Submesoscale Coastal Ocean Flows Detected by Very High Frequency Radar and Autonomous Underwater Vehicles

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ABSTRACT

Over a 29-day time series in July 1999, an ocean surface current radar (OSCR) in very high frequency (VHF) mode mapped the surface velocity field at 250-m resolution at 700 cells off Fort Lauderdale, Florida. During the experiment, autonomous underwater vehicles (AUVs), equipped with upward- and downward-looking 1.2-MHz acoustic Doppler current profilers (ADCPs), measured subsurface current structure over four to six radar cells during two mixed layer patterns on 9 and 27 July 1999. As these AUV sampling patterns were conducted over 500 m × 500 m and 500 m × 750 m areas, these missions required about 80–90 min (four radar sample intervals) to form four and seven synoptic snapshots, respectively.

Based on autocorrelation analyses of the profiler data, along-AUV-track subsurface profiles were averaged at 10-s intervals, mapped to a surface from 1.5–6.5 m, and compared to surface currents at more than 500 points for each snapshot. Comparisons between the surface and subsurface currents from the AUV revealed spatially averaged differences ranging from 4 to 26 cm s⁻¹ during these two experiments. The largest differences occurred when the surface and subsurface current vectors were orthogonal; otherwise, differences were O(10 cm s⁻¹). Scatterplots between 2-m and radar-derived surface currents indicated a consistent relationship with mooring data. From the seven spatial snapshots acquired during the second experiment, current profiles suggested a time-dependent oscillation that was corroborated by radar and moored ADCP data. Least squares fits of these profiles from sequential AUV snapshots to a simple model isolated an 9.2 ± 1 h oscillation where the along-shelf current was O(50 cm s⁻¹).

Spatially averaged current profiles from four and seven snapshots were subsequently time averaged to form a mean profile from each experiment. In the downwind directions, these mean profiles were compared to a wind-driven, logarithmic layer profile in the upper 6.5 m based on a 10-m surface winds. Regression analyses suggest a slope of 1.16 between the theoretical and observed mean profiles with a bias of about 3 cm s⁻¹. In this context, the averaged winds played a role in driving the coastal ocean circulation. These results further suggest that the spatial averaging by the radar is consistent when subsurface current variations are averaged over similar time and space scales.

1. Introduction

Given escalating interest in establishing coastal ocean observations, there has been an increased emphasis on connecting observatories using high-frequency (HF) radar techniques to map submesoscale to mesoscale surface velocity fields. These measurements have provided spatial context for the more conventional observational approaches using moorings, drifters, and ships during recent coastal experiments. An important measurement issue emerging from previous studies has been the range of the differences (4–25 cm s⁻¹) between the HF radar current measurements and those observed by Eulerian and Lagrangian methods (Paduan and Graber 1997).

Comparisons to conventional techniques, however, do not necessarily provide sufficient spatial coverage at high temporal resolution to understand areal averaging by a Doppler radar and to assess its relationship to upper-ocean subsurface structure over similar spatial scales. For example, rms differences between surface currents from an ocean surface current radar (OSCR) and subsurface currents (4 m) from a vector measuring current meter (VMCM) were 7 cm s⁻¹ over a 1 m s⁻¹ range from observations acquired during the Duck94 experiment (Shay et al. 1998b). Since measurement accuracies of a VMCM are 2 cm s⁻¹ (Weller and Davis...
1980), these differences are within the cited accuracy of 4–5 cm s$^{-1}$ for OSCR measurements. Teague et al. (2001) recently described a set of measurements acquired during the third Chesapeake Bay Outflow Plume Experiment (COPE-3) from the University of Michigan’s MultiChannel Radar system (MCR), which measures bulk surface currents over differing depths. Comparisons at five acoustic Doppler current profiler (ADCP) moorings in the radar domain revealed rms differences ranging from 5 to 20 cm s$^{-1}$ depending on the frequency and location within the radar domain. During this same period, subsurface current comparisons to OSCR-derived surface currents over a 14-day time series ranged between 7 and 11 cm s$^{-1}$ rms differences where the range of current variability exceeded 1 m s$^{-1}$ (Shay et al. 2003).

Previous results point to a reasonably good estimate of a radar-derived surface current compared to a subsurface current observation. However, a moored measurement is a single-point observation whereas a radar-derived surface current represents a spatial average over areas with dimensions of 0.6–4 km$^2$ depending on the horizontal resolution of the radar in either very high frequency (VHF) or HF mode, respectively. A key scientific issue in using HF radars has been the relationship between radar-derived surface current estimates and those determined from subsurface measurements over similar spatial footprints. The approach described herein attempts to examine this radar measurement issue.

Recent surface current observations from OSCR in VHF mode revealed complex surface current patterns in the South Florida Ocean Measurement Center (SFOMC) area located off Fort Lauderdale, Florida (Shay et al. 2000). These high-resolution surface current observations provided spatial context for repeated velocity profiles acquired by an autonomous underwater vehicle (AUV) over small-scale grids at a speed of 1.2 m s$^{-1}$ at 9-m depth (An et al. 2001; Dhanak et al. 2001). Downward- and upward-looking ADCP moorings and ship-based ADCP and conductivity–temperature–depth (CTD) measurements were also acquired during these AUV-based sampling schemes to examine submesoscale coastal ocean processes forced by energetic Florida current (FC) intrusions and vortices across the shelf break (Peters et al. 2002; Shay et al. 2002).

An AUV provides a novel approach to acquire oceanographic data to observe and understand submesoscale variability in the current and density structure (An et al. 2001). AUV-based measurements allow for a diversity of spatial–temporal resolution of oceanic variables over kilometer scales or less. This subsurface sampling approach benefits from improved platform stability and maneuverability of the AUV with enhanced positional capabilities in oceanic environments. To enable effective operations, an adaptive sampling strategy has to be chosen carefully to maximize the utility of the AUV sampling strategy relative to the imposed surface boundary conditions derived from radar-derived surface measurements. A fundamental step in developing AUV sampling algorithms is to characterize the spatially evolving environmental structure at the appropriate scales (Curtin et al. 1993).

To improve our understanding of this spatial averaging by VHF (and HF) radars, subsurface current profiles from repeated ADCP transects from an AUV underneath four to six cells are compared to radar-derived surface currents. As these subsurface mapping patterns required $\approx$80 min (4$\Delta t$, where $\Delta t$ is the radar sample at a 20-min interval) to complete, spatial variability in coastal oceanic flows was acquired at high spatial resolution inshore of the FC as it intruded across the shelf break. Accordingly, the experimental design is described in section 2. In section 3, spatially averaged current snapshots from two AUV experiments are used to isolate a 10-h oscillation found in the radar, mooring, and AUV data, and to compare the radar-derived surface current to the AUV-derived subsurface current. In section 4, time-mean profiles from each experiment are compared to theoretical log-layer estimates in the downwind directions. Results are summarized in section 5 with concluding remarks.

2. Surface and subsurface measurements

The experiment was conducted in July 1999 from Port Everglades to Hollywood Beach, Florida, which encompassed the SFOMC domain. In this section, the VHF radar and the AUV sensor suite are described where the emphasis is on observations to resolve submesoscale coastal ocean current variability (Table 1). Given the north–south alignment of the south Florida coastline, currents will be referred to as cross-shelf ($U$) and alongshelf ($V$) to represent east–west and north–south directions, respectively.

a. Surface wind observations

Surface atmospheric conditions observed from the National Oceanic and Atmospheric Administration’s (NOAA) Coastal-Marine Automated Network (C-MAN) stations at Fowey Rocks and Lake Worth, and at the northeast (NE) mooring (Table 1) were used to adjust surface winds to the 10-m level. While the C-MAN stations recorded data at hourly intervals, the NE surface mooring acquired data at 15-min intervals beginning on 15 July 1999. During the first mixed layer experiment (ML1), surface winds at Fowey Rocks ranged between 5 and 9 m s$^{-1}$ toward the west between yeardays 190 and 191 (9 and 10 July; Fig. 1a). This onshore wind averaged about 6.5 m s$^{-1}$. Based on Fairall et al. (1996), surface friction velocities ranged from 0.15 to 0.27 m s$^{-1}$ at Fowey Rocks (Fig. 1c). By contrast, northward surface winds were weaker during the ML2 experiment (yeardays 208–209; 27–28 July) as shown in Figs. 1a, b. Winds were directed toward the north at speeds of 4–5 m s$^{-1}$ where $u_a$ over this 12-h
Table 1. Summary of measurements. Notation: velocity vector, \((U, V, W)\); pressure, \(p\); temperature, \(T\); salinity, \(S\); buoyancy frequency, \(N\); wind speed and direction, \(Wi\); atmospheric pressure, \(P\); air temperature, \(T\); relative humidity, \(q\); and sea surface temperature, \(SST\). Note: mooring data sampled at 15-min intervals and the atmospheric conditions were sampled at 2 m above the surface. Hourly atmospheric conditions at Fowey Rocks C-MAN station were also used here.

<table>
<thead>
<tr>
<th>Platform</th>
<th>Sensor</th>
<th>Variable</th>
</tr>
</thead>
<tbody>
<tr>
<td>AUV</td>
<td>1.2-MHz ADCP upward- and downward-looking</td>
<td>(U, V, W)</td>
</tr>
<tr>
<td></td>
<td>CTD</td>
<td>(p, T, S)</td>
</tr>
<tr>
<td>OSCR</td>
<td>Doppler radar</td>
<td>(U, V)</td>
</tr>
<tr>
<td>Ship</td>
<td>CTD</td>
<td>(p, T, S, N)</td>
</tr>
<tr>
<td>Mooring</td>
<td>600-kHz ADCP</td>
<td>(U, V, W)</td>
</tr>
<tr>
<td></td>
<td>600-kHz ADCP</td>
<td>(U, V)</td>
</tr>
<tr>
<td></td>
<td>CTD</td>
<td>(T, S, N)</td>
</tr>
<tr>
<td>NE surface mooring</td>
<td>Coastal climate weather pack</td>
<td>(Wi, P, T, q, SST)</td>
</tr>
</tbody>
</table>

Period ranged from 0.02 m s\(^{-1}\) to as high as 0.16 m s\(^{-1}\) at Fowey Rocks. Surface frictional velocities at the NE mooring (shown below) ranged between 0.05 and 0.2 m s\(^{-1}\) based on adjusted 10-m records. Notice the marked similarities in the adjusted surface winds between Fowey Rocks and the NE mooring site separated by a distance of 65 km (An et al. 2001). Surface winds observed at the Lake Worth C-MAN station (not shown) indicated similar trends, suggestive of coherent wind patterns.

b. VHF radar

The OSCR radar system was deployed from 25 June to 10 August 1999. During this period, a 29-day continuous time series of vector surface currents was acquired at 20-min intervals starting on 9 July and ending 7 August 1999 (Shay et al. 2002). The system consisted of two VHF radar transmit and receive stations operating at 49.945 MHz that sensed electromagnetic signals scattered from surface gravity waves with a Bragg wavelength of 2.95 m (radar wavelength is 5.9 m). Note that the Bragg frequency is 0.72 Hz, and the offset of the first-order spectral peak from this Bragg frequency is proportional to the radial current for a Bragg wave advancing (positive) or receding (negative) from the radar station (Stewart and Joy 1974). The radar system mapped coastal ocean currents over a 7.5 km × 8 km domain with a horizontal resolution of 250 m at 700 grid points (Fig. 2). Radar sites were located in John...
FIG. 2. VHF radar grid domain (circles) relative to University of South Florida–Nova Southeastern University NE and SW current meter arrays (triangles), and bottom topography contoured at 10-m intervals to 50 m, then contoured at 50-m increments. Master and slave sites are located at John U. Lloyd State Park and Hollywood Beach, respectively. Two insets provide high-resolution sampling patterns in the IOD relative to OSCR cells for the AUV-based mixed layer experiments described in Table 2. Sections AA’ and BB’ from ML1 and ML2 are used in the analyses.

U. Lloyd State Park (master) and at an oceanfront site in Hollywood Beach, Florida (slave), yielding a baseline distance of 6.7 km. Each site consisted of a 4-element transmit and 30-element receiving array oriented at an angle of 37° (SW–NE at master) and 160° (SE–NW at slave). A total of 2078 snapshots of the two-dimensional surface current vector were acquired from 0320 UTC 9 July 1999 until 2340 UTC 6 August yielding a 29-day time series. Of the 2078 samples, only 69 samples were missing from this time series, equating to a 3.3% data loss in the snapshots. Previous experiments have yielded similar results ranging from 93% to 97% data return (Haus et al. 1998).

The geometric dilution of precision (GDOP) provides an estimate of the spatial dependence of observed surface current differences based on geometrical constraints (Chapman et al. 1997). Using the radar’s mean look direction (α), and the half angle (φ) between intersecting beams, expressions for the current components are

\[
\sigma_u = \left\{ \frac{2}{\sin^2(2\phi) + \cos^2(\alpha) \cos^2(\phi)} \sin^2(\alpha) \cos^2(\phi) \right\}^{1/2} \sigma, \tag{1}
\]

and

\[
\sigma_v = \left\{ \frac{2}{\sin^2(2\phi) + \cos^2(\alpha) \cos^2(\phi)} \sin^2(\alpha) \sin^2(\phi) \right\}^{1/2} \sigma, \tag{2}
\]
where \( \sigma \) represents rms current differences. The GDOP is a nondimensional number defined by the ratios of \( \sigma_x/\sigma \) and \( \sigma_y/\sigma \) in the along-shelf and cross-shelf components, respectively. As shown in Fig. 3a, the GDOP ranged from 0.75 to 2 for each component. In the core of the domain where a large fraction of the subsurface measurements were acquired, the GDOP for each radial current component was \( O(1) \). Close to the coast, however, the GDOP increased to a value of 2 over a 1.5–2-km distance as intersection angles (Fig. 3b) approached the outer limits of the envelope required to construct a vector current field from radial current data. In this VHF domain, optimal intersections angles are defined here as being between 30° and 150°. These angles encompassed most of the domain except for the grid points closest to the shore, and those just beyond the 40° limits in the far field (Shay et al. 2002).

c. Surface velocity fields

As shown in Fig. 4, an energetic surface current regime encompassed the second AUV experiment (ML2) from 27 to 28 July (yeardays 208 to 209) (Table 2). The AUV measurement domain will be referred to hereafter as the intensive observational domain (IOD). In the inner region of the IOD, surface currents of 30 cm s\(^{-1}\) were toward the south whereas offshore currents associated with the FC exceeded 1.4 m s\(^{-1}\) (Fig. 4a). This surface current pattern indicated large spatial gradients over small scales of \(<2\) km particularly along the shelf break where vorticities were large compared to \( f \) (Peters et al. 2002). Four hours later, surface currents decreased over the IOD; however, the FC remained in the radar footprint where currents were 1.4 m s\(^{-1}\) shown in Fig. 4b. A divergence region formed between the inner and outer parts of the IOD as currents were toward the north-west and east directions, respectively (Fig. 4c). This surface current divergence was associated with a cyclonically rotating ocean feature evident in the central portion of the radar domain. As shown in Fig. 4d, surface flows indicated northward flows for the inner and outer portions of the IOD. By 0000 UTC 28 July (yearday 209), the surface flow pattern suggested a cyclonically rotating feature with 60–70 cm s\(^{-1}\) tangential currents (Fig. 4e) and had marked asymmetric structure similar to the previously observed vortices. In the inner portion of the IOD, surface currents were about 30 cm s\(^{-1}\) directed toward the northeast, but were weaker (\(\approx 10\) cm s\(^{-1}\)) than those over the outer part of the IOD. Forty minutes later (Fig. 4f), a cyclonically rotating feature influenced the surface flows over the IOD. This asymmetric surface velocity structure supported wavelike structures and vortices that appeared to be propagating along the inner edge of the FC (Peters et al. 2002). These features may be more similar to the submesoscale vortices (Shay et al. 1998a) than to large spinoff eddies (Lee and Mayer 1977).

d. Stratification

To examine the upper-ocean stratification, the NE mooring data were used to determine the mean temperature and density conditions observed from a series of micro-cats at 1-, 5-, 10-, 15-, 20-, 30-, and 40-m sampling at 5-min intervals (Fig. 5). Temperatures between 5 and 10 m indicated similar time variations during ML2 when weakly stratified conditions persisted. Since the AUV measured fields at 9-m depth, mean profiles (defined here as the average conditions over the 12-h period) revealed oceanic conditions between 1 and 10 m, with small vertical density differences of less than \( 5 \times 10^{-4} \) gm cm\(^{-3}\). Shipboard CTD data indicated
Fig. 4. Surface current imagery during the ML2 experiment from 27 to 28 July 1999 relative to the region of ship- and AUV-based measurements (box in (a)) for (a) 1600 UTC 27 Jul, (b) 1940 UTC 27 Jul, (c) 2120 UTC 27 Jul, (d) 2300 UTC 27 Jul, (e) 0000 UTC 28 Jul, and (f) 0040 UTC 28 Jul. The color of the current vectors depicts the magnitude of the current.
agreement in the temperature profiles, but with slightly different density profiles due to salinity differences. Stronger stratification was evident beneath 10-m depth in the CTD and mooring data (Peters et al. 2002). This implies that the ML2 measurements beginning at 1.5 m and extending to 6.5 m were contained within a weakly stratified layer as opposed to a well-mixed surface layer. The episodic nature of the FC intrusions across the shelf break makes it difficult to define a well-mixed surface layer. For the purposes of this manuscript, the AUV missions will be referred to as the first (ML1) and second (ML2) mixed layer experiments.

e. AUV-based measurements

The Ocean Explorer (OEX) is a compact AUV that was used to map subsurface coastal ocean structure (An et al. 2001; Dhanak et al. 2001). Upgrades to the AUV sensor suite may be done in a plug-and-play mode, resulting in scalable and reconfigurable systems. At a speed of 1.2 m s\(^{-1}\) at 9 m ± 5 cm beneath the surface, the AUV mapped submesoscale, three-dimensional current variability using a pair of upward- and downward-looking 1.2-MHz ADCPs for nearly continuous periods ranging from 6 to 24 h within the IOD (Table 2). The upward-looking ADCP was programmed to have 0.5-m bins for the mixed layer (ML) and tidal (T) missions and 1.5-m bins in the downward-looking direction. For the bottom boundary layer (BBL) mission, higher-resolution bins of 0.5 m were set in the downward-looking ADCP. The downward-looking ADCP also performed bottom tracking, which provided underwater navigation. Sampling rates for these ADCPs were set to 1 Hz for the 1.5- and 0.5-m bins. A Falmouth Scientific Instrument CTD was used to map the temperature, salinity, and density fields at 9 m. During all missions, scientific and vehicle data were acquired by the OEX including time, temperature, salinity, current, AUV position (latitude, longitude, depth, altitude), and motion parameters (velocity, acceleration, angular rate, and attitude). The OEX was acoustically tracked from a chase boat using its onboard Trackpoint II system where data were integrated into the boat’s global positioning system (GPS) and flux-gate compass.

Within the IOD (see Fig. 2), the OEX sampled subsurface current velocities in water depths ranging from 20 to 35 m. For both ADCPs, only raw data were ac-

<table>
<thead>
<tr>
<th>Mission type</th>
<th>Date</th>
<th>Time (UTC)</th>
<th>AUV (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ML1</td>
<td>9</td>
<td>1145–2315</td>
<td>6</td>
</tr>
<tr>
<td>BBL</td>
<td>12</td>
<td>1300–2350</td>
<td>7</td>
</tr>
<tr>
<td>T1</td>
<td>15–16</td>
<td>2040–2300</td>
<td>15</td>
</tr>
<tr>
<td>T2</td>
<td>23–24</td>
<td>1300–1640</td>
<td>26</td>
</tr>
<tr>
<td>ML2</td>
<td>27–28</td>
<td>1230–0135</td>
<td>12</td>
</tr>
</tbody>
</table>

Fig. 5. (a) Temperature (°C) and (b) density (gm cm\(^{-3}\)) (left) time series and (right) average profiles during ML2. Time series represent 5 (solid), 10 (dotted), and 15 m (chain-dot) from the NE 50-m mooring. Profiles represent those derived from the mean (solid) and one standard deviation (dashed) from the mooring data and the circles are those averaged from shipboard CTD profiles acquired during the ML2 experiment.
required (no ensemble averaging) from the AUV. The ML1 mission was conducted over a period of 6 h and 15 min, and ML2 was completed over a 12-h period, which also included a turbulence package as part of the payload (Dhanak et al. 2001). The AUV preprogrammed, lawnmower pattern was repeatedly executed until its battery energy was depleted, resulting in four and seven snapshots for the ML1 (500 m × 500 m) and ML2 (500 m × 750 m) missions, respectively. During these missions, the OEX surfaced to acquire differential GPS fixes that bounded positional errors of ≈25 m (typically 10% of radar grid resolution). The time to complete one full pattern was approximately 80 min or four radar samples (Δτ = 20 min).

To facilitate a comparison to the radar-derived surface current measurements, AUV-derived current profiles were smoothed in the along-AUV-track directions. As shown in Fig. 6, differing timescales of 10, 20, and 30 s, corresponding to horizontal length scales of 12, 24, and 36 m for a steadily moving vehicle, were tested using autocorrelation methods. For an AUV speed of 1.2 m s⁻¹, the 10-s averaging period was optimal since autocorrelation levels were above 0.9, yielding a 12-m averaging interval for each profile. Based upon a 1-Hz sample interval for the 0.5-m bin data, measurement uncertainty over a 10-s interval was approximately 4 cm s⁻¹ whereas it was less than 2 cm s⁻¹ for the downward-looking ADCP averaged over a 1.5-m bin. The smallest resolvable horizontal wavelength in the measurements was 24 m. For each synoptic snapshot, these 10-s averaged data were gridded to a surface at the various depths beginning at 1.5-m depth (kinetic energy differences of the mapped current fields were typically 1%-7% less than the observed field). Contamination by sidelobe, surface reflections may induce additional uncertainty into near-surface ADCP measurements. For example, the range is given by $H[1 - \cos(\theta)]$ where $H$ is ~9 m and the transducer angle ($\theta$) is 30° (Teague et al. 2001). Thus, the first bin of usable AUV ADCP data is estimated to be 1.5–2 m. Radar-derived surface velocity fields were mapped to the same surface for comparison purposes over each 80-min synoptic snapshot at more than 500 points as described below.

3. Surface and subsurface comparisons

a. Vertical structure

Along one section during the ML2 mission (BB’ in Fig. 2), velocity profiler data from 1.5 to 6.5 m were spatially averaged along an east–west transect from each snapshot, and compared to the southwest (SW) and northeast (NE) ADCP mooring data (averaged over 80-min time intervals) as shown in Fig. 7. Cross-shelf flows were 40%-50% less energetic than along-shelf flows associated with the FC. The upper-ocean data suggest a depth-independent flow, consistent with ship transect data. Although AUV profiling was conducted over a 12-h period, these spatially averaged profiles indicated a current oscillation in the time-dependent variability from snapshot to snapshot. This energetic oscillation was apparent in the along-shelf flows with an ≈10 h period, which can be distinguished from weaker semi-diurnal tidal currents of 4–6 cm s⁻¹ (An et al. 2001). These motions were also observed at the NE and SW moorings located along the 50- and 20-m isobaths, respectively (see Fig. 2). The AUV snapshots captured this wavelike variability where the wavelength was found to be about 30 km for a wave period of ≈10 h period based on spectral analysis (Peters et al. 2002). At the SW mooring, this oscillation was similar but with a shifted phase and a smaller amplitude presumably due to the importance of bottom friction in the shallower water. These time-dependent current transects from the AUV are similar to the oscillatory motions observed at the moorings.

To isolate this observed wavelike variability, observed currents from the moorings and AUV were layer averaged (as per Fig. 7) from 3 to 6 m and 1.5 to 6.5 m, respectively, over the ≈80 min timescale. These layer-averaged data (from each sequential snapshot) were fit to a model (Rossby and Sanford 1976) to determine the carrier frequency of the wave form. For each trial frequency starting at 0.8 $\sigma_r$ and ending at 1.2 $\sigma_r$, layer-averaged, cross-shelf currents were fit to an expression of the form

$$U_r(t) = [A_r \cos(\sigma_r \delta t + \theta_r) + B_r \sin(\sigma_r \delta t + \theta_r)] + u_r(t), \quad (3)$$

and with a similar expression for the along-shelf component:
FIG. 7. (left) Cross-shelf and (right) along-shelf profiles spatially averaged along one AUV track during the ML2 (BB in Fig. 1) experiment on 27–28 Jul relative to the NW (blue) and SW (red) moorings for (a) 1349±1502, (b) 1523±1645, (c) 1709±1833, (d) 1903±2014, (e) 2043±2154 UTC, and (f) 2223±2334 UTC 27 Jul, and (g) 2353 UTC 27 Jul–0114 UTC 28 Jul. Along-shelf current scale is 2.5 times the cross-shelf current scale.

TABLE 3. Parameters of the observed oscillatory velocity for the U and V components derived from the Rossby and Sanford (1976) model fits encompassing the second mixed layer experiment.

<table>
<thead>
<tr>
<th>Platform</th>
<th>(A_u) (cm s(^{-1}))</th>
<th>(\theta_u) (°)</th>
<th>(A_v) (cm s(^{-1}))</th>
<th>(\theta_v) (°)</th>
<th>(T_p) (h)</th>
<th>(\sqrt{(u, v)}) (cm s(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>NE</td>
<td>16</td>
<td>-158</td>
<td>44</td>
<td>-8</td>
<td>11.0</td>
<td>14</td>
</tr>
<tr>
<td>AUV</td>
<td>14</td>
<td>-129</td>
<td>52</td>
<td>-64</td>
<td>9.2</td>
<td>4</td>
</tr>
<tr>
<td>SW</td>
<td>6</td>
<td>-46</td>
<td>32</td>
<td>-121</td>
<td>10.2</td>
<td>11</td>
</tr>
</tbody>
</table>

\[ V_i(t) = \left[ A_u \sin(\sigma_u \delta t + \theta_u) + B_u \cos(\sigma_u \delta t + \theta_u) \right] + v_i(t), \]  

where \(A_u\) and \(B_u\) represent Fourier amplitudes for the cross-shelf and along-shelf components, respectively; \(\delta t \approx 80\) min represents the time interval to complete one snapshot; \(\theta_u\) are the phase angles; and \(u_i\) and \(v_i\) represents unresolved currents (Marquardt 1963). The carrier frequency is defined as the frequency minimizing the covariance between the unresolved components \((u_r, v_r)\). Sensitivity tests have been reported elsewhere using a wave of known frequency (period) with an amplitude of 1 and 0.2 m s\(^{-1}\) and a random noise component of 10% of these input signals. The uncertainty in resolving the period was found to be ±1 h.

Results of the least squares fit are listed in Table 3 and shown in Fig. 8. In the cross-shelf direction, amplitudes from the mooring data were \(-16\) cm s\(^{-1}\) at the NE mooring (50 m) whereas the amplitudes at the SW mooring (20 m) were 6 cm s\(^{-1}\). The cross-shelf amplitude \((A_u)\) derived from the AUV was 14 cm s\(^{-1}\), which agreed with the \(A_u\) determined from the 50-m mooring as phase angles \((\theta_u)\) increased shoreward. By contrast, along-shelf current amplitudes ranged from 32 cm s\(^{-1}\) at the SW mooring to 44 cm s\(^{-1}\) at the NE mooring. The amplitude derived from the seven AUV snapshots was 52 cm s\(^{-1}\). In this component, the phase angle decreased toward the coast. The periods of the carrier signals at the mooring sites ranged from 10 to 11 h compared to about 9.2 h from the 12 h of AUV data. Using a 29-day time series of surface current data over the NE mooring, Peters et al. (2002) found a 10.2-h period oscillation in variance-conserving spectra from the surface current data where the horizontal wavelength was 30 km. Thus, this 9.2-h period is within the uncertainty of the approach of ±1 h in resolving the wave period. Rms amplitudes defined here as \(\sqrt{(u_r, v_r)}\) ranged from 4 to 14 cm s\(^{-1}\). These larger differences at the mooring sites were due to the lack of time dependence in model amplitudes (3, 4). That is, amplitudes were assumed to have the same value over a 3-day time series used in the fit. The 4 cm s\(^{-1}\) difference suggests a good fit between the model and the AUV current data.

b. Radar- and AUV-derived current snapshots

The mapped velocity fields from the radar and the AUV are compared at each of these points to assess the
relationship between subsurface structure and radar-derived surface velocity field. During the first snapshot of the ML1 experiment (Fig. 9a), currents revealed a predominant northward flow and evidence of an anticyclonic current veering with depth. The anticyclonic current veering during the second snapshot (Fig. 9b) became more pronounced as the angle between the surface and subsurface current vectors increased to more than 45°. As shown in Fig. 9c, weaker surface currents were directed toward the coast compared to the northward flows in the first snapshot. The 2-m subsurface currents decreased from 50 cm s⁻¹ to less than 15 cm s⁻¹. Current veering with depth was erratic at times due to weaker cross-shelf flows. By the fourth snapshot (Fig. 9d), currents reversed direction from a northward to a southward flow, but did not indicate any dominate spatial trends. Over the 6 h, these snapshots indicated a gradual cyclonic turning of the current field as observed flows were toward the north, northwest, west, and south to southwest directions.

During the ML2 experiment, surface and subsurface currents were aligned in the same direction with weak currents at both levels (Fig. 10a). As shown in Fig. 10b, currents flowed toward the south as the 2-m currents were more energetic than those observed in the surface layer. Surface currents subsequently increased and were directed toward the southeast whereas subsurface currents remained directed toward the south (Fig. 10c). Surface flows were less energetic than those observed at 2 m during the fourth snapshot (Fig. 10d). During the third and fourth snapshots, subsurface currents were nearly orthogonal to the surface currents. However, over the next averaging cycle, surface velocities of 30 cm s⁻¹ were toward the northeast direction whereas subsurface current directions were less than 30° to the right of the surface current (Fig. 10e). Cross-shelf current differences of 5–10 cm s⁻¹ occurred during this period when a surface current convergence zone developed within the IOD. In the northern part of the IOD, these directional differences exceeded 45° between surface and subsurface currents (Fig. 10f). By contrast, the alignment between the surface and subsurface current vector was less than 20° in the central and southern portions of the IOD. In the last snapshot (Fig. 10g), weaker currents were directed toward the west with magnitudes of 20 cm s⁻¹ in the core of the IOD. During this experiment, northward surface winds prevailed as shown in Fig. 1.

c. Areal averaging

As per these fields (Figs. 9 and 10), the areal sampling of radar signals over the cells is estimated by differ-
Fig. 9. Comparisons between the surface current (red arrow) and the 2-m subsurface current (blue arrow) from the AUV during the ML1 experiment at (a) 1545±1709, (b) 1717±1837, (c) 1845±2004, and (d) 2013±2130 UTC 9 Jul relative to the AUV track.

Ocercing surface and subsurface currents and spatially averaging them over 500 m × 500 m and 500 m × 750 m for the ML1 and ML2 experiments, respectively. For the areal averaged currents, differences ranged between 7 and 8 cm s⁻¹ during the first snapshot of ML1 (Table 4) as currents were flowing in the same direction. A difference of 22 cm s⁻¹ occurred during the second snapshot due to weaker cross-shelf surface flows directed toward the coast compared to the more energetic northward subsurface flows. By the third snapshot, these differences decreased to 16 and 6 cm s⁻¹ for the cross-shelf and along-shelf currents, respectively. For the fourth snapshot, averaged differences decreased to 7–9 cm s⁻¹. In the ML2 experiment, similar results were found as suggested by Fig. 10. The largest differences (20–26 cm s⁻¹) occurred during snapshots 3 and 4 when directional differences of up to 90° were observed. During the other snapshots, current differences, based on more than 500 spatial points, were in the 10 cm s⁻¹ range. Based on the seven snapshots, averaged current differences (in an arithmetic sense) ranged from 8 to 14 cm s⁻¹ in a regime where FC surface velocities as high as 1.4 m s⁻¹ were observed. This equates to an uncertainty of approximately 5%–20%, which is similar to previous observations. These results suggest a linkage between subsurface ocean structure and radar-derived current signals from 80-min (=1.3 h) sample intervals over the same spatial scales.

Given the 10-s averaging period of the AUV and the 20-min sample interval from the VHF radar, the scatter between the two platforms from the 11 snapshots is shown in Fig. 11. In the cross-shelf direction, the scatter ranged between ±30 cm s⁻¹ (Fig. 11a). Based on 30 samples from the NE mooring data comparisons during ML2, the regression curve had a slope of 1.5, centered approximately in the scatter. The histogram revealed that 95% of the current differences were from −30 to 20 cm s⁻¹. Similarly, along-shelf currents indicated multiple subsurface values (at ≈35 cm s⁻¹) during one radar sample (Fig. 11b). Regression analysis of the NE mooring data revealed a slope of O(1) with a bias of 9 cm s⁻¹. This slope generally followed with the scatter data, but was skewed toward more positive values. Notice that 95% of the data ranged between −20 and 25 cm s⁻¹, but with more current differences located between −15 and 10 cm s⁻¹. Even though the 10-s averaged data were subsampled at 30-s intervals, the analysis suggests a relationship between the radar-derived and AUV-derived current at 2 m, although it is not a perfect one.

Complex correlation coefficients and phase angles are estimated based on Kundu (1976). The phase angle represents the average cyclonic angle of the subsurface current vector with respect to the surface current vector. As shown in Fig. 12, the correlation coefficients from both experiments were 0.8 or above over the IOD. Correlation coefficients exceeded 0.9 in the eastern part of the domain due to the FC’s influence on coastal currents. In the western part of the domain, more complex coastal processes accounted for the slight decrease in the correlation indices. Subsurface currents generally veered anticyclonically relative to the surface velocity field, as phase angles, averaged over the four and seven snapshots, ranged from −20° to −30°. Less current veering was observed closer to the FC in the ML1 experiment.
compared to the coastal region. By contrast, phase angle gradients were oriented more in the along-shelf direction during ML2 (see Shay et al. 2002). Profiles of the correlation coefficients and phases revealed similar trends in the upper 6.5 m relative to the surface current (not shown). Correlation indices between the two independent platforms tended to be larger in ML2 (0.9) than in ML1 (0.85).

d. Mean current profiles

Spatially averaged current profiles from each snapshot (Figs. 9 and 10) were averaged over time from the four and seven snapshots from ML1 and ML2, respectively. As shown in Fig. 13a, mean currents exhibited structure and shear in the upper 6.5 m of the water column during ML1. In the cross-shelf component, the surface current was about 12 cm s$^{-1}$ toward the coast, and the subsurface current approached zero at about 5 m. By contrast, the more energetic along-shelf current was toward the north (i.e., the current at 7 m was 10 cm s$^{-1}$). In fact, the northward current component indicated more variability than in the cross-shelf direction as suggested by the standard deviations. Current shears between the surface and 3 m were also larger in the cross-shelf direction, which was the direction of the wind during ML1.

During ML2 (Fig. 13b), the cross-shelf current suggested more of layer-averaged flow toward the coast than observed during ML1 (i.e., small vertical shear). The northward current at the surface was 4 cm s$^{-1}$ and decreased to $\sim-4$ cm s$^{-1}$ at 3 m. Near-surface mean

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**Fig. 10.** Same as in Fig. 9 except for ML2 (27–28 Jul) at (a) 1349–1502, (b) 1523–1645, (c) 1709–1833, (d) 1903–2014, (e) 2043–2154, and (f) 2223–2334 UTC 27 Jul, and (g) 2353 UTC 27 Jul–0114 UTC 28 Jul.
TABLE 4. Summary of aerial-averaged surface and subsurface current difference and one std dev acquired by OSCR and the AUV (2–3 m) for the ML1 and ML2 experiments.

| Snapshot | Time (UTC) | Obs | $|U_o - U_2|$ | $|V_o - V_3|$ | $\sigma_{U_{o-2}}$ | $\sigma_{V_{o-3}}$ |
|----------|------------|-----|---------------|---------------|----------------|----------------|
| ML1      |            |     | (cm s$^{-1}$) | (cm s$^{-1}$) | (cm s$^{-1}$) | (cm s$^{-1}$) |
| 1        | 1545–1709  | 676 | 8             | 5             | 7             | 5             |
| 2        | 1717–1837  | 676 | 22            | 6             | 12            | 8             |
| 3        | 1845–2004  | 676 | 16            | 6             | 6             | 5             |
| 4        | 2013–2130  | 676 | 7             | 5             | 9             | 5             |
| T        | 2704       | 13  | 6             | 8             | 5             |               |
| ML2      |            |     | (cm s$^{-1}$) | (cm s$^{-1}$) | (cm s$^{-1}$) | (cm s$^{-1}$) |
| 1        | 1349–1502  | 558 | 4             | 3             | 10            | 8             |
| 2        | 1523–1645  | 581 | 10            | 7             | 12            | 7             |
| 3        | 1709–1833  | 554 | 25            | 6             | 26            | 4             |
| 4        | 1903–2014  | 487 | 5             | 4             | 21            | 16            |
| 5        | 2043–2154  | 525 | 14            | 7             | 10            | 5             |
| 6        | 2223–2334  | 513 | 19            | 10            | 11            | 5             |
| 7        | 2353–0114  | 568 | 10            | 6             | 12            | 10            |
| T        | 3786       | 12  | 6             | 14            | 8             |               |

Current shear of $O(10^{-1} \text{ s}^{-1})$ was larger in the along-shelf direction (northward) than in the cross-shelf direction (westward). As in the ML1, along-shelf currents were more variable than those in the cross-shelf directions owing to the presence of the FC where lateral shears were large (Peters et al. 2002). Of particular interest is the behavior of the mean profiles. Arithmetic differences based on summing the results from the four and seven snapshots ranged between 8 and 14 cm s$^{-1}$, which are within the expected differences from previous comparison studies (Table 4). Based on the mean profiles in the downwind directions, mean current differences were 6–8 cm s$^{-1}$ between the surface and 2 m during the two experiments.

4. Effect of surface winds

a. Surface wind stress

Surface wind time series (see Fig. 1) from the ML1 and ML2 experiments suggested forcing toward the east and north, respectively. In this context, the ML1 wind stress at 10 m ranged between 0.025 and 0.1 N m$^{-2}$ from the Fowey Rocks C-MAN station (Fig. 14). The atmospheric surface friction velocities were 0.15–0.27 m s$^{-1}$. This onshore wind stress (rotated 90° anticyclonically for a clearer presentation) was in the same direction as the cross-shelf mean current profile. During ML2, surface wind stress from the NE mooring was northward with a maximum value of 0.035 N m$^{-2}$, and was consistent with the along-shelf mean current profile (Fig. 14b). From these records, the maximum $u_w$ was estimated to be 0.2 m s$^{-1}$, which was greater than the maximum $u_w$ of 0.16 m s$^{-1}$ determined at Lake Worth (not shown). For the comparisons here, maximum $u_w$ values of 0.27 and 0.2 m s$^{-1}$ are used to assess the wind’s influence on the mean profiles in the downwind directions from both experiments. These estimated 10-m

![Fig. 11.](image)

![Fig. 12.](image)
surface stress estimates are accurate to within 20% from the Fowey Rocks C-MAN station and the NE mooring.

b. Logarithmic layer

Uncertainty in the HF-radar-derived surface currents has been attributed to several factors including surface winds. For example, Graber et al. (1997) estimated uncertainty in near-surface shears based on steady-state, Ekman dynamics for surface wind magnitudes. More recently, Teague et al. (2001) assessed differences in linear versus logarithmic, near-surface layers using data from the MCR and moored ADCP measurements acquired during COPE-3. Following Lentz (1992), the predicted wind shear from a logarithmic layer model, based on the profile method used in atmospheric boundary layer studies, is given by

$$\Delta u_p = \frac{u_w}{\kappa} \ln \left( \frac{z_1}{z_2} \right),$$  

where $\Delta u_p$ represents the wind difference between vertical levels $z_1$ and $z_2$, and $\kappa$ is the von Kármán constant, which has a range of values from 0.35 to 0.42 (Businger et al. 1971; Garratt 1992). To maximize the effect of the surface wind stress, $\kappa$ is set to 0.35. The atmospheric surface friction velocity is converted to an oceanic surface friction velocity ($w_u$) by multiplying by the square root of the ratio of the atmospheric and oceanic density. Simplifying the expression, the predicted near-surface current shear is

$$w_u(z_s) = u(z_s) + 1.16 \frac{u_w}{\kappa} \ln \left( \frac{z_1}{z_2} \right).$$  

where $C$ represents a fitting parameter based on the data and $z_s$ represents the depth of the surface velocity as determined from the ratio of the radar wavelength divided by $8\pi$ (Stewart and Joy 1974). For a VHF radar transmitting at 49.95 MHz, this depth is 0.23 m (Shay et al. 2002).

As shown in Fig. 15, theoretical shears were fit to the observed mean ocean current shears relative to the surface current in the downwind directions from the surface to 6.5 m to determine the slope ($C$) and bias. In estimating observed current shears, we have assumed that the mean surface current is primarily wind driven. Based on 2.1%–3.6% of the wind speed range, the wind-driven current is estimated to be 10–15 cm s$^{-1}$, which agrees with the observed mean cross-shelf current of ø11±12 cm s$^{-1}$. The scatter was fairly tight with a regression slope ($C$) of ø1.16. Biases between observed and theoretical shears were about 3 cm s$^{-1}$ as reflected in the histograms. Fits were not performed for the cross-shelf components given the persistence of the winds toward the east (north) during ML1 (ML2). Moreover, the cross-shelf component during the ML2 experiment suggests more of a layer-averaged current (Fig. 13b), which is inconsistent with weak wind-driven flows.

The theoretical profile based on the regression analysis is given by

$$\Delta u_p = C \frac{w_u}{\kappa} \ln \left( \frac{z_1}{z_2} \right).$$

where $\Delta u_p$ represents a fitting parameter based on the data and $z_1$ represents the depth of the surface velocity as determined from the ratio of the radar wavelength divided by $8\pi$. The theoretical profile based on the regression analysis accounted
for a large fraction of the observed structural variations between the surface and upper-ocean currents from the AUV. Differences of $\approx 2$ cm s$^{-1}$ occurred between 2 and 3 m in both profiles, and were within the measurement error of the radar and AUV measurements noted above. Maximum $u_*$ values were also used as opposed to the time series in Fig. 14 or mean wind conditions to place an upper bound on the results. In both downwind mean current profiles, the slope of the fit ($C \approx 1.16$) represents uncertainty in accurately determining $u_*$. In this context, radar measurements and near-surface currents must focus on understanding the behavior of near-surface current shears under differing oceanic and atmospheric conditions (i.e., Teague et al. 2001).

c. Discussion

One of the complicating effects of surface wind fields is in the formation of an Ekman layer, and the anticyclonic rotation of the subsurface current vector with depth. Based on surface friction velocities, the Ekman depth is estimated to be about 25–30 m, in agreement with Dhanak et al. (2001). This depth encompasses the entire depth in the IOD. In several snapshots, but not all, there is an anticyclonic veering of the current vector with depth. Furthermore, the Ekman solution to the momentum equations represents a steady-state response. Given the time-dependent behavior in the synoptic snapshots, the observed temporal variability violates this assumption. At the estimated Ekman depth, theoretical subsurface currents should be $\approx 4\%$ of the surface current flowing in the opposite direction. This equates to values less than 0.5 cm s$^{-1}$, which are not resolved from these subsurface current measurements.

During the Long-Term Upper Ocean Study (LOTUS), VMCMs were deployed at several levels and attached to a 3-m discus surface buoy equipped with an atmospheric sensing package (Briscoe and Weller 1984). Using these data, Price et al. (1987) found that the observed wind-driven transport and the averaged, wind-driven current were within 10% of the theoretical predictions, underscoring the importance of acquiring high-resolution measurements from a stationary platform to resolve these motions.

5. Concluding remarks

The VHF radar and AUV-based measurements provide a new perspective of small-scale coastal ocean processes over $<1$ km scales. One of the more difficult issues here was the choice of the appropriate averaging interval for the AUV-based measurements. The 10-s interval resulted in more coherent current profiles relative to the surface currents with less noise than the 1-s data. Except for snapshots when the surface and subsurface current directions were orthogonal, spatial averages over the 80-min period suggest that the radar measured an areal average in accord with subsurface structure. There were snapshots when these differences between the radar-derived and near-surface currents were less than 10 cm s$^{-1}$ with high correlation levels exceeding 0.85 over similar time- and space scales. Previous studies using mooring and ship-based current measurements generally lie within this same range (Chapman et al. 1997). Moreover, the AUV profiler data in the second experiment revealed a depth-independent flow, and an oscillation of about 9.2 ± 1 h. These findings were consistent with
spectral analysis of the radar and mooring time series data (Peters et al. 2002).

Time averaging the spatially averaged snapshots to form a mean current resolved the low-frequency response to the wind. Shay et al. (2002) ruled out the effects of waves and winds on the current structure. However, by examining 10-m adjusted surface winds at C-MAN stations and the NE mooring, surface winds affected near-surface layer currents in the downwind directions. Surface and subsurface current profiles suggested a near-surface, log-layer dependence using the maximum surface frictional velocities during each experiment. Even though winds were weak, mean downwind current components decayed logarithmically during ML1 and ML2. Subsurface current veering was observed during various snapshots, yet it was not consistently in the anticyclonic direction relative to the surface current in each snapshot. In this framework, the development of an Ekman layer remained unclear since it is a response to a time-independent wind field usually much longer than the local inertial period. As the duration of the ML2 experiment was only 12 h, the high-resolution data cannot resolve these effects.

Progress in coastal oceanography has been slower to evolve than deep-water oceanography owing to its complexity both observationally and theoretically. In this regime, fronts, boundary layers, internal waves, and turbulent processes contain short time- and space scale variations. The approach described herein has provided a submesoscale dataset to not only assess the spatial averaging of the radar, but to also demonstrate the compatibility of combining maturing technologies such as AUV and HF radar together with more traditional ADCP and CTD technologies to focus on submesoscale ocean processes. Embedded within this regime are unresolved subgrid-scale processes that are relatively unknown at the present time yet often parameterized in coastal models. As this approach contains an unprecedented level of detail for observing the coastal ocean, new insights on submesoscale processes will continue to unfold in the thorough analyses of the dataset.

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