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Determining the mean Gulf Stream and its recirculations through combining hydrographic and altimetric data

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The altimetric data from the first 2.5-year Geosat Exact Repeat Mission were used to estimate the mean sea surface height (SSH) field in the region of the Gulf Stream and its recirculation gyres. Assuming the instantaneous surface velocity field is composed of an eastward flowing jet and two westward recirculating flows, we used the time-varying surface data from the altimeter to determine the shape of the along-track mean SSH profiles and the historical hydrographic data to constrain the net SSH difference across the Gulf Stream system. The two-dimensional mean SSH field was determined by objectively mapping the mean height profiles along the ascending and descending tracks. The SSH jump across the mean Gulf Stream has a maximum of 1.15 m around 65°W and drops to an almost constant 0.9 m downstream of the New England Seamount Chain (NESC). While the SSH jump associated with the mean northern recirculating flow is mostly uniform, we found that the Gulf Stream's southern recirculation has two local gyres that are separated by the NESC. An attempt was then made to estimate the mean deep circulation in this region by comparing the mean SSH field derived from the altimetry data and the surface dynamic height field based on the historical hydrographic data. Despite the large uncertainties, the mean deep flow pattern thus estimated agrees favorably with the overall circulation pattern from the long-term current meter observations. Like the well-defined northern recirculation gyre, we found that a continuous southward flow exists along 57.5°W, which follows closely along the deep layer potential vorticity contours. To the south of the Gulf Stream, the deep circulation consists of two separated recirculation gyres; the recirculation gyre to the east of the NESC appears to be trapped around the Corner Rise.

1. Introduction

Satellite radar altimetry is a powerful observational tool for monitoring mesoscale to large-scale sea surface height (SSH) fluctuations (see, for example, special sections in the *Journal of Geophysical Research*, volume 95, issues C03 and C10, 1990). Its potential use in improving ocean predictability through data assimilation in numerical models is also a subject of increasing interest [e.g., *De Mey and Robinson*, 1987; *Malanotte-Rizzoli and Holland*, 1989; *White et al.*, 1990; *Mellor and Ezer*, 1991]. Due to the small ratio of the geographical changes in the mean SSH (1–2 m at most) to those of the Earth's gravitational field ($\sim$ 100 m typically), the mean SSH signal is usually lost when the unknown geoid is removed. For many oceanographic applications, however, the absolute (mean plus the time-varying) SSH information is desirable and this is particularly true for studies focusing on western boundary current regions, where the mean SSH is comparable to the time-varying SSH. For these regions, mean SSH derived from climatological hydrographic data (such as those by *Levitus* [1982] or *Robinson et al.* [1979]) cannot substitute for the mean SSH that is pertinent to a satellite altimetric mission, both because of the significant interannual changes of the boundary currents and because of the uncertainty in specifying the reference velocities.

In order to obtain the mean SSH field of the Gulf Stream pertinent to the Geosat Exact Repeat Mission (ERM), several methods have been proposed. In conjunction with concurrent Geosat overflights, *Mitchell et al.* [1990] carried out airborne expendable bathythermograph (AXBT) surveys and estimated the along-track geoid directly. *Glenn et al.* [1991] derived the mean SSH topography from a dynamic model updated with available in situ data. Using different modeling techniques (such as diagnostic calculation and data assimilation), *Ezer et al.* [1993] suggested several ways of reconstructing the mean SSH from model averages. A different approach of estimating the mean SSH field of the Gulf Stream was presented by *Kelly and Gille* [1990]. Using the fact that the large lateral excursions of the Gulf Stream cause the mean SSH to have a smoother profile than the instantaneous height profiles, they determined the mean SSH by successively fitting the time-varying SSH data to a simple kinematic model of the Gulf Stream. Applying this method to the Geosat subtrack from Bermuda to Cape Cod, *Kelly et al.* [1991] and *Joyce et al.* [1990] showed that the estimated absolute SSH profiles from the altimetry data agreed with those from the nearly simultaneous hydrographic and acoustic Doppler current profiler (ADCP) data within measurement errors.

The kinematic model of Kelly and Gille assumes the existence of the eastward flowing Gulf Stream; consequently, the estimated mean SSH remains constant away from the mean position of the Gulf Stream. Many previous stud-

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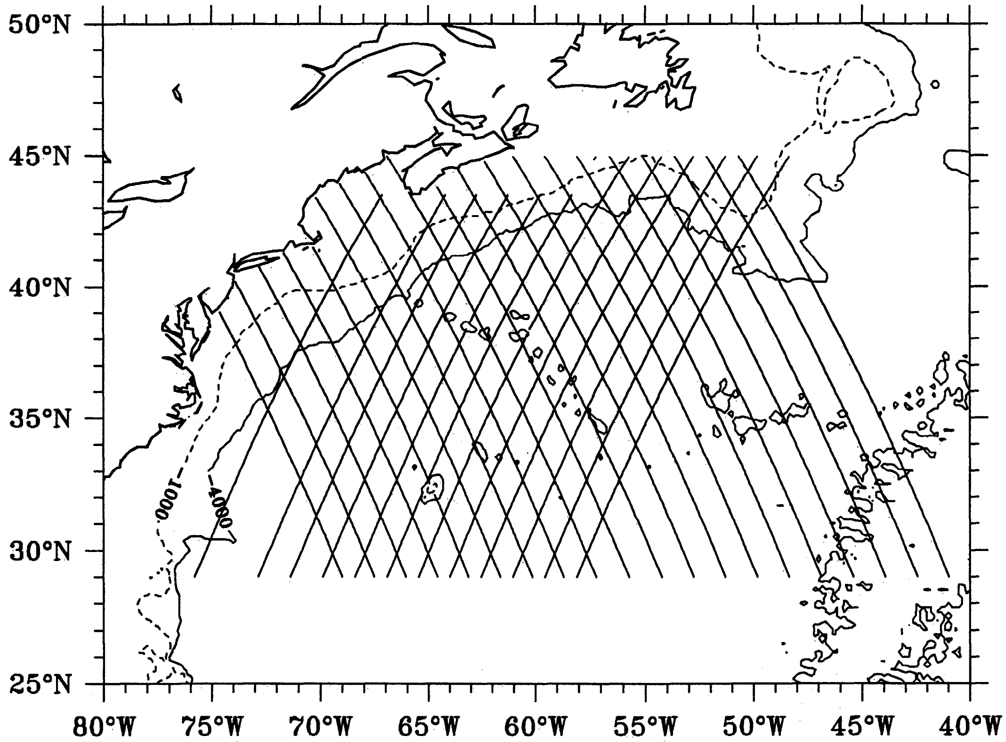

Figure 1. Distribution of the Geosat ascending and descending ground tracks used in this study to estimate the mean SSH field. Dashed lines denote the 1000-m isobaths, and solid lines the 4000-m isobaths.

ies have shown that the boundary currents are usually bordered by recirculation gyres after their separation from the coasts (e.g., for the Gulf Stream, *Worthington* [1976], *Hogg* [1983], *Richardson* [1985], *Hogg et al.* [1986], and for the Kuroshio/Kuroshio Extension, *Masuzawa* [1972], *Joyce and Schmitz* [1988], *Qiu and Joyce* [1992]). The existence of these recirculating flows undoubtedly affects the shape of the mean SSH. In order to improve the SSH estimation away from the eastward flowing boundary current, *Qiu* [1992] recently extended the kinematic model of Kelly and Gille by including westward flowing recirculating flows associated with the boundary currents. Applying this method to the two Geosat ascending tracks across the Kuroshio near 139°E, Qiu showed that the estimated intensity of the mean recirculation gyres is consistent with that derived from repeat hydrographic surveys and that the time changes of the recirculation gyres also agreed well with the available, quarterly in situ hydrographic surveys.

In this study, the method of *Qiu* [1992] is applied to the Gulf Stream and its northern and southern recirculation gyre regions from 73°W to 49°W and from 30°N to the continental shelf break along the 1000 m isobath (see Figure 1). The southern boundary is chosen at 30°N to include the entire southern recirculation gyre of the Gulf Stream. A two-dimensional mean SSH field in this region is determined by combining the mean height profiles estimated along the ascending and descending tracks. This is followed by a discussion of errors in the estimated mean SSH field. One issue also addressed in this study is whether we can use the mean SSH estimated from the satellite altimetric data as the velocity reference at the sea surface and combine it with climatological hydrographic data to better determine the mean oceanic circulation in the Gulf Stream and its recirculation gyre regions. Determining the "absolute" circulations (that is, with known reference velocities) in the Gulf Stream and its neighboring areas is, of course, a classical problem. Early models involving geostrophy, integrated mass and heat conservation have been used by *Wunsch* [1978] and *Wunsch and Grant* [1982], who solved the under-determined problem using an inverse method. Following these pioneering works, several recent studies have attempted to improve the inverse calculations by imposing reference velocities from different types of observations. For example, *Joyce et al.* [1986] added the surface velocity information from ADCP measurements to their inverse calculation, whereas *Mercier* [1989] incorporated long-term deep ocean current meter data. Use of the data from neutrally buoyant floats to constrain the inverse calculation has also been recently undertaken [*Mercier et al.*, 1993].

With its global coverage and temporal repetition, the satellite altimetry is a new observational tool that can possibly be used to improve the determination of the oceanic circulation in the northwestern Atlantic Ocean. Using the mean SSH estimated from the present study, we seek to explore this possibility and discuss the problems of combining the altimetric and hydrographic data taken over different time periods.

2. Description of Data

2.1. Hydrographic Data

The hydrographic data used in the present study are the Nansen bottle cast and low-resolution conductivity/salinity-temperature-depth (C/STD) data archived on a CD-ROM disk by the National Oceanographic Data Center [*NODC*, 1991]. The date of the archived data ranges from 1900

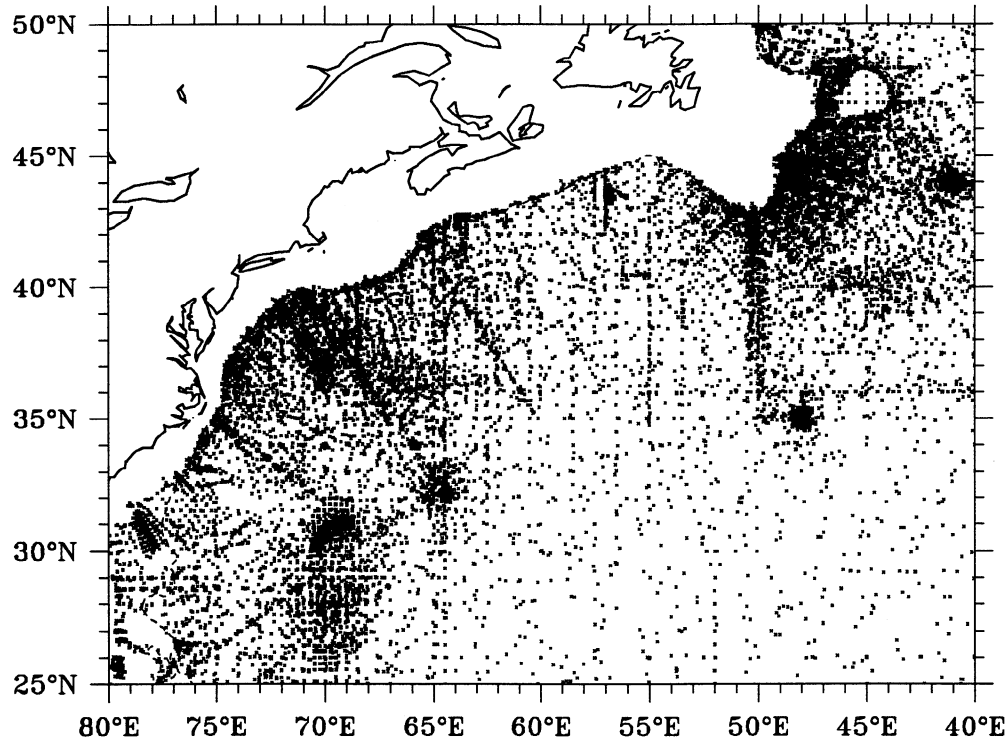

Figure 2. Locations of historic Nansen bottle cast and CTD/STD observations (1900 – 1990) archived by NODC. All observations plotted here are deeper than 500 m.

to 1990 with those prior to the year of 1973 having been used by *Levitus* [1982] in constructing the global atlas of the world ocean climatology. Because the work of Levitus was intended to map the entire world ocean, his choice of the influence radii used in the mapping procedure was largely controlled by areas where observations had been scarce. The northwestern Atlantic Ocean is, undoubtedly, one of the areas where observations are most densely distributed (Figure 2). The purpose of reconstructing the climatology of the water temperature and salinity here is to preserve the spatial structures of the Gulf Stream and its recirculation gyres as much as possible through choosing smaller influence radii for the objective mapping.

To do so, we first grouped all the temperature and salinity data on the disk into $1^\circ \times 1^\circ$ bins for the region shown in Figure 2. For each bin, a mean curve of the potential temperature versus salinity and its standard deviation values were computed. Data outside the two-standard-deviation boundaries were regarded as erroneous and were discarded. After excluding the erroneous data, we linearly interpolated the individual temperature and salinity (T/S) profiles to the standard depths used in the Levitus data set. At each depth, T/S values were mapped onto a $0.5^\circ \times 0.5^\circ$ grid using the objective mapping technique described by *Bretherton et al.* [1976]. The covariance function is assumed to be in the following form:

$$A_{ij} = F \exp\left[-\frac{\Delta x_{ij}^2}{R_x^2} - \frac{\Delta y_{ij}^2}{R_y^2}\right] + E\,\delta_{ij} \qquad (1)$$

where F is the covariance value of T or S at zero-lag, E is the variance of the error, which is taken here to be white noise, and Δx_{ij} and Δy_{ij} are the zonal and meridional distances between the points i and j, respectively. The zonal and meridional decorrelation scales (R_x and R_y) in (1) essentially determine the smoothness of the mapped T/S fields and, ideally, they should be determined from the independent information of the mean T/S fields. Lacking such information, we have subjectively (through trial and error) chosen $R_x = R_y = 600$ km, such that the mapped T/S and their associated error fields are spatially smooth.

Figure 3 shows the mean SSH (dynamic height relative to 3000-m depth) calculated from the above objectively mapped T/S fields. Not surprisingly, while the large-scale pattern of the SSH is similar to that estimated by Levitus (for example, his Figure 67), Figure 3 captures a less smeared-out picture of the Gulf Stream and its recirculation gyres. Similar mean SSH maps that retain the fine structure of the Gulf Stream have been presented by *Fukumori et al.* [1991]. In the following discussions, we will refer to the mean SSH field shown in Figure 3 as $<h_c>$.

2.2. Geosat ERM Data

The altimetric data used in this study are those from the first 54 repeat cycles of the Geosat ERM (November 1986 to April, 1989). All available data along the ascending and descending tracks shown in Figure 1 are used. These ground tracks crisscross the Gulf Stream after its separation from Cape Hatteras and before its bifurcation into the northeastward flowing North Atlantic Current and the eastward flowing Azores Current around 47°W (see Figure 3). (The descending track that passes through 74°W and 30°N is not used because of a severe data dropout, which prevented us from estimating the along-track mean SSH using the model described below.)

For each of the 32 selected tracks, the raw altimeter height data from 0° to 50°N were first adjusted for tides, water va-

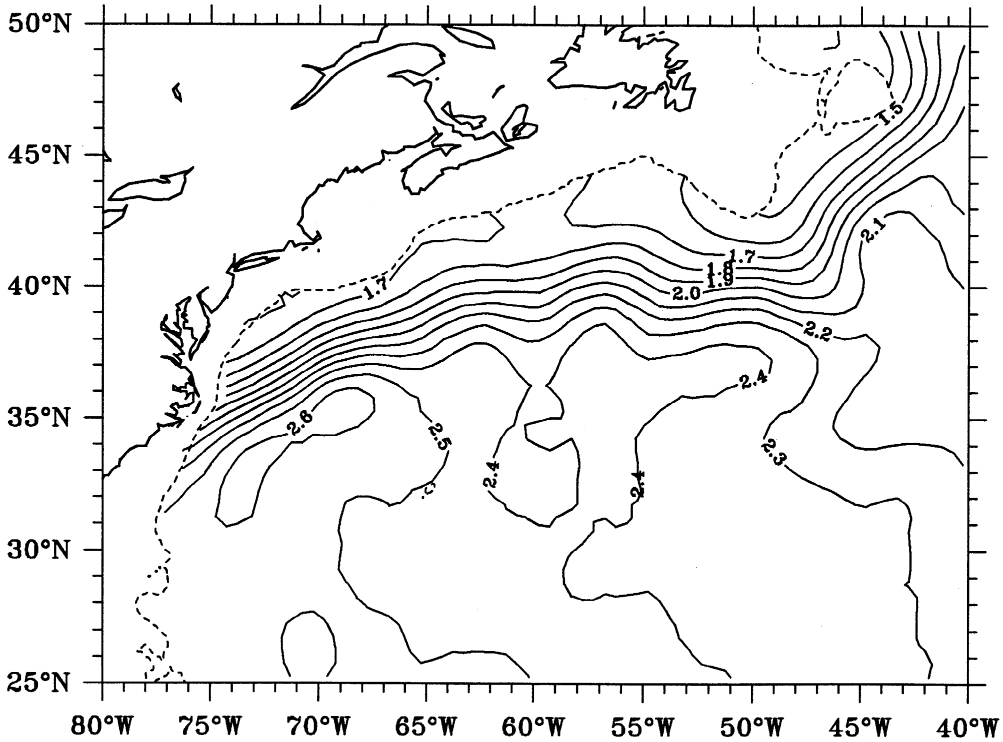

Figure 3. Sea surface dynamic height field (0/3000m) calculated from the objectively mapped historic hydrographic data. Along the continental slope where water depth is shallower than 3000m, the reference level is set at the ocean bottom. Contour intervals are 0.1 m and dashed lines denote the 1000-m isobaths.

por, tropospheric and ionospheric delays, and surface pressure according to correction factors provided on the NODC CD-ROMs [*Cheney et al.*, 1991]. The data were then edited to remove obvious anomalous points and interpolated to a grid with an alongtrack resolution of 0.98 s (6.6 km). Orbital errors with a frequency of one cycle per satellite revolution were removed by fitting the height profile to a sinusoid with a period of 6064 s. To prevent mesoscale height variations due to currents and the geoid from biasing the orbit correction, the least squares fit to the sinusoid was weighted by the inverse of the height variance [*Caruso et al.*, 1990]. The time-varying height profiles were finally computed by subtracting from each corrected height profile the temporally averaged height profile.

3. Reconstructing the Mean SSH from the Geosat Data

We start with a short review of the kinematic jet model proposed by *Kelly and Gille* [1990] and extended to include recirculating flows by *Qiu* [1992]. The basic idea of the model is as follows: due to the large lateral excursions of a boundary current, the mean SSH profile across the current has a more gradual slope than the instantaneous height profiles. Assuming the boundary current has a Gaussian-shaped instantaneous surface velocity profile

$$u_s(y) = a_1 \exp\left[\frac{-(y-a_2)^2}{2{a_3}^2}\right], \tag{2}$$

this distinctive slope characteristic enables us to estimate the boundary current's position (a_2), width (a_3), and strength (a_1) from the altimetrically derived residual height data. The along-track synthetic height profile of this boundary current is

$$h_s(y) = -\frac{f}{g} a_1 a_3 \sqrt{\pi/2}\, \mathrm{erf}\left(\frac{y-a_2}{\sqrt{2}a_3}\right), \tag{3}$$

where $\mathrm{erf}(y)$ is the error function, and the temporal average of these synthetic height profiles gives an estimate of the mean height profile $<h_s>$. Iteratively minimizing the difference between the individual synthetic height profile h_s and the profile of the time-dependent component plus the synthetic mean, $h' + <h_s>$ improves the estimate of the $<h_s>$ profile. It can be shown that the $<h_s>$ profile converges to the mean SSH if the jet's position changes are comparable to the jet's mean width.

This method can also be applied to a boundary current system in which westward recirculating flows exist:

$$u_r(y,t) = a_1 \exp\left[\frac{-(y-a_2)^2}{2{a_3}^2}\right] - b_1 \exp\left[\frac{-(y-b_2)^2}{2{b_3}^2}\right] - c_1 \exp\left[\frac{-(y-c_2)^2}{2{b_3}^2}\right], \tag{4}$$

where b_i and c_i are the parameters for the recirculating westward flows south and north of the boundary current. While such an elaborate model for the surface velocity profile gives a more accurate representation of the Gulf Stream, the recirculation gyres' relatively large spatial scales and their relatively constant position usually violate the convergence criterion, namely, that the changes in the jet's position be on the same order as the jet's width. In other words, while the position and width changes of the recirculation gyres may be evaluated with this method, their intensities can no longer be uniquely determined. To determine the intensities of the recirculation gyres, *Qiu* [1992] constrained the model by re-

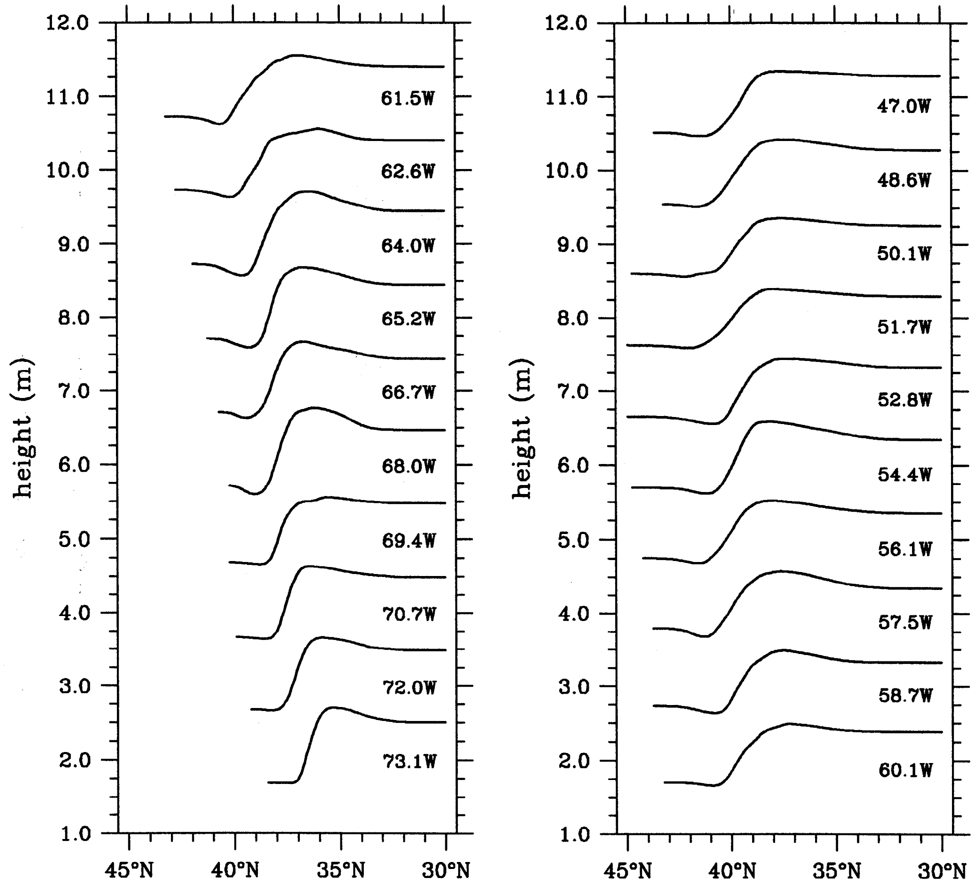

Figure 4. Mean SSH profiles along the Geosat ascending tracks estimated from the kinematic model of the Gulf Stream (including recirculation gyres) described in section 3. The longitude labeled to the right of each profile indicates the center position of the Gulf Stream along that ground track.

quiring that the mean surface height jump, $\delta h_{\rm net}$, across the entire boundary current system (eastward jet plus the recirculation gyres) match that determined from climatological hydrographic data. Although this method specifies the total mean surface transport of the boundary current system, the detailed along-track pattern of the mean SSH (such as the partition between the mean eastward and westward surface transport) is determined by the Geosat altimetric data.

This kinematic model of the boundary current system is applied here to the 32 Geosat tracks shown in Figure 1 (for details of the model calculations, readers are referred to *Qiu* [1992]). The constant, $\delta h_{\rm net}$, for each ground track is determined from Figure 3, namely, $\delta h_{\rm net} = \langle h_c \rangle$ at 30°N $- \langle h_c \rangle$ at the shelf break. Figures 4 and 5 show the mean SSH profiles and the SSH differences across the eastward flowing Gulf Stream ($\delta h_{\rm GS}$) and across the northern and southern recirculating flows ($\delta h_{\rm nr}$ and $\delta h_{\rm sr}$) for the ascending tracks. The result of $\delta h_{\rm GS}$ in Figure 5c is similar to that obtained by *Kelly* [1991], who modeled the Gulf Stream as a single eastward flowing jet: the SSH jump across the mean Gulf Stream increases to a maximum around 68°W to 64°W and it drops to an almost constant value, 0.85 m, after traversing the New England Seamount Chain (NESC). (Notice that because the Gulf Stream has a nodal point in its path near 70°W, the present study has possibly underestimated $\delta h_{\rm GS}$ there due to the lack of meandering by the jet.)

The SSH difference across the mean northern recirculating flow, as shown in Figure 5b, has a nearly constant amplitude of about 0.10 m in the deep ocean basin extending from the Georges Bank to the Grand Banks (except near 61°W, where a locally confined minimum exists). In contrast, the SSH difference across the mean southern recirculating flow reveals the existence of two plateaus separated by the NESC (Figure 5d). It is of interest to note that the $\langle h_c \rangle$ map in Figure 3 presents a rather similar pattern: the SSH to the south of the Gulf Stream is composed of two semiclosed, high SSH areas (i.e., with larger $\delta h_{\rm sr}$ values), that are separated by the NESC (see Figure 1 for the bottom topography). Notice that this agreement is not a result of our specification of $\delta h_{\rm net}$ from the $\langle h_c \rangle$ map in order to constrain the net surface transport. No double plateau structures exist in the zonal dependence of $\delta h_{\rm net}$ (Figure 5a) and, as we have mentioned above, the partition of $\delta h_{\rm net} = \delta h_{\rm GS} - \delta h_{\rm nr} - \delta h_{\rm sr}$ is solely determined by the Geosat altimetric data.

To obtain the two-dimensional mean SSH field, we combined the mean height profiles independently estimated along the ascending and descending tracks by again using the objective mapping method (1). The zero-lag covariance and the zonal and meridional decorrelation scales for the mapping are estimated from the along-track mean height profiles, namely, $F = 0.1\,{\rm m}^2$, $R_x = 4°$ longitude, and $R_y = 2.5°$ latitude. The error variance E is chosen to be $0.012\,{\rm m}^2$; this value is adopted from the study by S. Gille (personal communications, 1992) who estimated the errors associated with the nonlinear parameter fitting of the kine-

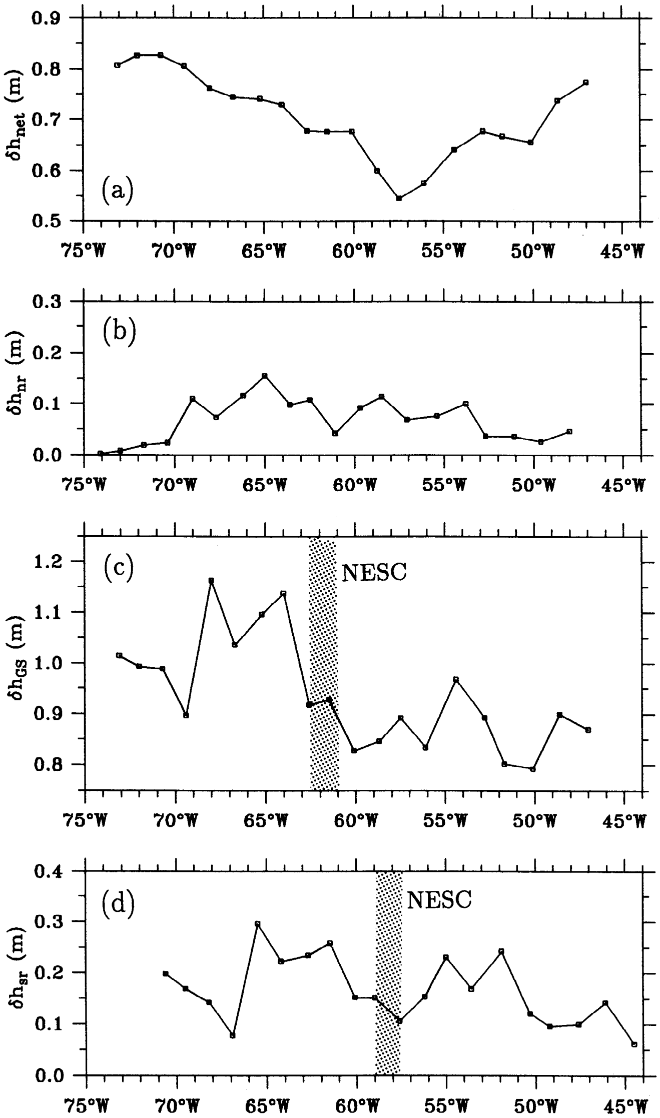

Figure 5. Mean SSH difference across (a) the entire Gulf Stream system (from 30°N to the North American continental slope), (b) the mean westward recirculating flow north of the Gulf Stream, (c) the mean eastward flowing Gulf Stream, and (d) the mean westward recirculating flow south of the Gulf Stream, along the Geosat ascending tracks. Notice that $\delta h_{net} \equiv \delta h_{GS} - \delta h_{nr} - \delta h_{sr}$, and that while δh_{net} are specified from the climatological values (Figure 3), the partitions between δh_{GS}, δh_{nr}, and δh_{sr} are determined by the altimetrically measured time-varying height data. Shaded bands in (c) and (d) denote the locations where the mean Gulf Stream and the southern recirculation gyre intersect the NESC.

matic model using the Monte Carlo simulation technique. Figure 6a shows the objectively mapped mean SSH field in the region from 73°W to 49°W. The SSH gradient of the mean Gulf Stream in Figure 6 is much sharper (by a factor of 2) than its counterpart in Figure 3. One obvious reason for this is that the Gulf Stream is well sampled in the cross-stream direction by the Geosat altimeter, which allows the use of a smaller meridional decorrelation scale in mapping the mean SSH field. Another reason for the discrepancies between the two maps is attributable to the fact that Figure 6a shows the absolute mean SSH field, whereas $<h_c>$ in Figure 3 is the mean SSH referenced to the 3000-m depth. We will return to this point in the next section.

The errors associated with the mean SSH field of Figure 6a are essentially uniform in space with a rms value of 0.021 m, except near the edges of the mapping area where they can be as large as 0.045 m (Figure 6b). Apart from the errors associated with the altimetric data, a different type of error can arise due to uncertainty of the net flow of the mean Gulf Stream system. By forcing the SSH jump acoss the entire Gulf Stream system to match that determined from the climatological hydrographic data ($\delta h_{\rm net}$), we have implicitly assumed that the net flow is zero at 3000-m depth when integrated from 30°N to the North America continental slope. If the recirculation gyres are driven locally by the eddy fluxes from the Gulf Stream instabilities, this assumption of no integrated net flow is justifiable. On the other hand, if a mean through flow exists at 3000-m depth, this will result in a net height difference, thus violating the assumption. One candidate for such a mean throughflow in this region is the North Atlantic deep western boundary current (DWBC), which is formed convectively in the Norwegian and Labrador Seas and flows southwestward along the continental slope to replenish the deep interior ocean. Previous long-term moored current measurements showed that the DWBC has a mean along-slope velocity of about $0.05\,\mathrm{m\,s^{-1}}$ [*Luyten*, 1977; *Pickart and Watts*, 1990; *Watts*, 1991]. A typical width of the DWBC of 100 km, then, amounts to a net height jump of about 0.05 m at 3000-m depth. The deep extension of the mean Gulf Stream, however, can contribute to a height jump opposite to that induced by the southwestward flowing DWBC: a recent study by *Pickart* [1992] showed the thermal shear associated with the mean Gulf Stream can reach deeper than 4000 m. Without detailed knowledge of these mean through flows, we have retained the no-net-flow assumption here, but it should be remembered that the errors associated with the mean SSH in Figure 6 are larger than those (0.021 m) estimated from the altimetric data alone. Translating into the geostrophic velocities, an error of 0.021 m in the height field results in an uncertainty of about $0.03\,\mathrm{m\,s^{-1}}$.

4. Estimating the Mean Deep Circulation of the Gulf Stream

In the last section, we reconstructed the mean SSH field in the Gulf Stream and its neighboring regions using the Geosat altimetric data. Using this mean SSH field as a reference, we explore here how we may combine this information with the result from the hydrographic data (section 2.1) to obtain a reasonable picture of the mean deep circulation. Given the distinctly different nature of the altimetric and the hydrographic measurements, we immediately encounter the following two problems. The first is the sampling difference, with the cross-stream structure of the mean Gulf Stream better resolved by the altimetric observations. To resolve this problem, we remapped the SSH field from the altimetric data using the same zonal and meridional decorrelation scales employed for the $<h_c>$ map (namely, $R_x = R_y = 600$ km). By doing so, we are comparing the mean SSH fields with similar horizontal scales. Because $<h_c>$ is relative to 3000-m depth, subtracting it from the remapped SSH field of the altimetric data now gives the height field at the reference level (Figure 7).

The second problem associated with combining the altimetric and the hydrographic data is the difference in the

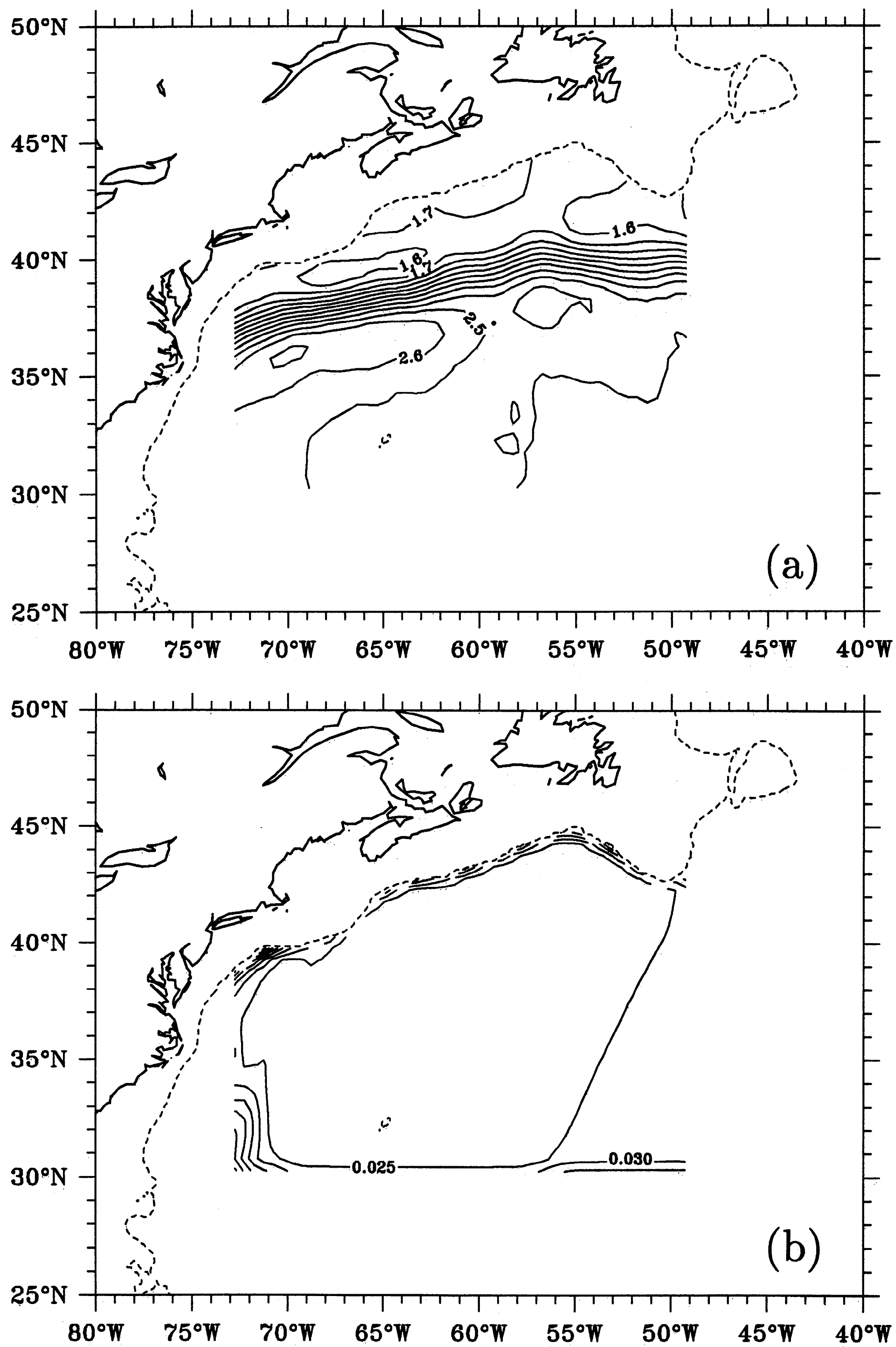

Figure 6. (a) Mean SSH field objectively mapped from the mean height profiles that are independently estimated along the ascending and descending ground tracks. (b) Corresponding error map. Contour intervals are (a) 0.1 m and (b) 0.005 m. Dashed lines denote the 1000-m isobaths.

averaging time period: whereas the $<h_c>$ map was based on hydrographic surveys over decades, Figure 6a was reconstructed from the Geosat data over a 2.5-year time period. Comparing the axis positions of the Gulf Stream from the two SSH maps (Figure 8) reveals that while the paths of the Gulf Stream more or less coincide with each other downstream of 69°W, a clear difference exists where the Gulf Stream separates from the continental slope. As also shown by *Gangopadhyay et al.* [1992] using satellite infrared images, separation of the Gulf Stream during the Geosat ERM period occurred at a more northerly latitude than the climatological average. In the present calculation, this in-

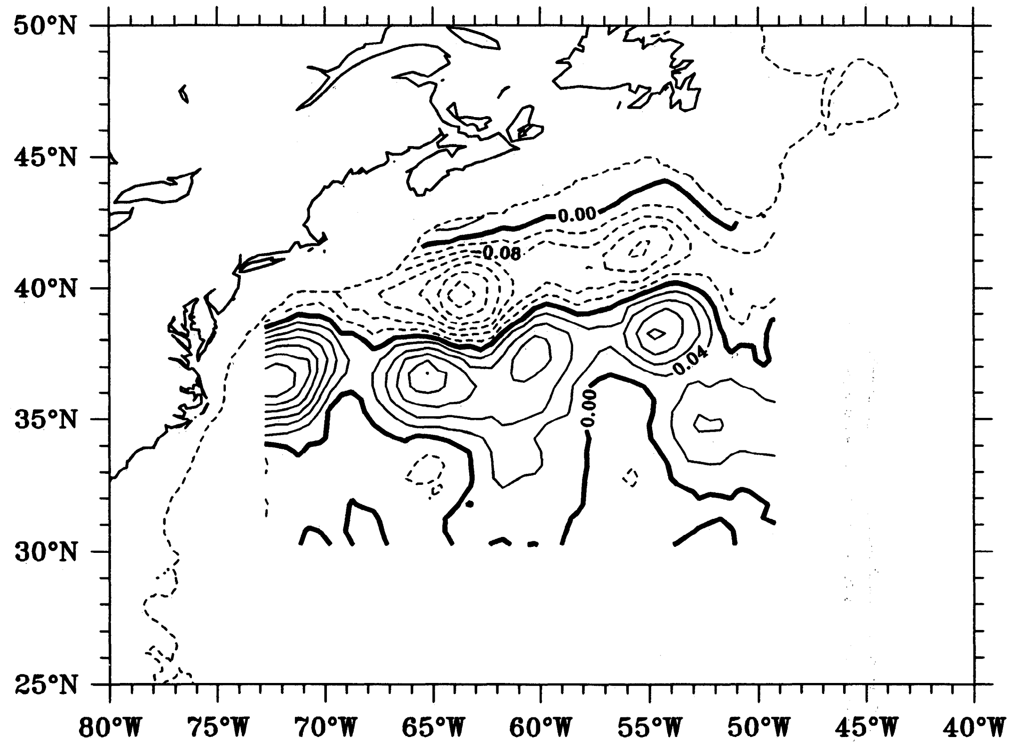

Figure 7. Height field at 3000-m depth calculated from subtracting the climatological SSH field (Figure 3) from the mean SSH field objectively mapped from the altimetric data (using $R_x = R_y = 600$ km). Contour intervals are 0.04 m.

terannual change in the separation latitude gives rise to a strong anticyclonic circulation in the deep height field (west of 69°W in Figure 7). On the basis of available deep observations of the Gulf Stream, this circulation is obviously an artifact due to the northward shift of the mean Gulf Stream in the Geosat ERM period.

This second problem is more difficult in the sense that it can only be satisfactorily solved with contemporaneous,

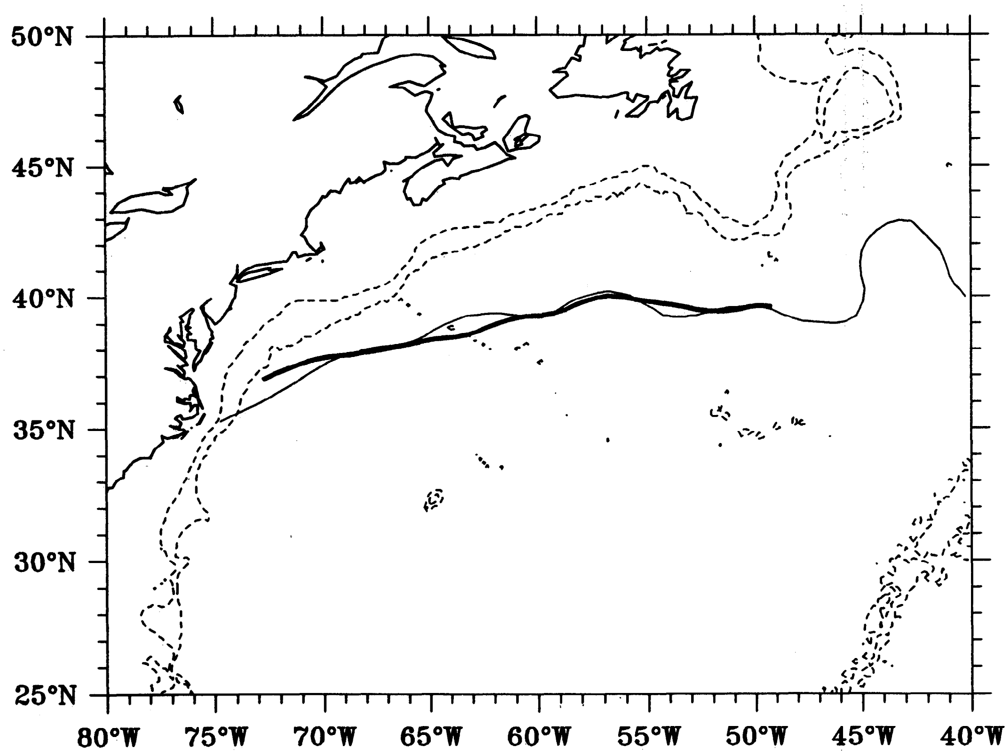

Figure 8. Mean Gulf Stream axes from the climatological SSH field (thin solid line) and from the mean SSH field estimated from the Geosat altimetric data (bold solid line). Here, the Gulf Stream axes are the isolines of 2.1 m in Figures 3 and 6a.

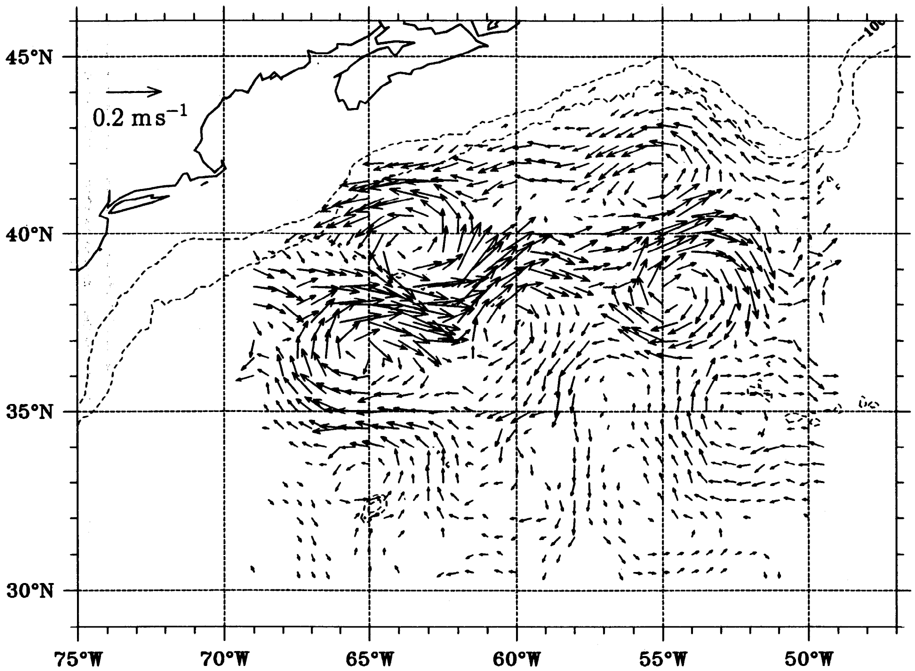

Figure 9. Flow patterns at 3000-m depth deduced geostrophically from Figure 7 (east of 69°W). Velocity vectors in areas shallower than 3000 m indicate flows at the bottom of the ocean. Vectors with velocity magnitude smaller than 0.02 $m s^{-1}$ are omitted.

long-term altimetric and hydrographic data. For this reason, the upstream Gulf Stream region (west of 69°W) is excluded from the following discussions. In the downstream Gulf Stream region, discrepancies in the current paths are generally small and we expect the deep flow patterns, especially away from the Gulf Stream axis, to be less affected by the interannual changes. Figure 9 shows the horizontal velocity vectors converted from the height field of Figure 7 (velocities with magnitude smaller than 0.02 $m s^{-1}$ have been omitted). As a comparison, Figure 10 shows the mean current vectors from *Hogg et al.* [1986], who compiled all available, direct current measurements below 3000-m depth (except over the continental slope where some of the measurements were shallower). Because the vertical velocity shear is expected to weaken at this deep ocean level and is likely to be surpassed by the uncertainty of the estimated velocities themselves (> 0.03 $m s^{-1}$, as we have noted in the previous section), no attempt was made to quantitatively compare velocities with Figure 10 at the depths of individual current meters. The following discussion is a qualitative comparison between Figures 9 and 10.

One area in the western North Atlantic where abundant direct measurements have been taken is along the 55°W meridian. Both Figure 10 and the study by *Richardson* [1985] reveal that the deep circulation there is composed of an eastward mean flow between 37° and 39°N flanked by two westward mean flows. Both the westward and eastward mean flows north of 37°N are well captured in Figure 9 and they follow closely the isopachs of the deep layer (i.e., the ambient potential vorticity contours in the deep layer below the thermocline, see the boldly drawn lines in Figure 10). In contrast to the persistent westward mean flow observed south of 37°N along 55°W, Figure 9 shows that the flow there is more or less northward and seems to be a part of the anticyclonic circulation trapped around the Corner Rise. Agreement between the two figures is also good around 59°W and 39°N, where east/northeastward mean flows again follow closely along the deep layer potential vorticity contours. Along the continental slope between 60°W and 65°W, both Figures 9 and 10 indicate the existence of an along-slope, southwestward mean flow. The result of the present study suggests that part of this flow may veer eastward into the mean deep Gulf Stream (Figure 9).

Comparison between the two results is more difficult south of the Gulf Stream because of the scarcity of direct measurements. Along the 4400-m isopach of the deep layer, Figure 9 shows the presence of a continuous southward flow; one direct measurement at 57.5°W and 33°N also seems to suggest such a southward flow, although the observed speed is much larger. To the west of the NESC, there are mooring sites where the agreement between the observed and the estimated mean flows is poor (e.g., at 61°W, 36°N and at 63°W, 37°N), but there are also mooring sites where the agreement is favorable (e.g., at 59°W, 36°N and at 60°W, 34°N).

Despite the large uncertainties associated with the estimated mean SSH field of Figure 6, the overall pattern of the deep circulation east of 69°W (Figure 9) is consistent with that suggested by the direct current measurements. In addition, Fig.9 reveals several new features of the deep circulation, for example, the existence of a continuous southward flow along a deep layer potential vorticity contour between 55°W and 60°W, an anticyclonic mean circulation around the Corner Rise, and a second southern recirculation gyre to the west of the NESC (cf. Figure 5d). All these features imply a strong interaction between the deep mean flow and the bottom topography. It is worth noting that a recent numerical study by *Ezer* [1993, his Figure 2b] showed the simulated deep flow patterns (extending below 3000 m) on both sides of the Gulf Stream very similar to those derived

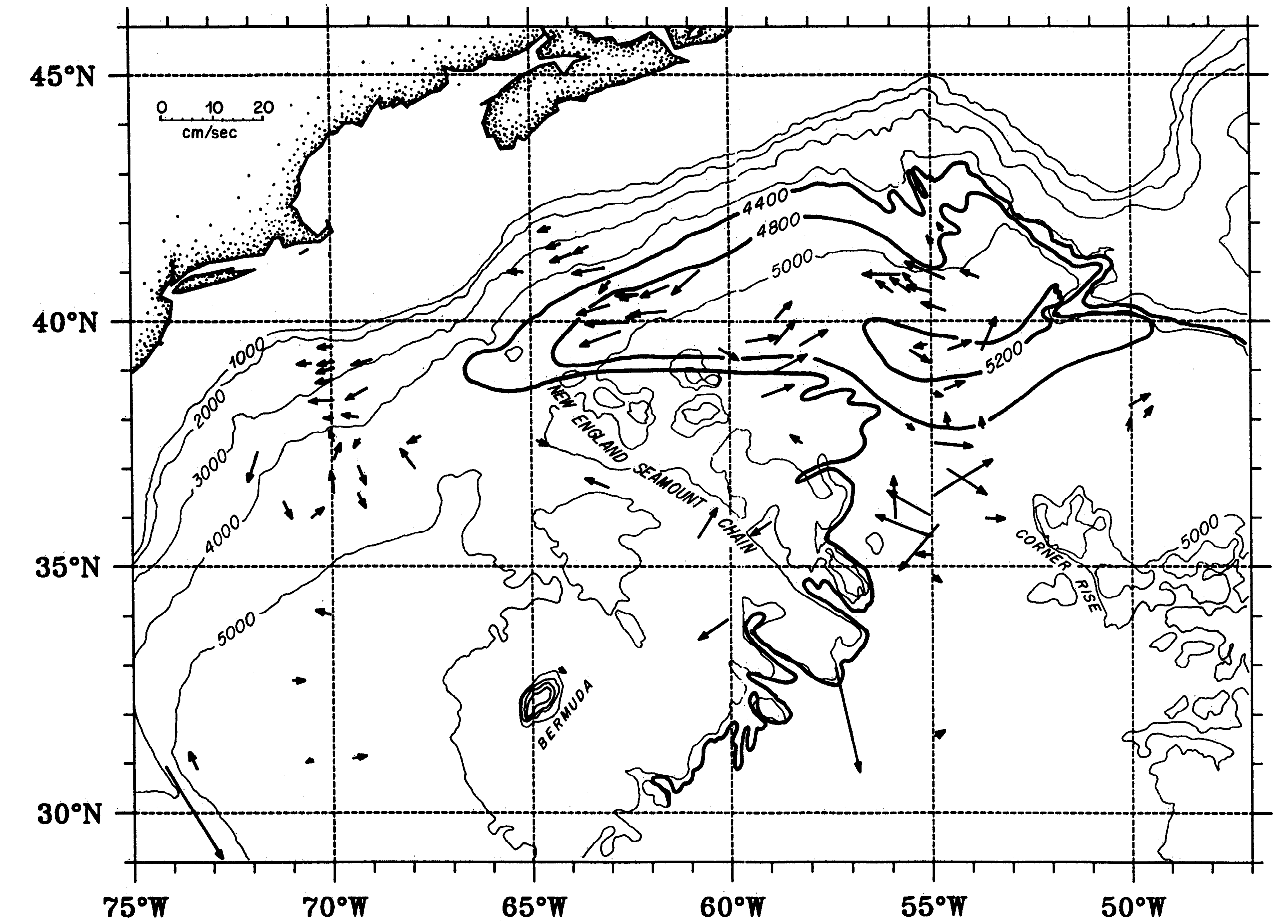

Figure 10. Flow patterns from long-term moored deep current meter measurements. Vectors shown here are primarily adopted from *Hogg et al.* [1986, Figure 1c], but include the results from the 13 deep current meters along 55°W from the recent SYNOP program (courtesy of N. Hogg). The boldly drawn lines are the isopachs of the deep layer below the main thermocline [see *Hogg and Stommel*, 1985].

from the present study. From model simulations, he further demonstrated that these deep gyres are the result of the interaction of the Gulf Stream with the NESC: the deep gyres were absent from simulations where the NESC was eliminated .

5. Summary and Conclusions

The purpose of the present study has been twofold. The first is to estimate a two-dimensional mean SSH field that is pertinent to the Geosat ERM period in the region of the Gulf Stream and its recirculation gyres. Determining the mean SSH field makes it possible to obtain the absolute surface height field which has many oceanographic applications. Second, we explored the possibility of using the mean SSH field estimated from the altimetric data as a reference at the sea surface and combining it with the historical hydrographic data to determine the deep mean circulation in this region.

To obtain the two-dimensional mean SSH field, we first estimated the mean SSH profiles across the Gulf Stream system (from 30°N to the North American continental slope) along the Geosat ascending and descending tracks. By extending the single-jet Gulf Stream model of *Kelly and Gille* [1990], we included the westward recirculating flows on the two sides of the Gulf Stream. Initial estimations of the positions, widths, and intensities of the instantaneous Gulf Stream and the recirculating flows were based on the time-varying SSH data derived from the Geosat altimeter. The along-track profile of the mean SSH was successively improved by fitting the synthetic height data to the synthetic mean plus the time-varying height data. The total height difference across the Gulf Stream system was constrained by the height values determined from the historical hydrographic data with a reference level at 3000 m. This constraint is equivalent to assuming a zero net zonal flow across the Gulf Stream system at 3000-m depth between 30°N and the continental slope.

The two-dimensional mean SSH field was determined by combining the mean height profiles along the ascending and descending tracks through the objective mapping technique. The SSH jump across the mean Gulf Stream (or the mean surface transport of the Gulf Stream) has a maximum around 65°W (~ 1.15 m), and drops and remains almost constant (~ 0.90 m) downstream of the NESC. The SSH jump associated with the mean northern recirculating flow is largely independent of the downstream location in the deep ocean basin between 70°W and 53°W. In contrast, the intensity of the southern recirculation gyre has a double-peak structure with two local recirculation gyres separated by the NESC. This double-peak structure is also evident in the surface dynamic height field calculated from the historical hydrographic data.

The along-track mean SSH profiles determined from the

Geosat altimetric data were next used to estimate the deep mean circulation in the region of the Gulf Stream and its recirculation gyres. Mismatches in the mean position of the Gulf Stream occur due to the difference in the averaging periods and the Gulf Stream's interannual changes. This problem was particularly severe where the Gulf Stream separates from the continental slope and it has prevented us from estimating the mean deep circulations in the region west of 69°W. Downstream of 69°W, the deep flow pattern deduced by subtracting the climatological SSH field from the mean SSH field determined from the Geosat data agreed well with the overall deep circulation pattern indicated from the long-term current meter observations. As previously noted by *Hogg et al.* [1986], we found a well-defined northern recirculation gyre exists along the closed contours of the deep layer potential vorticity. Also revealed by the estimation of the mean deep flow is (1) the presence of a continuous southward flow along a deep layer potential vorticity contour along 57.5°W and (2) the two southern recirculation gyres separated by the NESC. The recirculation gyre to the east of the NESC appears to circulate closely around the Corner Rise.

There are three major uncertainties in the present estimate of the deep mean circulation by combining the altimetric and hydrographic data: errors in estimating the mean SSH field from the Geosat data (which induces an uncertainty of $0.03\,\mathrm{m\,s^{-1}}$ for velocities), the assumption of zero net zonal flow at the 3000-m depth, and the interannual changes in the Gulf Stream. Despite these problems, we believe that the present method could be useful for establishing an overall flow pattern in the deep ocean of other western boundary currents, such as the Kuroshio Extension, where long-term deep current measurements have been extremely scarce. Second, with on-going altimetric missions of ERS-1 and TOPEX/Poseidon and future missions planned, a mean SSH field based on longer time series of the altimetric data will be possible. Mean SSH fields formed from both hydrographic and altimetric data taken over the same time period would help avoid the problem associated with the interannual changes of the boundary currents and provide a more reliable picture of the deep mean circulation.

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REFERENCES

Bretherton, F.P., R.E. Davis, and C.B. Fandry, A technique for objective analysis and design of oceanographic experiments applied to MODE-73, *Deep Sea Res., 23*, 559–581, 1976.

Caruso, M.J., Z. Sirkes, P.J. Flament, and M.K. Baker, Altimeter processing tools for analyzing mesoscale ocean features, *Tech. Rep. WHOI-90-45*, Woods Hole Oceanogr. Inst., Woods Hole, Mass., 1990.

Cheney, R.E., N.S. Doyle, B.C. Douglas, R.W. Agreen, L. Miller, E.L. Timmerman, and D.C. McAdoo, The Complete Geosat altimeter GDR handbook, *NOAA Manual NOS NGS 7*, 77 pp., NOAA, Natl. Ocean Serv., Rockville, Md., 1991.

De Mey, P. and A.R. Robinson, Assimilation of altimeter eddy fields in a limited-area quasi-geostrophic model, *J. Phys. Oceanogr., 17*, 2280–2293, 1987.

Ezer, T., On the interaction between the Gulf Stream and the New England Seamount Chain, *J. Phys. Oceanogr.*, in press, 1993.

Ezer, T., G.L. Mellor, D.-S. Ko, and Z. Sirkes, A comparison of Gulf Stream sea surface height fields derived from Geosat altimeter data and those derived from sea surface temperature data, *J. Atmos. Oceanic Technol., 10*, 76–87, 1993.

Fukumori, I., F. Martel, and C. Wunsch, The hydrography of the North Atlantic in the early 1980s, An atlas, *Progr. Oceanogr., 27*, 1–110, 1991.

Gangopadhyay, A., P. Cornillon, and D.R. Watts, A test of the Parsons-Veronis hypothesis on the separation of the Gulf Stream, *J. Phys. Oceanogr., 22*, 1286–1301, 1992.

Glenn, S.M., D.L. Porter, and A.R. Robinson, A synthetic geoid validation of Geosat mesoscale dynamic topography in the Gulf Stream region, *J. Geophys. Res., 96*, 7145–7166, 1991.

Hogg, N.G., A note on the deep circulation of the western North Atlantic: Its nature and causes, *Deep Sea Res., 30*, 945–961, 1983.

Hogg, N.G., On the transport of the Gulf Stream between Cape Hatteras and the Grand Banks, *Deep Sea Res., 39*, 1231–1246, 1992.

Hogg, N.G., and H. Stommel, On the relation between the deep circulation and the Gulf Stream, *Deep Sea Res., 32*, 1181–1193, 1985.

Hogg, N.G., R.P. Pickart, R.M. Hendry, and W.J. Smethie, Jr., The northern recirculation gyre of the Gulf Stream, *Deep Sea Res., 33*, 1139–1165, 1986.

Joyce, T.M., and W.J. Schmitz, Jr., Zonal velocity structure and transport in the Kuroshio Extension, *J. Phys. Oceanogr., 18*, 1484–1494, 1988.

Joyce, T.M., C. Wunsch, and S.D. Pierce, Synoptic Gulf Stream velocity profiles through simultaneous inversion of hydrographic and acoustic Doppler data, *J. Geophys. Res., 91*, 7573–7585, 1986.

Joyce, T.M., K.A. Kelly, D.M. Schubert, and M.J. Caruso, Shipboard and altimetric studies of rapid Gulf Stream variability between Cape Cod and Bermuda, *Deep Sea Res., 37*, 879–910, 1990.

Kelly, K.A., The meandering Gulf Stream as seen by the Geosat altimeter: Surface transport, position, and velocity variance from 73° to 46°W, *J. Geophys. Res., 96*, 16,721–16,738, 1991.

Kelly, K.A., and S.T. Gille, Gulf Stream surface transport and statistics at 69°W from the Geosat altimeter, *J. Geophys. Res., 95*, 3149–3161, 1990.

Kelly, K.A., T.M. Joyce, D.M. Schubert, and M.J. Caruso, The mean sea surface height and geoid along the Geosat subtrack from Bermuda to Cape Cod, *J. Geophys. Res., 96*, 12,699–12,709, 1991.

Levitus, S., Climatological Atlas of the World Ocean, *NOAA Prof. Pap. 13*, 173 pp., U.S. Government Printing Office, Washington, D.C., 1982.

Luyten, J.R., Scales of motion in the deep Gulf Stream and across the continental rise, *J. Mar. Res., 35*, 49–74, 1977.

Malanotte-Rizzoli, P. and W.R. Holland, Assimilation of altimetric data into an ocean circulation model: Space versus time resolution studies, *J. Phys. Oceanogr., 19*, 1507–1534, 1989.

Masuzawa, J., Water characteristics of the North Pacific central region, in *Kuroshio–Its Physical Aspects*, edited by H. Stommel and K. Yoshida, pp. 95–128, University of Tokyo Press, Tokyo, 1972.

Mellor, G.L. and T. Ezer, A Gulf Stream model and an altimetry assimilation scheme, *J. Geophys. Res., 96*, 8779–8795, 1991.

Mercier, H., A study of the time-averaged circulation in the western North Atlantic by simultaneous nonlinear inversion of hydrographic and current meter data, *Deep Sea Res., 36*, 297–313, 1989.

Mercier, H., M. Ollitrault, and P.Y. LeTraon, An inverse model of the North Atlantic general circulation using Lagrangian float data, *J. Phys. Oceanogr., 23*, 689–715, 1993.

Mitchell, J.M., J.M. Dastugue, W.J. Teague, and R. Hallock, The estimation of geoid profiles in the northwest Atlantic from simultaneous satellite altimetry and airborne expendable bathythermograph sections, *J. Geophys. Res., 95*, 17,965–17,977, 1990.

Pickart, R.S., Space-time variability of the deep western boundary current oxygen core, *J. Phys. Oceanogr., 22*, 1047–1061, 1992.

Pickart, R.S. and D.R. Watts, Deep western boundary current variability at Cape Hatteras, *J. Mar. Res., 48*, 765–791, 1990.

Qiu, B., Recirculation and seasonal change of the Kuroshio from altimetric data, *J. Geophys. Res., 97*, 17,801–17,811, 1992.

Qiu, B., and T.M. Joyce, Interannual variability in the mid- and low-latitude western North Pacific, *J. Phys. Oceanogr., 22*, 1062–1079, 1992.

Richardson, P.L., Average velocity and transport of the Gulf Stream near 55°W, *J. Mar. Res., 43*, 83–111, 1985.

Robinson, M., R. Bauer, and E. Schroeder, Atlas of North Atlantic – Indian Ocean monthly mean temperatures and mean salinities of the surface layer, Dep. of the Navy, Washington, D.C., 1979.

Watts, D.R., Equatorward currents in temperatures 1.8°–6°C on the continental slope in the mid-Atlantic bight, in *Deep Convection and Deep Water Formation in the Oceans*, edited by P.C. Chue and J.C. Gascard, pp. 183–196, Elsevier, New York, 1991.

White, W.B., C.-K. Tai, and W.R. Holland, Continuous assimilation of simulated Geosat altimetric sea level into an eddy-resolving numerical ocean model, Part 1, Sea level differences, *J. Geophys. Res., 95*, 3219–3234, 1990.

Worthington, L.V., On the North Atlantic circulation, *Johns Hopkins Oceanogr. Stud., 6*, 110pp., 1976.

Wunsch, C., The North Atlantic general circulation west of 50°N determined by inverse methods, *Rev. Geophys., 16*, 583–620, 1978.

Wunsch, C. and B. Grant, Towards the general circulation of the North Atlantic Ocean, *Progr. Oceanogr., 1*, 1–59, 1982.

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