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REAL-TIME SATELLITE ALTIMETRY

High-quality sea-surface height data less than 48 hours old are now available from the Geosat altimeter using an automated or remotely operated personal-computer-based processing system. Regional data sets include total dynamic topography (computed using the new "synthetic" geoid method) in addition to wind speed and wave height. Satellite altimetry, which helps locate ocean fronts and eddies, is being provided to assist in various at-sea operations. Experiments are described in which real-time altimeter data have been used in conjunction with ships, aircraft, and a numerical ocean model.

INTRODUCTION

A real-time data system has been developed at APL to produce scientifically usable sea-surface height, wind, and wave height data within 48 hours of the time of measurements. This new data system is implemented on a personal-computer-based work station rather than the usual room full of large machines. The processing is automated from the input of a raw data tape to the output of hard-copy scientific graphs and digital data files. In addition, the data system can be operated remotely. These capabilities have allowed satellite altimetry to take on an important new dimension, namely, to affect at-sea operations as they happen. Many at-sea operations are influenced by the physical and acoustic properties of fronts and eddies, and the altimeter's all-weather ability to help locate those features can be an important aid to ships at sea. Acoustic properties change at fronts and eddies, and knowledge of their locations is important to Navy operations; because strong currents are associated with them, they are important to ship routing; because water properties change, fishing is affected; because understanding their dynamics involves placement of *in situ* instruments by ships and aircraft, their locations must be known.

A significant new application is the input of altimeter data to a numerical ocean circulation model to forecast more accurately the evolution of ocean mesoscale features. In fact, real-time altimetry has been used for the past two years with Harvard's Gulfcast Project, described by Porter et al. elsewhere in this issue. (Real time is defined here as time that is small compared with the evolutionary time scale of the features of interest. We take it to mean small compared with about 10 days, the time scale of mesoscale ocean fronts and eddies.) These new applications of real-time data greatly increase the value of the satellite.

Altimetry locates fronts and eddies by measuring the changes they cause in sea-surface topography. With the development of the new method of computing total dynamic topography using a "synthetic" geoid, the ability to locate fronts and eddies from altimeter data is enhanced.

The special but ubiquitous balance of forces between pressure changes caused by sea-surface height differences and those caused by ocean currents on a rotating earth is called the "geostrophic balance."[1] A consequence of this force balance is that when one looks downstream in a front or eddy, the sea-surface shape is "uphill" to the right (in the Northern Hemisphere). For example, in the Gulf Stream, which flows from west to east, the sea-surface height rises (about 1 m) from north to south across the Stream. Cold rings, which are shed to the south of the Stream and spin counterclockwise, are round "valleys" in the ocean surface. Warm rings, which are shed to the north of the Stream and spin clockwise, are isolated "hills" on the ocean surface. These height changes are the same in any major front or eddy. In the Gulf of Mexico, the clockwise rings shed by the Loop Current are high in the center relative to the surrounding water. In the north central Atlantic, a fairly flat mean sea surface is expected because there are no major currents in the area. The East Iceland Polar Front flows from west to east and separates the polar water to the north from the Atlantic water to the south, with a consequent rise in sea-surface height from north to south across the front.

In this article, we define an idealized altimeter measurement. A discussion of altimeter-derived mean sea surfaces and synthetic geoids in a number of contexts follows along with a description of the real-time data system. Next, we offer several examples, in the regions mentioned above, of dynamic topography computed in real time and used at sea.

DYNAMIC TOPOGRAPHY

Instantaneous Topography

The components of an idealized altimeter measurement of sea-surface height are shown in Figure 1. The fundamental quantity of interest is the dynamic topography, η, defined as the distance between the physical sea surface and the earth's geoid. The distance, H_s, between the physical sea surface and a reference ellipsoid* (Fig. 1) is

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*We use the 1979 IUGG reference ellipsoid given by $(x/a)^2 + (y/a)^2 + (z/b)^2 = 1$, where $a = 6378.137$ km, and the flattening, $f \equiv (a - b)/a = 1/298.257$.
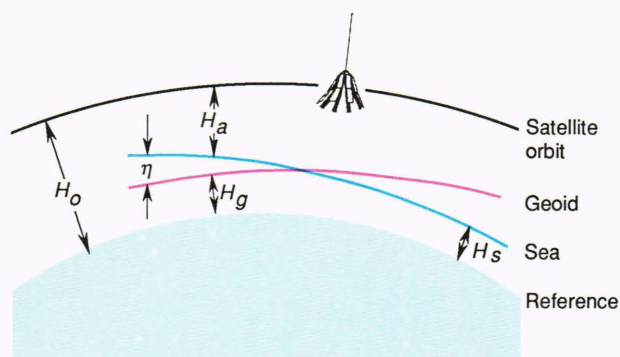
Figure 1. Definition sketch of an idealized measurement of sea-surface height by satellite altimetry. The dynamic topography, η, appearing in Equation 2, is the quantity of interest.

$$H_s = H_o - H_a , \qquad (1)$$

where H_o is the height of the satellite above the ellipsoid, and H_a is the height of the satellite above the physical sea surface. With the known height, H_g, of the geoid above the reference ellipsoid, the dynamic topography, η, is

$$\eta = H_s - H_g . \qquad (2)$$

The dynamic topography would be identically zero if the water were at rest relative to the Earth.[1] (Note that both Eqs. 1 and 2 involve a small difference between two larger numbers. The terms on the left and right sides of Eq. 1 are on the order of 10 m and 800 km, respectively; for Eq. 2 they are on the order of tens of centimeters and tens of meters, respectively. The results are therefore quite sensitive to errors of measurement in any of the terms. Much of the effort in using satellite altimetry measurements for oceanography results from the need to minimize those errors.[2-4])

Mean Sea Surface and Synthetic Geoid

In most cases, the accurate, small-scale geoid required in Equation 2 is not available. There are several oceanographic situations in which a synthetic geoid may be used in place of H_g in Equation 2 to give the correct value of η. When there is no mean current (the simplest case), the mean topography will be zero, $\bar{\eta} \equiv 0$. The mean of Equation 2 shows that $\bar{H}_s$, the mean sea-surface height itself (computed from altimeter and orbit data by Eq. 1), is the synthetic geoid estimate:

$$\overline{H}_s = H_g . \qquad (3)$$

Equation 3 shows that when there is no mean current (or one that is weak compared with currents caused by instantaneous fronts and eddies), as in the north central Atlantic or most of the Gulf of Mexico, a synthetic geoid can be estimated *from satellite data alone*. When there is a mean ocean circulation (as in a western boundary current, or an open ocean front that meanders about its usual position), additional information from a nu-

merical model and *in situ* measurements must be used (see Porter et al., this issue). Examples of dynamic topography computed using different estimates of a synthetic geoid are given in the section "Real-Time Altimetry and *in Situ* Measurements."

SYSTEM OVERVIEW

The overall structure of the satellite data system is shown in Figure 2. The altimeter height is received directly from Geosat at the APL ground station, where the telemetry is immediately converted to digital form and recorded on computer tape. This sensor data record tape, which is produced daily and is generally available about 24 hours after the measurements were made on board the satellite, is the starting point for real-time computations.

The altimeter measurement must be corrected for the effects of the atmosphere on the propagation of the radar pulse to and from the ocean surface. The corrections depend on atmospheric temperature, pressure, and solar flux,[2-4] variables that are not measured by the satellite and must be obtained from other sources. We obtain daily atmospheric temperature and pressure from the Navy's Fleet Numerical Oceanography Center in
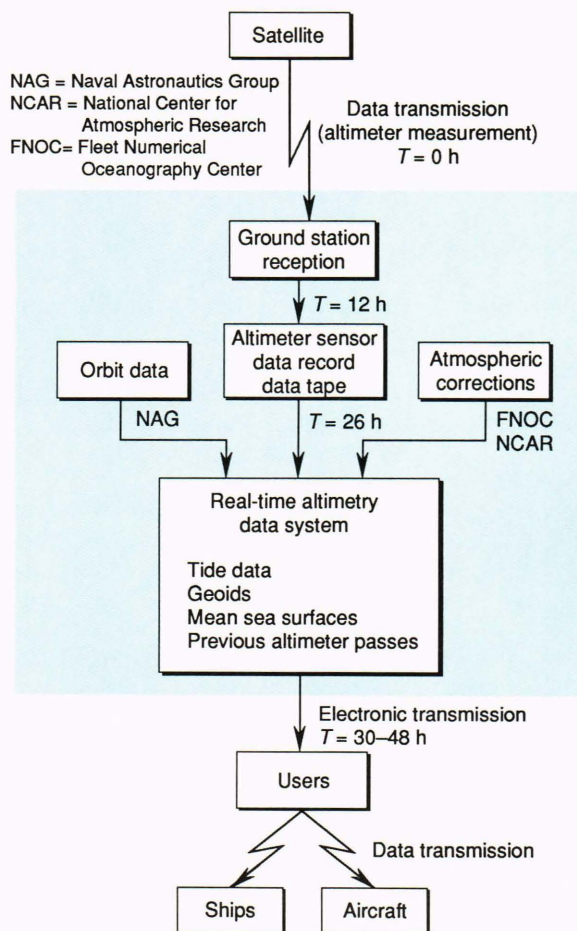

Figure 2. Overview of the real-time Geosat altimetry data processing system, from the time of measurement to transmission to users at sea.

Monterey, Calif. The solar flux is obtained daily from the Royal Canadian Observatory in Ottawa via the National Center for Atmospheric Research in Boulder, Colo. The variables are brought into the data system during the 24 hours before the sensor data record tape is available, and are ready to use when the tape arrives. Corrections for ocean tides are also made.[5]

To complete the computation of Equation 1, the satellite orbit height is computed from a worldwide satellite tracking network by the Naval Astronautics Group in Point Mugu, Calif.

To arrive at the dynamic topography, the geoid height must be subtracted, as in Equation 2. The new and very promising technique of using a synthetic geoid (computed from previous altimeter measurements and an ocean model; see Porter et al., this issue) is used whenever possible in our real-time system. The older well-known techniques of subtracting a mean sea surface or a previous single altimeter measurement (in place of H_g in Eq. 1) are used when a synthetic geoid is not yet available for the particular area of interest. Examples of these techniques follow; each is from a project in which real-time altimetry has been used during at-sea operations.

REAL-TIME ALTIMETRY AND *IN SITU* MEASUREMENTS

The Gulf Stream

For the past two years, real-time altimetry data have been provided to Harvard University for initializing an ocean circulation model in the Gulfcast Project (see Porter et al., this issue). In the forecasting project, all available measurements are used to initialize a numerical model that forecasts the next week's development of the Gulf Stream and its warm and cold rings. The initialization is crucial to an accurate forecast, and the required data—obtained by means of dedicated Airborne Expendable Bathythermograph (AXBT) flights, *in situ* hydrographic measurements, and infrared images—are expensive, difficult to obtain, and sometimes simply unavailable. Recently, the full dynamic topography, computed by subtracting the synthetic geoid, has been used in this project with dramatic results.

In Figure 3, the dynamic topography from the altimeter is compared with that of a five-day model forecast (which also incorporates *in situ* measurements). The two agree very well on the position and magnitude of the large Gulf Stream signal. The clear altimeter signature of a warm ring is slightly north of and smaller than that of the model. Experience has shown that in such situations, which often occur when the model does not have enough *in situ* data for accurate initialization, the altimeter is correct. Then, the model initialization is changed to incorporate the more accurate altimeter measurement. At the southern end of the data coverage (Fig. 3), the altimeter shows a small cold ring that was entirely missed by the model, which had forecast the ring to be farther west. This again shows how altimeter-derived dynamic topography can be used, in place of AXBT data or when clouds obscure infrared images, to improve knowledge of the state of the ocean. In a sub-
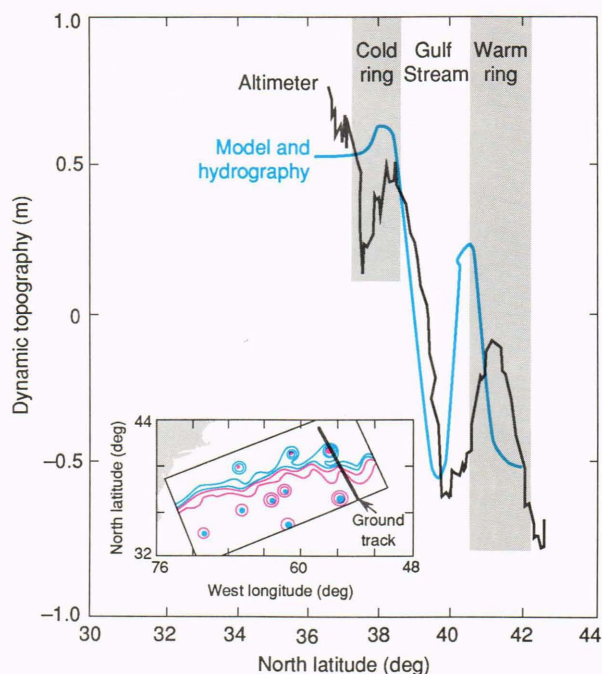

Figure 3. Example of real-time dynamic topography in the Gulf Stream region, computed using a synthetic geoid, compared with that of the Harvard Gulfcast model initialization. The inset shows the satellite ground track and the model initial positions of the Gulf Stream and the rings. The data are for 8 March 1989. A solid blue center indicates a cold ring, and a solid red center indicates a warm ring. The contours are streamlines that are proportional to the sea-surface height. Blue indicates lower height and lower temperature than red. Note the excellent agreement for the Gulf Stream, the slightly different position of the warm ring along the indicated ground track, and the presence in the altimeter data of a cold ring that was missed entirely by the model.

sequent initialization, the ring is shifted east in the model to its correct position (i.e., according to the altimeter measurement), and the next forecast is more accurate.

The Gulf of Mexico

The Loop Current of the Gulf of Mexico enters the Gulf from the Yucatan Straits, forms a large clockwise loop, and exits through the Florida Straits to become the Gulf Stream. Like other major ocean current systems, the Loop Current of the Gulf of Mexico, which fluctuates in the eastern part of the Gulf, sheds rings that propagate westward away from it. The strong currents in the rings affect offshore drilling and other operations in the area. Historically, satellite infrared data have been used along with data from periodic ship cruises to monitor the life cycles of the rings. During warm months, however, the surface temperature of the Gulf of Mexico is too uniform for infrared data to be useful, and satellite altimetry provides the only remote measurements of the currents. For the past year, altimeter-derived dynamic topography has been used in concert with ship and air surveys of the region, both to monitor Loop Current eddies and to compare the altimeter measurement with the *in situ* data.[6] In the summer of 1988, when the world's largest offshore drilling rig was being

deployed in the Gulf of Mexico, real-time altimeter data were used to help monitor a large Loop Current ring and to help direct the placement of ships and aircraft.

A synthetic geoid has not yet been computed for the Gulf of Mexico. In its absence, a mean sea-surface height H_s can be used in Equation 1 instead of the synthetic geoid, as discussed earlier (Eq. 3). A mean sea-surface height has been computed from a year of altimeter data, using only those data for which rings and Loop Current were absent, so that $\bar{\eta} = 0$, and Equation 3 applies. The resulting dynamic topography is compared with that derived from *in situ* data in Figure 4.[6] The agreement in slope of the topography is quite good. The slightly northern position of the ring in the *in situ* data is accounted for by the time difference (several days) between the altimeter and the *in situ* measurements, when the ring was propagating west and south. If one allows for this shift, the two measurements agree within 4 cm root mean square, near the limit of accuracy of the altimeter measurement.

The North Central Atlantic

In the north central Atlantic Ocean, weak and scattered current filaments are all that remain of the once mighty Gulf Stream. On the average, only a very weak mean circulation would be expected in this region, and a simple, long-term mean sea surface computed from altimeter data via Equation 1 can be taken as an estimate of the geoid, as given in Equation 3. This situation is simpler than the one in the Gulf of Mexico because times during which a large meandering current is in the area do not have to be excluded: there are no large currents in the area. An example of dynamic topography from this region is shown in Figure 5, taken from the Joint Global Ocean Flux Study,[7] during which this real-time dynamic topography was supplied to ships at sea to help place *in situ* measuring devices. As seen in Figure 5, unexpectedly large mesoscale features (40 cm) were found in the area. The source of those eddies and their effect on the life cycle of the important spring bloom of plankton are under further study.[7]

The East Iceland Polar Front

Between Iceland and the Faeroe Islands lies a meandering ocean front that separates the Atlantic and polar water masses. Because this front is often obscured by clouds, altimetry provides the only way to remotely monitor its movements. When the real-time altimetry data system became operational in May 1987, neither a synthetic geoid nor a mean sea surface was available for this region. Under such circumstances, the changes in dynamic topography can be computed by differencing the altimeter's sea-surface height measurements at two different times along the same ground track. This technique provides an easy, quick, and useful way to provide real-time altimetry data in a new region of the ocean where little is known. For several months in 1987, the Harvard ocean model was set up to operate in that region.[8] A special series of AXBT measurements was made around the front, and APL provided real-time dynamic topography differences, again both to help in model in-
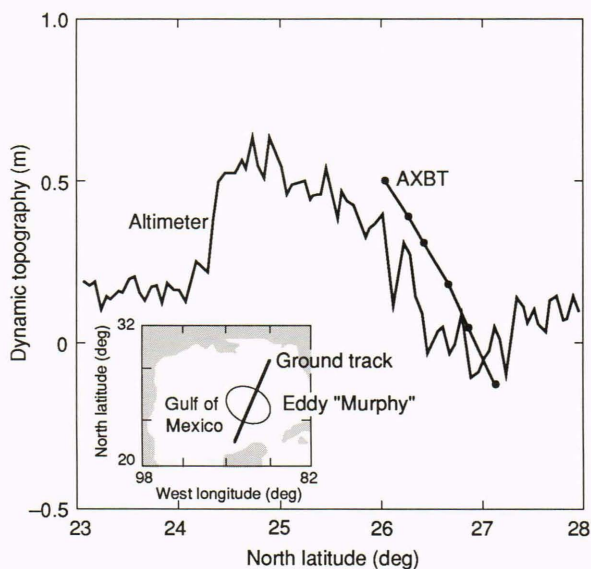

Figure 4. Example of real-time dynamic topography in the Gulf of Mexico region (20 June 1988), computed using an altimeter-derived mean sea surface. The ground track and the position of the large Loop Current eddy "Murphy" are shown (inset). The good agreement with AXBT data is discussed in Ref. 6.
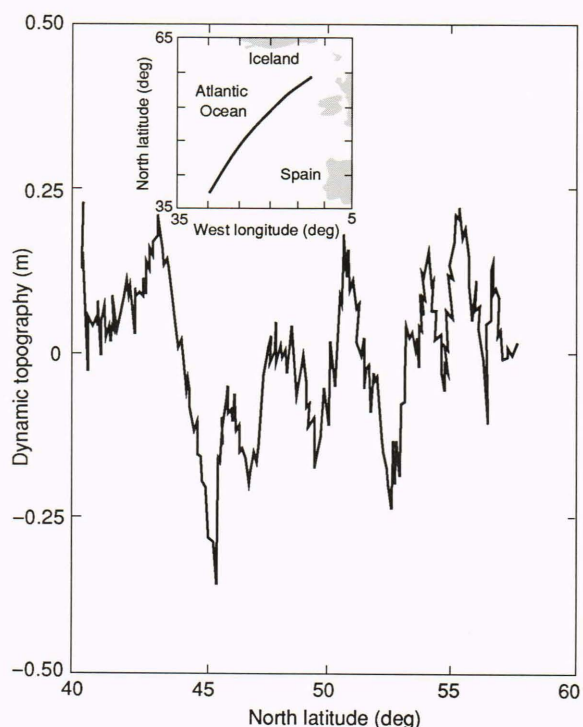

Figure 5. Example of real-time dynamic topography in the north central Atlantic (the inset shows the ground track), taken from the Joint Global Ocean Flux Study. (Reprinted, with permission, from Ref. 7.) The surprisingly large mesoscale features found in this presumably "quiet" region of the Atlantic are still under investigation.

itializations and to help locate where *in situ* measurements should be made. A comparison of the altimeter

topography with the corresponding topography computed from the model and *in situ* measurements is shown in Figure 6.[8] The measurements agree on the position and magnitude of the front.

CONCLUSION

A real-time data system for producing high-quality scientific Geosat altimeter data has been developed. Total dynamic topography is now available within 48 hours of the time the altimeter measurements were made. Although not discussed here, wind and wave height, which can be computed from altimeter data, are also included in the real-time data stream.

The APL real-time altimeter data system has been used successfully for nearly two years, providing dynamic topography (in a variety of digital and hard-copy formats) for many different regions of the world's oceans (Fig. 7), including the Gulf Stream ring and meander region (1987–1989), the Gulf of Mexico (1988–1989), the north central Atlantic (the Joint Global Ocean Flux Study, 1989,[7] and the Athena experiment, 1988[9]), the East Iceland Polar Front (1987[8]), and the northeast Pacific (the NEPAC experiment, 1988–1989).

Various real-time altimeter data products have been provided for different users and purposes, such as helping to direct ships at sea making *in situ* measurements. Additional uses of the data have included planning more effective and efficient AXBT flights, initializing a numerical ocean circulation model, and providing the only available physical measurements in remote, cloudy regions. The information has been provided to academia and industry as part of a collaborative effort to assess the accuracy of altimeter measurements by comparing them with other data.

The altimeter real-time data system has been reduced in size to an elaborately configured, desktop, personal-computer–based system that can be operated locally or remotely. This compact, automated system makes real-time altimetry ready for development into portable and perhaps even seaworthy systems. A realization of these possibilities would open the door to many new and exciting applications of satellite altimetry.

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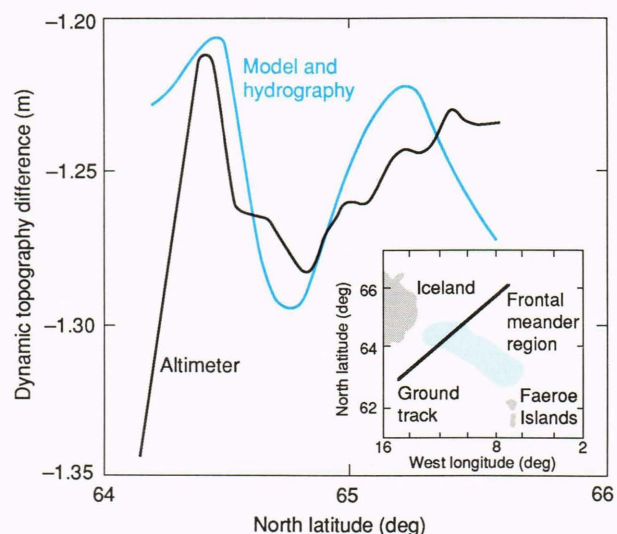[9] Calman, J., *An Atlas of Altimetry Data for the Athena Experiment*, JHU/APL STH-88-096 (1988).

Figure 6. Example of real-time dynamic topography changes near the East Iceland Polar Front. The data are the differences between 11 July 1987 and 29 May 1987. The data locate the Front within the general frontal meander region. Comparisons with *in situ* and model data are discussed in Ref. 8.
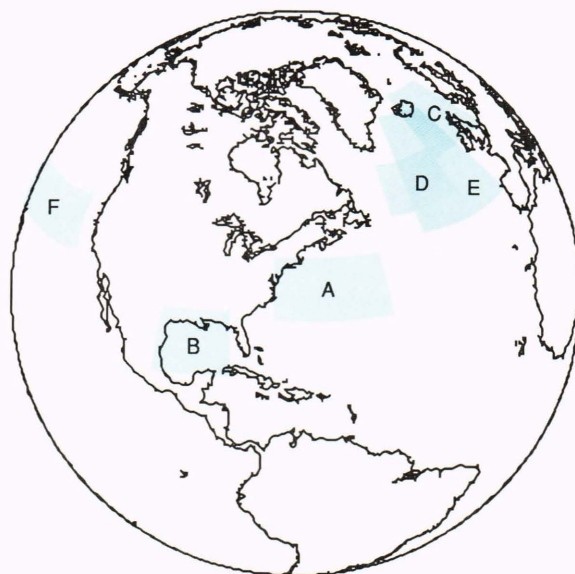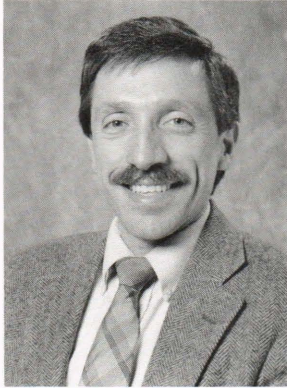

Figure 7. Ocean regions in which the real-time data processing system has been used. A = Gulfcast region. B = Gulf of Mexico studies. C = East Iceland Polar Front. D = Athena experiment. E = Joint Global Ocean Flux Study. F = NEPAC experiment.

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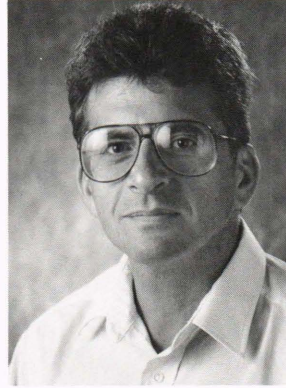
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