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Validation of the Geostrophic Method for Estimating Zonal Currents at the Equator From Geosat Altimeter Data

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The applicability of satellite altimeter data for estimating zonal current variability at the equator is assessed using the meridionally differenced form of the geostrophic balance. Estimates of geostrophic zonal flow anomalies in the equatorial Pacific have been deduced from 17-day collinear altimeter data during the first year of the Geosat Exact Repeat Mission, November 1986 to November 1987. Altimeter-derived geostrophic estimates agree well with in situ zonal current variability. Comparison of low-frequency, near-surface zonal current observed from equatorial moorings at 165°E, 140°W, and 110°W yield correlations of 0.83, 0.85, and 0.51, respectively, with a mean rms difference of 23 cm s^{-1}. The geostrophic currents were calculated from all available ascending and descending Geosat tracks within ±4.5° of longitude from each mooring site. The inclusion of up to 11 ascending and descending Geosat tracks within the 9° band for every 17-day repeat effectively reduced the temporal sampling interval to 1.5 days at 165°E and 140°W. However, only ascending tracks were available at 110°W. Alongtrack sea surface heights were first smoothed using a combination of linear and nonlinear filters. The 6.8 km alongtrack spacing of the altimeter measurements provides sufficient resolution for the effective filtering of small-scale meridional noise, both instrumental and oceanic. High-frequency temporal variability, such as noise and ageostrophic motions, was suppressed with a 31-day Hanning filter. Sea level and zonal velocity solutions from a tropical Pacific numerical model were used as proxy data sets in order to estimate errors induced into the geostrophic calculation by the Geosat space-time sampling.

1. INTRODUCTION

One of the principal advantages of satellite oceanography is the potential for global monitoring of ocean circulation. In this regard, satellite altimeters such as Geosat will be used to measure the global sea level, which in turn will be used to provide estimates of surface geostrophic current variability on time scales from months to years. With improvements to the precision of altimetric measurements for future missions such as TOPEX/POSEIDON, the estimation of absolute geostrophic currents may be possible. It is expected that such an unprecedented spatial and temporal description of the surface geostrophic flow field will lead to significant advances in our understanding of the large-scale ocean circulation and its fluctuations. This is evidenced further by the role altimeter measurements are anticipated to play in large-scale experiments such as the World Ocean Circulation Experiment and the Tropical Ocean–Global Atmosphere program [cf. *Stewart and Lefebvre*, 1987].

The utilization of satellite altimetry to monitor circulation in the tropics poses an interesting set of problems. Changes in the mass and heat of the tropical oceans, especially the tropical Pacific, are critical to climate change; yet the sea level expression of this upper ocean variability is only of the order of several centimeters for mean seasonal conditions and at most a few tens of centimeters during extreme El Niño events [*Wyrtki and Leslie*, 1980; *Delcroix and Gautier*, 1987]. Zonal currents at the equator in balance with the mass field are among the most energetic anywhere, however, and therefore must be taken into account in any description of the global ocean circulation. Detection of current variability is complicated by stringent observational accuracies required at equatorial latitudes for estimating geostrophic currents because the horizontal component of the Coriolis force tends to zero.

Most discussions of the use of satellite altimetry for monitoring currents within ±2°–3° of the equator treat this equatorial band as an exceptional region where geostrophy is not expected to apply to first order [cf. *Stewart et al.*, 1986]. This neglect of the circulation at the equator was certainly the case for the few studies prior to Geosat where the limited Seasat altimeter data set was used either to infer the intramonthly variability of surface geostrophic currents or to construct an estimate of the large-scale mean geostrophic circulation. *Cheney et al.* [1983] used the root-mean-square (rms) sea height variability measured by the Seasat altimeter as an index of the variability of surface geostrophic currents during 25 days in 1978. Of particular note was the detection of significant (although small compared with the mid-latitude variability) 4- to 6-cm sea level variability in the vicinity of the North Equatorial Current and North Equatorial Countercurrent in the tropical Pacific Ocean. No significant sea level variability was detected along the equator, and hence no inferences were made with respect to current variability at the equator. *Tai* [1983] used the full 3 months of Seasat altimeter data to construct a mean sea surface topography with low-order spherical harmonics for the Pacific Ocean basin from 50°N to 50°S. In this study, estimates of the absolute geostrophic current were computed to within 10° of the equator. More recently, *Tapley et al.* [1988] have constructed a mean sea surface from the Seasat data with higher-order spherical harmonics. The resulting sea surface topography was used to estimate the mean surface geostrophic flow field on a 5° by 5° grid up to within 2.5° of the equator.

However, this exclusion of geostrophic currents within an

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equatorial band, or more precisely the equatorial waveguide, may not be necessary. Recent comparisons between direct equatorial current measurements with geostrophic velocities derived from dynamic height calculations suggest that the low-frequency fluctuations of these currents at the equator are reasonably well represented by a form of the geostrophic approximation. *Picaut et al.* [1989] provide a concise review of the use of the meridionally differentiated form of the geostrophic balance to estimate zonal velocity at the equator. In their study, meridional arrays of thermistor chains and equatorial current meter moorings were used to investigate the limitations of the geostrophic relation for estimating zonal equatorial currents. Comparisons with the direct current measurements in the equatorial Pacific indicated that geostrophic estimates of the current variability were optimal for periods greater than 30 days and with a 1°–1.5° latitudinal scale for the geostrophic calculation. One of the conclusions of this work was that it may be possible to derive useful indices of the flow field at the equator from satellite altimeter measurements of sea level.

The advent of the Geosat altimeter mission provides the first opportunity to map or monitor the global variability of surface geostrophic currents through a complete seasonal cycle and longer. The 72° inclination of the Geosat orbit that transects the major equatorial currents together with the unprecedented alongtrack resolution (6.8 km) for collinear repeats inspired us to test this concept of using satellite altimeter measurements of sea level to estimate the geostrophic flow field right at the equator. If successful, this would then permit a truly global perspective of the surface geostrophic circulation.

Previous uses of the Geosat altimeter data for the tropical Pacific Ocean were restricted to the use of crossover differences in order to describe the sea level variability during the 18-month classified Geodetic Mission and approximately 7 months of the Exact Repeat Mission (ERM) [*Miller et al.*, 1988; *Cheney and Miller*, 1988]. One fortuitous aspect of the Geosat mission was that it coincided with the El Niño event of 1986–1987. Sea level variability from crossover analyses on a 2° by 8° grid were used by *Cheney and Miller* [1988] to track the equatorial Pacific response to westerly wind bursts during the onset of this event. The dense space-time coverage of the altimeter data set permitted the detection of equatorial Kelvin wave propagation and the associated narrow meridional scales, of the order of 200 km, characteristic of the equatorial waveguide. Comparisons with a limited number of tide gauge measurements indicated that the Geosat altimeter measurements in the tropical Pacific were accurate to within an rms difference of 3 cm.

To date there have been few, if any, attempts to compare altimetrically derived geostrophic current estimates with direct current measurements. Instead, the few comparisons that have been made with in situ observations have been restricted to a few point measurements of sea level. Thus in this paper we set out to intercompare geostrophic current estimates derived from Geosat altimeter data with direct current observations. In view of the low sea level amplitudes in the tropics, as well as the sensitivity of the geostrophic approximation to small sea level perturbations near the equator, we choose to investigate one of the more stringent tests of the use of altimeter observations to estimate ocean currents. The purpose of this work then is to determine the applicability of the geostrophic method for estimating zonal currents at the equator using satellite altimeter data.

In the next section we describe the data we use: the first year of collinear sea surface heights from the Geosat Exact Repeat Mission and the direct current measurements from three equatorial moorings in the Pacific Ocean. Next, the methodology for using the meridionally differenced form of the geostrophic approximation is presented. This is followed by a description of the alongtrack, zonal, and temporal filtering that was required to remove instrument noise, oceanic noise, and most ageostrophic motion from the Geosat data. In parallel with the development of these specific techniques for processing Geosat altimeter data, sea level from a numerical ocean model of the tropical Pacific was used as a proxy data set to address questions pertaining to the influence of the unique space-time sampling characteristics of the Geosat altimeter when estimating the low-frequency zonal geostrophic current at the equator. In the final section the applicability of the geostrophic method for estimating the flow field at the equator from satellite altimeter measurements is discussed and summarized.

2. DATA

2.1. *Geosat Altimeter Data*

The Geosat data used in the present study correspond to the first 22 cycles of the 17-day ERM covering the period November 8, 1986, to November 18, 1987. Repeated ground tracks have a 72° inclination and an equatorial separation of 164 km, although the separation between ascending and descending tracks exactly at the equator is approximately 82 km (Figure 1). The alongtrack spacing of the altimeter data is 6.8 km and corresponds to the 1-s averages on the geophysical data records (GDRs) [*Cheney et al.*, 1987]. Corrected sea surface heights processed from the GDRs were kindly provided to us by C. Koblinsky of the NASA Goddard Space Flight Center (GSFC). The processed data were obtained by spatially interpolating each repeat cycle of Geosat data using a tenth-order Hermite interpolation algorithm. In order to get a corrected sea surface height, several factors were applied following the suggestions of *Cheney et al.* [1987]. These corrections included ionospheric refraction, dry tropospheric refraction, wet tropospheric refraction (using Fleet Numerical Oceanography Center (FNOC) water vapor estimates), sea state bias (2% of significant wave height), tides [*Schwiderski*, 1980], and inverted barometer (FNOC pressure). Orbits were provided by the Naval Astronautics Group and had an rms accuracy of about 3.5 m. The data were low-pass filtered to remove instrument noise at the shortest scales following the technique described by *Cheney et al.* [1983]. The processing to remove orbit error also followed the technique outlined by that paper; however in the GSFC processing the orbit error was filtered out of demeaned collinear tracks by detrending each pass over 2500 km segments with a least squares fit quadratic function (including a bias and linear trend terms).

The final product delivered to us by NASA GSFC consists of collinear deviations from a mean in order to suppress the influence of the geoid. Note that this procedure also suppresses the mean surface topography related to ocean circulation. Therefore all the data used in this paper are relative to their mean over the time period November 8, 1986, to

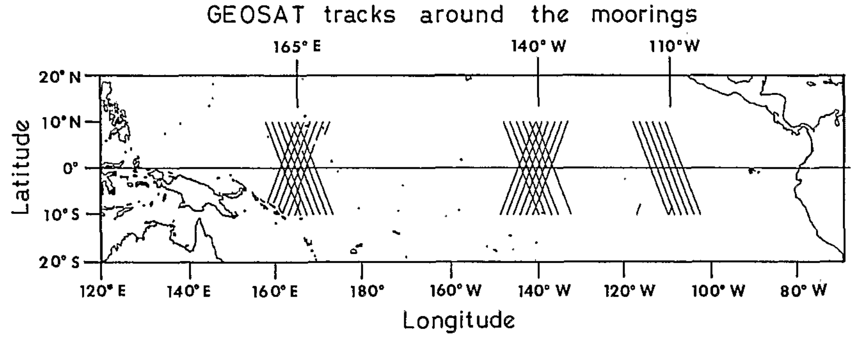

Fig. 1. Geosat 17-day repeat ground tracks around the three equatorial current meter moorings at 165°E, 140°W, and 110°W.

November 18, 1987. Alongtrack means were computed from a minimum of 20 collinear repeats out of a possible maximum of 22 repeats. Tracks for which less than 20 good repeats were available were omitted from the analysis, leading to gaps in the Geosat data used for the present study. Gaps along ground tracks also arise when data fail to pass a standard deviation criterion for the original 10 per second data [*Cheney et al.*, 1987]. Figure 1 shows evidence of such gaps, especially near 110°W where only data from the ascending tracks were available. This figure also shows the subset of the Geosat data which has been used in this study. It is restricted to the equatorial tracks 10°N to 10°S surrounding the moorings located at 165°E, 140°W, and 110°W. In this data set, gaps smaller than 68 km (half the final derivative length; see section 3) were filled through a simple linear interpolation in order to maximize the number of tracks in our calculation. The accuracy of these Geosat data in the tropical Pacific has been studied by various authors. Using the crossover difference technique, and comparing with various time series from tide gauges, inverted echo sounders, and thermistor chains at several locations in the tropical Pacific, *Cheney et al.* [1989] suggest that the rms accuracy is about 3 cm. Over the November 8, 1986, to November 18, 1987, period, *Delcroix et al.* [1990] found an rms accuracy of 4 cm by comparing collinear Geosat data with in situ data from seven conductivity-temperature-depth (CTD) sections and thermistor chains in the western Pacific.

2.2. *Equatorial Current Meter Mooring Data*

The current meter mooring time series used in this study were collected from taut-wire surface moorings at nominal locations of 0°, 110°W; 0°, 140°W; and 0°, 165°E, in depths of 3.7 km, 4.3 km, and 4.4 km, respectively. Data were internally recorded at 15-min intervals from 6–7 EG&G model 610 vector averaging current meters (VACMs) in the upper 250–300 m, then processed to daily averages as discussed by *Freitag et al.* [1987]. Instrumental errors in near-surface equatorial velocity measurements from VACMs are <5 cm s^{-1} [*Halpern*, 1987]. The shallowest records from each mooring (10 m at 110°W and 140°W; 50 m at 165°W) were used in this study for comparison with the Geosat-inferred velocities for the period November 8, 1986, to November 18, 1987. A 66-day record gap at 140°W (March 8 to May 12, 1987) was filled by extrapolating 25-m data to 10 m based on a linear least squares regression fit of 10 m and 25 m daily time series. The correlation coefficient for 330 overlapping days of 10 m and 25 m data for the study period was 0.99, suggesting that the regression fill provides a very good representation of the variability at 10 m. The time series at 165°E begins on December 13, 1986. The 50-m current variability at 165°E is representative of the flow measured nearer to the surface as discussed by *McPhaden et al.* [1990]. For a 164-day period in 1986, the correlation coefficient for daily averaged 10-m and 50-m zonal velocity data was 0.87 and the rms difference was 19 cm s^{-1}.

3. METHODOLOGY

The standard form of the geostrophic equation for the zonal flow field

$$fu = (-1/\rho)p_y$$

is indeterminate for $y = 0$ and therefore useless at the equator. For this special case, *Jerlov* [1953], *Tsuchiya* [1955], and *Hidaka* [1955] have suggested the use of the second derivative of the meridional pressure field on an equatorial β plane ($f = \beta y$):

$$\beta u = (-1/\rho)p_{yy}$$

This geostrophic relation at the equator has been utilized with some success by various authors [e.g., *Hayes*, 1982; *Lukas and Firing*, 1984]. When applied to sea surface height deviations η relative to the geoid, this relation becomes

$$\beta u = -g\eta_{yy}$$

Because of the small second derivative term and division by β, the resulting geostrophic current is very sensitive to small variations of sea level at the equator. For example, with the use of a finite difference form of the second derivative over a 1° meridional grid, sea level noise of 1 cm uncorrelated over the grid size will give an error of 138 cm s^{-1}. Using dynamic height topography from density profiles every 1 km along a single transect between 3°N and 3°S, *Moum et al.* [1987] found evidence of a geostrophically balanced equatorial undercurrent at 140°W at the time of their transect. The detection of this geostrophic balance was made possible by using a meridional filter to suppress the small-scale noise in the dynamic height field. From moored thermistor chains at 2°N and 2°S and current-temperature moorings at 0° along 165°E and 110°W, *Picaut et al.* [1989] showed that low-pass time-filtered equatorial current oscillations (periods greater than 1 month) are reasonably well represented by the cur-

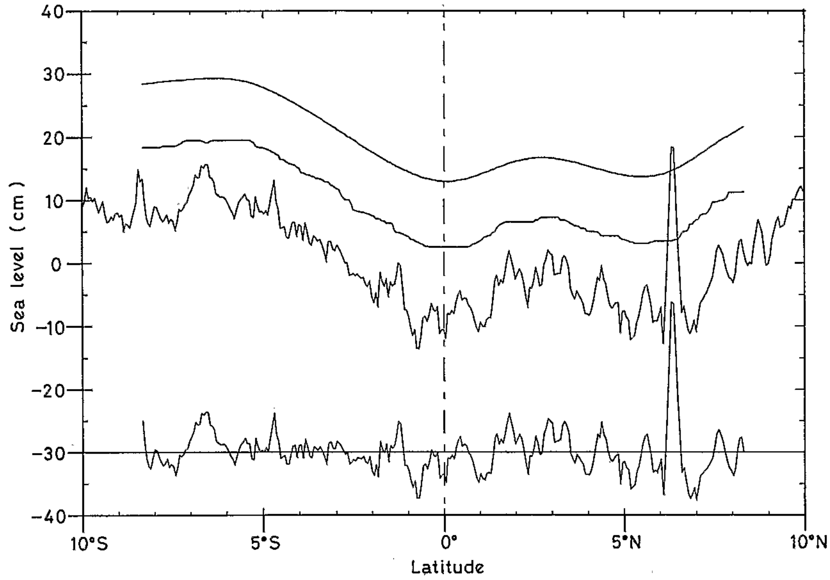

Fig. 2. Corrected sea surface heights for an individual Geosat pass (centered at zero). The same alongtrack series after the application of a nonlinear median filter is shown second from the top (shifted by 10 cm). The top curve is the final alongtrack profile after the application of a linear Hanning filter. This is the profile that is used to calculate the sea level curvature at the equator. The small-scale variability removed by the two-step filtering is depicted at the bottom.

vature of the meridional pressure field. Since the altimeter measurements are strongly affected by oceanic and instrumental noise, the two previous studies suggest that a judicious combination of filtering in space and time may have to be applied to the Geosat data in order to determine surface geostrophic currents at the equator. While the 6.8-km alongtrack spacing should provide sufficient resolution for the effective filtering of small-scale meridional noise, the temporal resolution afforded by the 17-day repeat cycle is too coarse to permit the efficient filtering of periods less than 1 month.

3.1. *Alongtrack Filtering*

From the 1-s average corrected sea surface heights, it appears that a significant amount of impulsive noise remains with alongtrack scales generally less than 1° (Figure 2). These spikes cannot be interpreted as the signature of oceanic current variability, and therefore they need to be suppressed from the data height record. Thus a nonlinear median filter [*Brock*, 1986] was first used on the alongtrack data. The resulting record indicates some remaining slight irregularities which were then filtered out with a linear Hanning filter. The length of both filters was chosen to be identical and was determined by the technique detailed in this subsection. For a particular filter length, the geostrophic current is estimated by the second derivative of the sea surface height anomaly (using a second-order finite difference scheme) along the specific track closest to each of the three mooring sites for all 20 to 22 repeat cycles. The resulting calculated currents are then compared with the observed daily mean currents at the date when the track intersects the equator for each cycle. A linear regression finally quantifies the degree of comparison between the calculated and the observed currents. These comparisons are surprisingly good at the 165°E and 140°W mooring sites (significant at the 99% confidence level), given the fact that they are made with instantaneous geostrophic calculations. Poor comparisons at 110°W could be explained by strong 20-day oscillations [*Halpern et al.*, 1988] which were present at the time of the observations (Figure 6*a*).

The use of various filter lengths indicates that the optimum choice is approximately 400 km and that the current intercomparisons do not change very much within the filter range 300–500 km. In the same manner we find that the optimum meridional grid size, Δy, for the second-derivative calculation is 136 km, although the intercomparisons are not very sensitive to Δy between 60 and 200 km. This last result agrees with results of *Moum et al.* [1987] and *Picaut et al.* [1989], who found that the optimum meridional grid size for estimating geostrophic current at the equator is approximately 100–160 km. Moreover, these choices of grid size and filter length are consistent with previous estimates of the meridional length scales in the tropics. For example, J. Picaut and R. Tournier (manuscript in preparation, 1989) found that a 4° latitude Fourier filter was best for their geostrophic equatorial current calculation, *White et al.* [1985] found the meridional decorrelation scale in the tropical Pacific thermal structure to be 300 km, and the alongtrack decorrelation scale for Geosat sea level anomaly data in the western tropical Pacific has been determined to be 500–600 km (T. Delcroix, personal communication, 1989).

3.2. *Zonal-Temporal Filtering*

Despite the previous good correlation between the instantaneous observed currents and currents calculated using the Geosat data from the track closest to the 165°E and 140°W mooring sites, the resulting 17-day time interval is too coarse for a fair sampling of surface current variability. The importance of high-frequency variability along the equator [*Halpern et al.*, 1988] and the noise introduced in an instantaneous geostrophic calculation [*Hayes*, 1982; *Moum et al.*, 1987] demands finer temporal resolution. For example, the

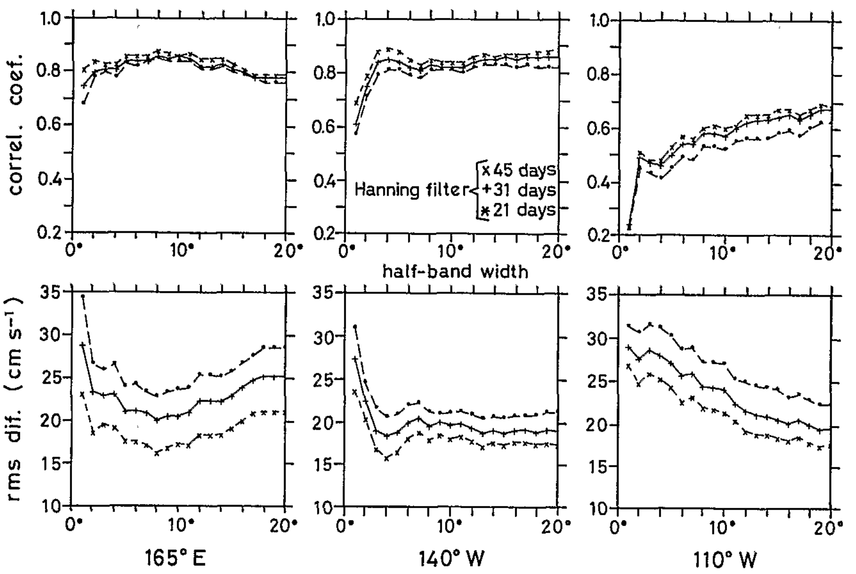

Fig. 3. Correlation and rms difference between low-pass-filtered zonal current measured at the 165°E, 140°W, and 110°W equatorial moorings and geostrophic zonal current calculated from all ascending and descending Geosat altimeter data within a longitudinal band of variable width centered at the mooring sites.

current intercomparison is not particularly good at 110°W, where high-frequency variability is energetic. However, comparison with geostrophic estimates computed from Geosat tracks within several degrees of 165°E or 140°E indicates that it may be possible to increase the number of coherent geostrophic estimates within the vicinity of the mooring site and thereby reduce the original 17-day sampling time interval. The combination of geostrophic estimates deduced from all ascending and descending tracks over a ±4.5° longitudinal band centered at a mooring site permits a constant 1.5-day time interval. If this band is extended to ±12.5° of longitude, the temporal sampling interval could be reduced to about 0.5 day. The finer the temporal resolution, the more effective the low-pass filter will be in suppressing high-frequency noise in the geostrophic calculation. On the other hand, as the size of the longitudinal band is increased, in order to augment the number of retrievals per 17 days, the less meaningful the combination of calculated currents may become if the zonal decorrelation scale of the geostrophic currents is exceeded.

A precise study of the zonal decorrelation scale of equatorial currents has not yet been done, but an estimate of this scale can be anticipated from several studies. *Firing and Lukas* [1985] found that if the data from the different Hawaii-to-Tahiti Shuttle transects (150°W, 153°W, and 158°W) were combined together without regard to longitude, periods equal to or greater than 6 months were fairly well represented. *Halpern* [1987] found that the coherence between current time series from moorings at 108°W and 110°W was above the 95% confidence level for periods greater than 6–7 days. *McPhaden and Taft* [1988] found that the 30° zonal separation between the 140°W and 110°W moorings was representative of the coherence scales for zonal current variations along the equator at periods greater than 50 days. For our specific study, the first thing we want to determine is the zonal scales over which individual 17-day sampled geostrophic estimates can contribute to a meaningful description of the zonal flow relative to the in situ data at the mooring site. Figure 3 represents the correlation coefficients and the rms differences, over the 22 repeat cycles, between the low-pass-filtered observed currents and the geostrophic currents calculated from all ascending and descending tracks within a longitudinal band of variable width centered at each mooring site. Hanning filters of 21-, 31-, and 45-day lengths were used to low-pass filter the observed and altimeter-derived current time series. For the 165°E mooring the correlation coefficients are high for all zonal bandwidths chosen. For the 31-day Hanning filter, the maximum correlation of 0.86 and a minimum rms difference of 20 cm s^{-1} correspond to an 8° longitudinal half bandwidth. For the 140°W mooring and the same Hanning filter, the maximum correlation (0.86) and the minimum rms difference (18 cm s^{-1}) are more notable than at 165°E because there is a clearly defined peak for a longitudinal half bandwidth of 4°. On the other hand, at the 110°W mooring there is no optimal bandwidth. The correlation coefficient increases and the rms difference decreases monotonically with an increase in the zonal bandwidth. As was noted previously, this could be due to the presence of a dominant 20-day oscillation in the eastern equatorial Pacific and also to the lack of most descending tracks around this mooring (Figure 1).

With these results in mind, we decide to combine the currents calculated from all ascending and descending tracks within ±4.5° from each mooring site. The choice of a 9° band was guided by the fact that the Geosat orbit configuration results in one ascending or one descending track within this band every 1.5 days. Thus both a regular and a frequent sampling of the geostrophic currents are obtained. Figures 4*a* and 5*a* show the superposition of the geostrophic time series and the corresponding near surface observed current series at 165°E and 140°W, respectively. As was noted in section 2 all series are relative to their mean over the common period. Energetic high-frequency variability is obvious in the calculated geostrophic series and is probably due to some remaining instrumental noise, ageostrophic high-frequency motion, and errors resulting from the space-

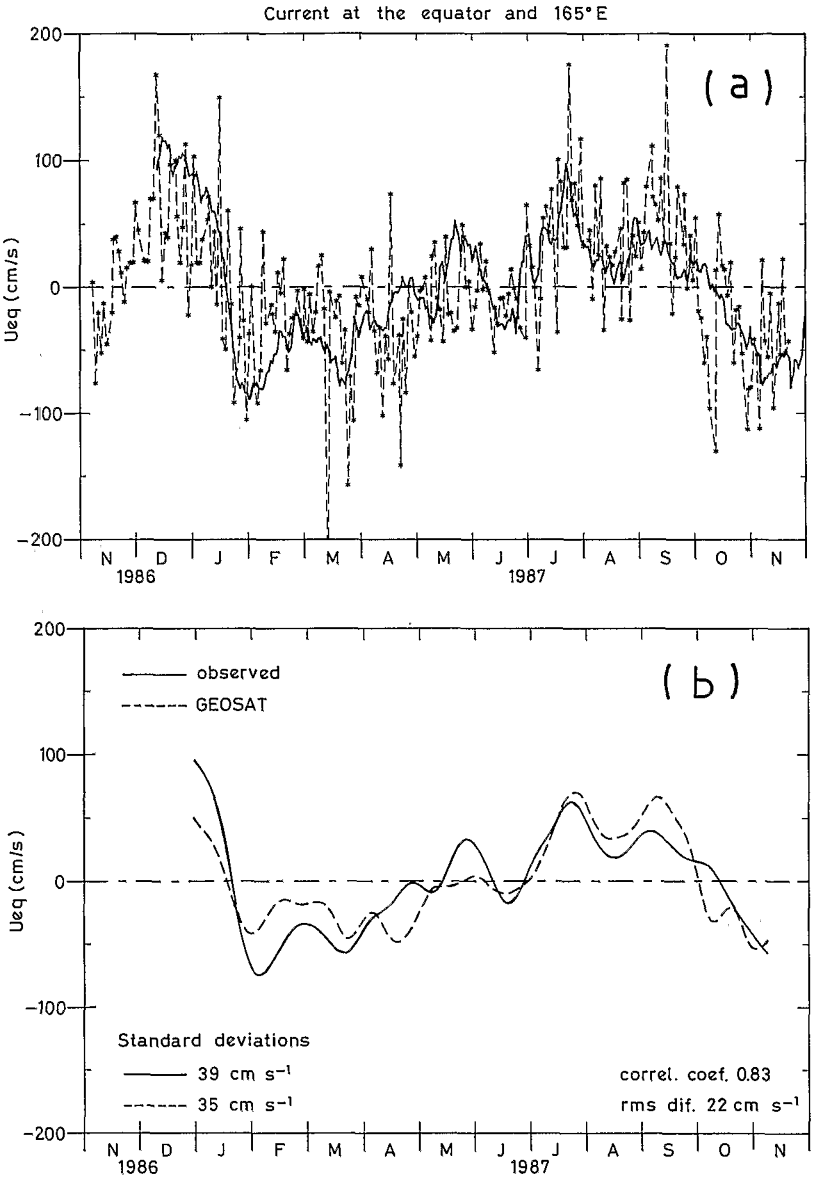

Fig. 4. Geostrophic zonal flow estimated from Geosat altimeter data (dashed line) and daily averaged near-surface zonal flow measured directly from an equatorial mooring at 165°E (solid line). (*a*) Daily mooring time series and 1.5-day Geosat time series. (*b*) Time series low-pass filtered with a 31-day Hanning filter.

time combination technique. Because of a few geophysically unrealistic geostrophic current results (greater than 2 m s^{-1}), mostly a consequence of alongtrack linear interpolation and some remaining error near the equator, a 3 standard deviation rejection criterion is applied to the low-pass-filtered time series. This does not significantly affect any of the results that follow, as only 2–3% of the calculated data are rejected.

From Figures 4*a* and 5*a* it appears that the resulting geostrophic time series bear some resemblance to the observed time series at low frequency. Cross-spectrum analysis between the calculated and observed currents indicates that variability at periods less than about 40 days is incoherent. This is in contrast to the lower-frequency variability, which is mostly coherent and in phase at 140°W and 165°E. A Hanning filter of various lengths is applied to suppress this high-frequency variability. Following the results of Figure 3, a 31-day filter is a good compromise between the reduction of high-frequency noise and the length of the time series. The similarity between the calculated and observed low-frequency currents at 165°E and 140°W (Figures 4*b* and 5*b*) is now obvious and yields correlation coefficients of 0.83 and 0.85, respectively. The corresponding rms differences of 22 and 18 cm s^{-1}, respectively, compared with the 39 and 34 cm s^{-1} standard deviations of the filtered observed current, indicate that most of the low-frequency variations in the surface equatorial currents at 165°E and 140°W are represented by the low-frequency geostrophic currents deduced from the Geosat altimeter data.

A similar intercomparison at 110°W (Figures 6*a* and 6*b*) is less convincing. The correlation coefficient between the filtered series is 0.51. This is partly due to the fact that no descending tracks are available within ±4.5° from the 110°W mooring. This results in a 3-day sampling interval instead of a 1.5-day interval and therefore reduces the efficiency of the low-pass filter. As an estimate of the effect of this reduced sampling, when the same calculation is done at 140°W with

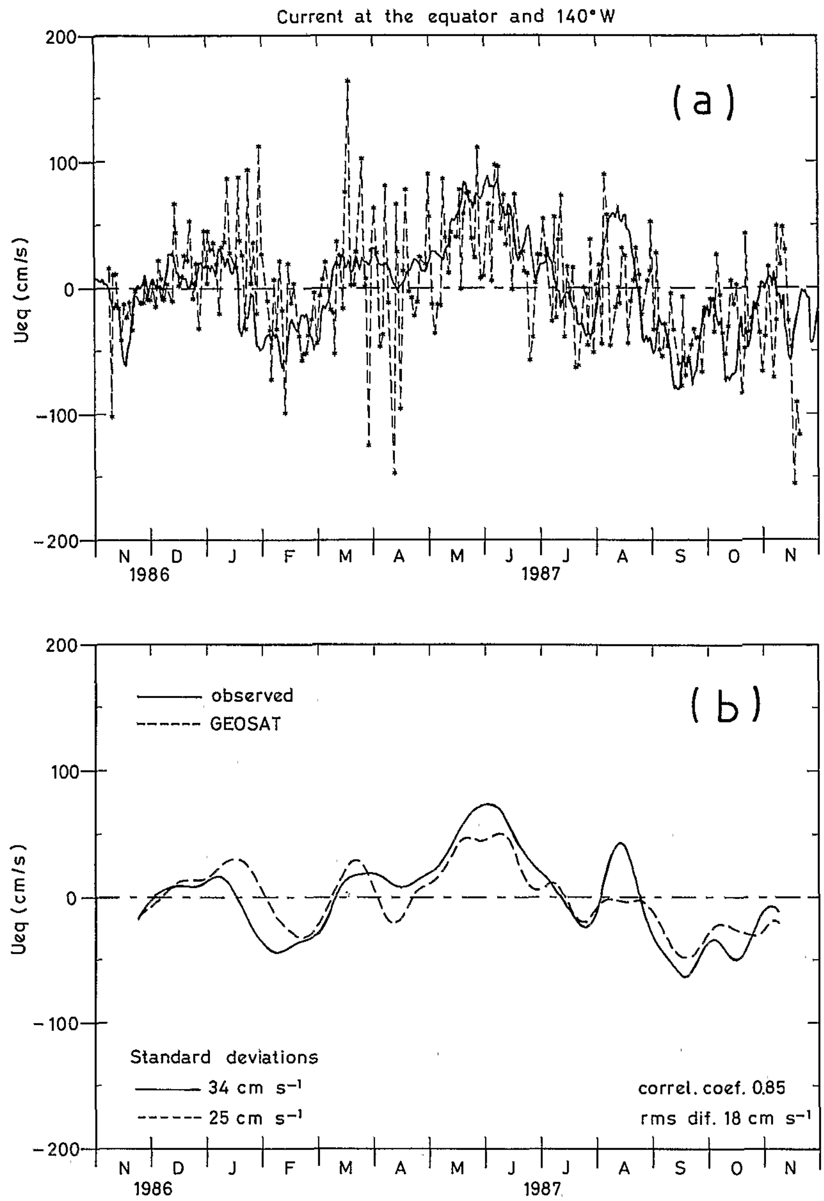

Fig. 5. Geostrophic zonal flow estimated from Geosat altimeter data (dashed line) and daily averaged near-surface zonal flow measured directly from an equatorial mooring at 140°W (solid line). (*a*) Daily mooring time series and 1.5-day Geosat time series. (*b*) Time series low-pass filtered with a 31-day Hanning filter.

only the ascending tracks within ±4.5° of the mooring, the correlation coefficient drops from 0.85 to 0.67. As may be seen in Figure 3, increasing the width of the band around the 110°W mooring to ±20° improves the correlation to 0.68 and reduces the rms to 19 cm s^{-1}. However, such an unrealistically large bandwidth degrades the results around the 140°W and 165°E moorings.

3.3. *Simulated Geosat Geostrophic Velocity Sampling Errors*

To investigate further the errors present in calculating geostrophic estimates at the equator, sea level from a tropical Pacific Ocean model is used as a proxy sea level data set. The availability of both model sea level and model zonal velocity fields allows us to address the use of the second meridional derivative of sea level as well as the unique space-time sampling characteristics of the Geosat altimeter for estimating low-frequency zonal geostrophic currents at the equator. For the purpose of the present sampling questions, the most basic description of equatorial ocean dynamics is provided by the linear shallow water wave equations. Sea level solutions from the numerical treatment of these equations consisting of four baroclinic modes were obtained in response to forcing by the monthly mean surface wind stress of the Florida State University analysis [*Goldenberg and O'Brien*, 1981] for 1979–1983. This period was chosen for studies of equatorial current sampling because it brackets a wide range of low-frequency variability; for instance, fairly regular mean seasonal conditions were present in 1979–1981 and were followed by one of the most extreme El Niño events on record in 1982–1983. The detailed discussion of the model sea level solutions and intercomparison with in situ

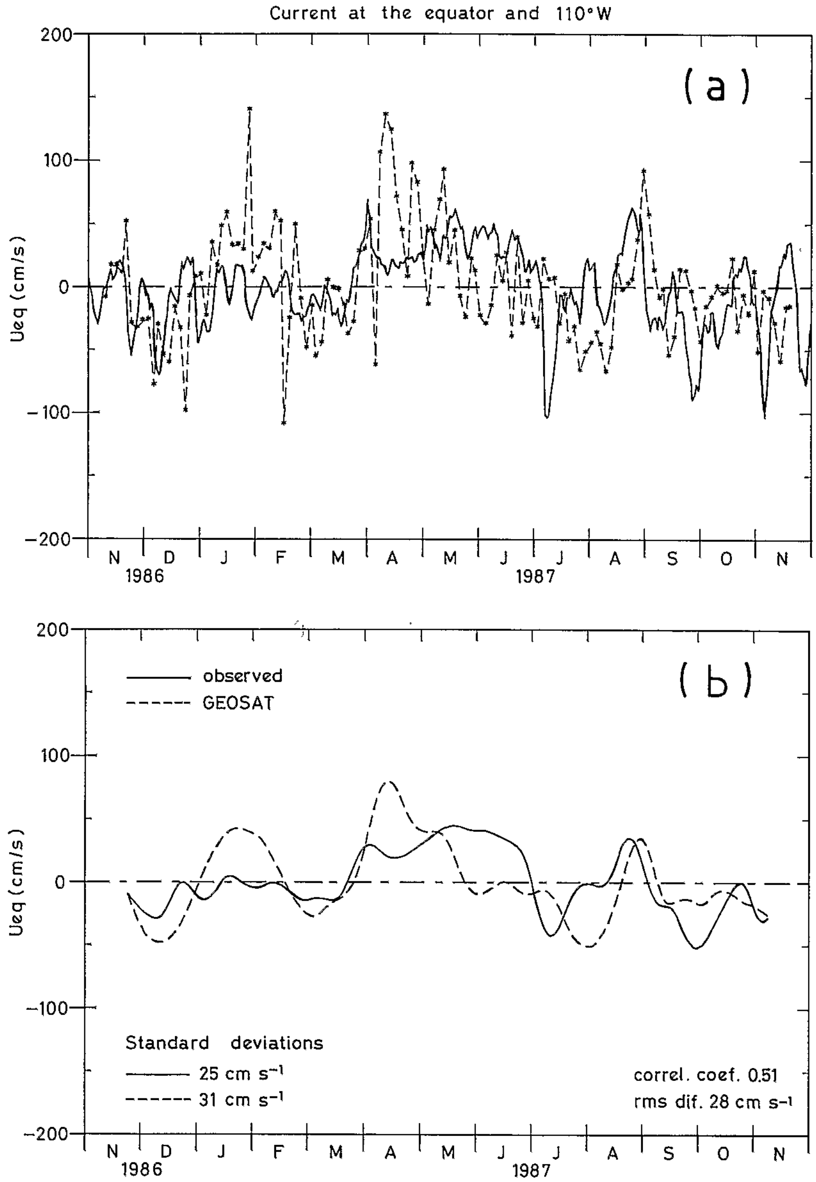

Fig. 6. Geostrophic zonal flow estimated from Geosat altimeter data (dashed line) and daily averaged near-surface zonal flow measured directly from an equatorial mooring at 110°W (solid line). (*a*) Daily mooring time series and 3-day Geosat time series. (*b*) Time series low-pass filtered with a 31–day Hanning filter.

estimates from tide gauges and dynamic heights derived from expendable bathythermograph (XBT) data is provided by *McPhaden et al.* [1988] for the mean seasonal cycle 1979–1981 and by *Busalacchi et al.* [1990] for the 1982–1983 El Niño.

The first question of interest is the degree to which the curvature of the model sea level at the equator is capable of being used to infer geostrophically the zonal model velocity at the mooring locations as a function of varying zonal and meridional scales in this simplified linear system. The best case scenario must be when η_{yy} is taken coincident in longitude with the equatorial model velocity. As a straightforward confirmation of this, the 5-year time series of zonal model velocity corresponding to the mooring locations at 165°E, 140°W, and 110°W were compared against the geostrophic estimates computed from the model sea level along the same meridians. The model grid size of 40 km was used for Δy, and a 6-day interval was used for Δt. Cross correlations and rms differences were performed between the model zonal velocity and the geostrophic estimate derived from the model sea level on a year-by-year basis, similar to that performed in section 3.2, and again for the entire 5-year record. At all three mooring sites and for all years the cross correlations were equal to 0.99, and the rms difference was always less than 4 cm s^{-1}. In view of the linear dynamics in the model and because the low-frequency equatorial variability has been shown to be essentially geostrophic [*Picaut et al.*, 1989], these statistics are not surprising and mean simply that the neglected effects such as v_{ty}, $\nabla^2 v_y$, and $(\tau^y)_y$ are of lesser order. Sampling the model sea level along a 72° inclined simulated altimeter track produced the same results.

With the directly coincident geostrophic estimates as a reference, the effect of the meridional, zonal, and temporal scales of the Geosat sampling and processing were addressed with the model sea level and equatorial model u field. The influence of meridional scales on the calculation of the geostrophic velocity estimate was investigated by taking increasingly larger Δy increments when computing η_{yy}. For Δy less than or equal to 200 km the cross correlation between the geostrophic estimates and the equatorial model velocity was always greater than 0.98, and the rms difference was less than 16 cm s^{-1}. The correlation decreased and the rms difference increased monotonically as Δy was increased beyond 200 km. These results are reflective of a 400-km decorrelation scale for the zonal velocity in the model and support the use of a 136-km Δy in the Geosat processing.

The effect of computing η_{yy} along a meridian other than at the mooring site was considered by sampling the model sea level at a distance 5° east or west of the mooring longitudes. In this instance the annual cross correlations between the geostrophic velocity estimated 5° away, and the model zonal velocity at the mooring longitude ranged between 0.80 and 0.97 with rms differences between 9 and 32 cm s^{-1}. The phase differences were such that geostrophic estimates west of the mooring site led the model u field time series by a few days, whereas the geostrophic estimates to the east lagged by a similar amount. No significant systematic differences were found to occur as a function either of mooring location or of year. In view of the phase differences on either side of the mooring locations it is reasonable to assume that some form of zonal averaging would produce higher correlations. Thus the model sea level was sampled at regular 1° intervals within a band ±5° about the mooring locations. All 11 geostrophic estimates were then averaged and found to be very similar to the geostrophic estimates along the same meridians as the moorings (0.99 correlation, 4–5 cm s^{-1} rms difference).

Finally, the model sea level field was sampled along the tracks of the 17-day repeat orbit of the Geosat ERM. All geostrophic estimates computed along track within ±5° of 165°E, 140°W, and 110°W were used to construct geostrophic velocity time series that were compared against the u field from the model at the mooring sites. A total of 13 ascending and descending samples were used within each 10° band and 17-day repeat. The annual cross correlations were between 0.91 and 0.98 with rms differences between 11 and 14 cm s^{-1}. Once again the comparisons were not sensitive to mooring location or year. Hence these comparisons suggest that the complicated space-time coverage afforded by a satellite altimeter such as Geosat does not seriously degrade the low-frequency estimation of the geostrophic flow field at the equator.

Spectra of the simulated altimeter-derived geostrophic time series and the model u field time series indicate that the space-time structure of the Geosat sampling introduces energy into estimates of the geostrophic current at spectral bands between 3 and 34 days. Seven percent of the total power in the geostrophic estimates is in the 3- to 34-day band, whereas all the power in the monthly mean wind forced model u field is at periods greater than or equal to 2 months. Approximately 60% of the power introduced into the 3- to 34-day band is split between the 17-day repeat period and the 3-day Nyquist period. To address the lack of high-frequency variability in the model (i.e., periods less than 2 months), spatially uncorrelated noise at smaller periods between 1 and 45 days and with amplitudes of 1–4 cm was added to the model sea level prior to the simulated Geosat sampling. Significant degradation of the geostrophic estimates occurred when the Geosat sampling was repeated. However, 80–98% of the original variance (periods greater than 60 days) was easily recovered via straightforward low-pass filtering in time.

4. DISCUSSION AND CONCLUSIONS

We have shown that on the basis of comparisons with in situ current data at three sites in the Pacific Ocean it is possible to make physically meaningful estimates of surface geostrophic zonal velocity variations at the equator using Geosat altimeter data. The high correlation (>0.8) and relatively small rms difference (about 20 cm s^{-1}) between the analyzed and observed currents at 140°W and 165°E is surprising when one considers that a 1-cm error in sea level, if uncorrelated over the 136-km grid on which our geostrophic flows were computed, would lead to errors of 92 cm s^{-1}.

The success of our Geosat computations depends on several factors which in combination reduce instrumental and geophysical noise. First, the meridional scales of the currents are large relative to the 6.8-km alongtrack resolution of the altimetric measurements, so that small-scale noise can be effectively filtered out of individual Geosat passes. The filter length of 400 km that proved optimal is consistent with a priori estimates of the meridional decorrelation scale for dynamic height and the equatorial radius of deformation. Second, the 3-cm error quoted by *Cheney and Miller* [1988] for 15-day-averaged data must be highly correlated over our computational grid so that large-scale noise in the Geosat altimetry data is filtered out by taking second derivatives of sea level. Otherwise, a 3-cm sea level error would lead to a 276 cm s^{-1} velocity error at the equator. Third, the zonal scales of the currents (about 10° for day-to-day variations) are large relative to the 82 km zonal resolution of the Geosat sample grid at the equator. This allowed compositing eleven 17-day repeat tracks around 140°W and 165°E to achieve an effective temporal resolution of 1.5 days. High-frequency variability that would otherwise have been aliased was therefore efficiently filtered out by means of a 31-day Hanning filter to reduce contamination of the low-frequency signals. This was also borne out by sampling studies using sea level solutions from a numerical ocean model as a proxy altimeter data set. At 110°W, where only six ascending tracks were available, the effective temporal resolution was coarser and the correlation with observed currents correspondingly lower. Fourth, the Geosat orbit inclination of 72° from the equator implies a near-orthogonal transect across the major equatorial currents. These geostrophic currents are primarily zonal (and indeed, right at the equator, they are exclusively zonal) so that there is little aliasing of zonal sea level variability into estimates of meridional sea level curvature which are the basis of our geostrophic computations. Finally, collinear analysis allows for calculations of equatorial geostrophic flow at a grid resolution within the optimal 100–150 km as determined by *Moum et al.* [1987] and *Picaut et al.* [1989] from in situ data. Conversely, crossover differences with an effective meridional resolution of approximately 250 km near the equator would lead to biased estimates of zonal geostrophic flow because of the tendency for coarsely resolved grids to underestimate sea level curvature.

The data discussed in this paper were collected during the 1986–1987 El Niño–Southern Oscillation (ENSO) event. Current variations during this time were anomalous relative to those in non-ENSO periods [*McPhaden et al.*, 1990; *McPhaden and Hayes*, 1990], though in the eastern Pacific the range of amplitudes near the surface was similar to non-ENSO years. The sea level deviations associated with these currents were of the order of 6 cm rms. Hence we expect that the application of our analysis technique to other periods will yield equally favorable results. Since the computation of geostrophic zonal currents is more sensitive to noise contamination at the equator than at higher latitudes, our results show promise for monitoring low-frequency geostrophic currents in the tropics in general. Moreover, the robust relation between equatorial current variability and relatively small changes in sea level implies that the increased precision from future altimeters such as TOPEX/POSEIDON may well allow for the estimation of absolute geostrophic currents up to and including the equator. Finally, this validation of the geostrophic method applied to altimeter data at the equator would have been impossible without the availability of direct current measurements. If the use of satellite altimeter data is to meet the expected potential for monitoring the global ocean circulation, then it is imperative that the validation of altimeter data go beyond straightforward comparisons with sea level measurements and include in situ current measurements as well.

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