections for the wet and dry troposphere are provided once each month by the Fleet Numerical Oceanographic Center and are not included in our near-real-time flow. The effect of omitting these two corrections is minimal (a few centimeters), however, because most of the tropospheric ef-

fect is removed, together with the orbit error in the initial adjustment. Further, it is only the variability of the tropospheric corrections that contributes to determinations of sea-level change as a function of time, and this variability is relatively small over most of the tropical oceans. In a subsequent article, we will examine this issue in more detail and discuss improved water-vapor fields recently produced for the 1985–87 period using data from two satellite instruments—NOAA's Tiros-N operational vertical sounder, and the special sensor microwave imager launched in 1987 as part of the Defense Meteorological Satellite Program (Emery, W., Born, G., Baldwin, D., and Norris, C., personal communication, 1989). Only through complete reprocessing of the Geosat data can the impact of these improved water vapor corrections be accurately assessed.

COMPUTATION OF SEA-LEVEL TIME SERIES

A combination of crossover and collinear difference methods is used to construct continuous sea-level time series spanning both the GM and ERM. First, a 2.5-year crossover difference time series is computed from April 1985 to November 1987, a period that extends through the first year of the ERM. In such a solution, the collinear ERM passes are analyzed, together with the noncollinear GM passes, strictly in terms of their crossings. Second, a collinear difference time series is computed at the same location using only ERM data from November 1986 to the present. The 1-year overlap between the two solutions (November 1986–November 1987) is used to adjust the collinear solution relative to the crossover solution, resulting in a continuous record beginning in 1985. Details about each of these steps are given in the following discussion.

The Crossover Difference Method

During the Geosat geodetic mission, the ground tracks seldom repeated, but instead formed a dense network with an average cross-track spacing of approximately 5 km. This generated an equally dense network of crossovers (intersections of the satellite ground track with itself). In 18 months, approximately 35 million crossovers were obtained over the global oceans. At each of these locations, the two crossing passes provided independent sea-level measurements at the same place but at different times. Differences of the sea-surface heights at the two times, or crossover differences, form the basis for studies of sea-level variability and time series from the geodetic mission.

Various authors have described the general technique used to process crossover differences into records of sea-level change as a function of time.[1,3,4] The method that we use is best documented by Milbert et al.[5] After routine environmental corrections are made, least-squares crossover difference adjustments are performed to eliminate time-dependent orbit error from long (about 10,000 km) arcs of data. Orbit error is usually modeled as a linear or quadratic trend over these arcs. The fully corrected crossover differences are then aggregated into relatively small cells for which sea-level time series can be computed.

Figure 1A shows a 2.5-year sea-level time series generated from Geosat crossover differences in the 2° × 1° (longitude × latitude) region adjacent to Christmas Island in the central Pacific. The least-squares solution yields one observation of sea level for each pass traversing the sample region. A typical 2° × 1° area is sampled by the altimeter only three times in approximately three weeks, but adjacent 2° × 1° time series can be combined to obtain improved temporal sampling. The individual measurements are then smoothed by objective analysis (assuming a 30-day decorrelation time) to form a continuous record with evenly spaced, daily values.

The Collinear Difference Method

Generation of sea-level variability and time series from ERM data using the method of collinear differences is similar in concept to the crossover method but simpler in terms of computations. During the ERM, the satellite obtains profiles of sea height along a fixed, global grid at 17-day intervals. Along a given ground track, the geoid is always the same from one pass to the next. A sequence of Geosat profiles can therefore be subtracted from the first pass to obtain a time series of sea-level change along the ground track. (Orbit error, as always, must first be removed from each pass as a linear or quadratic trend over an arc length of several thousand kilometers. We use one pass along each ground track as a reference profile and adjust all others so that they agree with this pass in a least-squares sense.) Altimeter profiles corrected for orbit error, tides, and environmental effects are then used to generate sea-level time series along each satellite ground track averaged over 1° latitude segments. Individual collinear time series are then combined by least-squares adjustment to construct sea-level records on a regular 2° × 1° grid over the ocean. Figure 1B shows the time series computed using the collinear method for the same location as in Figure 1A.

Combining Crossover and Collinear Time Series

The 1-year overlap (November 1986-87) between the two solutions described in Figures 1A and 1B is used to adjust the collinear record relative to the crossover record, resulting in a continuous record beginning in 1985. Figure 1C shows that the two solutions agree very well in the overlap with a typical rms difference of 1 to 2 cm. Once the combined time series are formed, it is a simple matter to extend them using collinear differences as more ERM data are collected. Construction of these long time series over entire ocean basins allows us to study large-scale, interannual changes in total water volume.

Accuracy of the Geosat Time Series

Sea-level records computed from Geosat can be compared with *in situ* measurements to obtain a measure of their accuracy. Island tide gauges are one obvious source of surface data for such comparisons because they are the only instruments capable of measuring sea level directly. Dynamic height computed from moored thermistor arrays are also valuable because the arrays can pro-
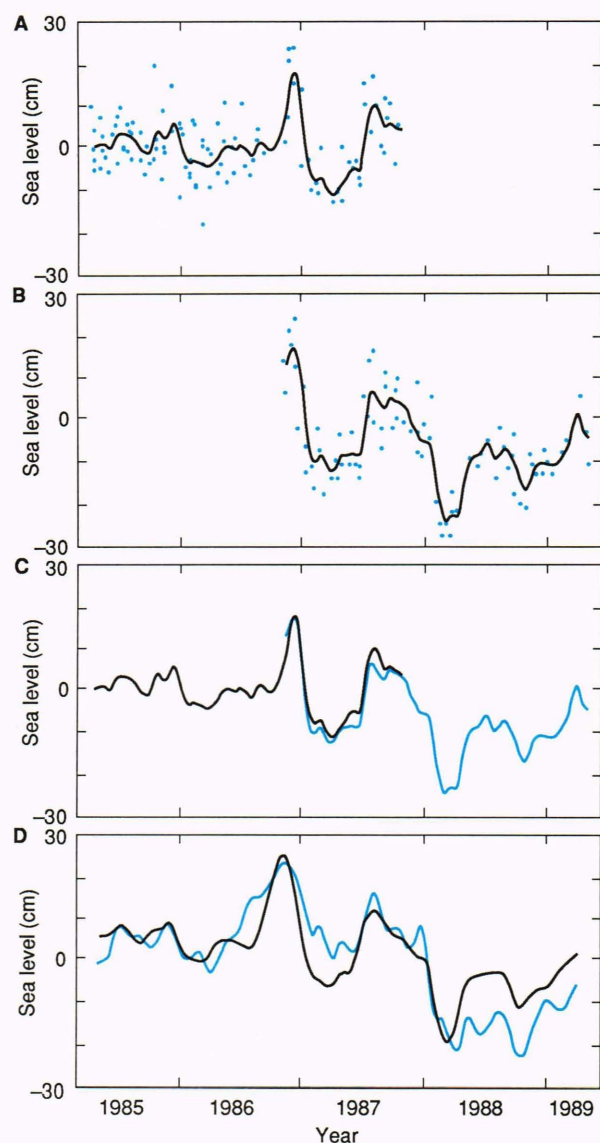
Figure 1. Construction of Geosat time series for the 2° × 1° region centered at 1°N, 157°W, near Christmas Island in the central equatorial Pacific. A. The 2.5-year record based on crossover differences. Dots indicate average sea-level heights derived from individual altimeter passes. The smooth curve is computed using objective analysis, where a 30-day decorrelation is assumed. B. Sea level determined from collinear differences. C. The 1-year overlap of the crossover and collinear records shown in Figures 1A and 1B enables the two to be combined into one continuous time series that can be extended as additional Geosat data are collected. In this figure, the two records (crossover, black; collinear, blue) are simply superimposed. D. Comparison of the Geosat sea-level time series (black) with tide gauge data (blue) from Christmas Island (1.9°N, 157.5°W). The rms difference is 5.9 cm with a 0.83 correlation. Calculations are based on monthly means.[7]

vide surface truth in the open ocean where island data are not available.

In a previous paper,[6] we compared Geosat GM time series with 14 tide gauge records and 2 moorings in the tropical Pacific. Average agreement of Geosat with the surface measurements was 3.7 cm rms with a correlation

of 0.68 for the 18-month period examined. Figure 1D shows results for the 4-year Christmas Island example. Based on monthly means, the rms difference of the altimeter and tide gauge records is 5.9 cm with a 0.83 correlation. The large rms difference appears to be due to damping of the altimeter signal by the quadratic orbit-error model used in this case. The tide gauge record has an rms amplitude of 10.5 cm compared with only 7.5 cm for the Geosat time series. This signal damping can be corrected by using an improved satellite ephemeris together with a linear orbit-error model that removes relatively little ocean signal. Water-vapor error is an additional source of uncertainty in the altimeter record. Despite these deficiencies, such comparisons demonstrate that the Geosat time series are sufficiently accurate to permit preliminary examination of tropical ocean phenomena.

TROPICAL SEA-LEVEL RESPONSE TO WIND

Sea-level changes in the tropics are driven primarily by changes in the large-scale wind field. An example of this relationship is shown in Figure 2, where we have superimposed a Geosat sea-level record from the central equatorial Pacific and a wind record that shows the average zonal component at 850 mbar in the far western Pacific (5°S to 5°N, 120°E to 160°E). The sea-level record has been lagged by 20 days (implying eastward propagation) to highlight the correlation between these two independent records. In general, bursts of westerly (positive) winds correspond to increasing sea level, while periods of pronounced easterly (negative) wind result in decreasing sea level. Miller et al.[8] and Cheney and Miller[9] showed that most of these sea-level anomalies were equatorially trapped Kelvin waves, a form of low-frequency wave motion that arises because the Coriolis parameter vanishes at the equator. These waves had sea-level signatures of 10 to 15 cm, propagation speeds in mid-ocean of approximately 2.5 m/s, and coherent zonal structure extending nearly across the Pacific Ocean. The period of most intense Kelvin wave activity was late 1986 and early 1987, during initiation of El Niño. This is consistent with the notion that short, intense bursts of westerly winds in the western Pacific help trigger the onset of El Niño through the generation of Kelvin waves.

MAPPING TROPICAL SEA LEVEL

Sea level in each of the three tropical oceans is determined monthly by using the most recently acquired Geosat data. Ground tracks of the data used for the updates are shown in Figure 3. In the Pacific and Atlantic oceans, all data obtained within 40° of the equator are used, yielding altimeter profiles up to 10,000 km long. Orbit error is modeled as a quadratic trend over these arcs, but a linear model is used for profiles shorter than about 3500 km. Slightly shorter arcs are used in the Indian Ocean, and the linear orbit error model is used for the entire region.

Examples of Geosat-derived sea-level maps for each of the tropical oceans are shown in Figures 4 through 6. Because of systematic errors in the satellite ephemer-
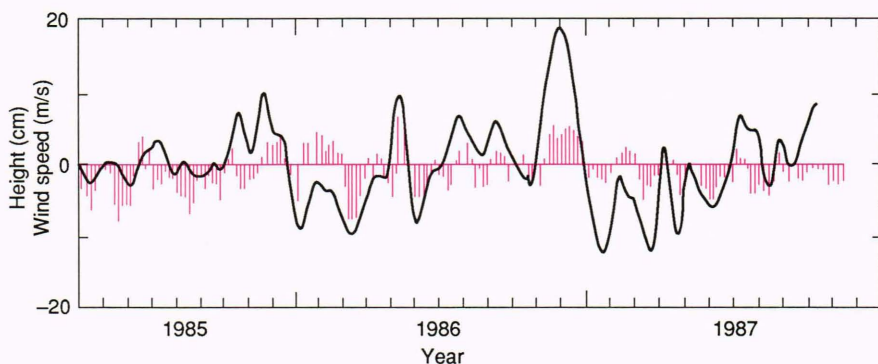
Figure 2. Geosat sea-level time series in the central equatorial Pacific compared against wind in the western Pacific. Sea level was computed from crossover differences in an 8° × 1° region centered at 162°W, 0°N. The zonal wind record (vertical bar) is at 850 mbar averaged between 5°S to 5°N and 120°E to 160°E. The sea-level record (smooth curve) has been lagged by 20 days. The good correlation indicates that many of the sea-level features are eastward-propagating Kelvin waves as discussed in Refs. 8 and 9. Sustained westerlies in November–December 1986 resulted in large-scale redistribution of water and marked the onset of the 1986–87 El Niño.
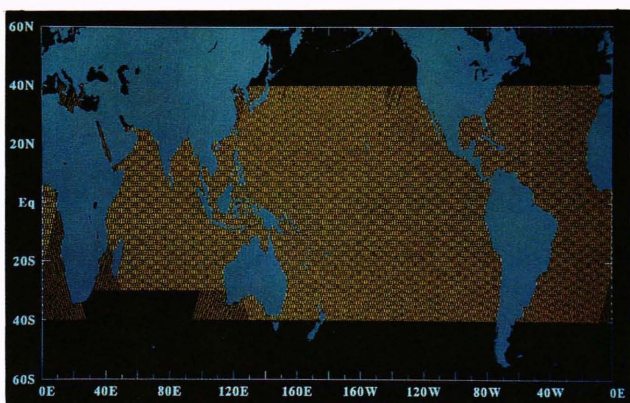
Figure 3. Ground tracks of Geosat ERM data used to monitor sea level in the tropical oceans.
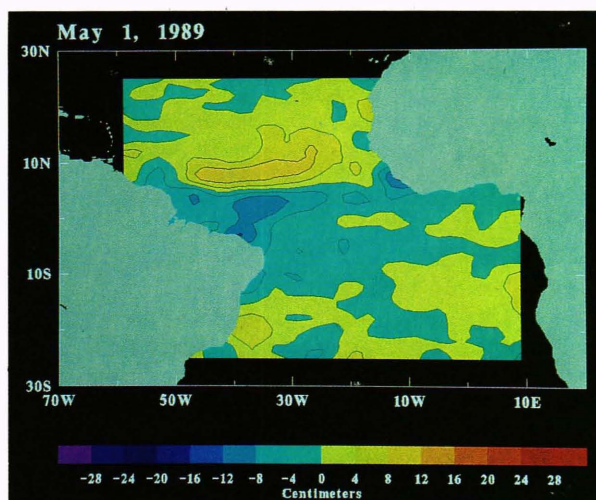
Figure 5. Atlantic sea-level anomalies, 1 May 1989, based on Geosat altimetry. The map is constructed from approximately 1200 time series in 2° × 1° areas. Anomalies represent departures from a 1-year mean, August 1987 to August 1988. Contours are at 4-cm intervals with negative values shaded.
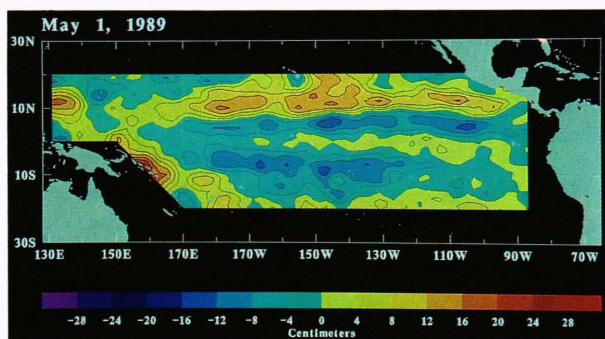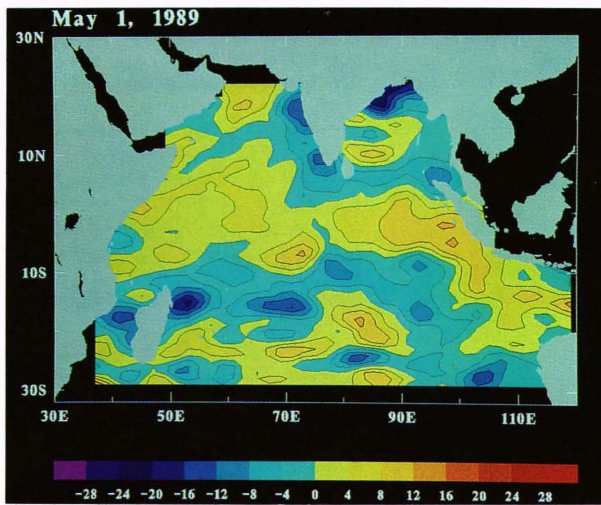

Figure 4. Pacific sea-level anomalies, 1 May 1989, based on Geosat altimetry. The map is constructed from approximately 2400 time series in 2° × 1° areas. Anomalies represent departures from a 1-year mean, April 1985 to April 1986. Contours are at 4-cm intervals with negative values shaded.

is and existing marine geoid models, we cannot determine sea level in an absolute sense—only its anomaly with respect to a reference period and its change with time. For example, in the Pacific we express all time series as anomalies relative to an annual mean sea level computed over the 12-month interval, April 1985 to

April 1986, a comparatively normal (i.e., a non-El Niño) period. In the Atlantic and Indian oceans, we refer all time series to the annual mean, August 1987 to August 1988. These maps show primarily the wind-driven, annual signal of sea level. For example, Pacific sea level (Fig. 4) reaches an annual minimum in the region within 10° of the equator in May, while positive anomalies dominate the off-equatorial bands between 10° and 20° in both hemispheres. In November, the zonally banded structure is the same, but with opposite sign (positive along the equator, negative at higher latitudes). Updated analyses of the Geosat data are published monthly,[10] along with other oceanographic and atmospheric analyses compiled in near-real time (1-month delay).

Of particular interest are long-term trends in sea level related to climatic phenomena such as El Niño in the Pacific. Figure 7 shows the result of combining all Geosat time series to produce averages over three broad areas of the Pacific: a northern band (8°N to 20°N), an
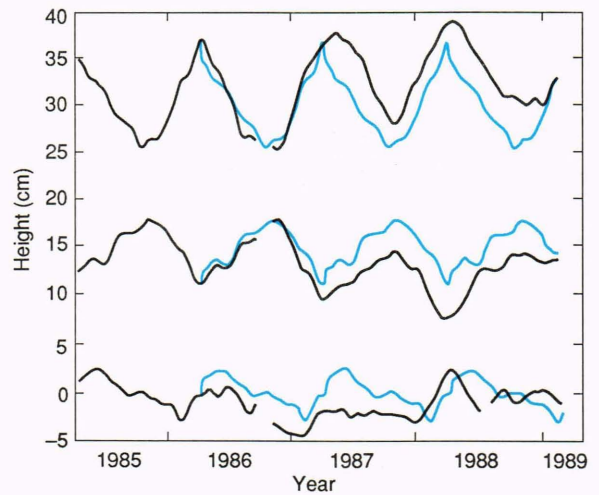
Figure 6. Indian Ocean sea-level anomalies, 1 May 1989, based on Geosat altimetry. The map is constructed from approximately 1400 time series in 2° × 1° areas. Anomalies represent departures from a 1-year mean, August 1987 to August 1988. Contours are at 4-cm intervals with negative values shaded.


Figure 7. Average sea level derived from Geosat data in three regions of the Pacific: (top) northern band, 8°N to 20°N; (middle) equatorial band, 7°S to 7°N; (bottom) southern band, 8°N to 20°S. Black curves represent the average sea level in each band during the 4-year period. Blue curves replicate the first year of the record in each band to enable a comparison of subsequent years. Anomalies are related to the 1986–87 El Niño.

equatorial band (7°S to 7°N), and a southern band (8°S to 20°S). Each band extends across the Pacific and includes approximately eight hundred 2° × 1° time series. The black curve is the 4-year record, and the blue curve is the first year (April 1985 to April 1986) replicated for comparison with subsequent years. The second year of the record is remarkably similar to the first, except in the southern band, where average sea level is decreased by 1 to 2 cm. Significant anomalies (4 to 5 cm) develop in all three bands, however, during the third year, with higher than normal sea level in the northern band, a corresponding deficit in the equatorial region, and continued low sea level in the south. In the two northernmost bands, these anomalies persist until the end of the fourth year, when sea level returns to 1985–86 levels. In the southern band, normal sea level is restored one year earlier.

The changes are related to El Niño. Cheney and Miller[9] show that during late 1986 and early 1987 the transport of water was primarily from west to east near the equator, in response to westerly wind bursts in the western Pacific and a general weakening of the trade winds throughout the tropics. Subsequently, the water moved northward, from the equatorial region into the north equatorial region.

This two-step process is illustrated in the sequence of Geosat maps in Figure 8. Conditions in November 1986, just before the beginning of El Niño, were relatively normal over most of the tropical Pacific. The band of positive sea level along the equator and the two negative bands near 10°N and 10°S are created by annual variations in the large-scale wind field. Conditions soon began to change, however. Sustained westerly winds dominated the far western Pacific (120°E to 160°E) from mid-November through the end of December, generat-

ing a series of eastward-propagating positive sea-level anomalies (known as downwelling Kelvin waves) along the equator. The Kelvin waves had sea-level signatures of 10 to 15 cm and can be seen in the December 1986 map superimposed on the already positive sea level in the equatorial band. Traveling at approximately 2.5 m/s, these internal waves required nearly two months to cross the Pacific. Their eastward progress from December to February can be followed in Figure 8. At the same time, sea level in the far western Pacific became increasingly negative as water was drained out of that area. By April 1987, negative sea level dominated most of the equatorial region across the Pacific.

Significant changes also occurred in the northern band. The sequence of maps shows sea level becoming increasingly positive in that area beginning in November 1986; westward propagation is also apparent. Conditions did not become anomalous, however, until March–April 1987, when sea level in the northern band had become significantly higher (5 cm higher on average) than normal (see also Fig. 7). For the next two years, sea level remained anomalous over most of the tropical Pacific until February 1989, when sea level returned to 1985–86 levels. We hope that by monitoring tropical Pacific sea level in near-real time, we may be able to better predict the arrival of the next El Niño.

CONCLUSIONS

The application of altimeter data to tropical ocean dynamics is one of the greatest challenges in satellite oceanography because of the small amplitude and large spatial scale of the sea-level signatures. Accurate altimetric determination of sea-level change as a function of time, however, is possible with appropriate processing. Comparison of Geosat time series with multiyear records from
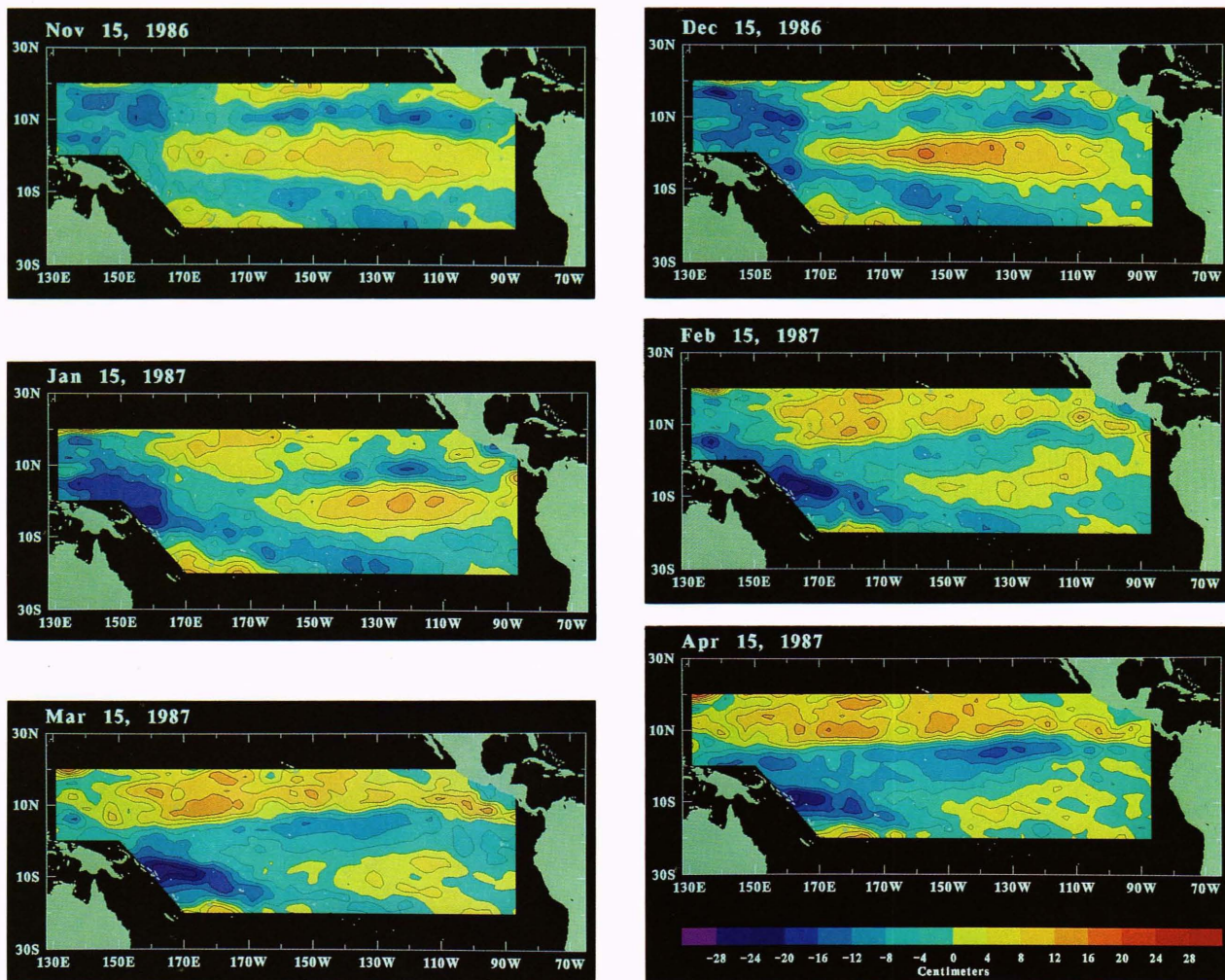
Figure 8. Sequence of Geosat-derived sea-level maps for the Pacific showing the beginning of the 1986–87 El Niño. Contours at 3-cm intervals show anomalies relative to the April 1985 to April 1986 mean. Eastward-propagating positive anomalies at the equator during December to February are Kelvin waves generated by westerly winds in the far western Pacific and mark the beginning of El Niño. As the event progresses, sea level becomes increasingly negative in the western Pacific and along the equator, while north of 8°N sea level gradually increases. This anomalous situation persisted throughout 1987 and 1988, eventually returning to normal in 1989.

island tide gauges in the tropical Pacific typically yields 4- to 6-cm rms agreement and correlations of 0.8 to 0.9. We should add that similar good agreement is obtained between the altimeter results and wind-driven ocean-circulation models. Such models represent the only means of obtaining spatial resolution comparable to that of the altimeter over entire ocean basins. Incorporation of altimeter data in wind-driven models of the tropical oceans will yield a powerful research tool that should lead to improved understanding of the combined ocean/atmosphere system.

Geosat marks the beginning of a series of satellite altimeter missions that should yield a decade or more of continuous global coverage. Such records are essential to obtain more complete descriptions of climatic phenomena such as El Niño. The Geosat mission has also permitted the first near-real-time monitoring of sea level over entire ocean basins, thus allowing observation of the 1986–87 El Niño as it evolved in the Pacific Ocean. This

monitoring effort continues today and has become an operational product; Geosat maps are published monthly by NOAA[10] for all three tropical oceans. In the next decade, with the possibility of several altimeter satellites operating simultaneously, global sea level may be monitored in near-real time as routinely as the weather is today.
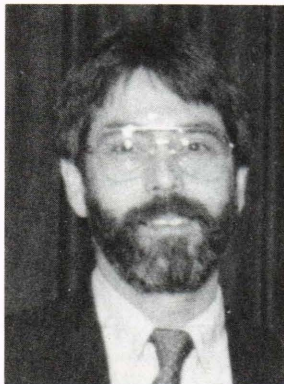
REFERENCES

[1] Cheney, R. E., Douglas, B. C., Agreen, R. W., Miller, L., Milbert, D., et al., "The GEOSAT Altimeter Mission: A Milestone in Satellite Oceanography," *Eos Trans. AGU*, **67**, 1354–1355 (1986).

[2] Cheney, R. E., Douglas, B. C., Agreen, R. W., Miller, L., Porter, D. L., et al., *GEOSAT Altimeter Geophysical Data Record User Handbook*, NOAA Tech. Memorandum NOS NGS-46, Rockville, Md. (1987).

[3] Fu, L.-L., and Chelton, D. B., "Observing Large-Scale Temporal Variability of Ocean Currents by Satellite Altimetry: With Application to the Antarctic Circumpolar Current," *J. Geophys. Res.* **90**, 4721–4739 (1985).

[4] Miller, L., Cheney, R. E., and Milbert, D., "Sea Level Time Series in the Equatorial Pacific from Satellite Altimetry," *Geophys. Res. Lett.* **13**, 475–478 (1986).
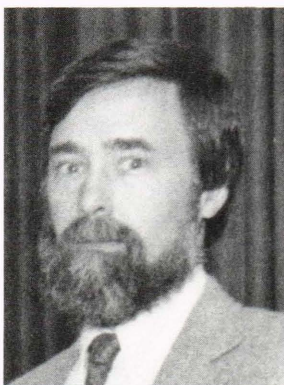
[5] Milbert, D., Douglas, B., Cheney, R., and Miller, L., "Calculation of Sea Level Time Series from Non-Collinear GEOSAT Altimeter Data," *Mar. Geod.* (in press) (1989).

[6] Cheney, R. E., Douglas, B. C., and Miller, L., "Evaluation of Geosat Altimeter Data with Application to Tropical Pacific Sea Level Variability," *J. Geophys. Res.* **94**, 4737–4747 (1989).

[7] Wyrtki, K., Kilonsky, B. J., and Nakahara, S., *The IGOSS Sea Level Pilot Project in the Pacific*, Data Report 003, University of Hawaii, Honolulu (1988).

[8] Miller, L., Cheney, R. E., and Douglas, B. C., "GEOSAT Altimeter Observations of Kelvin Waves and the 1986–87 El Niño," *Science* **239**, 52–54 (1988).

[9] Cheney, R. E., and Miller, L., "Mapping the 1986–87 El Niño with GEO-SAT Altimeter Data," *Eos Trans. AGU* **69**, 754–755 (1988).

[10] Kousky, V. E., *Climate Diagnostics Bulletin*, NOAA National Weather Service/Climate Analysis Center, Washington, D.C. (1989).

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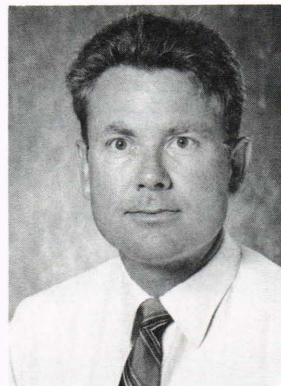
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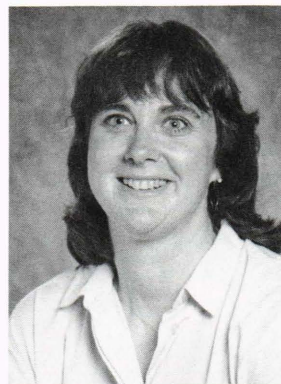
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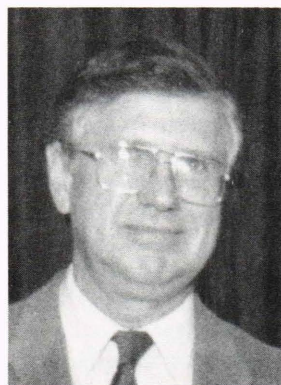
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