VHF Radar Detects Oceanic Submesoscale Vortex Along Florida Coast

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Escalating national interest in the coastal ocean underscores the need for high-quality surface current data that can improve our understanding of surface circulation and its impact on societal and environmental issues related to coastal pollution, beach restoration, oil spill mitigation, and coastal air-sea interaction. Coastal regimes exposed to strong ocean currents, surface waves, and winds during storm conditions may frequently require beach renourishment to restore valuable beaches that are key to local economies. Maintaining water quality is a problem, too, particularly where shipping dominates the traffic in and out of harbors. These environmental issues are increasingly difficult to manage due to evolving oceanic and atmospheric conditions. Inferring evolving spatial patterns of the coastal ocean current fields from single-point measurements such as moorings or drifters that propagate away from divergent flow regimes is difficult at best. The Doppler radar technique is one approach that effectively measures the evolution of surface current fields in near-real time.

The South Florida Ocean Measurement Center (SFOMC) is an observatory for coastal and deep ocean processes. It requires a suite of in situ oceanographic instruments to test and evaluate the performance of autonomous underwater vehicles (Figure 1). Given the narrow shelf off Ft. Lauderdale, this observatory is ideally suited for examining a spectrum of oceanic processes that may be forced or modulated by the Florida Current, an important component of the subtropical gyre circulation in the North Atlantic Ocean basin. Mesoscale variations of the Florida Current occur at many energetic current scales that impact the coastal ocean along the Florida Keys and eastern seaboard of the United States (see *Hogg and Johns* [1995] for a comprehensive review). Recent surface current observations from an Ocean Surface Current Radar (OSCR) using the Very High Frequency (VHF) mode reveal complex surface current patterns in the SFOMC area. For the first time, submesoscale vortices with diameters of 2–3 km were observed just inshore of the Florida Current. [Note: Submesoscale refers to an oceanic feature where its horizontal scale is less than or equal to the deformation radius. In the present case, the deformation radius is of the order of 10 km based on conductivity-temperature-depth profiles.] Now researchers are resolving even finer scales with surface current radar using the VHF mode.

While the use of radio pulses to probe ocean surface currents has received attention in recent coastal oceanographic experiments using High Frequency (HF) radar [*Prandle*, 1987; *Shay et al.*, 1995], the VHF mode provides higher-resolution surface current images. The OSCR VHF mode was deployed for the SFOMC 4-Dimensional Current Experiment from June 25–August 10, 1999. In both modes, radio waves are backscattered from the moving ocean surface by surface waves of one-half the incident radar wavelength. This Bragg scattering effect [*Stewart and Joy*, 1974] results in two discrete peaks in the Doppler spectrum. In the absence of a surface current, spectral peaks are symmetric and their frequencies are offset from the origin by an amount proportional to the surface wave phase speed and the radar wavelength. If there is an underlying surface current, Bragg peaks in the Doppler spectrum are displaced by the radial component of current along the radar's look direction. Using two radar stations sequentially transmitting radio waves resolves the two-dimensional velocity vector for placing the data into geographical context.

The VHF system used at SFOMC consisted of two transmit/receive stations operating at 50 MHZ that sensed electromagnetic signals scattered from surface gravity waves with 3-m wavelengths. Coastal ocean currents were mapped over a 7 km x 8.5 km domain at 20-min intervals with a horizontal resolution of 250 m at 700 grid points (Figure 1). The radars were located in John Lloyd State Park, Dania Beach, Florida (Master), and an oceanfront site in Hollywood Beach, Florida (Slave), which equated to a baseline distance of about 7 km. Each site consisted of a four-element transmit and thirty-element receiving array oriented at an angle of 37° (southwest-northeast at Master) and 160° (southeast-northwest at Slave) over a distance of 85 m. The manufacturer's cited accuracy of the vector current speed is 4 cm s^{-1}, and the

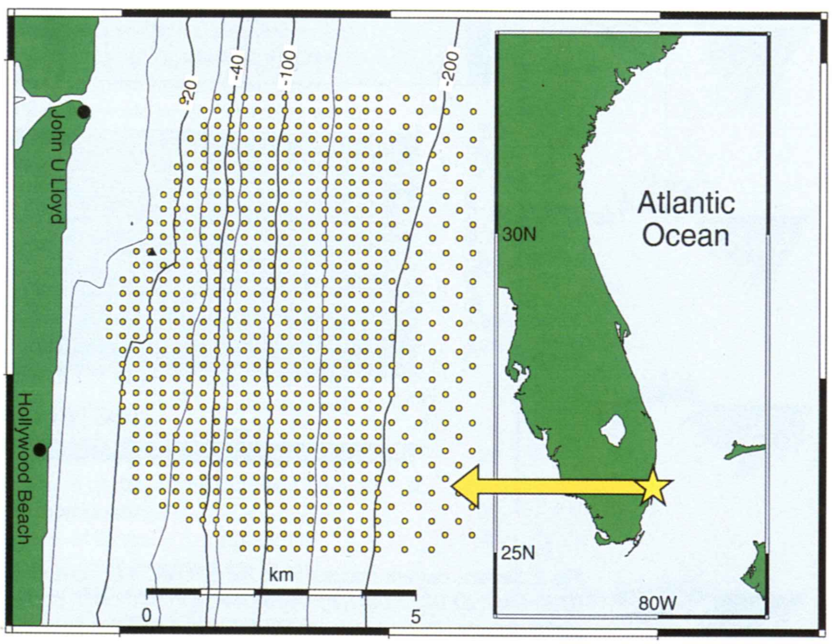

Fig. 1. Location of VHF Experiment in the South Florida Ocean Measurement Center off Ft. Lauderdale, Florida, relative to the OSCR cells (dots), bottom topography (contours in meters), and the 11 m mooring (triangle) deployed by NOVA University in cooperation with the University of South Florida. Inset shows location of SFOMC (star) relative to the southeast coast of the United States. The master and slave sites were located at John U. Lloyd State Park and Hollywood Beach, respectively.

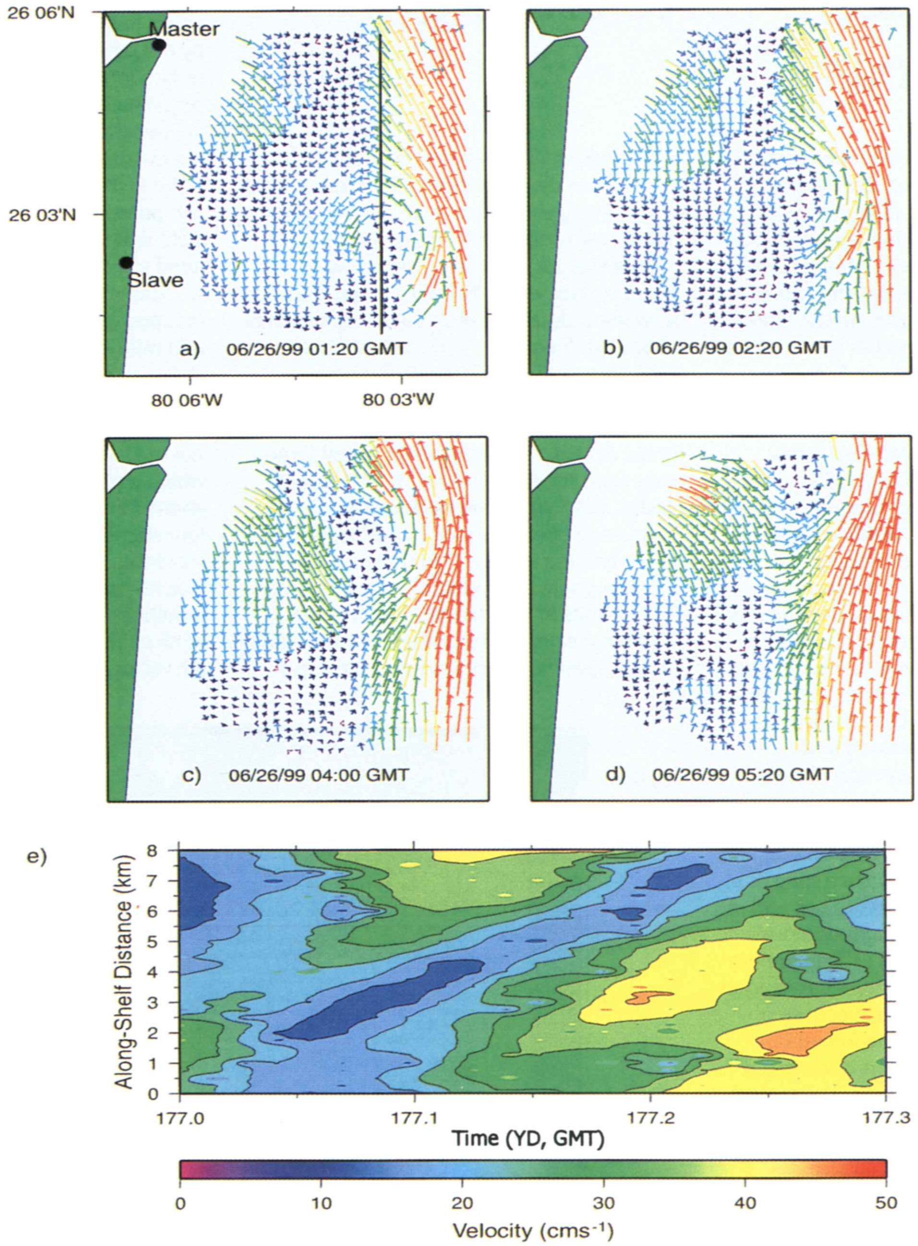

Fig. 2. Surface current images from the SFOMC 4-D Current Experiment on June 26, 1999: a) 0120 GMT; b) 0220 GMT; c) 0400 GMT; d) 0520 GMT; and e) the corresponding time-latitude series depicted by the black solid line in panel a. Color bar represents the velocity scale up to 50 cm s^{-1} in each panel, and the cell spacing between adjacent vectors is 250 m close to the coast and 500 m offshore. The path of the vortex is depicted by the near-zero current speed and has an approximate slope of 30 cm s^{-1} with the current speed scale (color bar) in panel e.

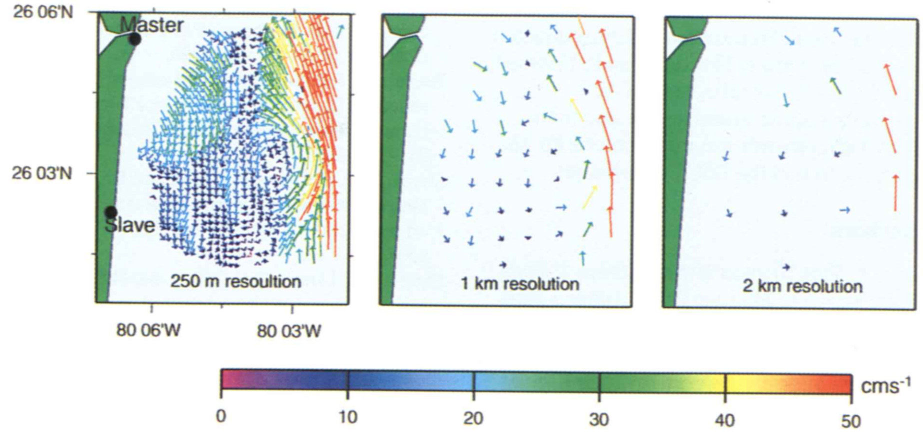

Fig. 3. Surface current image from the 0220 GMT sample for the 250 m, 1 km, and 2 km spatial resolution. The color bar represents the velocity scale as in Figure 2.

directional resolution is 5°. In previous experiments using HF-radar, RMS differences have been found to be about 7 cm s^{-1} over a range of 1 m s^{-1} current [*Shay et al.*, 1998a]. Since the Bragg wave for the VHF mode is 3 m, the measurements may be susceptible to larger errors induced by surface waves than in the HF-mode. However, during this experiment, winds and hence surface wave motions were relatively weak and did not significantly impact the higher resolution surface current measurements.

During this experiment, surface current observations revealed Florida Current intrusions over the shelf break, wavelike structures along the inshore edge of the current, and submesoscale vortices. One example started at 0120 GMT on June 26 (Figure 2a) when a submesoscale vortex was located along the southern part of the VHF-radar domain just inshore of the Florida Current. Surface currents within the vortex ranged between 20–30 cm s^{-1} at a diameter of about 1–1.25 km from the vortex's center. Along the inshore edge, surface currents were directed toward the south at 20 cm s^{-1}. A fraction of this variability was perhaps due to a buoyant outflow from Port Everglades attributed to excessive rainfall of more than 40 cm during June. Near-shore conductivity-temperature-depth profiles during the experiment revealed a fresh-water lens in the upper 2 m of the water column. Thus, it is likely that a buoyancy-driven current may have been generated by this fresh-water influx. Subsequently, the center of the vortex moved about 2 km northward, and the diameter of the submesoscale vortex remained about the same about one hour later (Figure 2b). By 0400 GMT, the vortex moved 3.5 km northward from its original position, and surface currents increased to about 50 cm s^{-1} at a radius of 1.5 km from its center (Figure 2c). As the feature interacted with the coastal current, the vortex began to develop an asymmetry in its horizontal structure. The vortex was located at the northern part of the radar domain by 0520 GMT (Figure 2d), and it remained attached to the Florida Current at that point.

To examine this submesoscale vortex translation, a latitude-time plot for June 26 is constructed from these data (Figure 2e). The vortex's northward displacement of about 6 km, as depicted by the small current speed, occurred over a 5-hr period. This translation speed of about 30 cm s^{-1} is roughly consistent with the propagation speed of spin-off eddies [*Lee and Mayer*, 1977] and near-inertial motions trapped and advected by the vorticity of the Florida Current [*Shay et al.*, 1998b]. However, these features had horizontal scales greater than 40 km compared to those found here of 2–3 km.

An important issue associated with surface current radar measurements deals with spatial resolution. For example, if OSCR's HF mode is used, the horizontal resolution decreases to a coarser resolution of 1–2 km (Figure 3). To illustrate this point, surface currents were subsampled to this resolution to reflect an HF-radar domain in these figures. Clearly, the observed 2–3 km scale vortex structure would not have been resolved. Moreover, if the sample interval is changed to 1–2 hr at this coarse spatial resolution, the evolution of the vortex would have been temporally aliased. Thus, a key question that emerges here is whether these features may have been present in previous sets of HF radar-derived surface current measurements at this coarse resolution. During this time interval and along the 11 m isobath, a comparison of the surface current to subsurface current measurements from an upward-looking Acoustic Doppler Current Profiler mooring revealed consistent behavior of the currents inshore of the vortex (Figure 4). Initially, surface currents were directed southward with velocities of 25 cm s^{-1} compared to about 10 cm s^{-1} in the subsurface layers.

However, during the time of vortex passage (further offshore), currents were directed northward at 15–25 cm s^{-1} from the surface to the bottom. Subsequently, the current vectors rotated cyclonically in time. Over depth, the currents tended to have similar magnitudes and veered in an anticyclonic direction, suggestive of a wind-driven current component. Surface and subsurface current observations acquired during the SFOMC experiment revealed complex circulation patterns (http://storm. rsmas.miami.edu/~nick; click on 4-D Current Experiment). Although it remains unclear as to the dynamics of these recurrent features, they appear to be linked to Florida Current intrusions over the shelf break and coastal current interactions. These high-resolution current images provide a new view of submesoscale surface current processes along the inshore edge of the Florida Current.

Six weeks of VHF-derived surface current measurements suggest complicated surface current signatures along the inshore edge of these strong western boundary currents than anticipated before the experiment. These coastal ocean processes occurred during quiescent atmospheric conditions. Thus, there is a need to improve our understanding of these physical processes and their spatial extent within the water column. That is, these observed features may be either trapped within the surface layer by shear processes or may have a vertical structure. In an adaptive sampling strategy, high-resolution data acquired from ships and AUVs are necessary to resolve the vertical extent or structure of these features [i.e., *Smith et al.*, 1998] and to assess their stability [*Paldor*, 1999]. Based on real-time surface

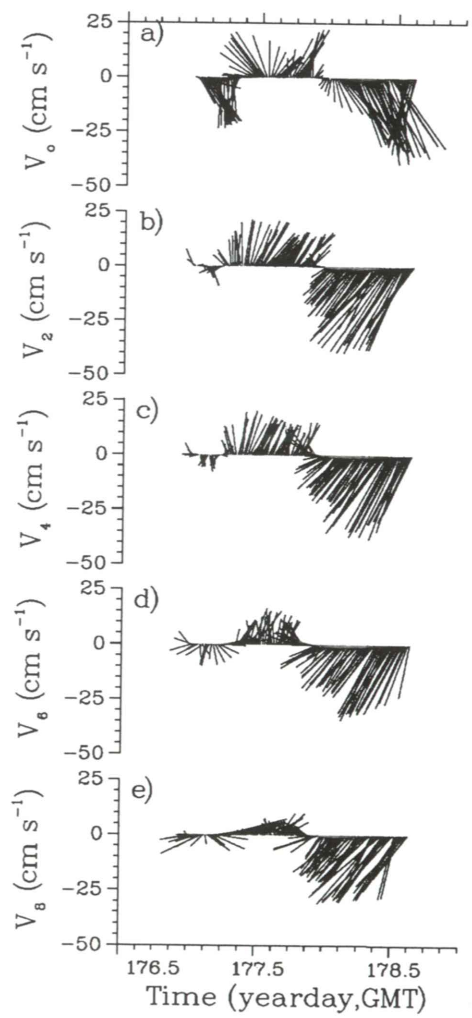

Fig. 4. Time series of vector currents at the 11 m mooring for the a) surface, b) 2 m, c) 4 m, d) 6 m, and e) 8 m in cm s^{-1}. The submesoscale ring occurred starting on year day 177 as per Figures 2 and 3.

current imagery, this suite of instrumentation will provide the four-dimensionality of observed coastal ocean flows. Ultimately, this determination of the vertical structure with horizontal and temporal scales will be needed to improve subgrid-scale parameterizations used in oceanic models. Given the wealth of information contained in these measurements, fundamental questions can be addressed regarding physical processes over the inner to mid-shelf surface circulation.

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