Ocean Surface Measurement Using Elevations from GEOS-3 Altimeter

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Remote sensing of the ocean surface topography from the GEOS-3 satellite has confirmed that the altimeter can detect the topographic changes relative to an equipotential surface and due to the dynamic processes, thus providing a direct measurement of the geostrophic component of the ocean surface current. Maps of the ocean surface topography calculated over a one-month period, with a 20-cm contour interval, are prepared for the last half of 1975. The Gulf Stream is observed by the rapid slope change shown by the crowding of contours. Cold eddies associated with the current are seen as roughly circular isolated depressions in the open ocean areas.

Introduction

A MAJOR task in physical oceanography is the development of techniques to measure and monitor the movement of large masses of water such as strong western boundary currents. Historically, these major ocean current systems have been identified using indirect hydrographic methods. Such methods not only require closely spaced hydrographic stations from which salinity and temperature measurements can be made, but also depend on the assumption of the existence of a reference surface of no motion. However, these traditional in situ measurements are not suitable for studying large-scale and fast-changing phenomena because of time and space limitations. These shortcomings in the traditional methods are partially overcome by remote sensing techniques. The first remote sensor that has been widely accepted by the oceanographic community is the infrared radiometer, which although synoptic, is limited by cloud cover. Also, the IR radiometer can only sense the thermal signature from the ocean surface which is subject to the changes of local meteorological forces.[1] Even under ideal conditions, the IR results can only indicate the surface boundary pattern and, furthermore, such information cannot be used to infer the magnitude of the current. A second remote sensing instrument, the radar altimeter, basically measures the distance from the satellite to the ocean surface. This distance can be referenced to an ellipsoid and thus can provide a direct measurement of the ocean surface topography. Two important types of information can be gathered from these direct measurements: 1) the oceanic geoid and oceanic levelling and 2) ocean surface topographic departures caused by such dynamic processes as currents and tides. This study addresses the second type of problem, specifically the Gulf Stream.

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Data Analysis Procedure

A satellite radar altimeter is an instrument which measures precisely the distance from a satellite platform to the ocean surface. The geometry of the measuring system is illustrated in Fig. 1. Ideally, the altitude measured by the altimeter can be represented as

$$h_a = h_s - h_g - \Delta h \pm \epsilon_n \tag{1}$$

where h_a is the measured altitude; h_s is the satellite height above a reference ellipsoid determined by satellite tracking data; h_g is the geoid height; Δh is the height deviation from the geoid due to dynamic processes in the ocean such as currents and tides; and ϵ_n is the random error in the measurement. In fact, since there may be geoidal and/or orbital errors, Δh may be biased by these uncertainties. Tide effects are not considered in this analysis since the tidal wavelength is much longer than the profiles being used. Typically the ranges and uncertainties of the terms in Eq. (1) are as follows: the range of h_s is between 800 and 900 km with an uncertainty of 5 m; h_g varies between -25 and -70 m with an uncertainty of 2-5 m in the area where the geoid is defined (16°-39°N, 60°-82°W)[2]; the expected range of Δh due to the Gulf Stream is 50-200 cm depending on velocity and latitude; finally, ϵ_n has a zero mean and a 70-cm standard deviation for intensive mode data averaged over 0.1 s by the altimeter.[3]

The GEOS-3 satellite was launched on April 9, 1975. Intensive coverage of the Gulf Stream using satellite altimetry began in July after a few months of operational checkout and data system evaluation. Data from all intensive mode passes acquired over the Gulf Stream during the months of July through Dec. 1975 are presented. The altimeter data used in this experiment utilize measurements made at a rate of 100 per second and averaged within the altimeter hardware to provide 10 averaged measurements per second.[3] The averaged altimeter measurements are preprocessed and converted to sea surface heights referenced to an ellipsoid. These preprocessed data are defined here as raw sea surface heights.[4] The data processing procedure used in this study is shown in Fig. 2 using data from orbit 1710. Figure 2A shows the raw sea surface heights which are edited if the present height differs from an 8-s linear prediction by more than 2 m (see Fig. 2B). Th edited time series is then smoothed using a sliding 81-point, equal weight, midpoint smoothing filter. Eight seconds of data, 81 points, or about 60 km in physical distance were

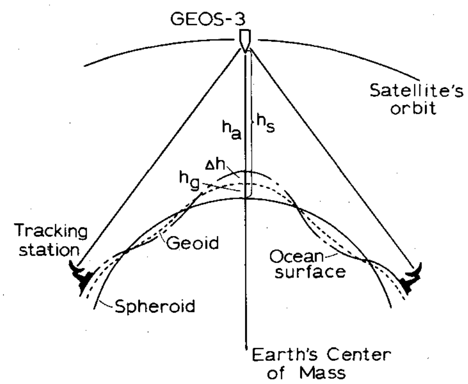

Fig. 1 GEOS-3 satellite geometry.

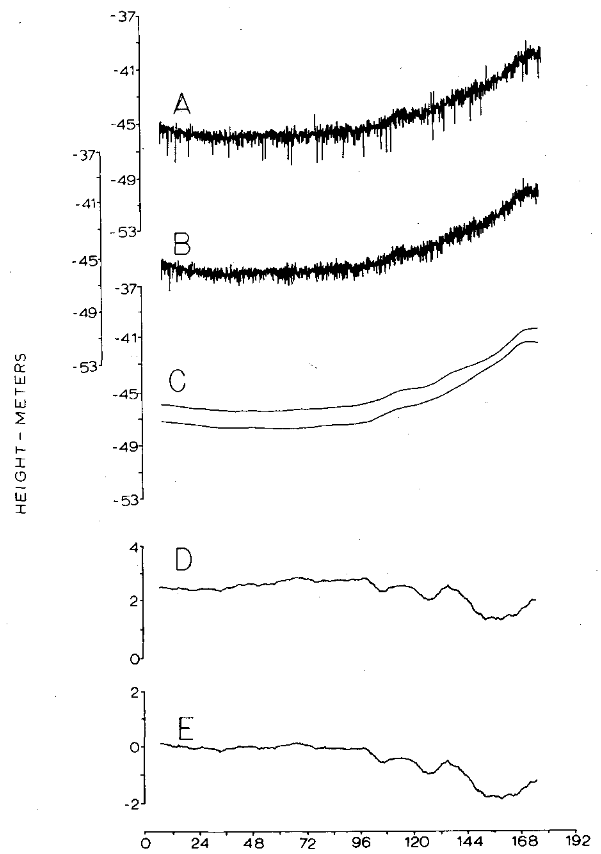

Fig. 2 Data processing diagram.

chosen so that the accuracy could be maintained below the 10-cm level as shown by

$$\text{accuracy} = E/\sqrt{N} \qquad (2)$$

where N is the number of points and E is the error with an rms value of 70 cm. After the filtering process, the smoothed sea surface heights are referenced to the March-Chang 5-ft × 5-ft gravimetric geoid[5] – an equipotential, level surface (see Fig. 2C). The result is a residual which is nearly linear in the open ocean as depicted in Fig. 2D. To minimize the error between the geoid and the filtered sea surface heights, a linear fit to the residuals is made in the open ocean out of range of the Gulf Stream boundaries. The straight line is then subtracted from all of the residuals, thus forcing the static portion of the profile to best fit the reference geoid. This procedure removes any potential orbital bias or slope errors and results in an estimate of the topographic height as shown on the profile on Fig. 2E. The height profiles for each month are combined using a minimum variance technique[6] to minimize the differences at the intersecting points. The adjusted values of the topographic heights which minimize the errors at the intersecting points are treated as the directly measured dynamic heights for the month. Contours are then drawn to represent the dynamic ocean surface averaged over one month.

Table 1 Monthly number of intensive GEOS-3 passes used in this study

Month	S-N	N-S	Total
July	10	12	22
Aug.	19	9	28
Sept.	23	13	36
Oct.	20	9	29
Nov.	23	9	32
Dec.	9	7	16
Total	104	59	163

Results

All 163 intensive GEOS-3 passes between July 1, 1975 and Dec. 31, 1975 that are available for processing have been used in this study. These passes consist of 104 south-to-north passes between Cape Kennedy and Cape Cod and 59 north-to-south passes between Bermuda and Cape Hatteras (see Table 1).

A surface topographic map was prepared for each month using the preceding data set (see Figs. 3 through 8). Although the number of passes for each month is relatively consistent ($\bar{x} = 27$ passes, $\sigma = 7$), their spatial distribution is not optimal. For this reason, the results are sometimes shown in dashed lines to indicate the areas where the data density is less than desirable. The values obtained by the minimum variance technique as the average adjusted sea surface heights for each intersection are interpolated into 20-cm interval contour lines to show the remaining topography. A short analysis of the results obtained for each month follows.

July

This month is quite early in the life of GEOS-3, and scheduling over the Gulf Stream is less than ideal. This results in large areas, particularly northeast of Cape Hatteras, which lack intersections. However, coverage immediately south of Cape Hatteras is good and results show a well defined Gulf Stream and two eddies: one at 34°N, 74°W and another at 30°N, 72.5°W (see Fig. 3).

August

The map for this month shows a relatively good distribution of passes with the exception of a band southeast from Cape Fear. The Gulf Stream is well defined between orbits 1682 and 1881 and northeast of Cape Hatteras to about 67°W, where a large meander is seen centered at 70°W. Several eddies are observed particularly at about 34°N, 71°W and at about 35°N, 67°W (see Fig. 4).

September

GEOS-3 altimeter coverage of the study area for this month is excellent; there are 145 intersections included in this map. The Gulf Stream is well defined in almost all of its extent, showing height differences of about 120 cm off Florida, 60 cm off Cape Hatteras, and about 100 cm at 70°W. Two eddies are observed at 34°N, 67°W and at 31°N, 75°W (see Fig. 5).

October

This month shows a remarkable Gulf Stream meander at about 68°W and a large eddy at 33°N, 73.5°W. Unfortunately this month lacks a north-to-south pass close to Cape Hatteras which would tie in other passes and yield a better Gulf Stream definition in the South Atlantic Bight (see Fig. 6).

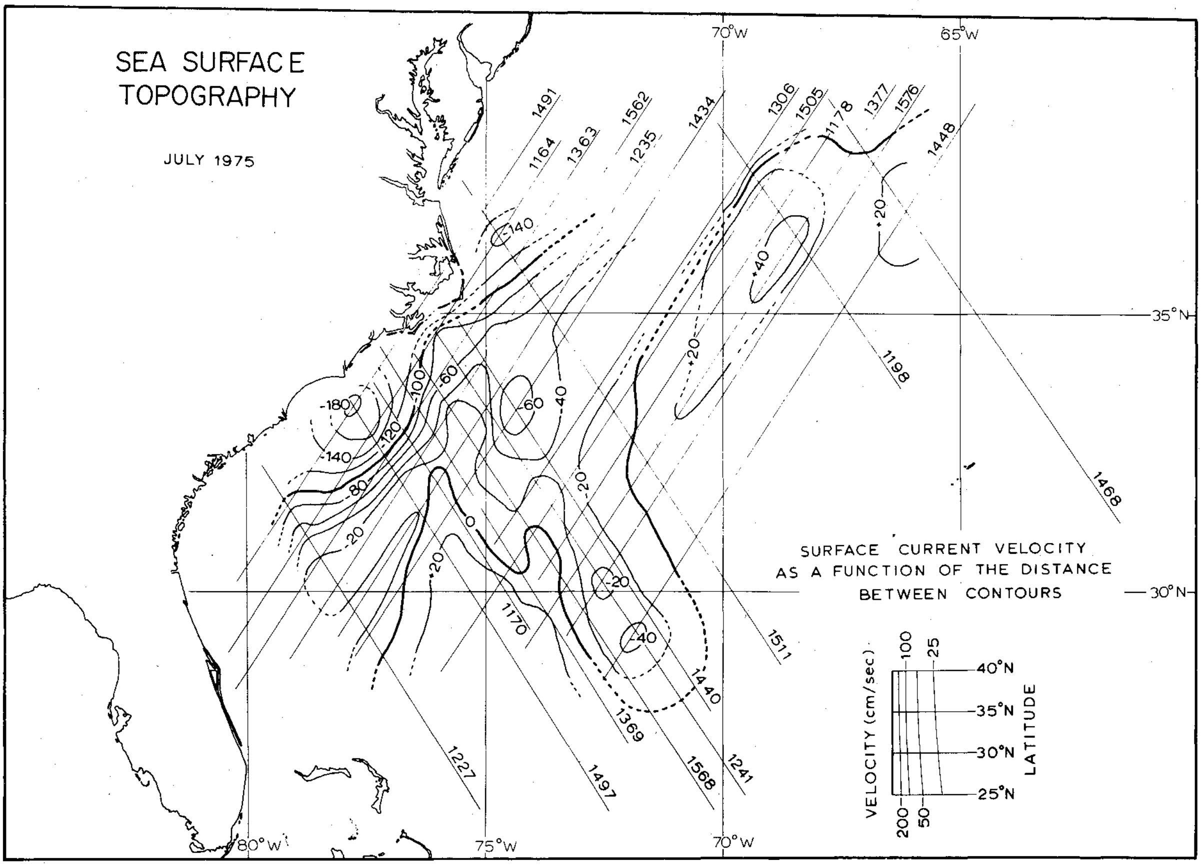

Fig. 3 Mean sea surface topography, July 1975.

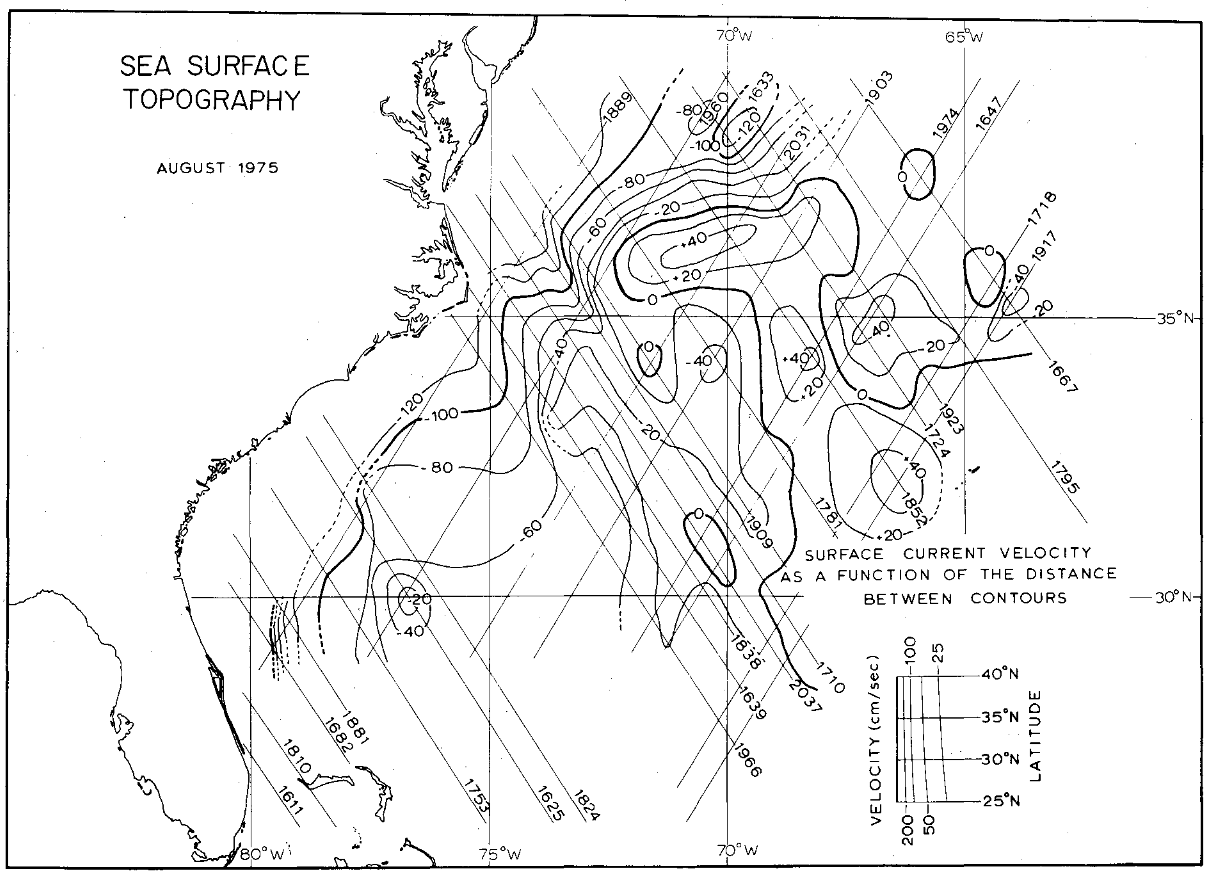

Fig. 4 Mean sea surface topography, Aug. 1975.

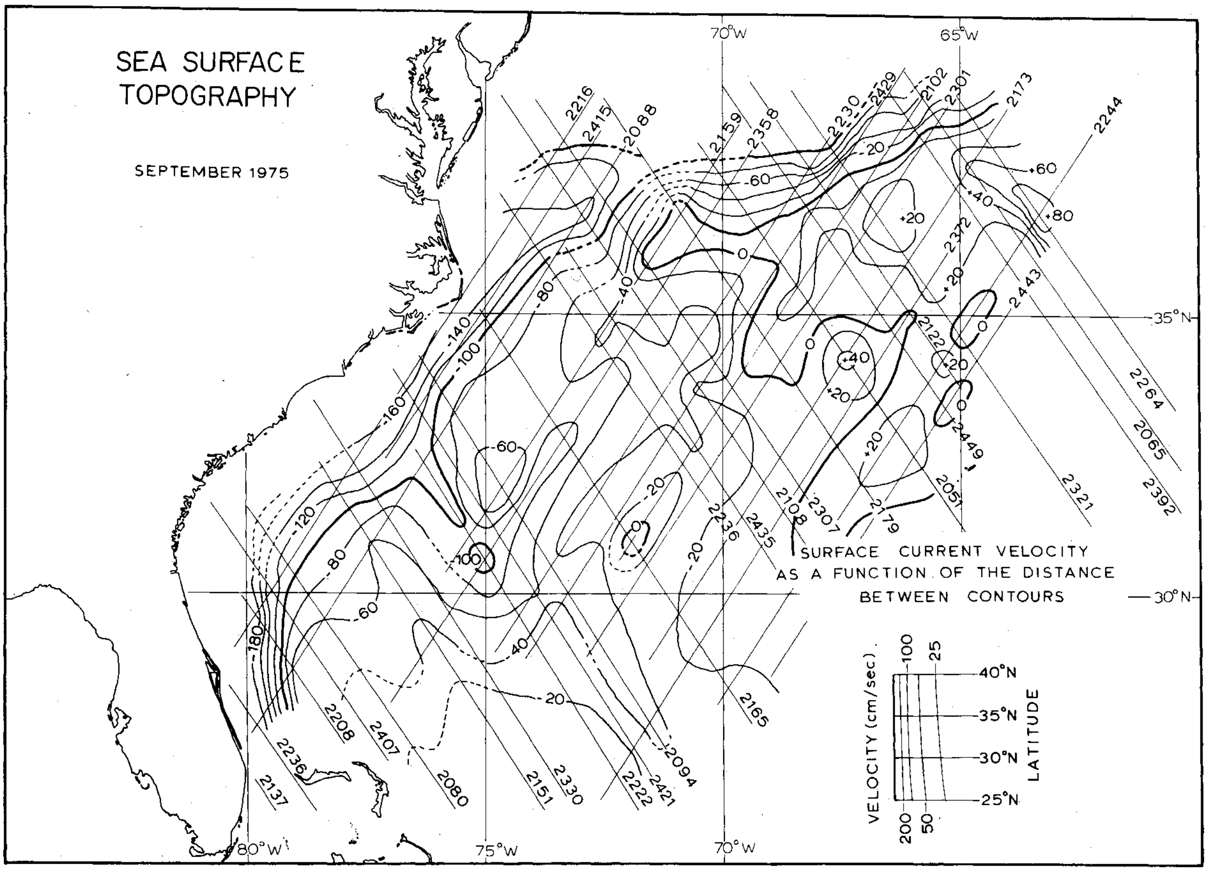

Fig. 5 Mean sea surface topography, Sept. 1975.

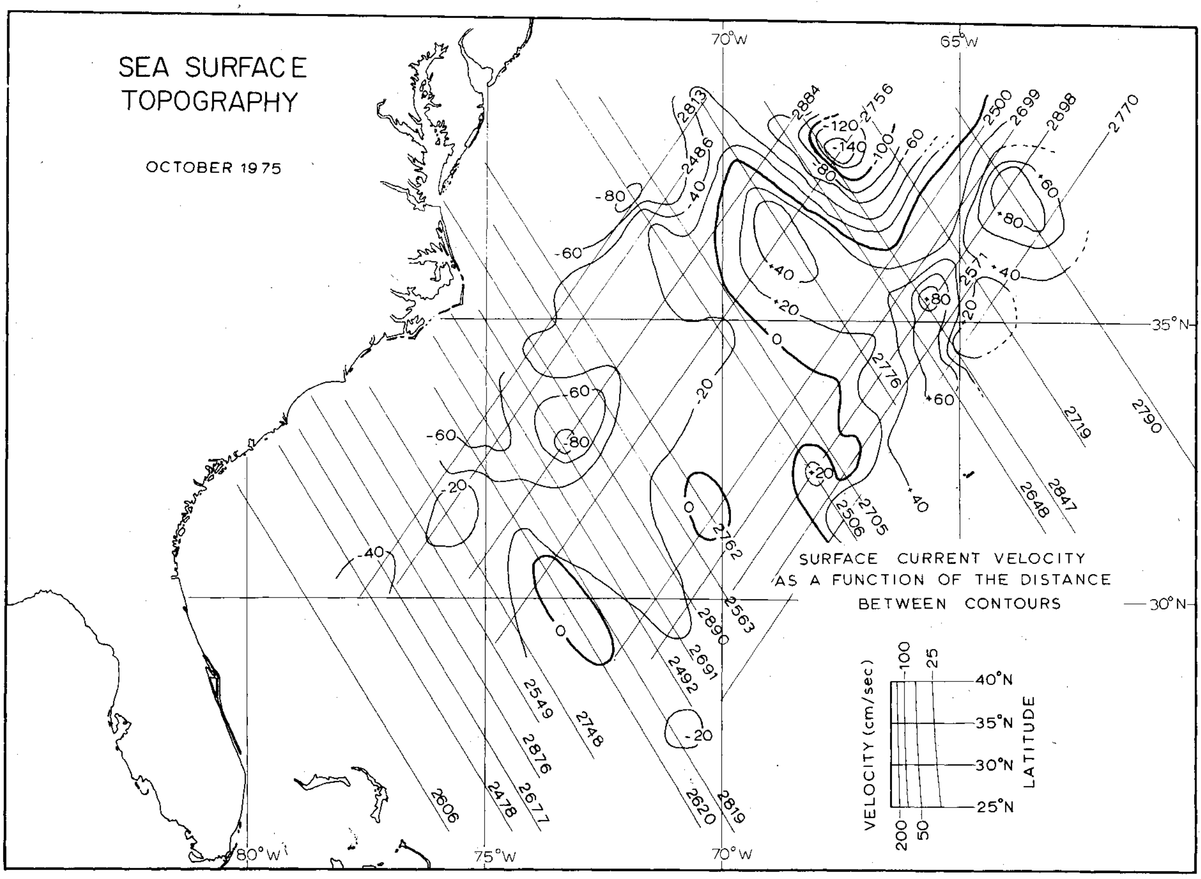

Fig. 6 Mean sea surface topography, Oct. 1975.

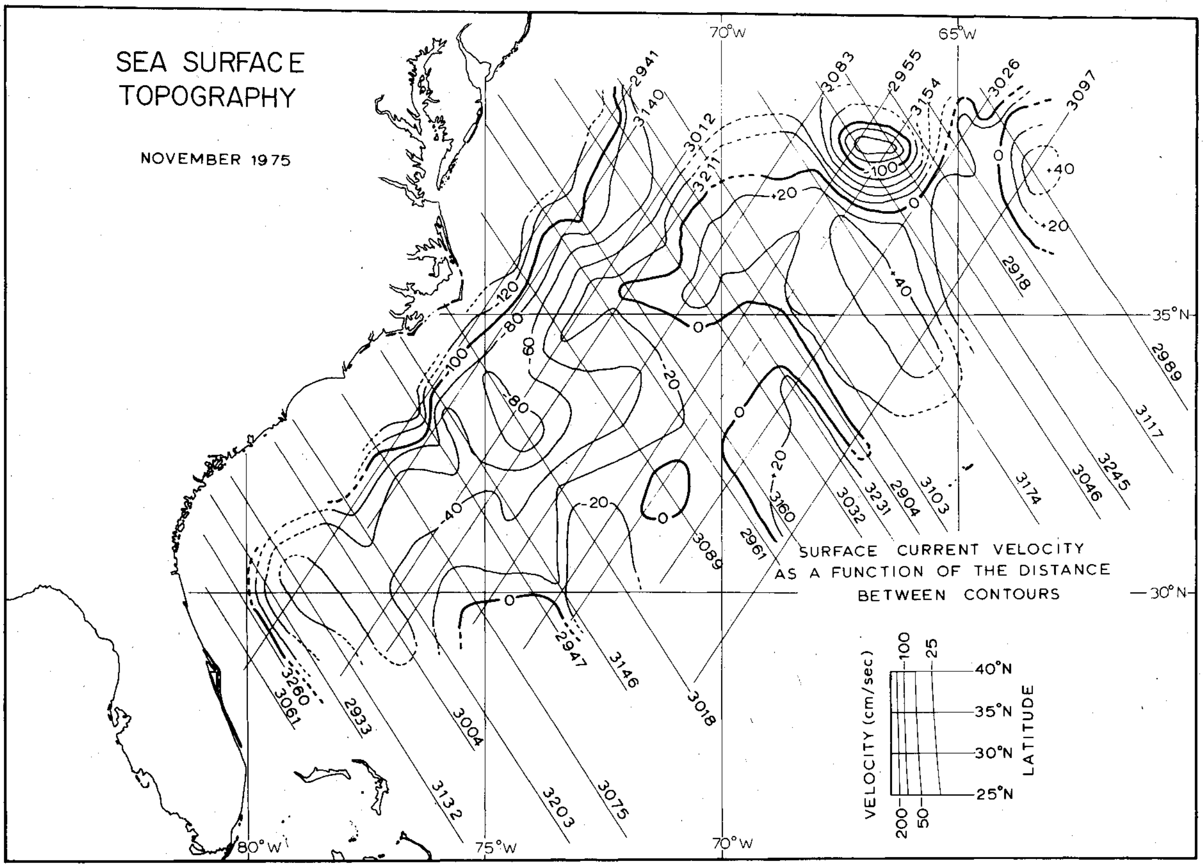

Fig. 7 Mean sea surface topography, Nov. 1975.

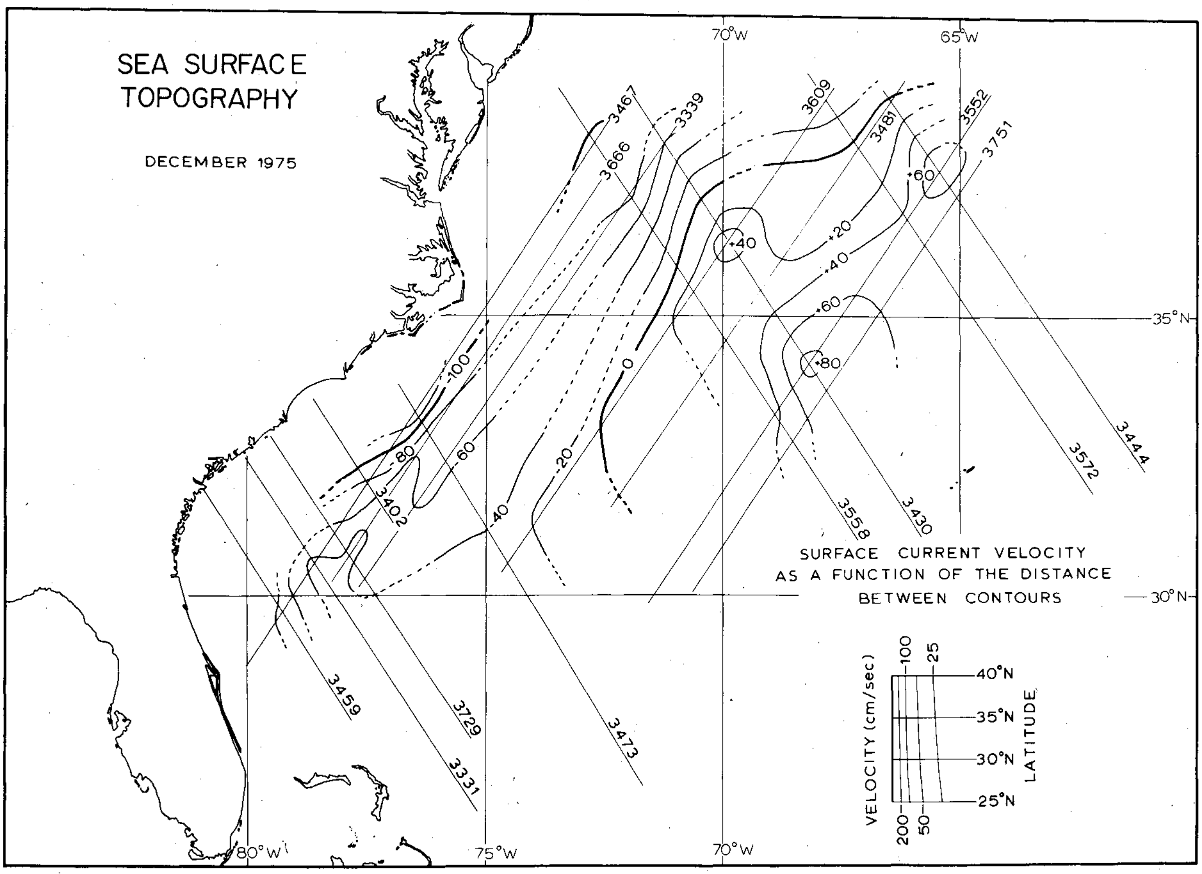

Fig. 8 Mean sea surface topography, Dec. 1975.

November

This month, having 111 intersections, ranks second only to September in terms of data density. The large Gulf Stream meander seen in October is still present but it has moved 1° to the east. A large depression is observed southeast of Raleigh Bay at about 33.5°N, 74.5°W (see Fig. 7).

December

This is perhaps the worst month in terms of number and distribution of passes. Unfortunately, the Gulf Stream is ill defined and there are no other dynamic features observed (see Fig. 8).

Accompanying the topographic maps is a scale which represents the relationship between the slope of the sea surface and the velocity of the ocean surface current computed using the geostrophic equation:

$$v_0 = \frac{g}{2\Omega \sin\phi} \cdot \frac{\Delta h}{\Delta L} \tag{3}$$

where v_0 is the surface velocity; g is the gravity acceleration at 980 cm/s^2; Ω is the angular speed of the Earth; ϕ is the latitude of the location; Δh is the total height anomaly and; ΔL is the horizontal distance over which the anomaly occurred.

Discussion

The general circulation associated with the sea surface topography shown in the six monthly maps have a remarkable similarity to that presented by other oceanographers using hydrographic measurements. The sea surface topographies compare favorably with those presented by Stommel.[7] The product presented here is much more detailed, both in time and space, since the altimeter can obtain many more measurements than a hydrographic vessel in a given period of time. Perhaps more importantly, it is a direct method of observation completely independently of the assumption of the level of no motion.

The quality of the results presented here can be somewhat dependent on the density of coverage and also on the fact that these are monthly averages and there is a certain degree of smearing when the passes are averaged. In a meandering sector of the Gulf Stream or within an eddy, an intersection may yield an average value which is different from the values of each pass comprising such intersection. Table 2 shows the means and standard deviations of the residuals obtained by the minimum variance method for each of the six months studied. The residuals are defined to be the adjusted value of the south-to-north pass minus the average adjusted value of the two passes within a point.

The six maps shown earlier corroborate the findings of previous authors who stated that the sea surface height difference across the Gulf Stream is approximately 1 m. Results presented here show that these differences vary from 60 to 120 cm, depending on the location and width of the current. A discrepancy is found between these results, which report a difference in sea level of about 120 cm just off Cape Hatteras, and those values reported by Iselin,[8] which average 55 cm between Miami and Cat Cay. This discrepancy may also be due to geoidal resolution along the shelf break. Also quite striking is the fact that, in the meander region, the current's eastern boundary is oftentimes more aptly delineated by the +20-cm contour line than by the zero contour line. This indicates the existence of countercurrents along the Gulf Stream as previously reported by Stommel.[7]

Comparison with *Gulfstream*, a monthly publication by the Department of Commerce derived mainly from IR data, shows that many features detected by GEOS-3 also are observed in the *Gulfstream* publication. Of particular interest is the identification by both sources of the large meander observed in the months of October and November. Cyclonic (cold) eddies of large magnitude are also reported in the same position; specific attention is drawn to the positioning of the cyclonic eddy shown at about 35°N in August and September 1975.

It should be pointed out that indeed the accuracy of the geoid may be the limiting factor in the present methodology. There are some anomalies observed at about 36°-39°N, 60°-65°W indicating sea surface heights as high as +80 cm. The high positive value and the recurrence of such anomaly are strong indications that the geoid may be poorly modeled in this area of the New England seamount chain. Another area of possible difficulty is along the continental shelf, where the geoidal anomalies caused by the shelf rise can reach 3-5 m. However, if the surface topographic changes were due to these geoidal errors, the residuals should be stationary in space and time. But, comparison of the topographic maps from month to month indicate clear changes, and these are in general agreement with the monthly IR maps. Such prominent features as shown in the South Atlantic Bight in the months of July and November are good examples. This rationale suggests that the height signals are indeed caused by the Gulf Stream.

Table 2 Monthly mean and standard deviation of the residuals (in cm) for all intersections

Month	$\bar{x}$	σ	N
July	0.01	11.7	81
Aug.	−0.00	10.2	99
Sept.	0.00	15.5	141
Oct.	−0.00	15.7	95
Nov.	0.00	14.3	111
Dec.	0.04	10.7	29

Conclusions

In conclusion, it has been demonstrated that the radar altimeter can provide dynamic profiles of the sea surface. These profiles can be further processed to yield sea surface topographic maps. However, improvements can be made by obtaining better time/space data density using more than one satellite, which would enable a better resolution of shorter time-scale phenomena. Also needed is better local and global geoid definition in anticipation of a 10-cm resolution altimeter and detailed studies of other error sources in altimeter calibration such as sea state and propagation. Finally a well coordinated in situ and remote sensing approach is necessary to provide all information needed to fully understand the dynamic processes of ocean circulation.

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