# A Test of Ocean Surface-Current Mapping with Over-the-Horizon Radar

T. M. Georges, J. A. Harlan, R. R. Leben, and R. A. Lematta

***Abstract*—A two-day test with a decametric over-the-horizon (OTH or ionospheric) radar in Virginia attempted to map the radial component of ocean surface currents over a 210 000-km$^2$ area that includes the Florida Straits and parts of the Gulf of Mexico as distant as 1500 km. Ionospheric motions distort and bias individual measurements, but their effects are mitigated by a combination of strategies that take advantage of the different space and time scales of oceanic and ionospheric motions. In addition, nearby land echoes are used as zero-Doppler references to correct for ionospheric shifts. The result is a composite picture of the Florida Current and ancillary surface flows with 10–15-km resolution. The picture agrees quantitatively with known currents in the region, but reveals dynamical features with new detail. Concurrent sea-surface topography in the Gulf of Mexico, derived using tandem altimetric observations from the TOPEX/Poseidon and ERS-1 satellites, confirms that a region where the OTH radar measures a southwestward current greater than 1 m/s$^{-1}$ coincides with the confluence of the Tortugas Gyre and the Gulf of Mexico Loop Current. These results suggest that consistent surface current maps can be constructed by using OTH radar to repeatedly interrogate a region of interest, perhaps over several days.***

***Index Terms*— Currents, ionosphere, oceanography, remote sensing.**

## I. INTRODUCTION

SURFACE-CURRENT measurements with high space and time resolution and large areal coverage are difficult and scarce in the open ocean. They are of particular interest in the vicinity of the Gulf Stream and its eddy field, which contain most of that ocean region's kinetic energy and affect the Atlantic Ocean's thermohaline circulation. Shore-based high-frequency (HF or 3–30 MHz) radars, such as the commercially available CODAR [1], [2] and OSCR [3], [4] systems, have been used to map offshore surface currents over areas approaching 1000 km$^2$ with a resolution of about 1 km and 4 cm/s$^{-1}$. HF radars have the advantage of being able to map currents over fixed areas, through clouds and rain, but their useful range has so far been limited to the radio horizon—usually about 50 km.

Attempts to extend the range of HF current-mapping radars by using ionospheric reflections have met with limited success. The reason is that ionospheric motions shift the sea-echo spectrum in the same way that currents do, making it difficult to separate the two effects. In addition, multiple radar paths through the ionosphere cause Doppler spreading and prevent accurate current estimates. Because no satisfactory way to estimate and remove these ionospheric distortions has yet been found, they present the main obstacle to extracting all but the strongest surface currents from ionospherically reflected sea echoes.

Here we describe a surface-current mapping test by using an over-the-horizon (OTH) radar, in which we attempt to remove ionospheric distortions and biases by repeatedly interrogating the same ocean region and constructing a composite current map from the most reliable data subsets. Reliability is measured with an empirical data-quality index, and biases are removed using zero-Doppler land echoes and methods that take advantage of the different space and time scales of oceanic and ionospheric motions. Our main conclusion is that, with care, consistent surface-current maps can be constructed using OTH radar by repeatedly interrogating a region of interest, perhaps over many days, and selecting the data of highest quality.

We begin by briefly describing the method by which HF radars measure ocean surface currents and the particular difficulties encountered when extending the range of these measurements by using ionospheric reflections. Next, we examine the nature of ionospheric distortions and ways to avoid or remove them. Then we describe our radar test and show evidence that our processing methods are effective, including a comparison with concurrent satellite altimetry. Finally, we interpret the resulting current map, which reveals ocean dynamical features in the Florida Straits with new clarity.

## II. HOW HF RADARS MEASURE OCEAN CURRENTS

HF current-mapping radars use line-of-sight and ground-wave illumination of the sea surface to measure the spectrum of echoes backscattered from Bragg-resonant ocean waves, typically 6–12-m long. In the absence of currents, the sea-echo spectrum consists, to first order, of two sharp lines with equal positive and negative Doppler shifts corresponding to the phase velocity of ocean waves of one-half the radar wavelength traveling toward and away from the radar. A

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constant surface current transports the ocean waves, so that their apparent phase velocity, as measured by a stationary observer, is the sum of the phase velocity in still water and the component of near-surface current in the direction of wave travel [8]. One HF radar can, therefore, infer radial surface current from the amount of displacement of the “Bragg lines” of the echo spectrum from symmetry about zero Doppler. To measure surface-current vectors, two radars must interrogate a common ocean area and combine their radial current measurements. Employing the usual radar techniques for resolving echoes in range and azimuth, a pair of such shore-based radars can effectively map surface current, for example in bays and estuaries, to ranges of about 50 km, with a resolution of a few kilometers. HF radars typically measure the currents in the ocean’s upper meter [8].

## III. EXTENDING HF RADAR CURRENT MEASUREMENTS OVER THE HORIZON

Because HF radio waves reflected from the ionosphere can reach great ranges (up to 3500 km in one ‘hop’), it was at first thought that the range of current-mapping radars could be usefully extended in this manner to cover millions, instead of hundreds, of square kilometers of open ocean. Except for two intervening ionospheric reflections, the physical principles are identical to those just described for ground-wave radars.

Two obstacles stand in the way, however, the first is the need for very large aperture antenna arrays. Beams of 1° or less in azimuth are required to resolve the most interesting ocean current features at ranges of 1000 km and more. For a frequency of 15 MHz, for example, a 1° beam would require a 1-km aperture. Maresca and Carlson [5] used a large-aperture OTH radar in California to measure longshore currents associated with hurricanes Anita and Babe off the Texas coast. Trizna [6] measured Gulf Stream currents in the North Atlantic as far as 1400 km from a Navy radar in Virginia by using reflections from a stable ionospheric $E$ layer. Georges and Harlan [7] used an Air Force OTH radar in Maine to map a portion of the Gulf Stream and a cold-core ring off Cape Hatteras.

The second obstacle is the distortion the sea echo suffers after two reflections from the ionosphere (one outgoing and the other on the return path). Ionospheric reflection (or more accurately, refraction) and space-time multipath can spread and shift the sea-echo spectrum, making it difficult to measure exact Doppler shifts and to distinguish Doppler shifts caused by the currents from those caused by ionospheric motions. Maresca and Carlson [5] compensated for ionospheric shifts over a 3000-km $F$-layer path by using nearby land echoes as zero-Doppler references. This approach is effective when a fixed target (or one with a known radial velocity) is available, but the area over which such corrections are valid is unknown. Devising better ways to avoid and correct for ionospheric biases and distortions requires an understanding of the space-time scales of the ionospheric motions that cause them. The fact that ionospherically induced Doppler shifts typically vary on scales of minutes to hours, whereas the ocean currents we want to map remain stable for days or weeks [15], offers an opportunity to use simple filtering methods to separate the two effects.

## IV. THE NATURE OF THE IONOSPHERIC DISTORTIONS

Ionospheric motions and irregularities continuously shift the phase of the received sea echo by changing the length of the two-way radar path through it. These phase fluctuations are normally indistinguishable from and are often of the same order of magnitude as the Doppler shifts (rate of change of phase) caused by radial ocean currents, that is, a few tenths of a hertz. If radial currents are derived from ionospherically shifted sea echoes, current measurements become biased. Ionospheric bias is caused both by the diurnal formation and dissipation of the ionospheric layers themselves and by shorter-term dynamical features, such as wavelike traveling ionospheric disturbances (TID’s). TID’s cause the layers to undulate with periods from minutes to about an hour, but their detailed structure is usually unknown. Smaller scale TID’s (i.e., those whose wavelength is smaller than the length of the radar ray path through the ionosphere) cause ionospheric multipath and spectral broadening that prevent accurate estimates of spectral shift. Ionospheric motions on time scales comparable to the radar’s coherent integration time also broaden the sea-echo spectrum and prevent accurate location of the Bragg-line peak frequencies, from which currents are derived.

The stability of ionospheric reflections also depends profoundly on which layer is used, which in turn depends on the radar frequency selected. The $E$ layer and the somewhat higher $F1$ layer exhibit similar and somewhat predictable seasonal, diurnal, and solar-cycle climatologies, while the still higher $F2$ layer is more sensitive to dynamical (eg., TID) effects and is less predictable. Real-time diagnostic soundings of the ionosphere, both overhead and over the actual radar path, are therefore an integral part of OTH radar-frequency management. They tell which frequencies can reach a given range and which ionospheric layer reflects them.

The dominant ionospheric time scales of concern in OTH radar measurements are the diurnal cycle and the time scale of TID’s (less than one hour). The amplitude of these fluctuations increases with the height of the layer, that is, the lower the layer, the more stable the reflection. There is also a tendency toward shorter-period fluctuations in the lower layers. For current measurements, therefore, we try to use frequencies that reflect from the $E$ or $F1$ layer. Because they are strongly solar-controlled, these layers are strongest and most stable near midday and during the summer.

The spatial scales of ionospheric motions determine how uniform Doppler shifts are over the radar’s dwell area. Ionospheric motions on longer time (such as diurnal) scales tend to produce more spatially uniform Doppler shifts than do motions on shorter (such as TID) scales. Uniform Doppler shifts over a dwell region uniformly bias the current map and are easier to estimate and remove, for example, by using land echoes.

## V. AVOIDING IONOSPHERIC DISTORTIONS

Ionospheric distortions can be *avoided before* they occur and *filtered after* they occur. To avoid distortions, operational OTH radars use real-time sweep-frequency diagnostic soundings of the ionosphere, both overhead and using ground-backscatter over the actual radar path, to permit optimum choice of operating frequency for the desired range and azimuth. The optimum frequency for military applications, whose purpose is to find and track weak targets, is not necessarily the optimum frequency for ocean-current mapping. Sea clutter, as it is called in military circles, is very strong, often 60 dB or more above atmospheric noise, so the strength of the clutter—our signal—is usually not a problem. Of more concern in ocean-current measurements is spectral smearing and multipath as well as large Doppler shifts, which prevent accurate estimates of the incremental Doppler shift caused by the currents. A frequency chosen to maximize echo strength in a given dwell region may produce unacceptable multipath Doppler distortion.

Kotaki and Georges [11] compared the sharpness of sea-echo spectra (a quality index) obtained with an OTH radar with simultaneous diagnostic soundings. A useful diagnostic for this purpose is the sweep-frequency backscatter ionogram. They found ways to use these soundings to select operating frequencies that were less likely to suffer multipath distortion. By using frequencies away from the ionogram's leading edge, for example, one avoids high-angle/low-angle multipath, at some cost in echo strength. A trained operator can recognize other patterns in the backscatter ionogram that indicate which frequencies are likely to result in multilayer multipath.

An even better diagnostic tool is a real-time display of the sea-echo spectrum versus range in each radar beam. Judicious use of broad-spectrum backscatter ionograms (which are part of the systems described here) helps avoid obvious causes of multipath, but it does not guarantee that spreading will not occur. Real-time inspection of the sea-echo spectra themselves and adjusting radar parameters to optimize their sharpness are the best ways to optimize data quality.

Although the diurnal ionospheric climatology is qualitatively known, the magnitude of the ionospheric bias on a given day cannot be accurately predicted. In the morning hours, while the layer is forming, large positive Doppler shifts cause a decreasing positive current bias. In the afternoon, when the layer is dissipating, there is an increasingly negative current bias and greater variability. During the midday hours, the bias tends to be stable and near zero. This pattern is consistent with the known strong solar control of the $E$ and $F1$ layers. Selecting times of the day when this bias is small and remains stable improves data consistency.

These patterns are illustrated by the results of two current-mapping tests conducted with the Air Force OTH-B radar in Maine [12], which is similar to the one used for this current-mapping test. For nine days in 1993 and 1994, we illuminated a 240 000-km$^2$ ocean area to the east and south of Cape Hatteras, NC, by using reflections from a normal summertime $E$ layer. We averaged hourly current estimates over the entire area, reasoning that any hour-to-hour changes in this spatial average would be due only to ionospheric effects. Fig. 1 shows the computed areal-average current versus time of day for the nine days. In general, early morning and late afternoon operation is to be avoided. Near midday, a consistent pattern, in which the current bias is small and changes slowly, offers some hope of estimating and removing it. We have not yet studied the corresponding patterns for the $F1$ and $F2$ layers, but they are expected to be more complicated. $F$-layer reflections impose larger Doppler fluctuations whose removal may require averaging over several days as well as more advanced time-domain methods for removing ionospheric frequency modulation [13].

## VI. FILTERING IONOSPHERIC EFFECTS

In addition to avoiding ionospheric distortions by judiciously selecting radar parameters, we also cull unsuitable data by using an objective data-quality index and combine radar data in space and time to take advantage of the different space and time scales of oceanic and ionospheric motions. Compensating for ionospheric effects, therefore, requires both spatial and temporal bias correction, using land echoes when available, and the rejection of broadened spectra. These strategies are not yet entirely automatic and will require intelligent assessment of individual cases for some time to come.

Simple low-pass temporal filtering is accomplished by averaging sea-echo spectra over a sequence of time dwells spaced over an hour or more. This attenuates short-term (TID) changes in ionospheric frequency shift, while bringing out the spatial structure of the unchanging shifts caused by ocean currents. Also, computing a spatial-average current over a dwell region (as described in the previous section) provides an estimate of the dwell-to-dwell temporal changes in ionospheric frequency shift (such as the diurnal component) that are coherent over that dwell region. This estimate can be used to partially correct for ionospheric shifts on a dwell-to-dwell basis before temporal averaging.

The most valuable tool for dealing with ionospheric distortion is an objective sharpness or quality filter that is applied to time-averaged sea-echo spectra. For example, when combining data from a given ocean cell that were obtained at different times, we select only data exceeding an empirically determined quality threshold. Spectral sharpness is degraded by ionospheric variations during the coherent dwell time by spatial multipath, by interference and meteor echoes, and even by differential current-induced shifts within a radar cell.

When nearby land echoes are present, we use the technique of Maresca and Carlson [5] to estimate and remove the ionospheric bias from current measurements. It is not well known over what ocean area these land echoes can be used to correct for ionospheric biases, but in this test, we checked the consistency of land-echo Doppler shifts from Florida, Cuba, and the Bahamas to see how the land-echo correction varies over distances of a few hundred kilometers. We found that the current standard deviation resulting from variation of the Doppler shift of good quality land echoes over a radar dwell region (defined later) ranged between 0.07 and 0.16 m/s$^{-1}$.

We judge the effectiveness of these methods for removing ionospheric distortion mainly by spatial and temporal consistency, that is, if the same large and small-scale features appear hour after hour and day after day, we conclude that they are caused by ocean currents and not by the ionosphere. In the measurements described here, for example, we compare the

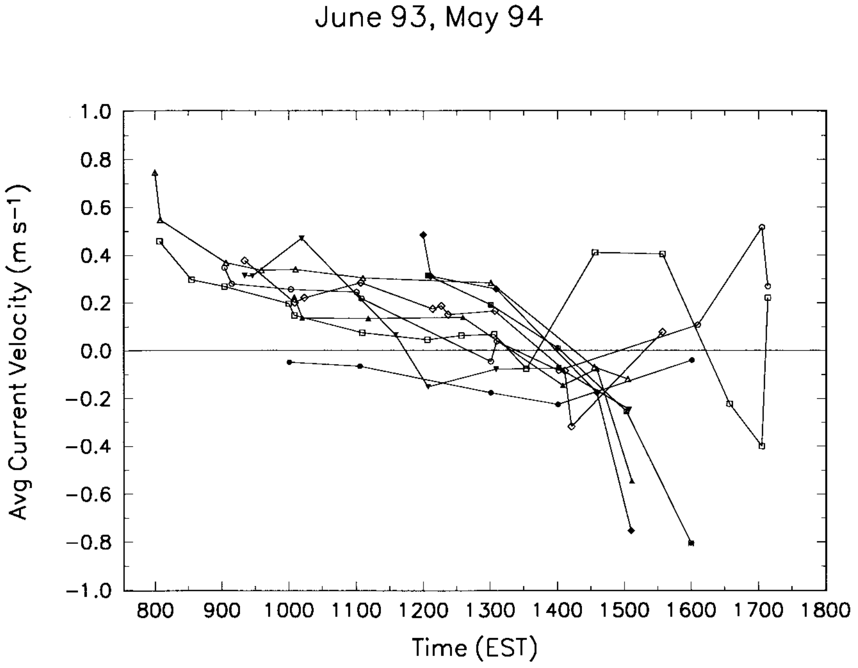

Fig. 1. Hourly radar-derived ocean surface current averaged over a 240 000-km$^2$ area off Cape Hatteras, NC, by the Air Force OTH-B radar. The nine curves are derived from measurements taken on June 16–19, 1993 and May 23–27, 1994. The variability throughout the day shows the current bias introduced by the diurnal part of ionospheric *E*-layer motion. The decreasing positive current (Doppler shift) in the morning hours and the increasing negative shift in the afternoon are consistent with the known strong solar control of the *E* layer. Such biases can be estimated and removed. The most stable reflections occur near midday, where ionospheric Doppler is small. Near the end of the day, spectral broadening increases, causing a spectral quality filter to limit the size of the area averaged and increasing the variance of the average current.

current maps obtained during two independent time intervals on the same day.

## VII. THE RADAR MEASUREMENTS

On August 10 and 11, 1994, we conducted the first current-mapping test using the U.S. Navy's Relocatable Over-The-Horizon Radar (ROTHR), south of Norfolk, VA. The radar transmitted southward and achieved a nominal 0.5° azimuthal resolution with a 2.58-km-long linear-phased receiving array, consisting of 372 twin-monopole elements. For this test, four *dwell-illumination regions*, or *DIR*s, were used that are nominally 8° wide in azimuth and 326-km long in range. (Later tests have used a DIR that has twice this range extent.) The receiving antenna array divides each DIR into 16 azimuth beams, and range resolution is achieved by using 25-kHz FM-CW modulation and a 128-point range transform. A radar cell on the ocean surface, therefore, measured about 6 km in range by 15 km in azimuth for the 15-MHz frequency and range used in this test.

The four DIR's illuminated a 210 000 km$^2$ ocean region that includes the Florida Straits and part of the Gulf of Mexico, about 5% of the ROTHR's total coverage. The measurements used a coherent integration time of 24.6 s, giving a Doppler resolution of 0.041 Hz. For a 15-MHz radar frequency, the corresponding current resolution is only 0.42 m/s$^{-1}$. Incoherently averaging up to ten spectra and using a three-point parabolic interpolation to locate spectral peaks more accurately, we can achieve a current resolution exceeding 0.1 m/s$^{-1}$. Greater current (Doppler) resolution is obtainable by using longer coherent integration or autoregressive spectral estimators, but the limits imposed on current-measurement accuracy by ionospheric effects are not yet known.

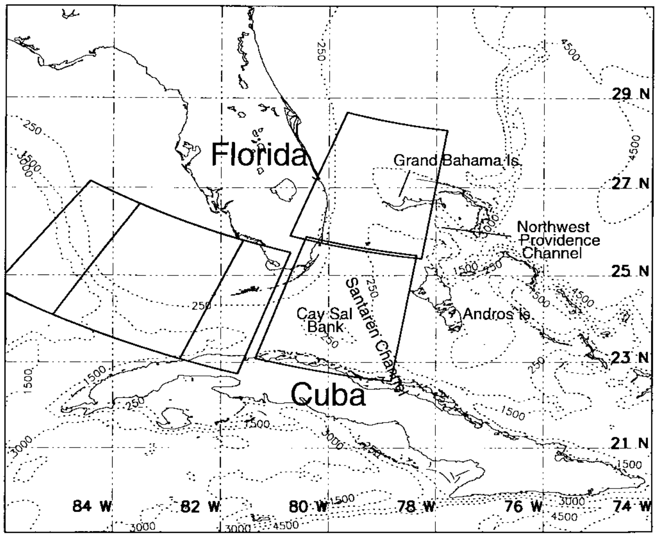

Fig. 2. Bathymetry (in meters) of the ocean region illuminated by the OTH radar in Virginia during this test. The specific regions interrogated during the two days are outlined, and bathymetric features discussed in the text are labeled.

Fig. 2 shows the specific areas illuminated during this test, superimposed on the bathymetry of the ocean region. Land echoes from Florida, the Bahamas, and Cuba were used to correct the current for ionospheric shifts. Fig. 3 shows the radial current map obtained by combining data collected by the ROTHR on August 10 and 11, 1994. The map was

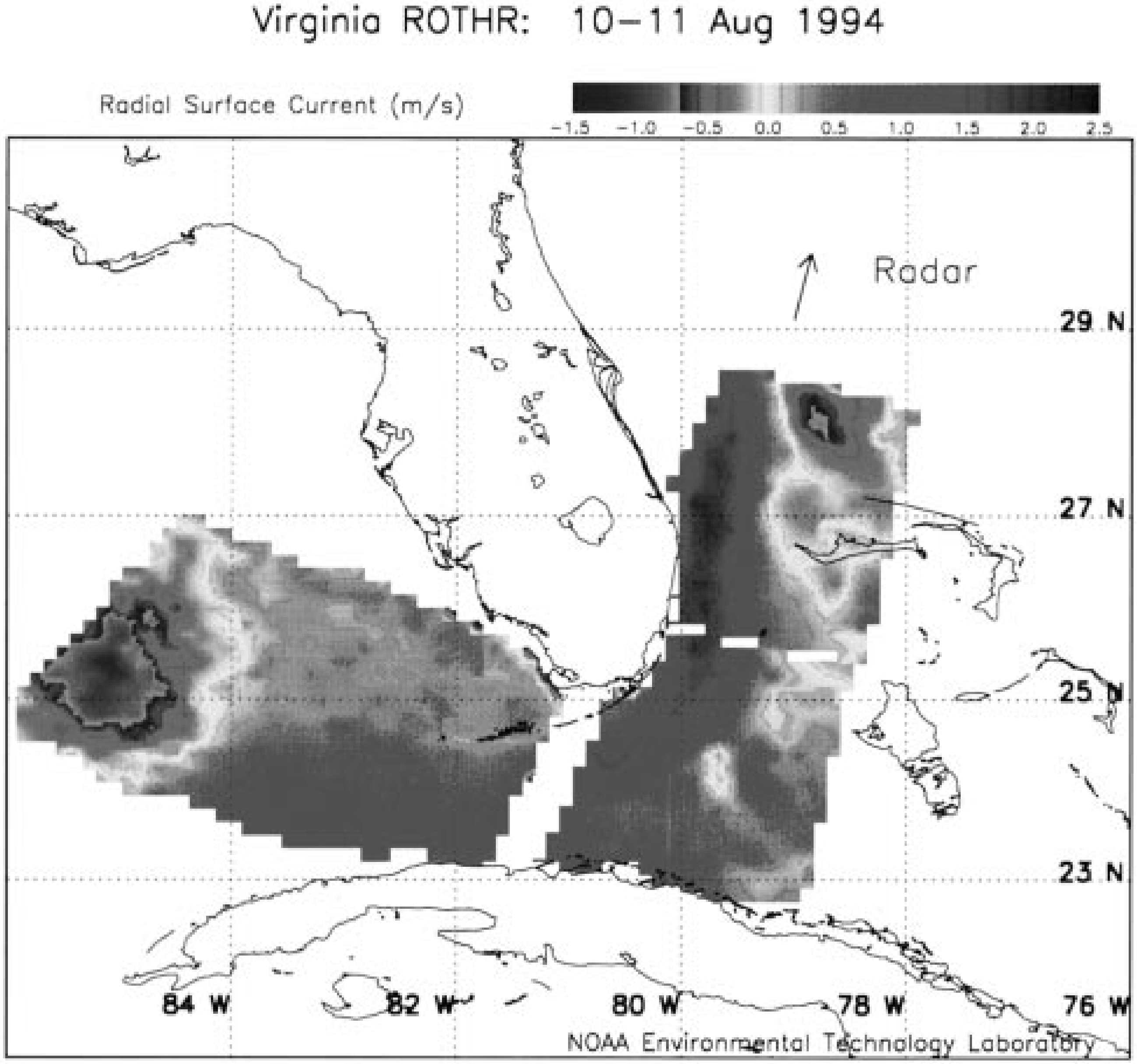

Fig. 3. On August 10 and 11, 1994, this map of the radial component of ocean surface current was obtained by the U.S. Navy ROTHR over-the-horizon radar south of Norfolk, VA. The nominal spatial resolution is 15 km. The core of the Florida Current, visible in red, has a maximum speed of about 2 m/s (4 kt). Other features include 1) a region of 1-m/s southward surface flow north of Grand Bahama Island, 2) a cyclonic eddy west of Andros Island in the Santaren Channel, 3) contributions to the Florida Current from the east, and 4) a 1-m/s radial-current component at the extreme west edge of the coverage area, believed to be the combined effect of the Gulf Stream Loop Current and a cyclonic eddy (Tortugas Gyre) off the west coast of Florida. The area shown here is about 5% of the whole ROTHR coverage.

produced using radar data alone; that is, data were not fitted to any circulation model. Data were combined in a way that emphasizes data of highest quality (i.e., spectral sharpness). As a result, most of the data that comprise this map were obtained during about one hour on August 11th, when propagation was most stable. The data from the westernmost part of the coverage was obtained on August 10th. In combining current measurements from two days, we considered the possibility that tidal currents in the region could introduce biases, but we found experimental [15] and model [10] evidence that the magnitudes of the tidal current components there are less than the accuracy of our radar measurements.

The main features of the map are consistent over the two days. Warm colors (orange and red) indicate surface currents approaching the radar, that is, roughly northward, and cool colors (blue and green) indicate receding (roughly southward) radial currents. Yellow represents a nearly zero radial component. The features of this current map are interpreted in Section IX; first, we ask whether one should have confidence in these measurements.

## VIII. VALIDATION AND ACCURACY

Unlike space-based microwave scatterometry and radiometry, OTH radar-current measurements do not require empirical

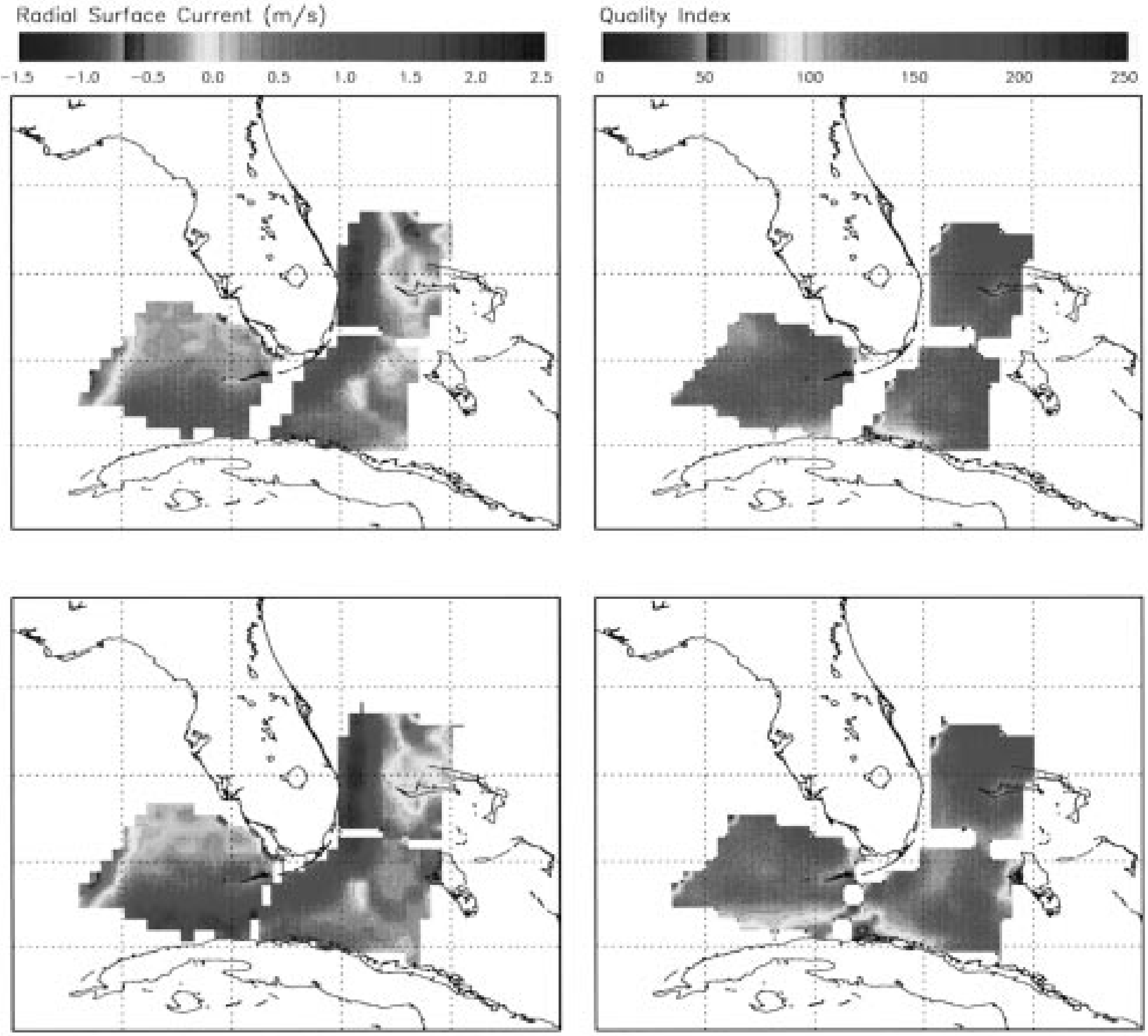

Fig. 4. By separating the current measurements shown in Fig. 3 into two independent time intervals, we measure the consistency of the radar-derived currents.

calibration, so the idea of simultaneous ground-truthing is not central to its validity. This is fortunate since there are virtually no routine surface-current measurements in the open ocean. (In 1990, the Florida Straits were heavily instrumented with moored current meters for a survey supported by the Minerals Management Service [14]–[18].) In 1995, however, a shipborne acoustic-Doppler current profiler was deployed into the Gulf of Mexico during a ROTHR current-mapping test. The rms difference in the radial currents measured by the two disparate techniques during the three-day test was 21 cm/s$^{-1}$ [19].

Because point measurements are only crudely comparable with the 100-km$^2$ areal average performed by the radar, additional validation of OTH radar-current maps relies on spatial and temporal consistency and on comparisons with historical and climatological *in-situ* sources and space-based remote sensors, such as radar altimeters. In the presence of ionospheric distortions, the accuracy of its measurements depends mainly on internal quality controls provided, for example, by monitoring spectral broadening, and by properties of land echoes.

Errors in estimating the position of spectral peaks in the sea echo contribute about 10-cm/s$^{-1}$ uncertainty in these radial current measurements. The additional errors caused by ionospheric motions can be estimated by comparing two independent radar measurements over the same region at slightly different times. To do so, the data that comprise Fig. 3 were divided into two time intervals, each about one hour long, that provide independent current maps of the same region. The two maps, shown in Fig. 4, consistently reproduce the same major features, though with slightly lower overall data quality. Each current map was separately corrected by using zero-Doppler land-echo references. Any remaining differences in the maps are attributable to errors in estimating the land-echo shifts and any variability of the ionospheric shifts over the radar-dwell areas. To quantify such errors, we show, in Fig. 5, the distribution of 1460 point-by-point differences in radar-derived radial current speeds for the two time intervals. By plotting those differences versus the objective quality index, we show that, as expected, higher quality measurements are more consistent than lower quality ones. If we limit the comparison to points where the quality exceeded 100 (arbitrary units), the mean difference is 9 cm/s$^{-1}$ and the rms difference is 25 cm/s$^{-1}$.

We have also qualitatively validated the westernmost portion of the ROTHR current map with geostrophic velocity estimates for the Gulf of Mexico, derived from the altimeter observations of sea-surface topography from the TOPEX/Poseidon and ERS-1 satellites. TOPEX/Poseidon is a radar altimeter mission conducted jointly by the United States National Aeronautics and Space Administration (NASA) and the French space agency, Centre National d'Etudes Spatiales (CNES). ERS-1 was the first European Remote Sensing Satellite launched by the European Space Agency (ESA). Both satellites provide near-global sea level measurements. The TOPEX altimeter uses a dual-frequency altimeter with 1–2-cm accuracy along a 10-day repeating ground track [20]. During the two-day ROTHR test, the ERS-1 mission was in a geodetic mapping phase with a repeat cycle of 168 days. Altimeter range measurements from both satellites are referenced to a "climatological" mean surface for the Gulf [21] and interpolated using an objective analysis (OA) technique to produce maps of the sea-surface height anomaly. Maps for a given analysis date are computed using TOPEX and ERS-1 data centered on the analysis date with 100-km spatial and 12-day temporal correlation scales used in the OA weighting. A mean sea-surface height field is added to the anomaly maps to estimate the total dynamic height topography. The mean is computed from a model solution obtained by assimilation of the 1993 TOPEX/Poseidon and ERS-1 data into a general circulation model of the Gulf of Mexico [15]. Surface currents can be estimated from sea-surface topography, assuming geostrophy. The next section compares the ROTHR-derived radial currents with altimeter-derived geostrophic currents.

## IX. INTERPRETATION OF THE CURRENT MAP

The feature that is obvious, even in this map of radial current component only, is the core of the Florida Current, with a maximum speed of 2 m/s$^{-1}$ where it rounds the tip of Florida and flows northward along the eastern Florida coast. The large-scale structure of this radar-derived current map agrees quantitatively with what is known about the Florida Current [14]–[18], but the radar map resolves additional structural details of the region that are not routinely observable using existing current sensors. These include a region of 1-m/s$^{-1}$ southward surface flow (blue) north of Grand Bahama Island, a cyclonic eddy (the red-green couplet) west of Andros Island, contributions to the Florida Current from the east, and a 1-m/s$^{-1}$ radial current jet (blue) at the extreme west edge of the coverage area, believed to be associated with the Gulf of Mexico Loop Current. We next examine some of these features in detail.

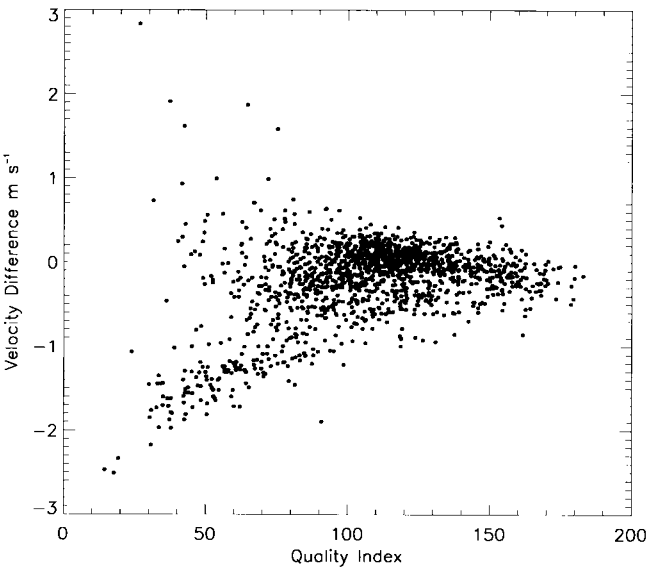

Fig. 5. Here, we plot the difference in radar-derived currents at 1460 points on the ocean in the two adjaent time intervals shown in Fig. 4. Plotting these differences versus an objective data-quality index shows, as expected, that consistency depends on data quality.

### A. Loop Current Jet

Fig. 6 shows contours of the estimated total dynamic topography in the Gulf of Mexico for August 10, 1994, coincident with the ROTHR radial-current observations. The dominant feature in the map is a 60-cm high, associated with the northward penetration of the Loop Current into the Gulf. The Loop Current is the portion of the Gulf Stream system within the Gulf of Mexico that 'loops' or meanders anticyclonically to connect the Yucatan Current (flowing north through the Yucatan Channel) with the Florida Current (exiting east through the south Florida Straits). The anticyclonic circulation deflects the ocean surface to produce the observed high in sea-surface topography.

A 20-cm low, indicating cyclonic circulation is visible (in blue) between the Loop Current and the Florida shelf. This feature is a quasipermanent cyclonic gyre that forms off the Dry Tortugas during times of northward penetrations of the Loop Current into the Gulf [23] and has been named the Tortugas Gyre [24]. Satellite imagery supports the hypothesis that the gyre results from cold perturbations that form on the northern boundary of the Loop Current and propagate along-stream into the region [25]. The gyre is often, but not always, associated with the shedding of large anticyclonic rings from the Loop Current [23]. (TOPEX/Poseidon altimetry in September revealed that a large anticyclone was shed from the Loop Current, just one month after the observations reported here.) Thus, the region of southward flow in excess of 1 m/s$^{-1}$ near 85°W, 25°N indicated on the radar map (Fig. 3) appears to be due to the confluence of the Loop Current and the Tortugas Gyre. This is in agreement with historical hydrographic estimates of surface geostrophic speeds in this region, which were also reported in excess of 1 m/s$^{-1}$ [23].

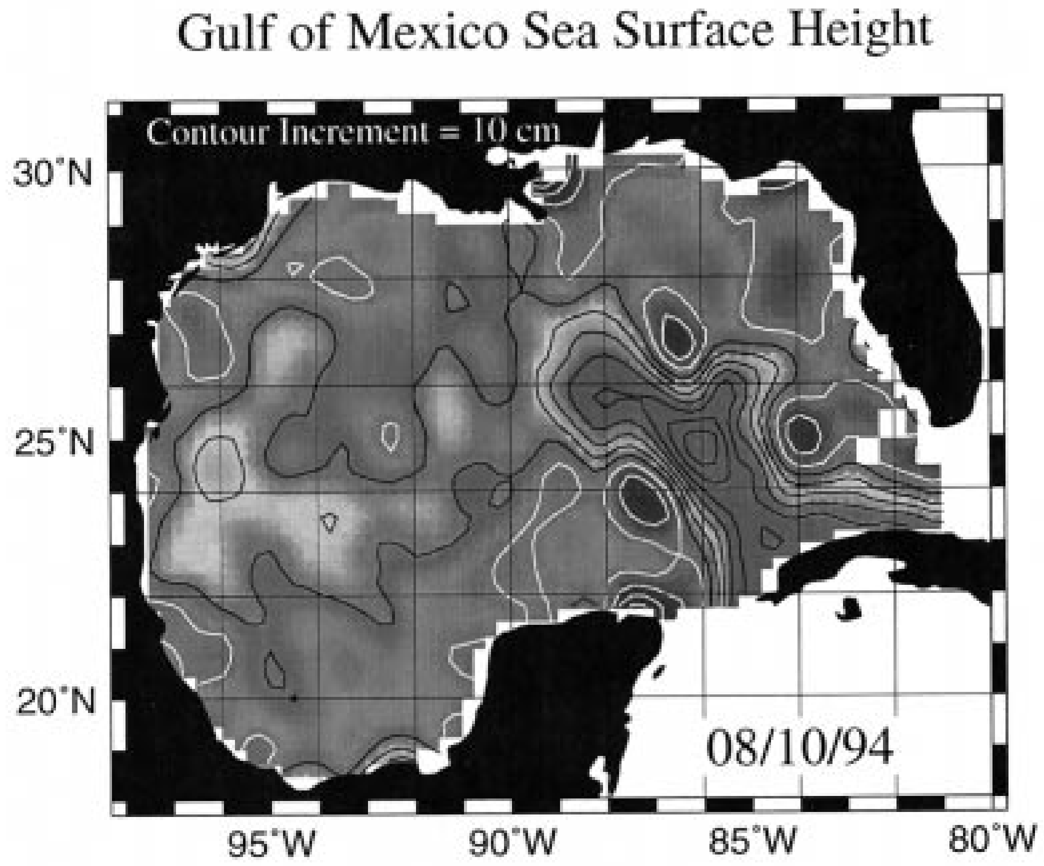

Fig. 6. Sea-surface topography in the Gulf of Mexico derived from TOPEX and ERS-1 altimetry. The surface, displayed as deviations from the Rapp mean surface, shows conditions on 10 August, 1994. The red "hill," more than 60-cm high, is at the center of the Gulf of Mexico Loop Current, and the plot's contours correspond roughly to current streamlines. Also of interest is the depression (in blue) indicating a cyclonic eddy (the Tortugas Gyre) between the Loop Current and South Florida. These two counter-rotating features combine to pump a strong southward current between them at 25°N, 85°N, also seen by the ROTHR.

The observed ROTHR radial currents can also be compared quantitatively with the altimeter-derived geostrophic velocities in the region. The peak ROTHR radial current observed is 1.2-m/s$^{-1}$ (±0.2 {m/s$^{-1}$}) away from the radar site near the confluence of the Loop Current and the Tortugas Gyre (25.5°N, 85°W). In comparison, the maximum altimeter-derived geostrophic current in the radial direction from the ROTHR site is 1.8 m/s$^{-1}$ at 25.5°N, 84.75°W. However, geostrophic estimates of velocities near an eddy or meander differ from the observed currents because the geostrophic computation does not include centrifugal forces [9]. For cyclonic eddies, the geostrophic velocities overestimate the tangential velocity according to

$$v_g = v[1 + v/(fr)]$$

where $v_g$ is the geostrophic velocity, $v$ is the observed current, $f$ is the Coriolis parameter, and $r$ is the radius-to-eddy center. Assuming that the maximum ROTHR radial current (1.2 m/s$^{-1}$± 0.2) corresponds to the true tangential velocity at a radius of 50–100 km from the cyclonic gyre center, the geostrophic contribution would fall between 1.2 and 2.0 m/s$^{-1}$. Since the altimeter-derived geostrophic component is 1.8 m/s$^{-1}$, there is quantitative agreement between the available coincident observations within the accuracy of the estimation techniques.

### *B. Santaren Eddy*

The flow through the Santaren Channel (24°N, 79.5°W), though quite variable, is believed to contribute 1.8 Sv on average to the Florida Current [18]. An interesting surface-current feature detected by the ROTHR is the cyclonic eddy (the red-green doublet) west of Andros Island (24.5°N, 78°W). The eddy is at the entrance to the channel, and ROTHR observations indicate a southward flow to the east of a shallow coral bank called the Cay Sal Bank (24°N, 80°W) and northward flow on the east side of the channel [20]. The feature is located between TOPEX ground tracks and so cannot be validated by coincident altimeter observations. Some historical current-meter records exist, however. An array of three current-meter moorings was placed across the Santaren Channel in November 1990 as a part of a Minerals Management Service (MMS) one-year field study of the Florida Current, performed by Science Applications International Corp., Raleigh, NC. Full descriptions of the design of the array and data collected are included in the final report to the MMS [17]. These current meter records and coincident AVHRR thermal imagery indicated the set-up of a cyclonic eddy or current reversals within the channel that were associated with offshore shifts in the Florida Current axis [15], [18]. Radar measurements with time continuity would establish the extent to which this feature persists.

### C. Strong Southern Flow North of Grand Bahama

Southward flow of almost 1 m/s$^{-1}$ in this shallow region is indicated by the blue contours centered at 28°N, 78.8°W. It appears to be associated with a cyclonic eddy on the eastern boundary of the Florida Current. The cyclones or "shingles" on the inner (i.e., western/shelf) side of the current have been extensively studied, but much less is known about variability on the eastern side north of Grand Bahama Island. Infrared imagery [14] often shows warm Florida Current waters flowing to the east in the region, and earlier studies [16], [17] show warm water flowing to the east that may be associated with cyclones on the eastern boundary of the Florida Current.

### D. Eddy Flow in the Northwest Providence Channel

This channel (26°N, 78.5°W) is believed to contribute 1.2 Sv on average to the Florida Current, but the flow in the channel is known to be highly variable with eddy motions common [18]. The surface-current features revealed by the radar confirm this complexity, although details cannot easily be deduced from only the radial component measured by one radar. The surface flow away from the Florida Current in the northern half of the channel (just south of Grand Bahama I) is consistent with extensive *in-situ* current measurements there in 1990 and 1991 [18]. One possibility that is consistent with the radar observations is the existence of counter-rotating eddies within the channel.

Qualitative comparisons can sometimes be made between the OTH radar-current maps and feature-tracking using high-resolution sea-surface thermal patterns available from satellite (AVHRR) imagery. Unfortunately, the thermal signatures of the currents are often masked from June through October by a shallow surface layer of warm water over the Gulf. Such was the case in August 1994.

## X. CONCLUSION

A single example of a high-resolution map of radial surface currents suggests that OTH radar could be useful for mapping the surface circulation of the Intra-Americas Sea. A single radar maps only one component of the current vector, namely, the component along a radar radial. As with the CODAR and OSCR systems, two radars with overlapping coverage are required to map current vectors. In the test described here, only one OTH radar was used, and the area illuminated is only about 5% of the total ocean area covered by the ROTHR system. As of mid-1995, two Navy ROTHR radars, one in Virginia and another in Texas, provide overlapping coverage of the southern Gulf of Mexico, the Caribbean Sea, and part of the tropical Atlantic Ocean. Results of the first attempt to map ocean surface current vectors with dual OTH radars have already been reported [22].

Little is known about the circulation and its variability in and around the straits and channels of the West Indies and about the variable contributions to Florida Current transport by its subsidiary channels. Mapping ocean surface current vectors with time continuity in this region could give new insight into the structure and evolution of the Intra-Americas component of the Gulf Stream system. Blending of ROTHR ocean surface current velocities with TOPEX/POSEIDON and ERS-2 altimetry to take advantage of the complementary nature of these remote sensing systems is being actively pursued.

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