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REX AND GEOSAT: PROGRESS IN THE FIRST YEAR

The major objectives, plans, and some preliminary progress of the Northwest Atlantic Regional Energetics Experiment (REX) in which sea-surface topography from GEOSAT plays a major role are presented. In addition, a description is provided of those facets of the GEOSAT missions and hardware that have significant impact on the use of this satellite system for the measurement of sea-surface topography, particularly mesoscale topography. Some preliminary comparisons of REX-collected in-situ data and GEOSAT altimetry are included.

INTRODUCTION

The formulation of a suitable satellite system for the global observation of the world's oceans is rapidly becoming an important thrust within the oceanographic research and development communities. Major focal points are the Navy's GEOSAT satellite and the associated Northwest Atlantic Regional Energetics Experiment (REX).

This is an overview of the research objectives, specific plans, and progress after the first year of the field experiment for the multidisciplinary Northwest Atlantic REX. This article is an updated version of Ref. 1, which presented REX plans and was written before the March 1985 launch of GEOSAT. We present in this update a brief account of the progress of REX after the first year of the field components of the experiment.

Ocean topography in the Gulf Stream/Northwest Atlantic region, as collected by GEOSAT, plays a major role in REX, which represents the first concurrent application of several developing oceanographic techniques. The goal is to increase the fundamental process-oriented knowledge of the dynamics and energetics of the Gulf Stream and its associated rings. Thus, the program is ambitious with regard to both the technologies used and the fundamental physics studied. The major experiment (see Fig. 1) centers around the analysis of the following information:

1. Topographic data from GEOSAT;
2. A long time series of sea-surface and thermocline fluctuations collected via arrays of inverted echo sounders with pressure gauges (IES/PGs);
3. Extensive airborne expendable bathythermograph (AXBT) surveys using new equipment that can measure to depths greater than 700 meters;
4. Results of regional, eddy-resolving numerical models (eventually using much of the above data as model inputs and as a means of refining model dynamics).

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SCIENTIFIC OBJECTIVES OF REX

An understanding of the dynamics of the oceanic mesoscale is inseparably linked to the technical ability to observe and simulate numerically the mesoscale circulation. Holland et al.[2] provide an excellent review of the major scientific questions now being addressed via eddy-resolving numerical simulation. Interestingly, the context of much of their discussion is the same as that for REX: regional mesoscale energetics. Also in common with REX are several major questions Holland et al.[2] raise:

1. What processes account for the presence of mesoscale variability?
2. Do mesoscale phenomena play a fundamental role in the character of the time-mean circulation?
3. Can the effects of mesoscale circulation be parameterized in terms of mean field quantities?

In addition to these questions, it is clear that meaningful future work must address the impact of the sparsely measured barotropic (depth-dependent) mode of ocean circulation and the interaction of the circulation with bathymetry. Numerical modeling studies performed at the Naval Ocean Research and Development Activity (NORDA)[3] indicate that the introduction of the barotropic mode into regional Gulf Stream models leads to both a decrease in the spatial and temporal scales of rings and meanders and to the occurrence of Stream bifurcation phenomena.

Further, the subsequent indirect interaction of the circulation (i.e., the seamounts do not physically penetrate into the upper layer in these simulations) with the strong bathymetry of the New England Seamount Chain enhances the frequency of ring generation somewhat to the west of the seamounts and induces a persistent meander in the mean Gulf Stream path over the Seamount Chain itself.

Observational evidence suggests that the effects of the seamounts on the space/time scales of the stream fluctuations are maintained far downstream (eastward) of the seamounts themselves.[4] In fact, a valid question for

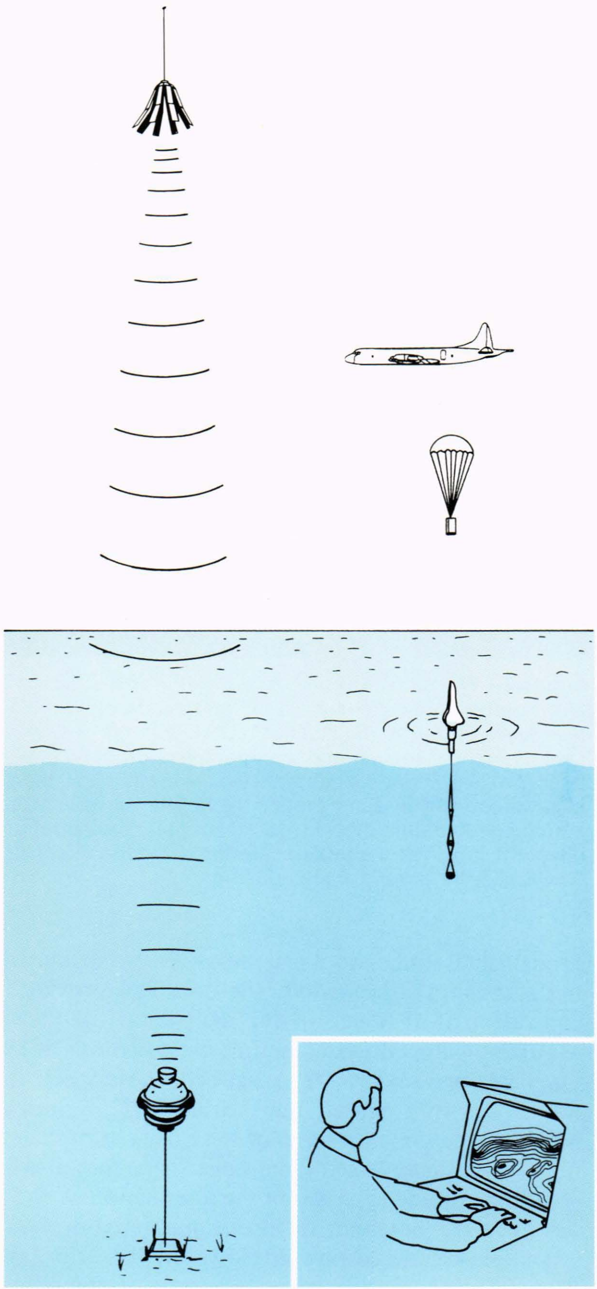


Figure 1—Artist's concept of the Northwest Atlantic REX. The major components of REX are sea-surface topography provided by GEOSAT, field data collected from bottom-moored IES/PGs and regional AXBT surveys, and extensive regional numerical modeling studies.

REX is: Does a Gulf Stream (i.e., a coherent jet) exist downstream of the New England Seamounts? Of course, the relative order of the interaction of the bathymetry with the circulation depends largely on the relative strength of the barotropic mode of the circulation. There are four other fundamental scientific questions to be addressed by REX:

1. What are the pertinent space/time scales of Stream fluctuations in the region of the New England Seamount Chain?
2. What is the relative importance of the barotropic and low-order baroclinic (depth-dependent) modes in governing the circulation within the REX region?
3. How is mesoscale vertical structure influenced by interaction with bathymetry?
4. What are typical energy partitions within the REX region? For example, what are the relative amounts of available potential energy and kinetic energy?

A major difficulty in using GEOSAT-measured sea level in the REX region has been the removal of "background" geoidal effects. This is particularly a problem because warm core rings tend to be quasistationary in the seamount region as a result of topographic (i.e., bathymetric) trapping.[4] On the other hand, numerical models of the circulation in the Gulf of Mexico successfully use synthesized altimetry even when a considerable geoid error is included as part of the synthesized data.[5] In the Northwest Atlantic, the best available gravimetric geoids will be used to help alleviate at least some of the potential problem. During the GEOSAT Exact Repeat Mission (GEOSAT-ERM), the collection of sea-level measurements along repeated ground tracks largely provides a simple solution to the geoid problem (see the following section).

Comparisons between the REX data and model results will represent a major local extension of the initial comparisons made by Schmitz and Holland.[6,7] Additionally, the unique ability of REX-collected IES/PG data and of altimeter topographic residuals to respond to barotropic and low-order baroclinic fluctuations makes prospects for these REX data particularly exciting. REX represents a logical next step, following the Mid-Ocean Dynamics Experiment (MODE) and POLYMODE, in the study of the oceanic mesoscale in a high-variability ocean region.

GEOSAT: THE MISSIONS

As implied by the acronym GEOSAT (GEOdesy SATellite), the satellite's primary mission is to improve the marine geoid. During the initial 18-month period after postlaunch calibration and checkout, GEOSAT collected precise measurements of the range from the satellite to the surface of the ocean by means of Ku-band radar. Coupled with an independent measure of the satellite's position relative to the global TRANET system of radiometric tracking stations, a measure of sea level relative to the earth's center of mass is recovered with an absolute accuracy of the order of 1 meter radially.

The significant components of sea level are

1. The marine geoid, with typical undulation scales of 10^3 to 10^4 kilometers wavelength and as much as 10^2 meters amplitude;
2. Ocean topography arising from ocean circulation over many scales (on the oceanic mesoscale, typical scales are 10^2 kilometers wavelength with 1 meter amplitude);
3. Tides arising from astronomical forces with typical wavelengths of 10^3 to 10^4 kilometers and amplitudes of 10^{-1} to 1 meter.

REX focuses on the analysis of the ocean-topography component of the sea-level measurement, particularly on the scales associated with the ocean mesoscale. (See Ref. 8 for a thorough introductory discussion of the techniques of satellite altimetry.)

The primary geodetic mission data are being used to satisfy the operational needs of U.S. military inertial and strategic navigation systems; therefore, raw range measurements collected during the first 18-month period are not widely available to the oceanographic research community. The basic approach taken to satisfy the satellite's geodetic objectives has been to place GEOSAT initially in an orbit for which the ground tracks fill in the spatial gaps left in the Seasat coverage by that satellite's early demise in 1979. Because high spatial resolution is desired for the geodetic objectives, GEOSAT has laid down a very tightly spaced global mesh of ground tracks.

The major oceanographic objective for GEOSAT is the use of the altimeter for observation of the oceanic mesoscale topography. In general, a nonrepeating pattern of ground tracks does not allow for the unambiguous separation of the geoidal and topographic components of measured sea level except in limited regions where extremely precise gravimetric geoids have been measured. Thus, would-be oceanographic research users of the topographic data collected during the initial 18-month mission have been faced with a number of logistical and technical restrictions (e.g., the initial orbit is nonrepeating).

In 1981, mesoscale oceanography was formally recognized as the secondary objective of the overall GEOSAT mission. To accomplish that objective, Mitchell[9] proposed the extended oceanographic mission or GEOSAT-ERM. During the two-year GEOSAT-ERM, which began at the end of the nominal 18-month geodetic mission (October 1986), GEOSAT's orbit was slightly modified in order to place the satellite in a so-called collinear or exact repeat orbit, with a repeat period of 17 days. Repeat periods of between 10 and 40 days are the most appropriate for the quasisynoptic recovery of the topographic signal associated with the oceanic mesoscale. As well as providing nearly optimum sampling for mesoscale oceanographic studies, this choice of an exact repeat orbit allows for wider dissemination of GEOSAT-ERM range data, greatly increasing the research utility of the data. From the particular 17-day exact repeat orbit selected, the GEOSAT-ERM provides for no significant geoid recovery beyond that already possible using unclassified Seasat data. Thus, the orbit is specifically designed to alleviate any national security issues with regard to range data collected during the GEOSAT-ERM.[10]

Figure 2 shows the pattern of GEOSAT-ERM ground tracks laid down during a 17-day period in the REX region. The 17-day exact repeat orbit provides a global grid of 244 orbits with tracks equally spaced 164 kilometers apart at the equator (see the article by Born et al. elsewhere in this issue). Data collected over the global grid of GEOSAT-ERM ground tracks prove invaluable for

Figure 2—The pattern of ground tracks in the Northwest Atlantic along which sea-surface topographic fluctuations will be measured during the GEOSAT-ERM. During the two-year mission, global sea-surface topographic fluctuations will be collected in a 17-day repeat cycle (i.e., every 17th day the satellite will overfly the same ground track). The background sea-surface temperature mosaic is a recent polar orbiter infrared image; it provides a spatial scale for comparison with the GEOSAT-ERM ground track spacing.

fundamental studies of global mesoscale variability. During a single 17-day period, the data will provide the equivalent of 75 years of ship drift data.[11]

Additionally, GEOSAT returns measurements of both significant wave height ($H_{1/3}$) and nadir wind-speed magnitude. As with Seasat, the measured $H_{1/3}$ values are based on the slope (in time) of the early return or leading edge of the reflected radar pulse. Inference of wind-speed magnitude is based on the attenuation of the radar pulse by the ocean surface as measured in the observed backscattered power. However, this article with its description of REX will concentrate on the oceanographic use of the topographic (range) data.

GEOSAT: DATA FLOW AND HARDWARE

The GEOSAT satellite was built and is being flown by APL under contract to the Navy. Data are routinely stored on board the satellite and are dumped approximately twice a day, when GEOSAT is in view of the single-command and playback ground station at APL's Satellite Control Facility. Within several hours of data receipt at APL, a quick-look version of the satellite's Sensor Data Record is transmitted from the APL ground station to NORDA at the National Space Technology Laboratories in Mississippi. At NORDA, the data are initially scrutinized by research oceanographers. The quick-look data are also used in a developmental program (the GEOSAT Ocean Applications Program (GOAP)), sponsored by the Oceanographer of the Navy, to produce near-real-time analyses of ocean mesoscale topography in a Northwest Atlantic test site (which coincides with the REX region shown in Fig. 3). For a more complete description of GOAP, see the article by Lybanon and Crout elsewhere in this issue.

As part of GOAP, geophysically valid wind and wave-height measurements and ice-edge maps of the Arctic and Antarctic are transmitted in near real time from NORDA to the Fleet Numerical Oceanography Center in Monterey, Calif. The GOAP quick-look data give REX experimenters timely information on the specific locations of mesoscale structures in the REX area, information that is particularly useful in targeting P-3 AXBT surveys, as well as in subsequent data analysis (for example, see Fig. 7).

On a longer time scale (one month or so after real time), precise orbital ephemerides, based on Doppler TRANET radiometric tracking data and computed by the Naval Surface Weapons Center at Dahlgren, Va., are subsequently used to produce a Geophysical Data Record. The Record is used to satisfy both the primary mission geodetic objective and many of the oceanographic research objectives, as well as to provide somewhat delayed corrections and checks on the quick-look developmental GOAP data.

Because the GEOSAT satellite and altimeter hardware are discussed in detail in other articles elsewhere in this issue, we discuss here only those details that have great oceanographic impact. In summary, the GEOSAT hardware configuration consists of a single-frequency (13.5-gigahertz) radar altimeter mounted on an improved GEOS-C bus. The GEOSAT altimeter subsystem is a significantly modified version of the Seasat altimeter with three major changes:

1. A gate window for tracking that is a factor of 2 wider,
2. A diminished time lag for automatic gain control resets,
3. An enhanced instrument range and range-rate digitization.

The above modifications result in a lower instrumental noise floor ($\pm$2-centimeter precision in GEOSAT range versus $\pm$3.5-centimeter precision in an analogous Seasat data stream) and an improved ability of the GEOSAT altimeter to track over ice and land. A major modification of Seasat design has been the use of a long-lived, low-power traveling wave tube amplifier on GEOSAT, resulting in predicted lifetimes of several years for the GEOSAT altimeter subsystem. In fact, it is the use of this low-power tube that made plans for the two-year GEOSAT-ERM feasible.

However, not all the differences between GEOSAT and Seasat design are entirely desirable from an oceanographic viewpoint. Some GEOSAT limitations are the following:

1. The lack of a boresighted radiometer for water-vapor concentration measurements with GEOSAT,
2. The lack of an active thruster-controlled attitude adjust system (the GEOS and GEOSAT configurations are gravity-gradient stabilized),
3. The lack of a laser retroreflector for range calibration independent of the nominal TRANET very-high-frequency and ultra-high-frequency radiometric tracking.

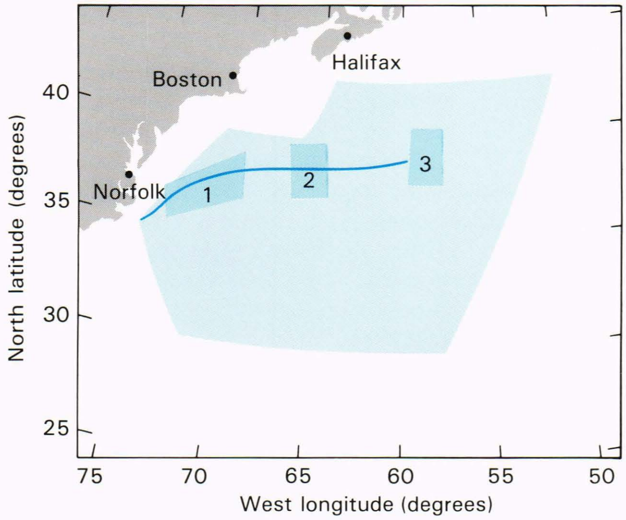


Figure 3—The Northwest Atlantic REX region with contoured bathymetry. NORDA arrays of IES/PGs were located in regions 2 and 3, far downstream of the recent University of Rhode Island array in region 1. The mean axis of the Gulf Stream (colored line) is from Ref. 12. The domain in which GEOSAT topography is available during the initial 18-month geodetic mission is outlined.

The impact of each of these shortcomings is discussed below.

Isolated instances of water-vapor-pathlength errors as large as 30 or perhaps even 40 centimeters may have been observed. During the GEOSAT-ERM, every attempt will be made to use the precise water-vapor pathlength corrections that will be available from the special sensor microwave imager scheduled to fly in 1987 on board a Defense Meteorological Satellite Program satellite. These corrections, albeit not always concurrent with altimeter overflights, should be available throughout much of the GEOSAT-ERM time frame. Long-wavelength (10^3 kilometers or greater) pathlength corrections, based on atmospheric model output, have been and will be made throughout both GEOSAT missions and are included as part of the GEOSAT Geophysical Data Record.

Errors in both range and wind-speed magnitude can result from any inaccuracy in knowledge of GEOSAT's attitude or nadir pointing angle. To overcome that potential problem, a scheme was devised for estimating attitude based on an analysis of the late ("trailing edge") return of the reflected radar pulse. Corrections based on the estimated attitude have been applied to both range and wind-speed magnitude as part of the ground data system processing. After application of the correction scheme, the estimated residual error in range due to off-nadir attitudes is no more than 2 centimeters (1σ) for wave heights ($H_{1/3}$) of 16 meters (the residual error decreases with diminishing $H_{1/3}$). The corresponding residual error in the automatic gain control, which responds to backscattered power of the pulse, is about 0.1 decibel, resulting in an approximate 0.7-meter-per-second (1σ) error in wind-speed magnitude at wind speeds near 20 meters per second.[13] The residual error in wind-speed magnitude diminishes with decreasing wind speeds. Thus, there seem to be no significant errors in range and wind-speed magnitude despite the lack of an active attitude-adjustment system.

Initial orbital ephemerides based on TRANET tracking allow for radially locating the satellite at approximately the 1-meter level of accuracy (this absolute accuracy is not to be confused with the relative point-to-point precision of the range measurement), which is adequate for many (though by no means all) oceanographic objectives. In particular, that accuracy is more than adequate for most mesoscale oceanographic studies. Note that the 1-meter error in absolute accuracy is due to a residual orbit determination error on very long wavelengths (i.e., on the order of the orbital circumference). A nominal 1-meter orbit-determination accuracy for GEOSAT represents a substantial improvement over the accuracy of the initial Seasat ephemerides.

The major contribution of GEOSAT, and more particularly the GEOSAT-ERM, to REX is and will be to provide oceanographic topography, defined as residual sea level after removal of the geoid and tides, on rapid (quasisynoptic) and broad (regional) scales. These topographic data play a key role in REX studies of the mesoscale dynamics and energetics in the Northwest Atlantic. During the geodetic portion of the GEOSAT mission, topography in the REX region is obtained by differencing GEOSAT-measured sea level with existing gravimetric/altimetric geoids of the region. The subsequent residuals (i.e., ocean topography) are widely available and are of use to the research community. Numerous Seasat studies (e.g., Ref. 14) have amply demonstrated the utility of Seasat altimetry in recovering mesoscale topography.

Two major shortcomings in the use of Seasat altimeter data were the short mission duration and a Seasat mission strategy that never placed the satellite in an orbit that could adequately resolve (both spatially and temporally) the mesoscale topography in the cross-track direction. Data collected during the GEOSAT-ERM will overcome some Seasat limitations. Additionally, the short-lived Seasat mission allowed for the collection of very few concurrent field measurements to accompany the satellite observations. During the GEOSAT missions, REX improves the situation by providing in-situ data collected from arrays of bottom-moored IES/PGs and extensive P-3 AXBT surveys.

REX FIELD PROGRAM

Field activities for REX focus on the collection and analysis of data from regional P-3 AXBT surveys and from two arrays (initially) of bottom-moored IES/PGs deployed slightly upstream and downstream of the New England Seamount Chain.[15] Figure 3 shows the two deployment regions of the IES/PGs along the mean axis of the Gulf Stream[12] from June 1985 to their subsequent recovery in June and July 1986. During that one-year period, seven IES/PGs were located in the western region (upstream of the Seamount Chain), and six IES/PGs were located in the eastern region (downstream of the Chain). All but one of the IES/PGs were successfully recovered (the northernmost instrument in the eastern array failed to release from the bottom).

The IES/PGs recorded hourly samples of bottom pressure and temperature, as well as round-trip acoustic travel time, for about 400 days. A typical segment of data is shown in Fig. 4 for the IES/PG at 40°N, 58°W. A low-pass filter, centered at 40 hours, was applied to the data to remove diurnal and shorter period fluctuations. Temperature data show episodic fluctuations of about 0.1°C or less. The acoustic travel time records the passage of a warm feature, followed by what seems to be the movement of the Gulf Stream front across the instrument. Shorter period, 3- to 4-day oscillations are also apparent in the record. Before filtering, the pressure record was dominated by diurnal and semidiurnal tidal components; the plot shows a mesoscale signal probably associated with the movement of the Gulf Stream front.

As discussed in Refs. 16, 17, and 18, the records may be interpreted in terms of fluctuations in dynamic heights and free-surface topography based on a knowledge (or climatological assumption) of the appropriate temperature-salinity characteristics of the region. Note that, while the IES/PG can collect a long-duration time series of barotropic and lowest order baroclinic fluctuations at fixed points in the ocean, the altimeter has the unique ability of providing rapid (quasisynoptic) regional monitoring of the free-surface fluctuations due to the sum of the barotropic and low-order baroclinic components. Comparison of these data may enable the extrapolation of lower order vertical structure information over a fairly broad REX region.

Sea-surface height anomaly is computed as

$$(\mathrm{SSH})' = D'/g + P_b'/\rho_b g$$

with

$$D'/g \sim c\tau'/2 ,$$

where D' is the dynamic height anomaly (local), P_b' is the bottom pressure anomaly, ρ_b is the density at the bottom, τ is the acoustic travel time fluctuation, and c is a conversion factor based on climatological data. (SSH)$'$ is plotted in Fig. 4, which shows a more complex structure (in time) than does τ', suggesting a significant role of the barotropic component. By combining data within each section, the position, direction, and intensity of the Gulf Stream front can be estimated as a function of time.

It is sometimes useful to view the ocean as two constant-density layers separated by an interface corresponding to the main thermocline, a representation that

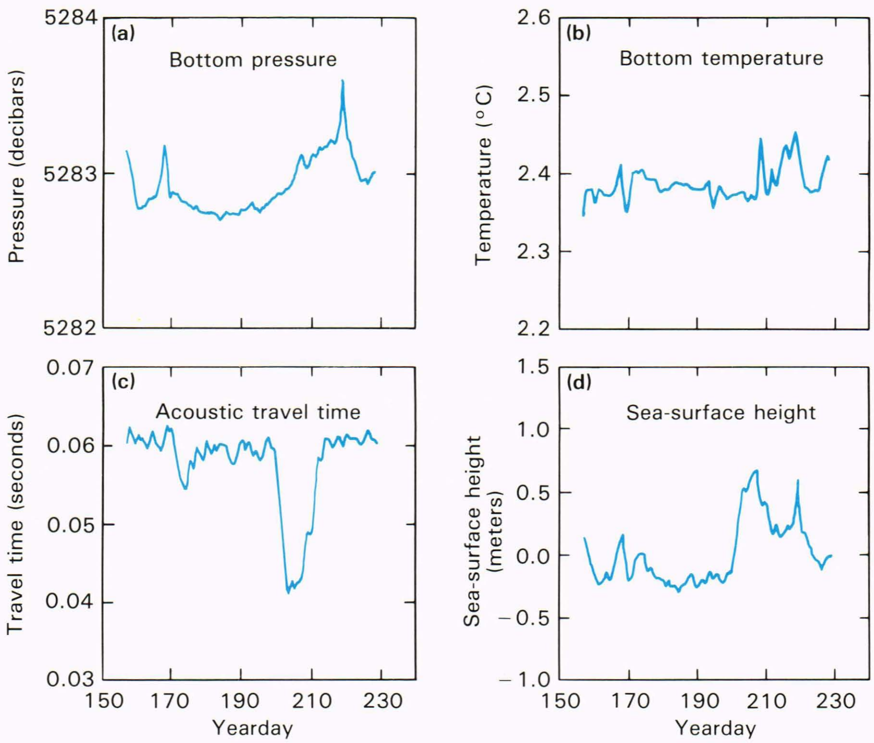


Figure 4—A 75-day segment of a complete IES/PG record (from REX instrument 10, located at 40°N, 58°W, from June 1985 to July 1986) consisting of time series of hourly readings.

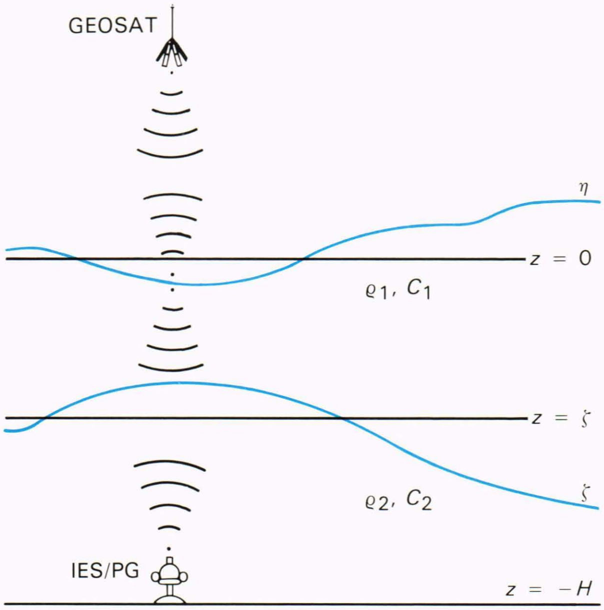
embodies much of mesoscale dynamics and provides a vehicle for comparing observations with a large genre of analytical and numerical models of ocean circulation. Figure 5 shows such a two-layer geometry, where ζ represents the thermocline depth, which, to a good approximation, is proportional to the dynamic height. The problem of deriving the fluctuations $\eta'((\mathrm{SSH})')$ and ζ' from the observed τ and $P_b{}'$ is reduced to the equations shown, where the layer densities and sound speeds are incorporated into the coefficients.

A major objective of the three regional AXBT surveys, carried out in 1985, has been to provide a regional quasisynoptic measure of the temperature structure associated with mesoscale features in the REX area. Each survey has originated from the Naval Air Test Center, Patuxent River, Md., with the major field-staging base in Bermuda. The initial AXBT survey was mounted soon after GEOSAT began returning validated data (May 1985).

Three flights using Navy P-3 aircraft were made on May 19, 21, and 23. The survey tracks for the three days are shown in Fig. 6 as superimposed on GEOSAT ground tracks during May 16 to 24. The background infrared image was taken by the Advanced Very High Resolution Radiometer on board the TIROS satellite on May 20, 1985.

Figure 7a illustrates the AXBT temperature section collected on May 19, 1985; the section is shown in Fig. 6 as the long red track running from south of Long Island to the Sargasso Sea west of Bermuda. Note that for the May survey only Navy Standard 400-meter AXBTs were available. The Gulf Stream front shows up as the strong thermal gradient just slightly north of 38°N. Note that the GEOSAT-measured sea level (in this case, computed using the near-real-time NORDA Data Record) responds to the Gulf Stream front with a rapid rise to the south of well over 1 meter (see Fig. 7b). Along the southern portion of the track, the AXBT section suggests a weak, subsurface cold-core ring at about 35°N (note the upward bowing of the isotherms). Again, the GEOSAT altimeter (Fig. 7b) responds with a slight depression in surface topography, further corroborating the presence of a subsurface ring.

A total of 27 near-surface drifters (actually old sonobuoys with their hydrophones used as drogues at 800 feet) were dropped from the P-3 aircraft along the same track. Figure 7c (solid curve) shows the near-surface current in the direction orthogonal to the survey/satellite ground track inferred from the drifters. Note the nearly 2-meter-per-second currents measured along the Gulf Stream front. The gradient in the observed surface topography is directly proportional to the surface geostrophic current in the cross-track direction. The red curve in Fig. 7c is the cross-track surface geostrophic current computed from the observed GEOSAT surface topography. GEOSAT quite successfully observes the high-velocity eastward core of the Gulf Stream current, as well as the basic structure of the drifter current profile. However, the GEOSAT-derived current has a tendency to overestimate greatly the return circulation along the southern portion of the Stream. It is likely that this is an artifact resulting from the removal of a geoidal reference surface that consists of a blend of shipboard gravimetry (on short wavelengths) with Seasat altimetry (on longer wavelengths). Thus, a residual version of the Gulf Stream exists even in the geoidal reference surface. Since the Gulf Stream was actually located farther south during the Seasat mission than its location during the



$$\zeta' = A\tau' + Bp'$$
$$\eta' = C\tau' + Dp'$$

Figure 5—A schematic diagram of the intercomparison between the overflying GEOSAT altimeter and the bottom-moored IES/PG. Equations express the relationships used to derive fluctuations in mean thermocline depth (ζ') and sea-surface topography (η') from the measured time series of acoustic round-trip travel time fluctuations (τ') and pressure fluctuations (p'). The coefficients $A, B, C,$ and D depend on the regional temperature–salinity characteristics. In the first equation, A is generally much larger than B (i.e., acoustic travel time fluctuations are dominated by thermocline fluctuations). In the second equation, both C and D may be of the same order (i.e., both barotropic and low-order baroclinic modes may be equally important in governing topographic fluctuations).

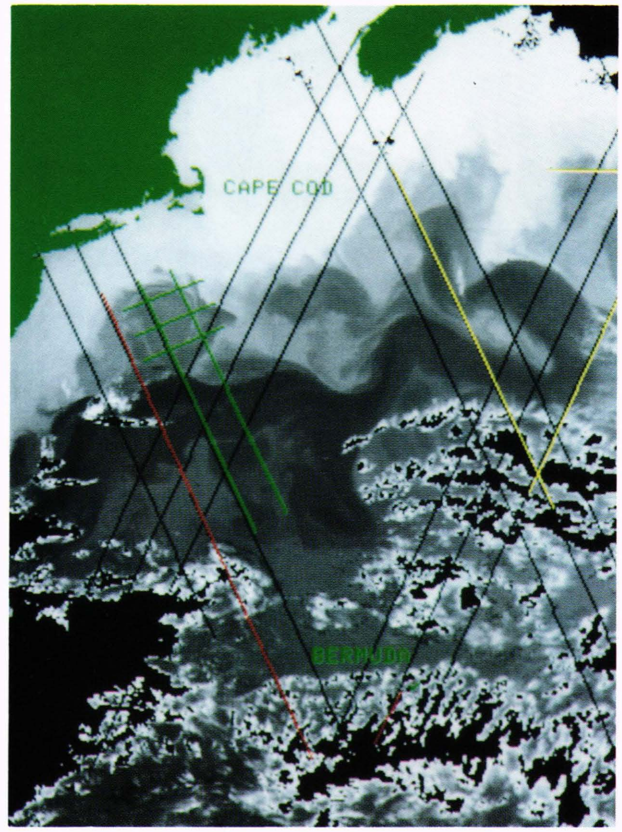


Figure 6—An AXBT survey pattern for the REX survey of May 1985. Each day of aircraft flights is shown in color: red is May 19, yellow is May 21, and green is May 23. The black tracks indicate GEOSAT overflights during the nine-day period (approximately May 16–24). Typically, AXBTs were spaced at regular 10-nautical-mile intervals along each aircraft track. Data collected along the long red track (May 19) are shown in Fig. 7.

early GEOSAT mission, there is a tendency for the GEOSAT residuals (computed using the geoidal surface) to overestimate the gradient along the southern edge of the Gulf Stream.[19] Of course, such shortcomings will be overcome with the collinear tracks of the GEOSAT-ERM.

During the surveys of August and December 1985, extensive use was made of the new Sippican deep AXBTs (Model ANSSQ-36, modified), which can measure to depths of at least 700 meters (see Fig. 8 for the AXBT survey grid carried out in August 1985). These deeper instruments have increased the usefulness of the AXBT data for studies of the available potential energy distribution within the REX region. Also, a comparison of sea level as measured from GEOSAT with the dynamic (baroclinic) topography, based on these AXBT data, may allow for an assessment of the relative roles played by the barotropic and baroclinic modes of the circulation. Extensive AXBT surveys will continue in the Northwest Atlantic in 1987.

REX NUMERICAL MODELING

Perhaps the major limitation on using any satellite-collected oceanographic data is the inability (for the most part) of the satellite sensor to penetrate the ocean surface.[20] Clearly, what is needed is either a means of direct observational augmentation (e.g., deep AXBT surveys) or an indirect means of inferring the internal density field associated with the ocean circulation based on the surface observation alone.

The most promising indirect approach seems to be the concurrent applications of satellite altimetry and regional, eddy-resolving numerical models of the ocean circulation. In fact, the collection of sea-surface topography via satellite altimeters and the subsequent assimilation of that topography into eddy-resolving numerical models promise to provide the cornerstone of any future global ocean-monitoring and prediction system.[21] The methodologies of satellite altimetry and eddy-resolving numerical modeling appear to be maturing rapidly and are clearly convergent over the time scale of the coming decade. Ocean dynamical modeling at NORDA has concentrated on the use of low-vertical-mode, eddy-resolving primitive-equation models (based on mass and momentum conservation rather than on direct vorticity constraints) in regional situations. Dynamical models have now become so realistic for some ocean regions that their results can be compared directly with altimetric data.[22]

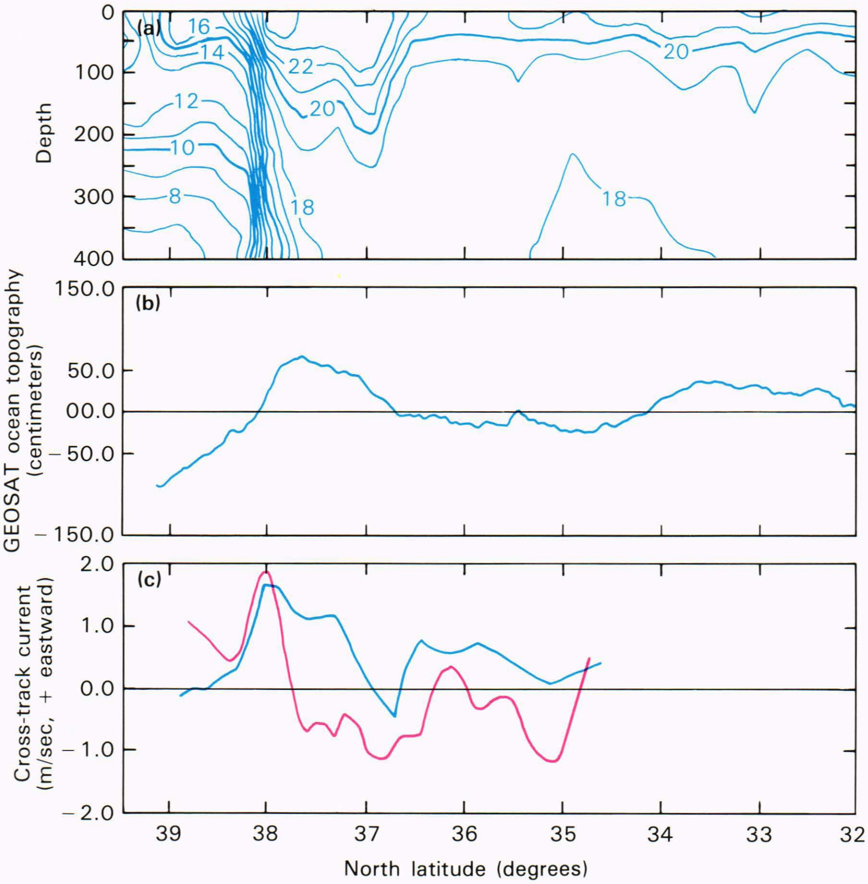


Figure 7—A comparison of in-situ and GEOSAT data along AXBT track 1 collected in the survey of May 1985 (see Fig. 6 for the track line). Data presented are (a) an AXBT-measured thermal section (surface to 400-meter depth) in degrees Celsius, (b) the GEOSAT -derived surface topography from a GEOSAT overflight within 24 hours of the AXBT data collection, and (c) the surface-drifter-derived cross-track currents (blue line) and GEOSAT-derived geostrophic surface currents (red line). See the section on the REX field program for further comments.

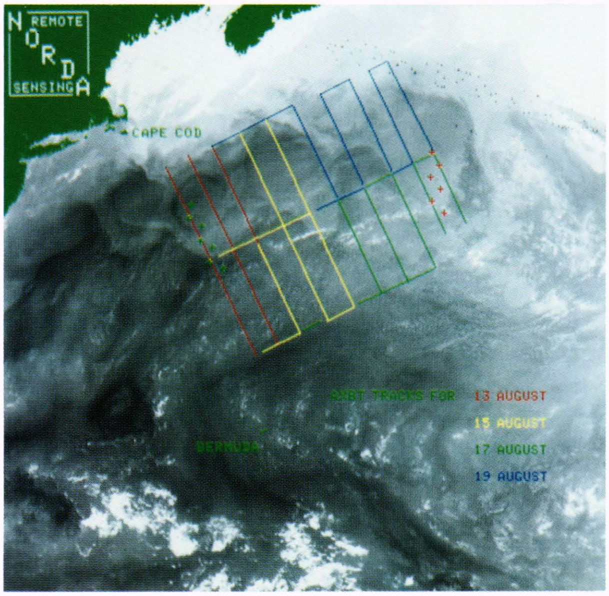


Figure 8—An AXBT survey grid for the REX survey of August 1985. Each day of aircraft flights is shown in the color key by date. Typically, AXBTs were spaced at regular 12-nautical-mile intervals along each track. GEOSAT overflew the three westernmost and the three easternmost survey tracks during the survey period. Additionally, simultaneous data were collected by the bottom-moored IES/PGs located in two arrays (the array to the east of the New England Seamount Chain is shown by red crosses and the array to the west of the seamounts is shown by green crosses).

Figure 9 compares topographic variability from GEOS-3 and Seasat crossovers[23] in the Gulf of Mexico with that observed in a two-layer model of the Gulf.[5] The major advantage of experiments within a bounded region[24] is the relative ease of specifying lateral boundary conditions as opposed to the difficulty with which these conditions must be prescribed in open-ocean domains (e.g., the Northwest Atlantic REX region). Numerous numerical experiments have been performed using the Hurlburt-Thompson models for the circulation of the Gulf of Mexico and simulated altimeter data. The latter is provided by sampling the model surface topography along ground tracks that represent realistic possibilities for future satellite altimeters. The studies by Kindle[25] were instrumental in selecting an appropriate range of repeat periods to consider for the GEOSAT-ERM. Perhaps the most encouraging interim result of the ongoing experiments has been the demonstration by Thompson[5] and Hurlburt[26] that, under some circumstances, the exclusive use of sea-surface topography is adequate for initializing multilayer, eddy-resolving models. These models also provide the diagnostic tool necessary to extrapolate the surface topography observed by the altimeter into an indirect measure of the deep pressure field (i.e., the lower field in these two- and three-layer models). Hence, the satellite altimeter appears to be very useful for both prognostic and diagnostic studies with regional, eddy-resolving numerical models.

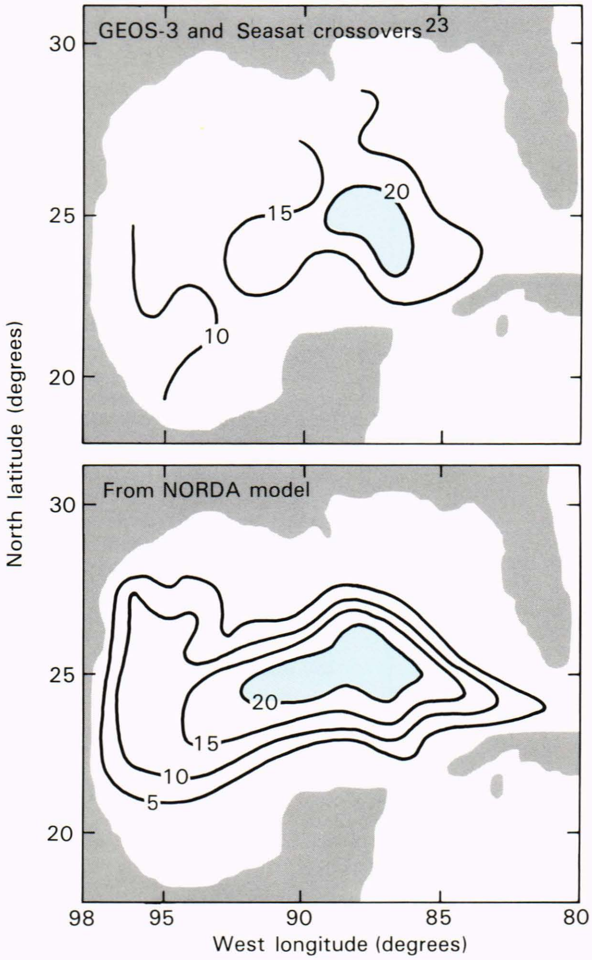


Figure 9—A comparison in the Gulf of Mexico between altimetric sea-surface variability[23] and surface variability as observed in numerical simulations.[5] Both the rms magnitude of the fluctuations and the geographic location of maximum variability are in excellent agreement. Additionally, the altimeter results suggest the same westward extension as seen in the model results. This westward extension is a result of the quasiperiodic pinch-off of eddies from the loop current and their subsequent westward propagation.

Finally, as noted in Refs. 9 and 27, the single satellite altimeter, flying in a collinear or exact repeat orbit, faces an unavoidable trade-off between the spatial and temporal scales that can be simultaneously sampled (Fig. 2). The longer the repeat period of the collinear orbit, the tighter the spacing of resulting ground tracks (a more enhanced spatial resolution results). Similarly, an increased temporal resolution (faster repeat period) results in an unavoidable decrease in the cross-track spatial resolution. The modeling studies of Kindle[25] indicate the applicability of the regional, eddy-resolving numerical model as a tool for alleviating the sampling dilemma. It appears that in some regions the model may be used to provide either an enhanced temporal or spatial resolution to the altimeter data set alone, possibly alleviating the unavoidable inadequacy of sampling with the single altimeter. While the open boundaries of the Northwest Atlantic REX region will admittedly be a problem, initial studies by Hurlburt and Thompson[3] suggest that realistic eddy-resolving models of the circulation of the Gulf Stream from Cape Hatteras to beyond the New England Seamounts are possible.

For example, Fig. 10 shows the bottom topography, instantaneous dynamic sea-surface height, and variance of the sea surface for a preliminary long-term (10-model-year) simulation using the NORDA limited-area, two-layer, primitive-equation model. Inflow transport is specified off Cape Hatteras, and outflow occurs through a 6-degree port east of the Grand Banks. The remaining boundaries are closed. Results from such numerical experiments will be used to interpret and compare with observations from the GEOSAT-ERM and in-situ REX data.

As a parallel effort to the Northwest Atlantic REX described in this article, GEOSAT-ERM will be used in diagnostic and prognostic studies of the bounded circulation in the Gulf of Mexico. Hence, the long-range objectives of the REX are not limited only to that section of the Gulf Stream as seen in Fig. 3 but also include the loop current far upstream of the initial Northwest Atlantic REX area.

REX SCHEDULE AND MILESTONES

As a result of the greatly increased oceanographic usefulness of GEOSAT topographic data during the GEOSAT-ERM, the Northwest Atlantic REX will be directly augmented by academic researchers supported under a special research project, called the Synoptic Ocean Prediction Program, sponsored by the Contracts Research Program of the Office of Naval Research. Like REX, that program will focus on western boundary current dynamics and ocean prediction. Additionally, the global usefulness of the GEOSAT-ERM for mesoscale studies will enhance other programs, including the Office of Naval Research Southern Oceans Program, the Minerals Management Service Gulf of Mexico Program (which has been extended in order to overlap with the GEOSAT-ERM), and the National Oceanic and Atmospheric Administration Tropical Oceans–Global Atmosphere Program.

During 1986–87, three additional sets of AXBT surveys will be carried out in the Northwest Atlantic. AXBTs (deep probes, where necessary) will be dropped along collinear ground tracks of the GEOSAT-ERM in near-synchronism with actual GEOSAT overflights. The inferred dynamic topography profile from those AXBT data will then be differenced with the GEOSAT-measured sea level along the appropriate track to provide a best estimate of the along-track geoid profile. Of course, the barotropic component of the surface topography represents a potential source of error in this analysis and may have to be accounted for. Subsequently, these along-track geoidal profiles can be used in the analysis of sea-level data from all successive passes of the satellite along the appropriate ground track. Thus, we anticipate that errors in the geoid model used for oceanographic analysis of sea-surface topography can be greatly reduced during the GEOSAT-ERM allowing for the measurement of regional, absolute ocean topography in the Northwest Atlantic.

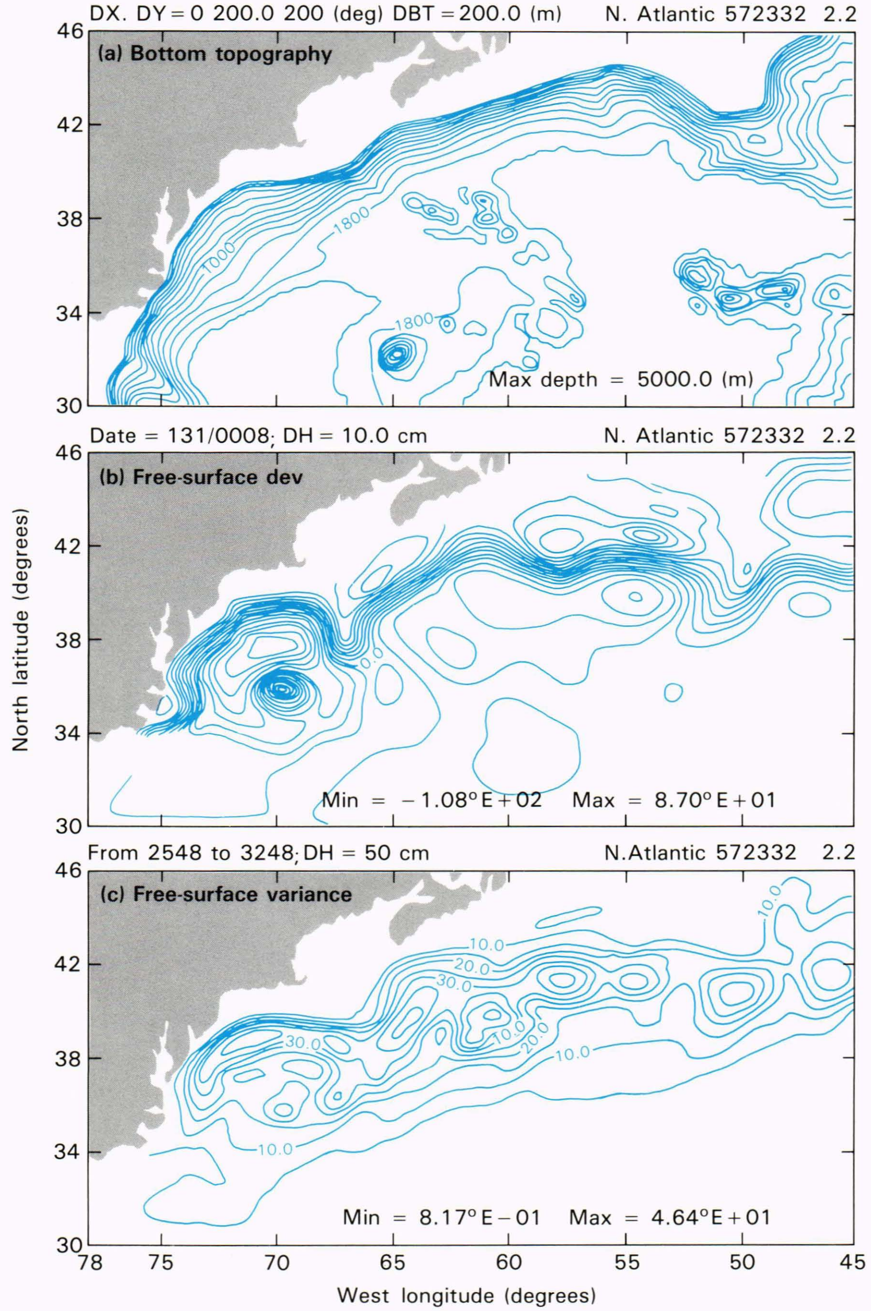


Figure 10—(a) Bottom topography, (b) instantaneous sea-surface height (in centimeters), and (c) rms variability of the sea surface from the NORDA two-layer primitive-equation, limited-area Gulf Stream model.

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ACKNOWLEDGMENTS—The Northwest Atlantic REX is sponsored under Program Elements 61153N (H. C. Eppert, Jr., Program Manager) by the Naval Ocean Research and Development Activity of the Office of Naval Research.