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Mean Sea Surface and Variability of the Gulf of Mexico Using Geosat Altimetry Data

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Geosat Exact Repeat Mission (ERM) altimetric measurements of the sea surface height in the Gulf of Mexico are used to determine the mean sea surface height with respect to the ellipsoid and mesoscale variability along Geosat ground tracks in the gulf for the time period from November 8, 1986, to November 25, 1988. The alongtrack mean sea surface is determined using a regional crossover adjustment procedure, in which the tilt and bias of mean arcs are estimated using a least squares technique to minimize the height differences at crossovers points. A mean surface generated using the Geosat ERM alongtrack mean is calculated and contrasted with a previously derived mean surface determined using GEOS 3 and Seasat crossover differences. This provides a first look at the variability in the mean between the time periods of 1987-1988 and 1975-1978. In addition, the alongtrack mesoscale variability time series has been produced from the Geosat ERM data set by using a robust orbit error removal algorithm to determine the variability of the sea surface height with respect to the alongtrack mean. A surface generated using the rms of this alongtrack time series shows good qualitative and quantitative agreement with previous in situ observations in the region. This study demonstrates the potential of satellite altimetry for oceanographic studies of the Gulf of Mexico.

1. INTRODUCTION

Previous studies have proven the viability of using colinear altimetric measurements to remotely observe the Loop Current intrusion and anticyclonic eddy shedding in the Gulf of Mexico [*Thompson et al.*, 1983; *Thompson*, 1986]. This is an important result since the thermal signature of the Loop Current and its associated eddies is undetectable in infrared satellite imagery from June through October because of a shallow surface layer of warm water covering the gulf. With the maneuvering of the Navy satellite Geosat into an exact repeat orbit, an unprecedented wealth of oceanographic data with a high degree of temporal and spatial resolution is now available for the study of gulf dynamics. The results presented here are an initial examination of the first 2 years of this data set.

The Loop Current exhibits little or no annual cycle, and eddy shedding from the Loop Current can occur at any time of the year, with shedding periods for large anticyclones ranging from 8 to 15 months [*Molinari*, 1980; *Vukovich*, 1988], although as many as three or four eddy sheddings may occur in 1 year [*Elliot*, 1979]. Results from a numerical model using a realistic constant inflow transport exhibited a mean period between major eddy sheddings of 327 days [*Hurlburt and Thompson*, 1980] as compared with 10.9 months for the average period determined by *Vukovich* [1988] from satellite IR image analysis. From these studies one would expect that during the time period under consideration here, at least two samples of major eddy shedding cycles would be observed. In fact, the variability time series produced for this study shows evidence of two shed eddies propagating westward for the entire length of the deep water basin of the gulf after shedding from the Loop Current. In addition, the last half of an eddy cycle in the western gulf appears at the beginning of the time series. Thus we have a sampling period for computation of a mean and the variability about that mean in the Gulf of Mexico which is sufficiently long to begin analysis. As additional data become available we will expand the time series and revise our preliminary estimates.

The only previously published altimetric mean sea surfaces with estimates in the Gulf of Mexico are a very short-term mean computed using an 18 day set of global Seasat data [*Marsh and Martin*, 1982] and a long-term mean computed using a combination of GEOS 3 and Seasat data [*Marsh et al.*, 1984]. The long-term gulf mean with respect to the ellipsoid, which we will hereinafter refer to as the Marsh mean, was based on a combination of the entire Seasat (3 months) and GEOS 3 (3.5 years) altimetric data sets. A technique of regional crossover adjustments simultaneously employing data from GEOS 3, Seasat and GEOS 3-Seasat crossovers was used to determine the Marsh mean. In addition, the crossover adjustment procedure gave an estimate of the rms variability in the region from the crossover difference statistics. The precision of the Marsh mean surface is approximately 15 cm, with horizontal resolution of 0.25°. To produce this mean surface from the alongtrack al-

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imetric data, a height estimation procedure was employed. This procedure used a biquadratic surface function having coefficients which were estimated by a weighted least squares procedure applied to the data within a 0.375° radius cap of the point estimated. We also used this method to produce surface maps from alongtrack data in the gulf with the influence region modified to be a 2° by 2° box centered on the estimate grid point.

Recent interest in satellite altimeters created the need for more accurate high-resolution mean dynamic topography in order to separate the geoid signal from mean surfaces calculated using altimetry. To this end a mean dynamic height for the Gulf of Mexico [*Maul and Herman*, 1985] was calculated using all available National Oceanographic Data Center (NODC) Nansen cast, conductivity-temperature-depth (CTD), and expendable bathy thermograph (XBT) data to produce the mean dynamic height of the basin at 25-km horizontal resolution, relative to 1000 dbar. The standard deviation about this mean relative to 450 dbar also was computed. The standard error of the mean surface is estimated at less than ± 2 dyn cm.

These two data sets represent benchmarks with which our mean and variability estimates in the Gulf of Mexico from the first 2 years of Geosat ERM will be compared. Additional comparisons will also be made to the Naval Ocean Research and Development Activity (NORDA) (now Naval Oceanographic and Atmospheric Research Laboratory (NOARL)) Gulf of Mexico general circulation model [*Hurlburt and Thompson*, 1980].

2. Characteristics of the Geosat Data Set

The first 44 repeat cycles of the Geosat ERM from November 8, 1986, to November 25, 1988, have been used in our analysis. A gridded and edited version [*Zlotnicki et al.*, 1989] of these first 2 years of Geosat altimetry was obtained from the NASA Ocean Data System at the Jet Propulsion Laboratory(JPL). The ground track coverage in the gulf assuming no data outages is shown in Figure 1, overlain on the bathymetry of the region.

Previous estimates of the global mean sea surface and variability from Geosat data have neglected to study the Gulf of Mexico because of data outages in the Geosat ERM data set [*Koblinsky*, 1988]. Typically, these data outages are due to solar radiation pressure torques interacting with the gravity gradient stabilization method used to control the attitude of the spacecraft [*Cheney et al.*, 1988]. In many instances, attitude perturbations are such that the altimeter fails to regain lock after the spacecraft's ground track comes off land. Since the gulf is a semienclosed basin, this results in very poor data coverage when the stabilization problem occurs. Unfortunately, these data outages tend to occur in several sequential exact repeat cycles (ERCs) over the gulf. This was evidenced early in the time series with ERC 1

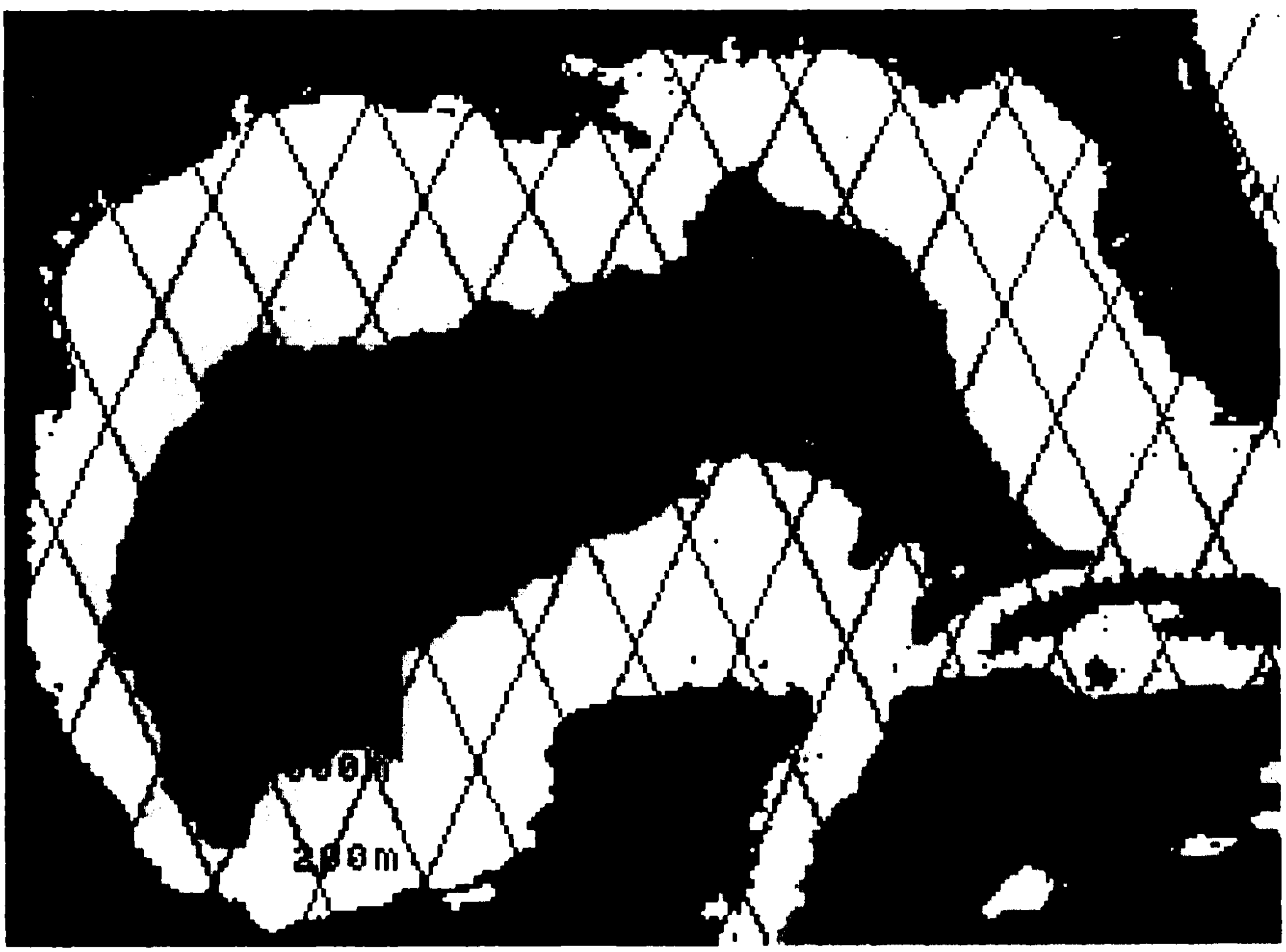

Fig. 1. Geosat groundtracks over bathymetry of the Gulf of Mexico.

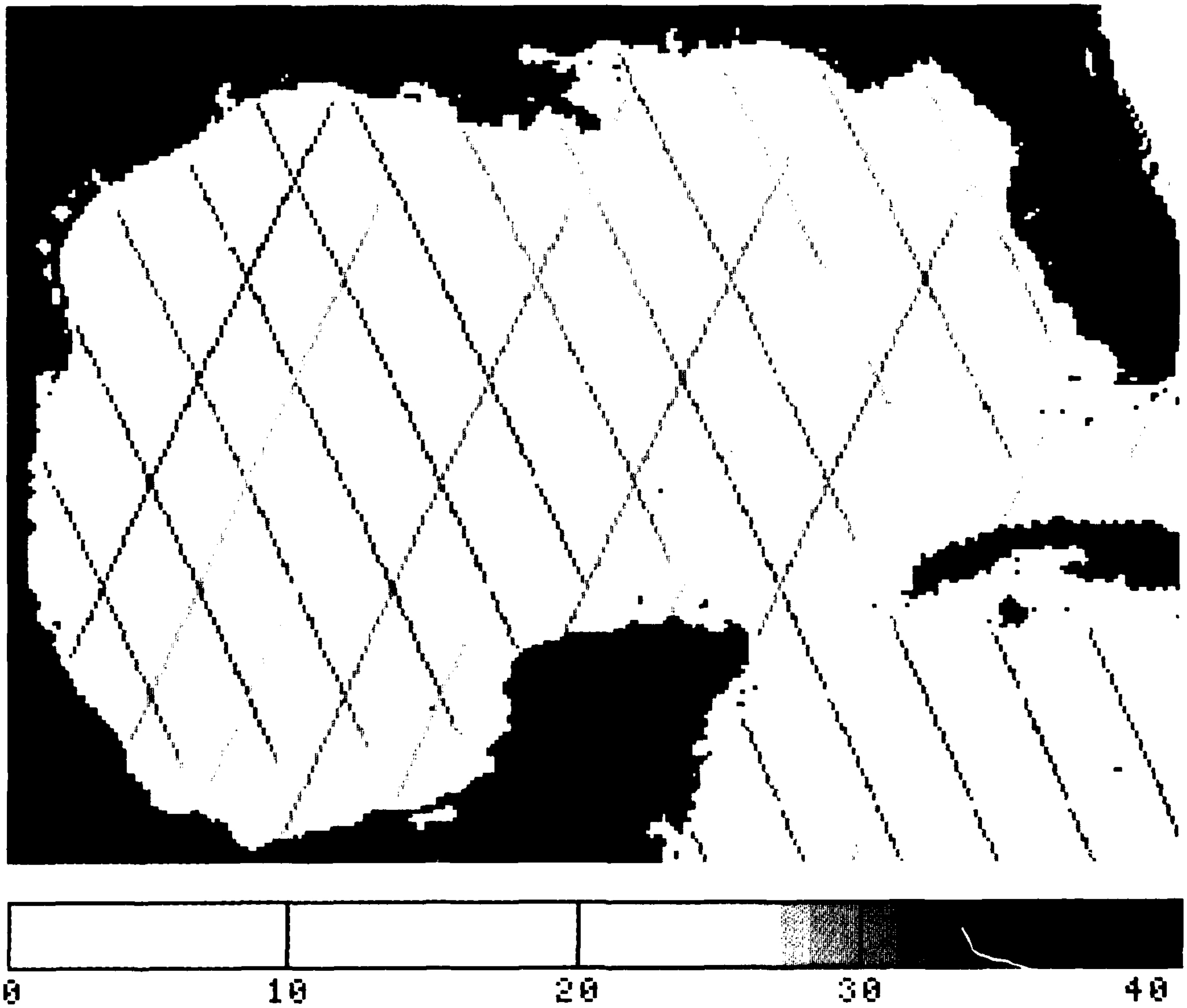

Fig. 2. Geosat data density over the Gulf of Mexico

through ERC 14 having moderate to excellent coverage followed by ERC 15 and ERC 16 with virtually no coverage. Moderate to severe data outages occurred in the gulf in summer 1987 (ERCs 15–18) and summer 1988 (ERCs 34–38). This phenomenon is correlated with the position of the sun relative to the Geosat orbit line of nodes and occurred again over the gulf in spring 1989. In addition, two outages were due to hardware difficulties aboard the spacecraft, including ERC 23 because of gyro problems and ERC 39 for battery reconditioning. To highlight possible data density influences on our estimates of the mean and variability surfaces, the alongtrack data density values are shown in Figure 2. Alongtrack points covered by fewer than 22 exact repeat cycles are shown as white. More densely sampled regions are shaded in gray, with black denoting perfect 44-cycle data coverage.

3. Calculation of the Altimetric Along Track Mean

We used a crossover adjustment technique to estimate the alongtrack tilt and bias corrections needed to remove the orbit error for each individual mean track across the basin. This method requires an accurate estimate of the alongtrack mean of each arc over the region.

The most difficult obstacle preventing an accurate realization of the mean is the alongtrack variability in the sampling of the height because of data editing and outages [*Chelton et al.*, 1989]. The mean height, $\overline{h}(x)$, in the alongtrack direction, x, is computed from $N(x)$ repeat altimetric samples. When the number of alongtrack samples, $N(x)$, varies due to data outages, the orbit error bias, which may be as large as 10 meters [*Haines et al.*, this issue] will cause discontinuous changes in the mean height wherever N changes value.

In some regions this problem can be avoided by rejecting all incomplete arcs, as is typically done for open ocean calculations of the mean. However, in regions near land, frequent total and partial data outages occur, and no editing method can be constructed which retains a viable number of samples over the region. This is illustrated by the large variations seen in the alongtrack data density over the gulf in Figure 2.

A method which solves this problem has been proposed [*Chelton et al.*, 1989]. This method uses the alongtrack derivatives to obtain an improved estimate of the mean which is not contaminated by the orbit error biases. It requires no further editing of the dataother than the removal of outliers and the proper gridding of the data. The improved alongtrack mean as implemented for this study is computed as follows:

1. To remove the orbit error bias from each repeat track, calculate the mean of the alongtrack first derivative (slope) using finite differences:

$$\frac{\overline{dh}(x)}{dx}$$

2. Integrate the slope to get the alongtrack mean sea height:

$$\overline{h}(x) = \int \frac{\overline{dh}(x)}{dx} dx \quad + \overline{h_0}$$

3. Fix the integration constant, $\overline{h}_0$, to the value of the mean sea surface height computed from the raw samples at x where $N(x)$ is largest. This can and should be done on each subinterval of any broken mean arc. Several broken arcs occur in the mean arcs used for computation of the mean surface in the Gulf of Mexico. These are caused by altimeter overflights of land masses such as Florida, Cuba, and the Yucatan.

To highlight the advantages of this mean relative to the conventional mean, an alongtrack rms difference of the two was calculated. The value found was 32 cm rms, which is entirely due to orbit bias aliased into the conventional mean. This large value underscores the need for this more accurate and robust method for computing the alongtrack mean (henceforth referred to as the improved alongtrack mean) to produce the Geosat altimetric mean surface and variability. It should be noted that the variability computed with respect to the conventional mean in the region would include large regions of variability due solely to the unwarranted 32-cm rms differences between the improved and conventional means.

4. ALTIMETRIC MEAN SEA SURFACES

Given alongtrack mean heights from the Geosat altimetric record, a mean surface can be constructed using a biquadratic surface estimation procedure employed for previous altimetric missions [*Marsh and Martin*, 1984]. However, because of residual orbit error in the alongtrack mean due to force model errors and propagated initial condition errors in the orbit, the mean surface would be quite inaccurate. A surface constructed in such a way from the alongtrack mean heights computed as was described in the preceding section would be adversely affected by the 3.5-m rms crossover differences of the mean arcs. To remove this residual orbit error, a regional crossover adjustment of the mean arcs is performed.

The crossover adjustment procedure uses mean crossover differences computed at 60 crossover points in the region. Fifty-four of the points were located over the Gulf of Mexico and six in the northwestern Caribbean. The least squares solution which minimizes the crossover differences is not well determined; a free mode exists in the problem. For the estimation of two parameters (tilt and bias) along each track, three parameters in the global minimization problem must be fixed before or during the solution procedure. The free mode is an arbitrarily oriented plane in space; thus for example, fixing the tilt and bias on an ascending arc and the tilt on a descending arc on any pair of crossing arcs of sufficient length will determine a suitable plane. Good results were obtained by setting the tilt and bias of an ascending arc (JPL-2799A) and the tilt of a descending arc (JPL-2585D) to zero. These arcs were selected because they are the longest arcs centered on the gulf. The estimation of the remaining tilt and bias parameters was achieved using the National Geodetic Survey Regional Crossover Adjustment Program version 2.0 [*Miller et al.*, 1986] employing a sparse, least squares solution method [*Milbert*, 1984]. To fix this surface to a suitable reference plane, the three parameters defining the free mode were determined by a multiple regression estimation of the best fit plane to the alongtrack differences between Geosat and Marsh mean arcs. Removing this plane from the Geosat arcs uniquely determines the free mode of the crossover adjustment procedure and allows direct comparison of our surface with the Marsh mean surface (see Plate 1). (Plate 1 is shown here in black and white. The color version can be found in the separate color section in this issue). Plate 1*a* shows the Geosat surface with the free mode plane removed, opposite the gridded Marsh mean surface (Plate 1*b*).

The Marsh mean surface was calculated using a regional crossover adjustment of individual arcs with a total of 15,865 crossover points. The estimate had an a postori 22-cm rms crossover difference residual. Our mean was computed from 60 crossover points using only mean arcs in the crossover adjustment procedure. It can be argued that the crossover differences computed from the mean have information from nearly 2000 crossovers of individual arcs at each crossover point assuming no data outages. The tilt and bias removal operation of the orbit error from the mean arcs succeeded in reducing the the initial 3.5-m Geosat rms crossover differences to 11 cm rms. The difference between the Marsh 22-cm rms and the Geosat 11-cm rms crossover differences is largely due to the alongtrack averaging of the Geosat arcs.

To highlight the variability in the mean between the two sampling time periods of altimetric measurements, the Geosat surface was differenced with the Marsh mean. Plate 2*a* shows the Geosat surface minus the gridded Marsh mean surface, and Plate 2*b* shows the surface estimated from the alongtrack difference of Geosat data with the Marsh mean surface height along Geosat ground tracks. (Plate 2 is shown here in black and white. The color version can be found in the separate color section in this issue.) The most pronounced difference between the two images shown in Plate 2 is the fine-scale detail seen in the difference relative to the high-resolution gridded Marsh mean. The difference between Plates 2*a* and 2*b* shows the effect of biquadratic surface estimation using only along track data to sample a highly varying spatial field. Many of the fine-scale features seen in Plate 2a are attributable to variation in the geoid due to abrupt bottom topography not sampled by the Geosat altimeter. Two notable regions appear as anomalous highs in the difference field: the Campeche Escarpment and the Florida Continental Shelf edge.

The difference maps shown in Plate 2 exhibit 50-cm relative differences of the means in regions of eddy activity in the gulf. These regions include the eastern gulf in the area of Loop Current instabilities, the western gulf along the mean eddy track and the western gulf continental shelf. The signs of the differences suggest that during the time

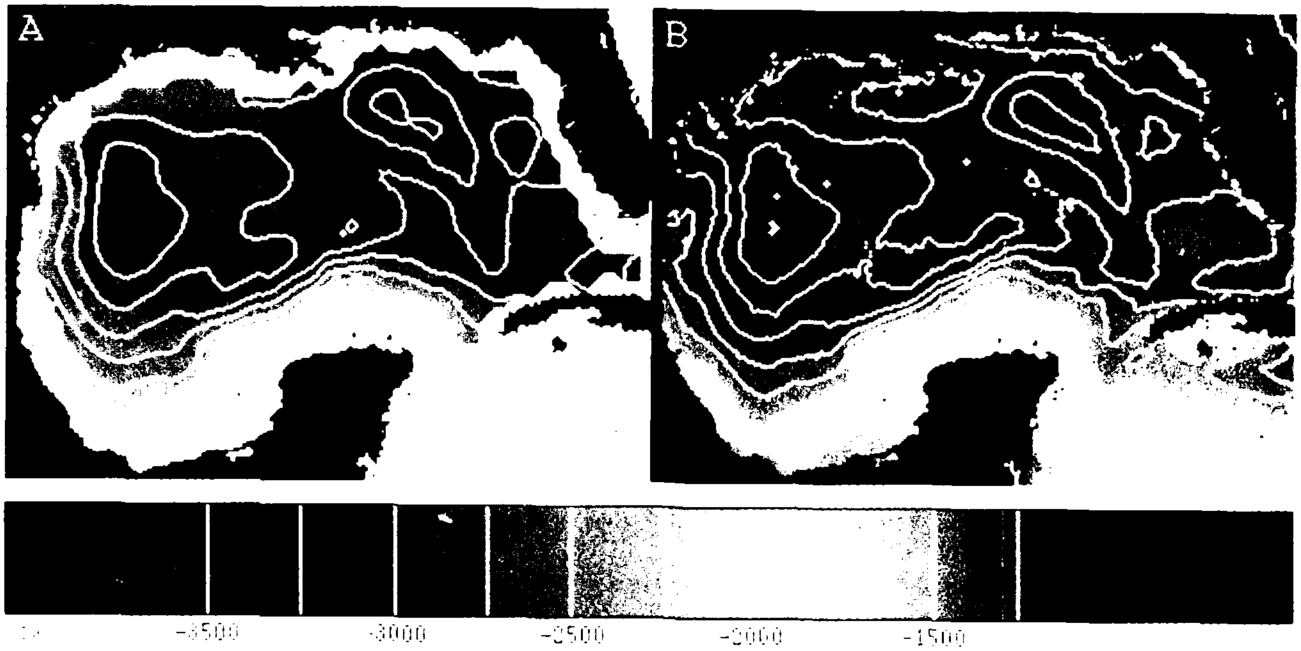

Plate 1. (a) Geosat mean surface versus (b) Marsh mean surface (The color version of this figure can be found in the separate color section in this issue.)

period of the Geosat data record, the Gulf of Mexico exhibited stronger, more intense eddy activity. It is known that a very strong eddy shedding event occurred in the Gulf in April 1988 [*Waddell et al.*, 1989]. However, it is premature to assume more intense activity in the Gulf during 1987 and 1988 until interannual variability of the mean surface can be studied using only the Geosat data record with comparison to independent in situ data in the region. This would help assess the effect of accuracy and temporal-spatial differences between the altimetric data sets used to construct the means.

An interesting low anomaly in the Geosat mean relative to the Marsh mean surfaces occurs in the Bay of Campeche over the continental shelf in a region of good data density. This feature appears to be valid (i.e. it is not an artifact of the processing), but we can offer no physical reasoning for its existence. Further comparison with the cycle-to-cycle variability in the region to determine if this is a temporally

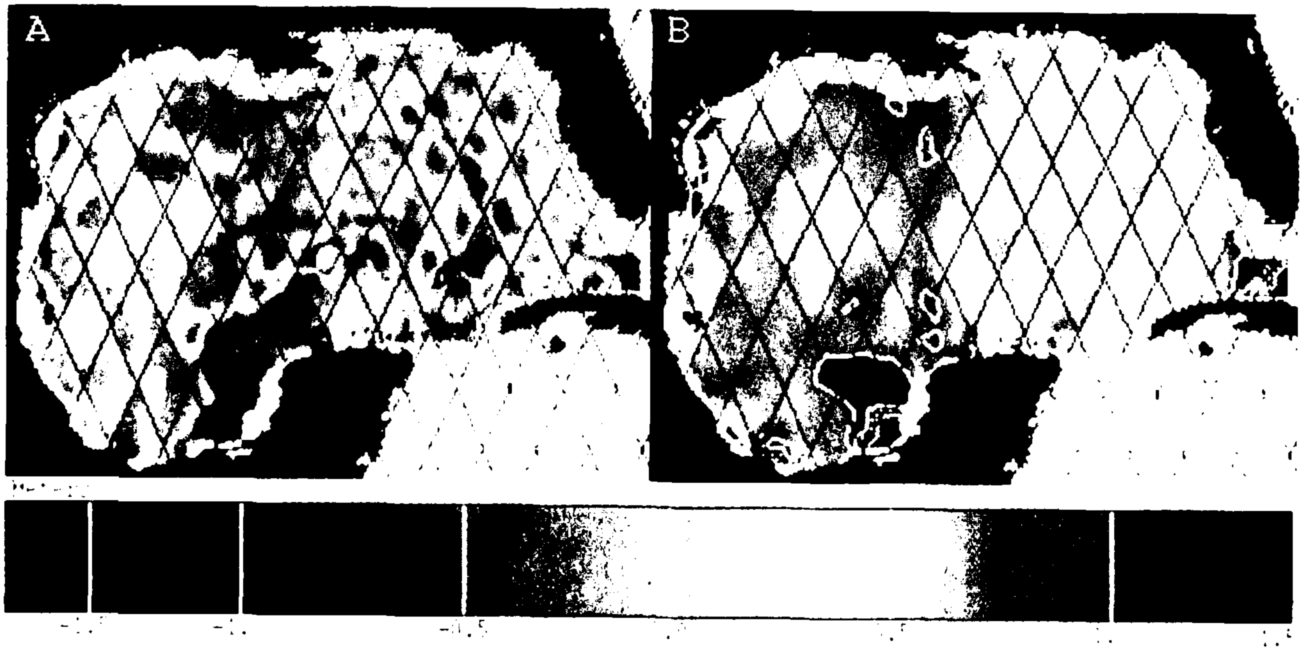

Plate 2. Mean surface difference maps: (a) Geosat minus Marsh gridded mean surface and (b) estimated surface from alongtrack difference of Geosat Marsh mean. (The color version of this figure can be found in the separate color section in this issue.)

intermittent feature may be fruitful. However, a look ahead to the variability map over this region shows no pronounced variability coinciding with this feature (Plate 4).

Further investigation of these mean surface anomalies is warranted. However, in producing an accurate mean over the Gulf of Mexico, we have validated a unique solution methodology for the estimation of mean surfaces using Geosat data, which is both efficient and straightforward in application. Furthermore, the alongtrack mean determined for each arc can be used to produce definitive sea surface height rms variability maps.

5. Calculation of the Variability With Respect to the Mean

Typically, when a regional crossover adjustment procedure is employed, the residual crossover difference statistics are used to determine an rms variability map. This is reasonable in large regions where the crossover point density is sufficient to resolve variability on the scales of interest. Unfortunately, the Gulf of Mexico exhibits small scale variability features [*Maul and Herman*, 1985] that cannot be resolved by the 54 Geosat ERM crossover points in the region.

To produce accurate variability maps of the gulf, we employ a robust orbit error removal algorithm to determine the variability of the sea surface height from individual tracks with respect to the improved alongtrack mean described previously. This algorithm relies on an iterative weighted least squares estimation of the orbit error (tilt and bias) in each pass relative to the mean. The method is applied as follows:

1. Calculate the alongtrack difference of the pass to be corrected with respect to the improved alongtrack mean at each grid point. This is the first estimate of the variability with respect to the mean. (The mean may be the mean with residual orbit error (section 3) or the detrended alongtrack mean (section 4) with no change in the variability estimate.)

2. Perform a linear regression to determine a tilt and bias associated with the variability estimate for each track. (This is identical to a weighted least squares estimate of tilt and bias with diagonal weighting matrix equal to the identity matrix, W=I.)

3. Detrend the estimated variability with the computed tilt and bias.

4. Calculate the variance of each alongtrack grid point and set the diagonal element of the weighting matrix corresponding to that point equal to the inverse of the variance.

5. Perform weighted least squares estimate of the tilt and bias using the current estimate of the variability with respect to the mean arc and the weighting matrix determined in step 4.

6. Repeat steps 3–5 until the process converges.

7. Repeat steps 1–6 for all altimetric passes in the region.

This method is robust in that it allows broken arcs and arcs of unequal length to be detrended relative to the mean. No significant editing of the JPL data set need be performed to estimate the variability. In addition, in regions of high variability relative to the mean, the iterative weighting procedure enforces smaller weights on the observations. This mitigates unwanted detrending of mesoscale features such as eddies and reduces end effects. Furthermore, outliers which are missed in editing will have minimal effect on the orbit error removal. We should emphasize that this method is not limited to linear estimation but may be used with quadratic or sinusoidal estimation of the orbit error.

A definitive study of the method is in preparation. However, validation of the method by direct application to the Gulf of Mexico has been achieved and will be described in the following section.

6. Mesoscale Variability Maps

The alongtrack rms variability in the Gulf of Mexico has been calculated using the corrected and detrended data produced using the algorithm described in the preceding section. No additional editing of the gridded JPL altimetry data set was performed. All unflagged data were used in the calculation of the alongtrack mean and in the estimation of the variability with respect to that mean. A surface representing the alongtrack variability was estimated using the biquadratic surface estimation procedure.

In Plate 3, we compare our altimetric estimate of the

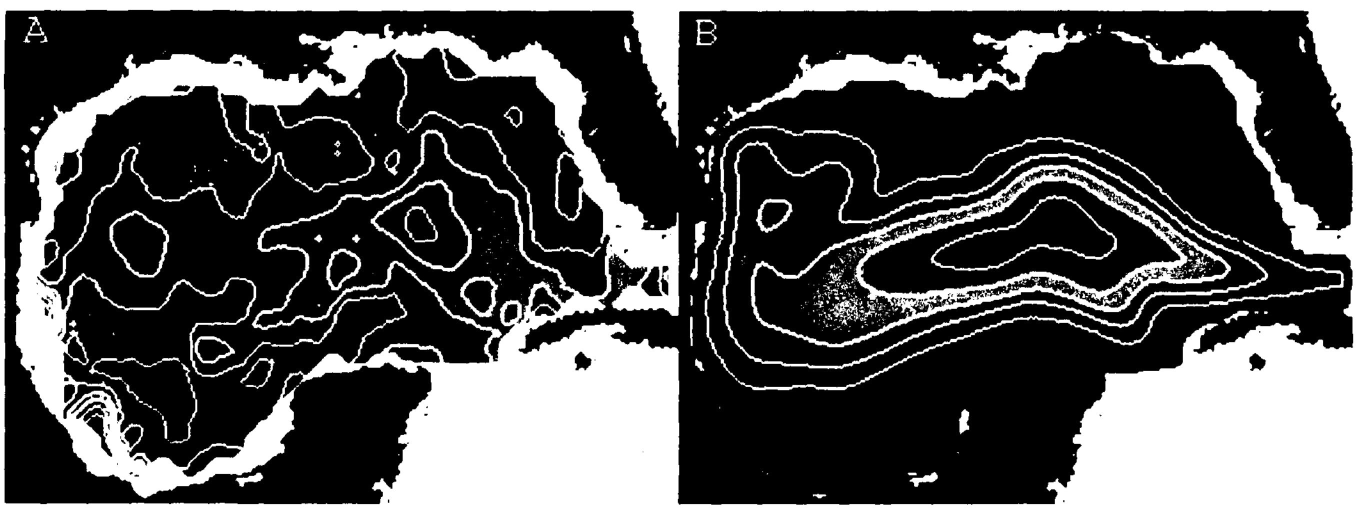

Plate 3. (a) Geosat height variability versus (b) Hurlburt–Thompson (NORDA) Gulf of Mexico model height variability. (The color version of this figure can be found in the separate color section in this issue.)

variability (Plate 3a) to the variability computed from three eddy shedding cycles of the NORDA Gulf of Mexico primitive equation model [*Hurlburt and Thompson*, 1980] in Plate 3b. (Plate 3 is shown here in black and white. The color version can be found in the separate color section in this issue.) The Hurlburt-Thompson (HT) model was driven by constant inflow transport with no direct wind forcing. The 23-cm peak rms value for the model variability is approximately 75% of the 30-cm rms variability in the Geosat ERM height data. Part of the difference is a result of neglecting transport variability through the Yucatan Strait, which is known to vary by almost 10 Sv about a mean of 30 Sv in the Florida Current [*Schott et al.*, 1988]. Likewise, any wind forcing would act to further increase the model estimation of the variability. Finally, in the HT model the upper layer current represents an average over a mean depth of 200 m. Surface geostrophic currents are 20–40% higher than the 200-m average (Evans and E. Waddell, Science Applications International Corporation, personal communication, 1989) in the Loop Current core. At present we are investigating the use of basin and global scale models to give estimates of the transport variability through the Yucatan Straits during this time period. Therefore to allow direct comparison of the two fields, we have scaled the model field by 1.4 before plotting. Several important characteristics to be noted in the comparison of the fields are (1) the high variability along mean eddy tracks to the west-southwest clearly seen in both the model solution and the Geosat ERM altimetry data set (note also the close correspondence to the Marsh variability [*Marsh et al.*, 1984]), (2) the high variability in the western gulf at 25°N where eddies are known to dissipate, and (3) a southwestern track of variability along the Campeche Escarpment in the altimetry variability which is not seen in the model solution. The first two characteristics are significant validations of the model. While variability along the Campeche Escarpment may reflect trapped waves and upwelling, we cannot say for certain it is not an artifact of the gridding of the altimetric data set. When the altimetric data set is gridded, height values are interpolated along track to lie on fixed latitudes determined from a reference circular orbit. When this is done over an abrupt topographic feature such as the Campeche Escarpment, variations in the geoid are aliased into the variability estimate and appear as regions of unrealistic high values if the data are not properly corrected for cross-track geoid gradient. In an attempt to correct this problem, the latitude bounds, including the depth from 200 m to 2000 m, of each track crossing the escarpment slope were determined using a detailed bathymetry map of the region. The altimetry data within these bounds were then eliminated from the variability solution. In all, four ascending tracks and three descending tracks were affected. A surface was estimated from the remaining alongtrack data and is shown in Plate 4*a* opposite the climatological rms variability of the Gulf relative to 450 dbar [*Maul and Herman*, 1985] in Plate 4*b*. (Plate 4 is shown here in black and white. The color version can be found in the separate color section in this issue.) In this case we have scaled the oceanographic climatology by 1.4 to reflect the limited reference depth and absence of any barotropic contribution in the hydrographic data.

An initially disconcerting result of the editing procedure was that all of the variability over the escarpment was not removed. The majority of the variability was eliminated as expected, but an isolated variability feature remained. The remarkable aspect of the remaining variability is that it correlates well with a similar feature appearing in the climatological data. Because of its location over the escarpment, occurrence in the temperature field, and absence from the model solution, the feature may represent baroclinic wind-driven processes over the abrupt topography. It is not know

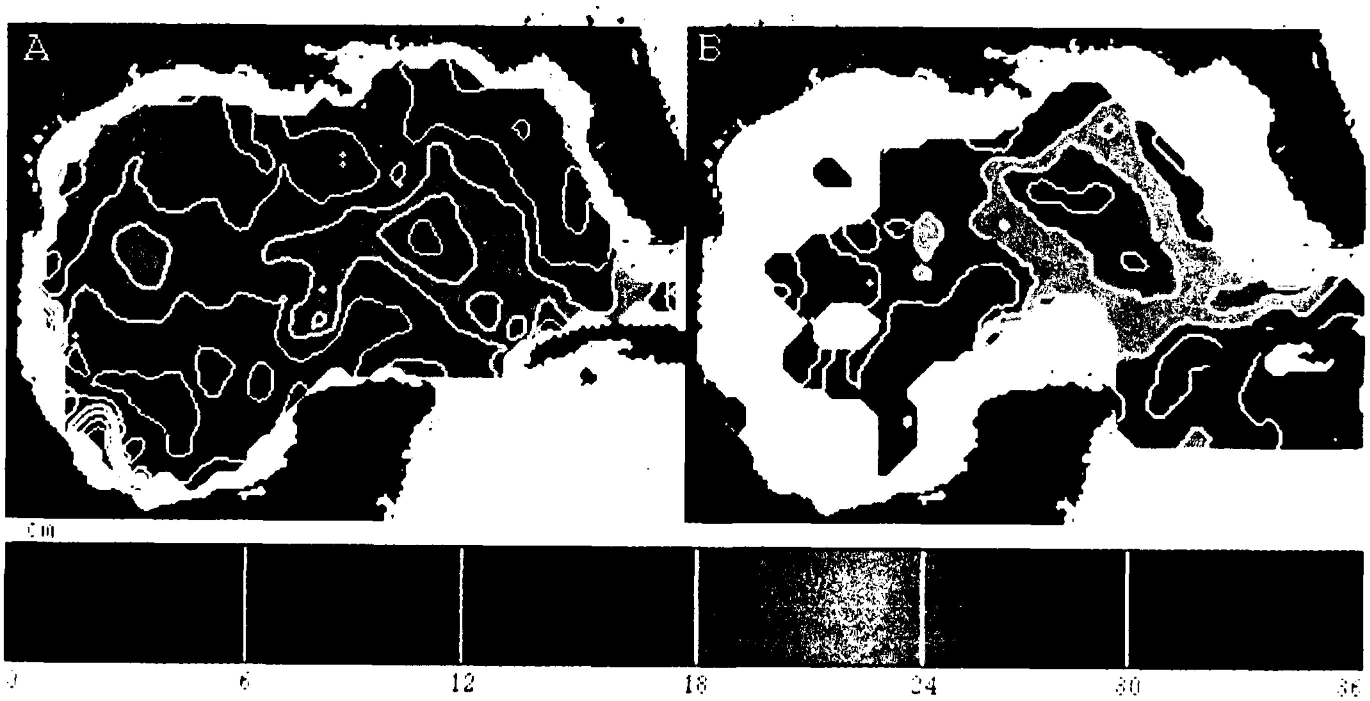

Plate 4. (a) Geosat height variability (edited) versus (b) in situ climatological rms variability [*Maul and Herman*, 1984]. (The color version of this figure can be found in the separate color section in this issue.)

whether the feature has a surface temperature signature and would consistently appear in satellite thermal imagery, although wind-driven coastal upwelling along the Campeche Bank has been observed [*Cochrane*, 1969] and studied using analytic and numerical models [*Kindle and O'Brien*, 1974].

Further comparison of the climatological and Geosat data shows additional interesting qualitative similarities: (1) variability in the region of the Mississippi River outflow, (2) double relative maxima in the Loop Current, though the location is not well correlated, (3) areas in the southwestern gulf showing pockets of high standard deviation [see *Maul and Herman*, 1985, p. 41] and (4) a variability maximum near the Florida Keys. Two dissimilarities should be noted: (1) a region of high variability in the altimetry data northwest of Cuba which may be due to poor data coverage (see data density plot, Figure 2) and (2) the larger geographic extent of the variability in the hydrographic data as compared with that for the altimetry. As previously noted, there are significant quantitative differences between the maps when the climatological estimate of the variability is viewed relative to 450 m, as published by Maul and Herman. The peak rms value in the climatological data is 22 cm relative to 450 dbar as opposed to 32 cm for the altimetric data. This difference is to be expected since 75% of the rms variability in the entire climatological data set (maximum depth sampled, 1000 m) is included in the upper 450 m of the gulf. This is quite reasonable in that it implies that just over 70% of the total variability is included in the upper 450 m. Furthermore, a significant additional baroclinic contribution to the variability would come from depths greater than 450 meters, as well as a barotropic contribution to which the hydrography is insensitive [*Thompson*, 1986].

7. CONCLUSIONS

Our initial investigation has produced definitive maps of the mean sea surface and mesoscale variability in the Gulf of Mexico based on 2 years of Geosat altimeter data. The methodology developed here could be fruitfully applied in other areas of the world's oceans. As with any initial study, as many questions have been raised as have been answered. Nevertheless, the combination of altimeter data, in situ observations, and realistic ocean models promises increased understanding of the dynamics of the Gulf of Mexico in particular and the global ocean in general.

Our next objective is the assimilation of Geosat data into dynamical models of the Gulf of Mexico in order to test procedures for directly ingesting altimetric data. This initial investigation has allowed the validation and testing of techniques for the computation of alongtrack means and variability with respect to the mean. The time series of variability with respect to the mean represents the most amenable data set for assimilation into numerical models.

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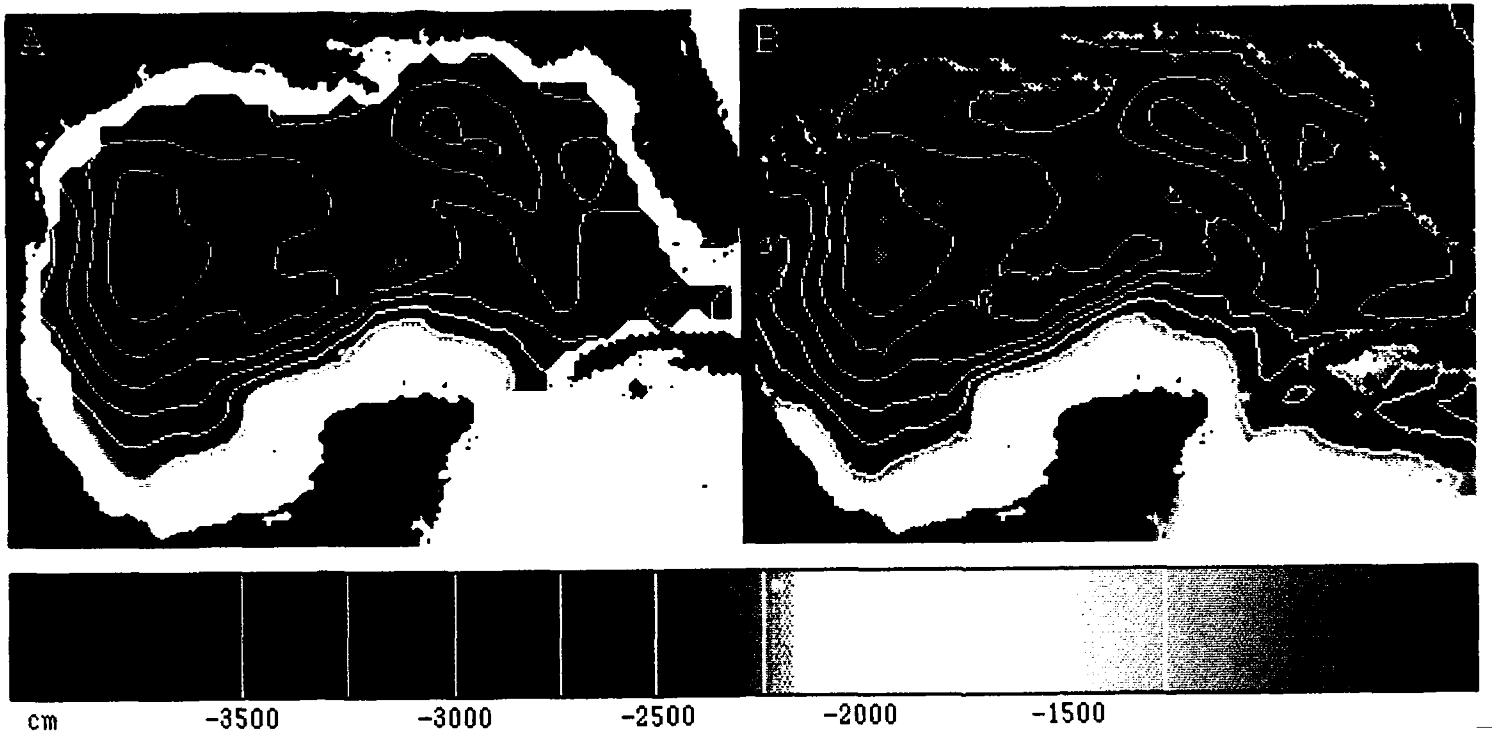

Plate 1 [*Leben et al.*]. (a) Geosat mean surface versus (b) Marsh mean surface.

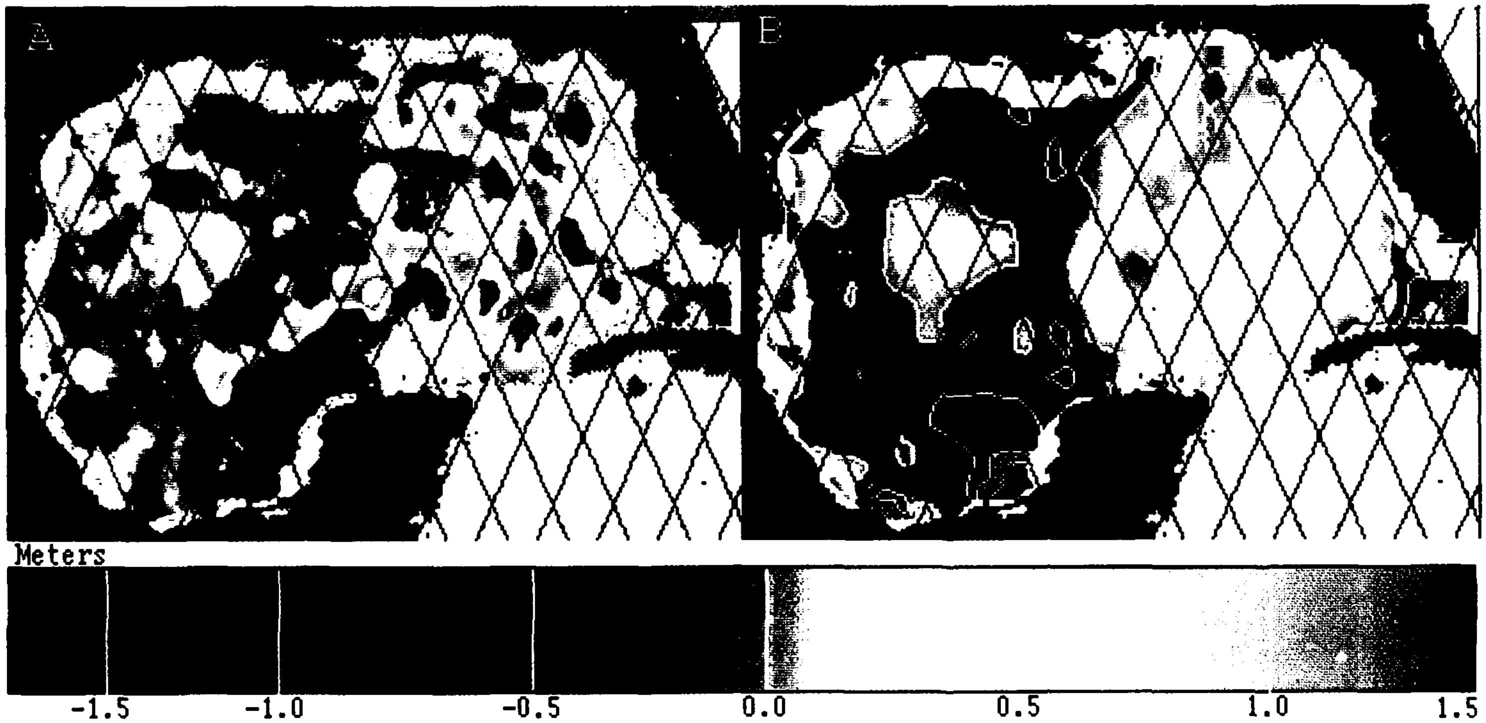

Plate 2 [*Leben et al.*]. Mean surface difference maps: (a) Geosat minus Marsh gridded mean surface and (b) estimated surface from alongtrack difference of Geosat Marsh mean.

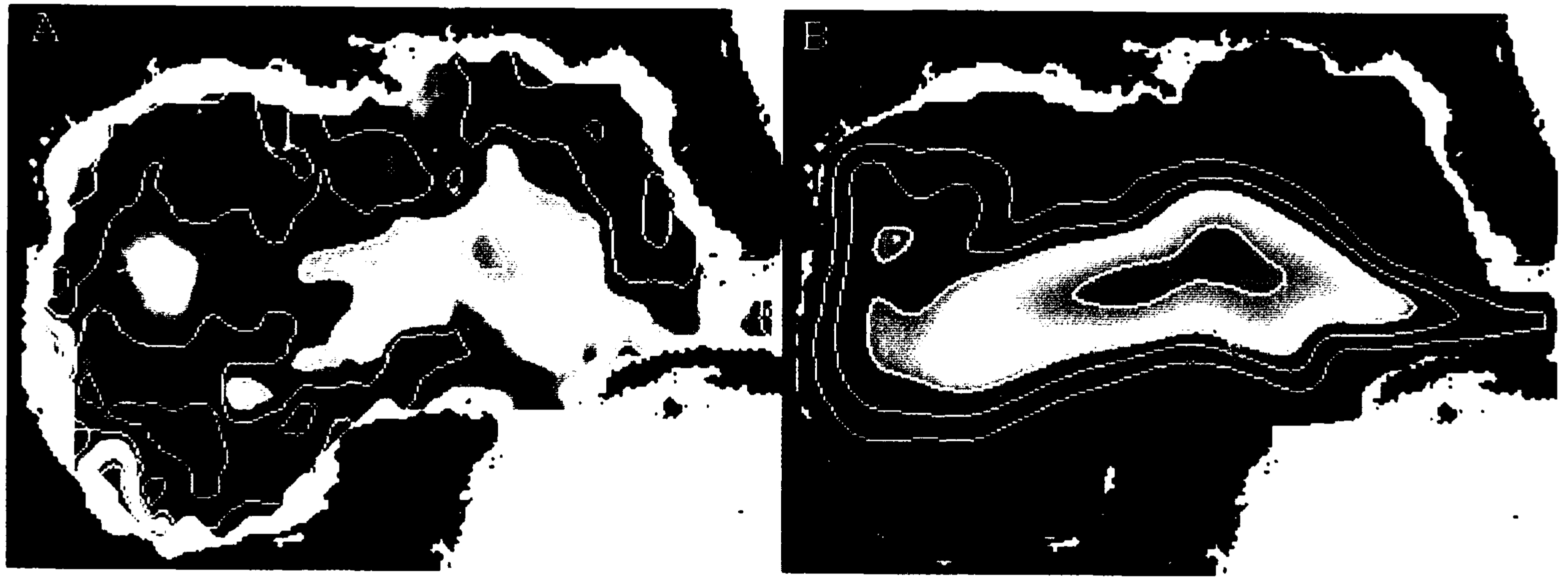

Plate 3 [*Leben et al.*]. (a) Geosat height variability versus (b) Hurlburt-Thompson (NORDA) Gulf of Mexico model height variability.

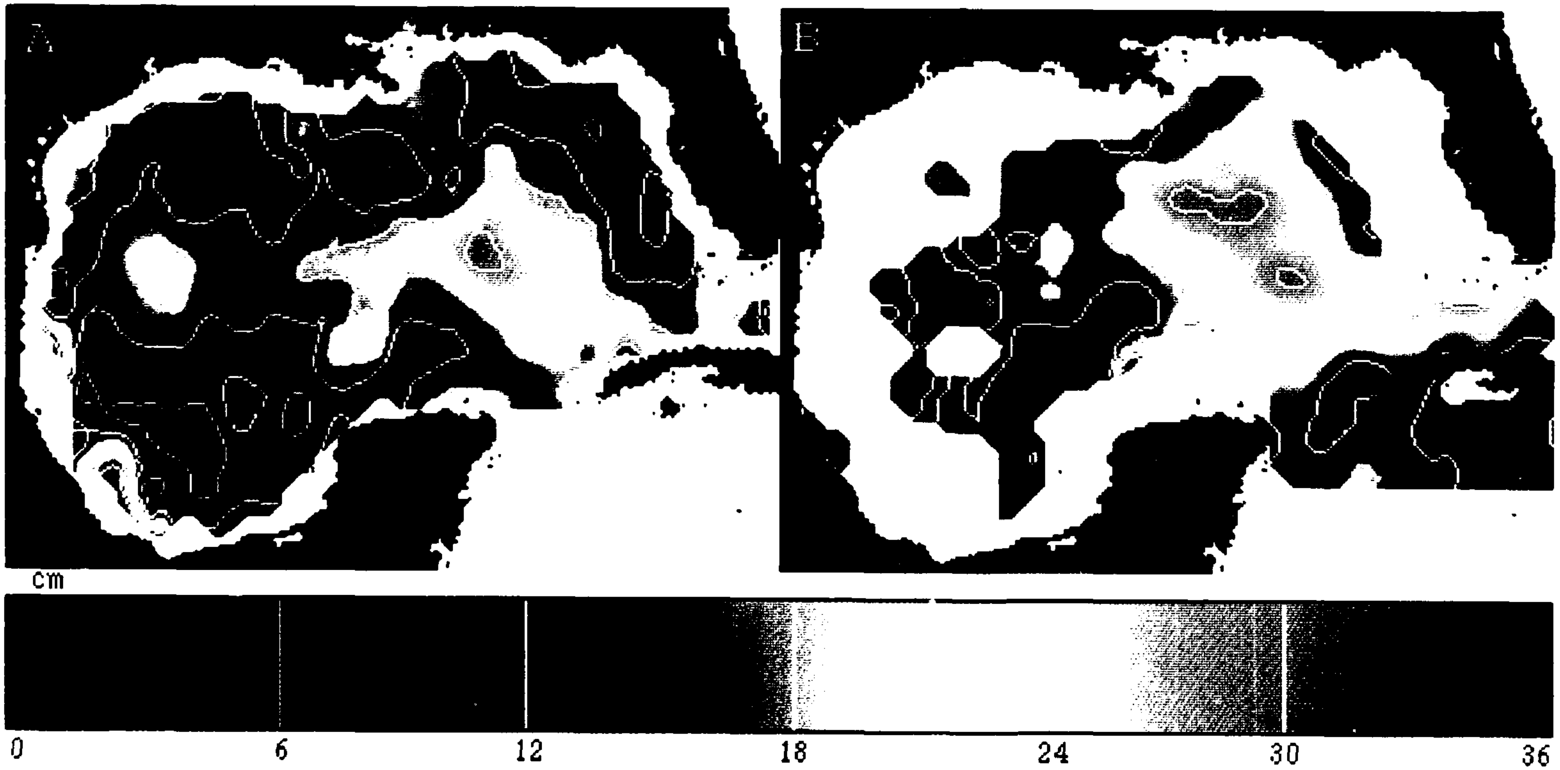

Plate 4 [*Leben et al.*]. (a) Geosat height variability (edited) versus (b) in situ climatological rms variability [*Maul and Herman*, 1984].