High Frequency Radar Mapping of Surface Currents Using WERA

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Abstract

A dual-station High Frequency Wellen Radar (WERA), transmitting at 16.045 MHz, was deployed along the west Florida Shelf during the summer of 2003. A 33-d, nearly continuous time series of radial and vector surface current fields was acquired starting on 23 Aug ending 25 Sep 2003. Over a 30-min sample interval, WERA mapped coastal ocean currents over an ≈ 40 km × 80 km domain with a horizontal resolution of 1.2 km at 2820 cells at least 80% of the time in phased-array mode. A total of 1628 snapshots of the vector surface currents were acquired with only 70 samples (4.3%) missing from the vector time series. Complex surface circulation patterns were observed that included coherent tidal currents, and wind-driven currents over the west Florida shelf.

Comparisons to subsurface measurements from moored acoustic Doppler current profiles revealed RMS Differences of 1 to 5 cm s\(^{-1}\) for both radial and cartesian current components. Regression analyses indicated slopes close to unity with biases ranging from -2 and 1.6 cm s\(^{-1}\) between surface and subsurface measurements at 4-m depth in the east-west (\(u\)) and north-south (\(v\)) components, respectively. Vector correlation coefficients were 0.9 with complex phases of -3 and 5° at EC4 (20-m isobath) and NA2 (25-m isobath) moorings, respectively. Maximum tidal amplitudes were 4 to 5 cm s\(^{-1}\) for the \(K_1\) and \(M_2\) constituents with weaker contributions from \(O_1\) and \(S_2\) tidal constituents. Vertical structure of the tidal currents indicated that the \(M_2\) tidal current was barotropic. Tidal currents explained from 25 to 40% of the observed surface current variance.

Detided surface currents were compared to 10-m winds at NA2 when the magnitude of the directional differences was less than ± 45°. Based on 60% of the time series, regression slopes were 0.02 to 0.03 in the east-west and north-south directions, respectively. These wind-driven surface currents account for 50 (25) % of the observed variance in the east-west (north-south) directions. During the passage of Tropical Storm Henri on 5 Sep 2003, cyclonically rotating surface winds ranged from 11 to 14 m s\(^{-1}\) and forced surface velocities of more than 35 cm s\(^{-1}\) as Henri made landfall north of Tampa Bay. These results suggest that the WERA measured the surface velocity well under weak to moderate wind conditions.
1 Introduction

Ocean surface current measurements have been one of the more elusive challenges to confront ocean scientists. Given increased national attention on the coastal ocean and in the planned networking of coastal ocean observatories, the acquisition of high quality surface current data is required to provide spatial context for the emerging suites of in situ instrumentation and the national coastal ocean backbone. In this framework, long-term monitoring of the surface circulation provides important data to study its impact on societally relevant issues such as search and rescue operations, coastal pollution from sewage plants, transport of harmful algae blooms (i.e. red tide), oil spills and their mitigation, beach erosion and renourishment, and air-sea interaction studies.

The Doppler radar technique has steadily evolved over the past five decades based on the pioneering work of Crombie (1955). Radar signals are backscattered from the moving ocean surface by resonant surface waves of one-half the incident radar wavelength. This Bragg scattering effect results in two discrete peaks in the Doppler spectrum (Stewart and Joy 1974). In the absence of a surface current, spectral peaks are symmetric about the Bragg frequency (\(\nu_b\)) offset from the origin by an amount proportional to \(2c_0\lambda^{-1}\), where \(c_0\) represents the linear phase speed of the surface wave and \(\lambda\) is the radar wavelength. If there is an underlying surface current, Bragg peaks in the Doppler spectra are displaced by an amount of \(\Delta\nu = 2V_{cr}\lambda^{-1}\), where \(V_{cr}\) is the radial current component along the radar’s look direction.

To resolve the 2-dimensional current fields, at least two radar stations are required where their separation determines the domain of the mapped region. Measurement accuracy for a vector current is a maximum for an angle of intersection of 90° between the two radial beams emanating from each of the radar site (Chapman et al. 1997). This error in resolving the current vectors increases as the intersection angle departs from this optimal value.

The concept of using High Frequency (HF) and Very High Frequency (VHF) radar pulses to probe ocean surface currents has received considerable attention in coastal oceanographic experiments in Europe and the United States (Gurgel et al. 1999a; Paduan and Graber 1997). Two systems that have been used primarily in these experiments are Coastal Ocean Dynamics Applications Radar (CODAR)
(Barrick 1987; Paduan and Rosenfeld 1996) and the Ocean Surface Current Radar (OSCR) (Prandle 1987; Shay et al. 1995). A WEllen RAdar (WERA) system has been recently developed that utilizes phased-array technology (Gurgel et al. 1999b). While all these systems are based on resonant Bragg backscatter, there is a fundamental difference in the methodology used to isolate the ocean area where scattering occurs. At a transmission frequency of 16.045Hz, WERA system requires 102-m (139-m) baseline distance for 12-(16-) element phased array to achieve a narrow beam, electronically steered over the illuminated ocean area (Table 1). Beamwidth is a function of the radar wavelength divided by the length of a phased array, which is 10° and 7.5° for the 12- and 16-element phased arrays, respectively. WERA may also be deployed in direction-finding mode similar to a CODAR except with a 4-element square receiver array. This feature makes WERA attractive for small, confined areas compared to the beach real estate required for the length of a phased array. Regardless, current direction resolution is more sensitive to beam patterns in direction-finding (DF) than in beam-forming (BF) algorithms (Gurgel et al. 1999).

Until recently, comparisons to conventional oceanographic measurements have been limited to tidal bands due in part to their large horizontal scales and well-defined periods (Prandle 1987; Paduan and Rosenfeld 1996). A series of coastal experiments have compared subsurface vector currents using measurements from fixed and moving platforms to surface currents from HF and Very High Frequency (VHF) radar (Prandle 1987; Shay al. 1995; 1998) and Very High Frequency (VHF) (Balsley et al. 1987; Shay et al. 2002, 2003). An important issue in these comparisons is related to range and bandwidth, which sets the horizontal resolution. For long-range HF systems using low frequencies (< 10 MHz), bandwidth is a premium, which causes the surface velocity measurement to be integrated over 36 to 144 km² areas (horizontal resolution of 6 to 12 km). Depending on the available bandwidth, a point measurement from a mooring centered in a cell may not represent of the area (resolution) the HF radar is sampling particularly if the region has high lateral surface current shear. By contrast, for moderate frequencies in the HF (12 to 30 MHz) and VHF (30-50 MHz) bands, bandwidth is usually available to resolve horizontal structure over ≈ 0.25 to 9 km² areas.

Over 1 km² areas, point-by-point comparisons have revealed both similarities and differences between
surface and subsurface current signals (Shay et al. 1998a,b; 2001; Chapman et al. 1997; Emery et al. 2004). Notwithstanding, HF and VHF radar-derived surface current measurements have correlated reasonably well with the surface mixed layer current structure. Depending on the depth of the subsurface current measurement and the venue, RMS differences have ranged between 7 to 20 cm s\(^{-1}\). In an NSF and ONR sponsored Duck94 experiment, comparisons to a Vector Measuring Current Meter (VMCM) at 4-m depth indicated an RMS difference of 7 cm s\(^{-1}\) over a range of 1 m s\(^{-1}\) from a 29-d time series. Given the VMCM’s measurement accuracy of \(\approx 2\) cm s\(^{-1}\) (Weller and Davis 1980), the accuracy for the surface current measurement was about 5 cm s\(^{-1}\), consistent with the OSCR cited values. Although differences still remain, radar-derived surface current measurements represent the integrated currents in the top meter (or less) of the water column \((\lambda/8\pi)\) (Stewart and Joy 1974) where winds and waves impact surface currents and near-surface current shears (Graber et al. 1997; Shay et al. 2003). For this study, the objective is to assess WERA performance in a regime where moored ADCPs were deployed as part of the University of South Florida’s Coastal Ocean Monitoring and Prediction System (Weisberg et al. 2002).

In the following manuscript, surface current observations acquired over the West Florida Shelf (WFS) from a WERA HF radar are described and compared to inner-shelf moorings at the 20-m and 25-m isobaths. This comparison also includes the radial currents from both mooring sites following Emery et al. (2004) as well as the cartesian current components. In addition to tidal influences (He and Weisberg 2002a), intermittent Loop Current intrusions (He and Weisberg 2003; Weisberg and He 2003), steady and transient winds (Li and Weisberg 1999; He and Weisberg 2002b) impact the coastal circulation pattern. For a uniform wind field, upwelling zones were found along the WFS including southwest of Tampa along the 25-m isobaths. This upwelling regime is also known as an Epicenter of Gymnodinium Breve or the harmful algae bloom known as red tide (Tester and Stiedinger 1997). These upwelled blooms are affected by surface currents as they are transported shoreward where they impact the fishing and tourist industries. In this broader context, the experimental design using WERA is described in Section 2 with observations given in Section 3. In Section 4, radial and vector surface and subsurface currents are compared from Aug/Sep 2003 experiment. Tidal and wind effects are addressed in Section
5. Results are summarized in Section 6 with concluding remarks.

2 Measurement Approach:

An HF-radar experiment was conducted in the summer of 2003 over the WFS using WERA (Gurgel et al. 1999a,b). In this section, the experimental design and WERA specifications are described with an assessment of radar-derived surface current signals.

2.1 WERA Characteristics

The WERA system transmits a frequency modulated continuous wave (FMCW) chirp at 0.26 sec intervals and avoids the blind range in front of the radar of interrupted FMCW (Gurgel et al. 1999a; Essen et al. 2000). As listed in Table 1 for both high-resolution and low-resolution versions, transmission frequencies of 16 and 30 MHz correspond to Bragg wavelengths of 9.4 and 5 m, respectively. The transmitter is arranged to encompass about a 120° swath. WERA has the flexibility to be configured into a direction finding (DF) array (such as CODAR) where 4 receive antennae are set up in a square array, or in beam-forming mode (BF) from a linear array consisting of 4n (where n=2,3,4) elements or channels. Generally, as the number of receiver antennae elements increase, the resolution of the current vector improves (Teague et al. 2001). A medium-range, high-horizontal resolution version has been designed where the range is ≈ 80 km with horizontal resolution of 1.2 km depending on the available bandwidth approved by the Federal Communication Commission. Higher spatial resolution requires bandwidth of more than 200 KHz (i.e. ± 100 KHz). Given its 0.26-sec chirp, temporal sampling can be as low a few minutes as the WERA system is FMCW as opposed to a pulsed radar such as OSCR (Prandle 1987). This sampling feature is attractive for high-current gradient regimes such as the Florida Current where time scales of variability are less than an hour (Peters et al. 2002).

2.2 Experimental Design

A dual-station WERA system was deployed along the WFS starting on 23 Aug and ending 25 Sept 2003 to remotely sense the surface circulation over moored ADCPs. During this period, a 33-d nearly continuous time series of radial and vector surface currents were acquired at 30-min intervals. The system consisted of two HF radar transmit/receive stations operating at 16.045 MHz that sensed the
electromagnetic signals scattered from surface gravity waves with wavelengths of 9.34 m. The HF radar system mapped coastal ocean currents over a 40 km × 80 km domain at 2820 cells (Fig. 1). Radar sites were located in Venice Beach, FL adjacent to the City of Venice Sewage Treatment Facility (27°4.71′N, 82°27.05′W) and at an oceanfront site along Coquina Beach, FL (27°27.36′N, 82°41.7′W), equating to a baseline distance of 45 km (i.e. approximately half the radar range). Each site consisted of a four-element transmit and a sixteen-element receiving array (spaced 9.34 m apart) oriented at angles of 251°T at Venice Beach and 240°T at Coquina Beach. Cable calibrations were conducted at the beginning, during and at the end of the deployment to monitor the variations in amplitudes and phases which were found to be minimal.

2.3 Radial and Vector Currents

The Bragg frequency is given by:

\[ \nu_b = \sqrt{\frac{g\nu_r}{\pi c}}, \]

where \( g \) is the acceleration of gravity (9.81 m s\(^{-1}\)), and \( \nu_r \) is the radar frequency (16.045 MHz). The resultant Bragg frequency is 0.408 Hz as shown in Fig. 2. Frequency offsets from this first-order, Bragg peak (\( \Delta \nu = \nu_o - \nu_b \)) are proportional to the radial current for a wave advancing (positive) or receding (negative) from the radar station (i.e. \( \Delta \nu = 2V_{cr}\lambda^{-1} \), where \( V_{cr} \) is the radial component of current along the direction of the radar). Given the range in the Doppler spectrum of ± 1.75 Hz, the maximum resolvable radial current is ± 16.3 m s\(^{-1}\). Notice that the first-order returns were above the Doppler spectra noise floor (≈ 60 dB) for both advancing and receding waves. At least two radar stations are required to provide the radial current from the Doppler spectra to calculate the 2-dimensional vector current.

Central to constructing reliable vector current fields from radial measurements is the intersection angle between the radials emanating from each radar station (Fig. 3). These intersection angles depend on beach topography, which sets the phased array’s geometrical constraints. In this HF domain, optimal intersection angles, defined here as 30° ≤ \( \alpha \) ≤ 150°, encompassed nearly the entire domain except for grid points closest to the shore, and those just beyond the 40° limits in the northwest and southwest.
corners of the HF radar domain. These outer limits were at the maximum range of the radar stations of \( \approx 80 \text{ km} \) (Table 1).

The Geometric Dilution Of Precision (GDOP) is used to quantitatively examine the spatial dependence of the observed current differences based on geometrical constraints. Using the radar’s mean look direction \( (\alpha) \), and the half-angle \( (\phi) \) between intersecting beams, Chapman et al. (1997), derived expressions for the error in the \( u \) and \( v \) current components:

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

and

\[
\sigma_v = \left\{ \frac{2 \sin^2(\alpha) \sin^2(\phi) + \cos^2(\alpha) \cos^2(\phi)}{\sin^2(2\phi)} \right\}^{1/2} \sigma_r, \tag{3}
\]

where \( \sigma \) represents RMS current differences. The GDOP value is defined as the ratios of \( \frac{\sigma_u}{\sigma_r} \) and \( \frac{\sigma_v}{\sigma_r} \) for the \( u \) and \( v \) current components, respectively. Over the HF radar domain (Fig. 3b), the GDOP value ranges from 1. to 2.25. In the core of the domain where ADCP measurements were acquired, the GDOP values for both the current components ranged from 1. to 1.25. Close to the coast, however, there was a large GDOP gradient that increased from 1 to 2 over a few km distance as intersection angles approached the 150\(^\circ\) limits (Fig. 3a).

As each cell \( (1.2 \text{ km} \times 1.2 \text{ km}) \) has its own unique bearing and distance from each site \((i.e. \text{Fig. 3a})\), the east-west current at any given cell is

\[
u = \frac{r_v \cos(\theta_v) - r_e \cos(\theta_e)}{\sin(\theta_e - \theta_v)}, \tag{4}
\]

and, the north-south current is

\[
u = \frac{r_v \sin(\theta_v) - r_e \sin(\theta_e)}{\sin(\theta_e - \theta_v)}, \tag{5}
\]

where \( r_{v,e} \) represent radial currents and \( \theta_{v,e} \) represent bearing angles relative to the boresites from the Venice Beach and Coquina Beach stations, respectively. As shown in Fig. 4, the returns of the vector current field \( (w = u + v) \) are constructed from (4,5) based on observed radial currents and bearing angles (Fig. 3a). Notice that the returns over the HF radar domain decreased for increasing distance from the Venice Beach site. While the quality of the returns exceeded over 70\% over the domain, they
exceeded over 90% in the central part of the WERA domain where the COMPS EC4 and NA2 moorings were located (Weisberg et al. 2002).

2.4 Signal to Noise Ratio

Over the course of the experiment, a total of 1628 half-hourly samples was acquired from 0320 GMT 23 August (YearDay 235) until 2340 GMT 25 Sept (YD 269). Of these samples, only 70 samples were missing from the vector time series, equating to a 4.2% loss of the snapshots. Previous phased array radar experiments have typically yielded data returns of 93 to 97% (Haus et al. 1998; 2000; Shay et al. 2002; Martinez-Pedraja et al. 2004). Thus, these experimental results from WERA were on the higher end of the limits with respect to overall data return relative to previous experimental results using OSCR.

For every sample from each WERA site, signal to noise ratios (SNR) were combined and averaged in time over the radar domain (Fig. 5). In the core of the WERA domain, SNR exceeded 12 suggestive of high-quality surface current measurements. As the far-field is approached, the SNR decreases to 6 and then to about 3. While SNR of 3 still implies relatively good data, the analysis contained herein places more confidence in the core of the domain where SNR ≥ 6. In general, higher spectral qualities are usually obtained close to the coast as signal strength attenuates away from the radar sites. The range of ground wave signals is a function of transmitter frequency, sea water conductivity and atmospheric conditions. As frequency increases into the VHF band, signals attenuate quicker than those of lower frequencies (Gurgel et al. 1999a). Sea surface conductivity also plays an important role in ground wave propagation. That is, as conductivity increases, signal attenuation decreases exponentially with distance offshore (Broche et al. 1987). HF radar signals attenuate quickly after just a few kilometers over fresh water which restricts the use of HF radar to saline environments.

3 Observations:

Observations include surface currents from WERA, surface winds from three sites, and subsurface currents from ADCP moorings deployed by USF as part of USF COMPS project. To facilitate comparisons between surface and subsurface currents, surface current data are smoothed by a 3-point Hanning window
and subsampled at hourly intervals to coincide with ADCP-measured current structure.

### 3.1 Surface Wind and Stress

Prevailing atmospheric conditions during the experiment were relatively calm as indicated by 24-hr low-pass filtered wind records adjusted to 10-m from the Venice Pier, the NA2 surface mooring (more details below), and NDBC Buoy 42036 (Fig. 6). The NDBC buoy was located at (28°30.37'N, 84°30.62'W), northwest of the radar domain. The NA2 surface buoy was located in the central portion of the radar footprint. The adjusted 10-m filtered winds were relatively weak over the 33-d period with a mean wind of 4.7 m s\(^{-1}\) towards the west-northwest (≈ 310°). During the passage of Tropical Storm Henri the 24-h low pass winds exceeded 8 m s\(^{-1}\) at NA2 and approached 12 m s\(^{-1}\) at the NDBC buoy (further offshore) directed northward. Note that in the unfiltered records, winds were more than 10 m s\(^{-1}\) and 14 m s\(^{-1}\) at both of these sites. The averaged wind stress components over the record, based on Fairall et al. (1996) algorithm, were -2.6 \times 10^{-2} and 2.4 \times 10^{-3} N m\(^{-2}\) in the east-west and north-south directions, respectively. This mean wind stress direction towards the west-northwest is consistent with surface winds derived from a summer climatology (Yang and Weisberg 1999). Theoretically, Ekman flows should be directed towards the north (355°) with a net transport towards the northeast (40°).

### 3.2 Surface Currents

An example of the observed surface current variability is shown in Fig. 7 over a 10-d period, including the passage of Tropical Storm Henri on 5 Sept. On 29 August (YD 240), surface velocities ranged between 15 to 25 cm s\(^{-1}\) over the radar footprint with flows directed toward the north-west. As Henri approached, cyclonically rotating winds forced northward surface flows with maximum surface currents over the inner shelf of more than 40 cm s\(^{-1}\) on 5 Sept (YD 247). Subsequently, surface currents of ≈ 25 cm s\(^{-1}\) over the outer part of the domain were directed shoreward after two hours. Inner-shelf surface velocities were oriented towards the north with maximum velocities of 35 to 40 cm s\(^{-1}\). On 6 Sept (YD 248), surface velocities of 25 cm s\(^{-1}\) were observed to have an east to north-east orientation as the winds relaxed. By 8 Sept (YD 250), surface currents decreased to pre-Henri levels of 15 to 20 cm s\(^{-1}\) over the WERA footprint. Of particular interest is the along-shelf structure, and the patchiness in
the surface currents which may be due to transient surface winds that occur over the WFS during the summer months. These surface velocity images over a 10-d time period exemplified an energetic coastal ocean response to Henri.

To further illustrate this spatial surface current variability, the standard deviation and covariance of the surface velocity are estimated from the 33-d time series (Fig. 8). The standard deviations of the \( u \) (Fig. 8a) and \( v \) (Fig. 8b) surface current components differed by a factor of two depending on their location in the radar domain. The standard deviation in the \( u \) component was a maximum of 10 cm s\(^{-1}\) in the far-field or outer periphery of the radar domain. Over the central and inner portions of the domain, standard deviations decreased to between 6 to 8 cm s\(^{-1}\). In the north-south current component, the standard deviation was similar except in the north central portion of the domain where the standard deviations exceeded 15 cm s\(^{-1}\). This region is in the far-field of the Venice site, and caution needs to be placed on these current estimates. However, this region is also closest to Tampa Bay and may be more influenced by the semidiurnal and diurnal tidal currents as discussed below. Time-averaged mean flows indicated a north-west mean current of 10 to 15 cm s\(^{-1}\), which is located on the right side of the mean wind stress direction of west-northwest noted above. This is also consistent with the WFS summertime circulation (Yang and Weisberg 1999). These mean currents were slightly stronger in the northern part of the domain. The covariance \((u'v')\) between the flows was less than zero over about 60\% of the domain. By contrast, covariances ranged from 10 to 20 cm\(^2\) s\(^{-2}\) in the northern portion with larger values in the northern-most tip (i.e. far-field of the Venice site).

### 3.3 Moored Measurements

As part of the COMPS program, the University of South Florida (USF) maintains moored ADCP arrays over the WFS shown in Fig. 1 (Weisberg et al. 2002). One set of current profiles is from an upward-looking ADCP mounted on a fixed bottom rack at the 20-m isobath (EC4), and the other instrument package is from a downward-looking ADCP mounted on a surface mooring at the 25-m isobath (NA2). Both emplacements used similar instruments: RD-Instruments, 300kHz Workhorse\(^{TM}\) ADCPs, sampling at 1 Hz for 300 pings per hourly ensemble from which one hourly velocity vector profile determination is made. Comparison tests between similar upward and downward-looking deployments on the same WFS
isobath (unpublished) demonstrate only nominal differences (within the manufacturers specifications) for these two deployment methods so these are not deemed to be important for the present study. For both deployments, the velocity profile data, sampled at 0.5 m intervals, were edited for near surface and bottom reflection effects, and then linearly interpolated to standard 1 m bins. Horizontal velocity vectors from the 20 m and 25 m isobath sites are thus available between 4 m and 17 m and between 4 m and 22 m of the surface, respectively. For the case of the upward-looking ADCP, the velocity closer to the surface is compromised by side-lobe reflection, and for the case of the downward-looking ADCP, the near-surface layer is missed by a combination of buoy geometry and an acoustic noise-related blanking distance (transit time) from the transducers to the first bin sampled. These two moorings, designated EC4 (20-m isobath) and NA2 (25-m isobath), are part of long-term monitoring programs on the WFS (COMPS, and now SEA-COOS). Their record lengths are of several years duration (see http://ocg6.marine.usf.edu), and the deployment coinciding with this WERA test was sub-sampled to provide the comparison data used here.

In addition to the oceanic measurements, the NA2 mooring also housed the Air-Sea Interaction ME-Teorological (ASIMET) sensor suit, designed by Woods Hole Oceanographic Institution. Measurements are: air temperature (AT), relative humidity (RH), barometric pressure (BP), wind speed and direction (WND), precipitation (PRC) and incident shortwave (SW) and longwave (LW) radiation. These ASIMET data are averaged from one-second samples over the last minute of a 20-minute sampling interval to provide values every 20-minutes. Measurement heights relative to mean sea level are 2.3 m for AT and RH (using a Rotronic MP-100F Humidity-Temperature Probe within an aspirated solar radiation shield) and for BP (using an AIR S2B sensor), 2.5 m for PRC (using an RM Young 50201 rain gauge), 2.6 m for SW and LW radiation (using Eppley PSP and PIR radiation modules, respectively) and 2.8 m for WND (using an RM Young 5103 wind module). Bulk sea surface temperature (SST) is also sampled once every 10 minutes by a bridle-mounted Seabird Inc. MicroCat (Mcat; SBE-37) located 0.9 m beneath the sea surface.

As shown in Fig. 9, coherent current structure was observed to 22-m depth. Surface currents at NA2 ranged from -30 to 35 cm s$^{-1}$ where larger values were observed during TS Henri. At 4-m depth,
the current ranged from $\pm 15 \text{ cm s}^{-1}$, decreasing to $\pm 10 \text{ cm s}^{-1}$ at 22-m depth. In the upper 8-m of the water column, there is evidence of a Henri response on YD 247. During Henri, the surface friction velocity ($u_*$) exceeded 0.5 m s$^{-1}$ based on Fairall et al. (1996). Under strong hurricane conditions, $u_*$ values typically range from 2 to 4 m s$^{-1}$. Subsequent to Henri, weak current oscillations were detected at the mooring excited during storm passage that do not appear to be inertially rotating with period of $\approx 26$ h. Notwithstanding, surface friction velocities over the remainder of the time series ranged between 0.1 to 0.3 m s$^{-1}$ associated with wind stresses ranging between -0.1 N m$^{-2}$ and 0.16 N m$^{-2}$.

$RMS$ differences between adjacent ADCP bins were examined from 4 to 22 m at NA2 and 4 m to 17 m at EC4 (not shown) to understand subsurface current variability. Bin-to-bin variability was $\approx 1$ cm s$^{-1}$ except between 6 and 7 m when the differences increased to about 2 cm s$^{-1}$ in the $v$ component at NA2. At EC4, the $RMS$ differences were slightly higher ranging between 1.5 to 2 cm s$^{-1}$ in the upper 9 m, then decreasing to 1 cm s$^{-1}$ at depth. These results suggest that the ADCP current measurements were representative of current structure variations.

4 Comparisons

Observations described above indicated sufficient veracity to warrant a comparison between radar-derived surface signals over a 1.44 km$^2$ area and subsurface measurements from the two cross-shelf ADCP moorings. One statistical measure of the correlation between two differing vector measurements is the complex correlation coefficient:

$$\gamma = \frac{\langle u_s u_b + v_s v_b \rangle + i \langle u_s v_b - v_s u_b \rangle}{\sqrt{\langle u_s^2 + v_s^2 \rangle} \sqrt{\langle u_b^2 + v_b^2 \rangle}},$$

and the complex phase angle,

$$\phi = \tan^{-1} \frac{\langle u_s v_b - v_s u_b \rangle}{\langle u_s u_b + v_s v_b \rangle},$$

where $\langle \ldots \rangle$ represents an average (based upon n points) (Kundu 1976) for the WERA surface ($s$) currents to 0.73 m and subsurface ($b$) ADCP-derived currents at 4-m at both NA2 and EC4. This phase angle represents the average cyclonic angle of the subsurface current vector with respect to the surface current vector. Standard $R^2$ values are estimated for radial current comparisons (Emery et al. 2004).
4.1 Radial Series

Radial currents on the upper 0.73 m from each radar site are compared to radial currents determined from the ADCP measurements at 4-m (Fig. 10). (Kinetic energy conserved in coordinate rotation). Comparisons at EC4 indicate good agreement using radial currents from Coquina Beach ($\theta = 204.5^\circ$) and Venice Beach ($\theta = 292^\circ$). In general, radial currents from Coquina Beach site indicate slightly better comparisons as the surface and 4-m currents track between -30 (during Henri) and 20 cm s$^{-1}$. The RMS difference (Table 2) was 3.4 cm s$^{-1}$ based on 814 data points. Relative to the Venice Site, radial currents ranged between -10 and 40 cm s$^{-1}$ with the larger values occurring during Henri. As both surface and 4-m radial currents track well, the RMS difference was 4.4 cm s$^{-1}$. Similar results were obtained for the NA2 mooring with RMS differences between 4.1 and 5.4 cm s$^{-1}$ for Coquina Beach ($\theta= 214.7^\circ$) and Venice ($\theta = 281.5^\circ$), respectively. Note that the $R^2$ were 0.92 and 0.81 for these radial current comparisons.

Regression analyses between the surface and 4-m radial currents (Fig. 10c,d) indicate a bias of -0.9 cm s$^{-1}$ and a slope of 0.83 relative to Coquina Beach. Radial currents from the Venice site indicate similar results with a bias of -1.1 cm s$^{-1}$ with a slope of 0.88. For both sets of radial currents at EC4, reveal little scatter with similar results at the NA2 mooring. Notice that the perfect comparison (bias=0,slope=1) suggests a slight offset between surface and 4-m currents. Thus, surface and 4-m radial current comparisons indicate sufficient veracity for the 2-dimensional vector current comparisons at the two ADCP sites below.

4.2 Vector Series

As shown in Fig. 11, surface current components are compared to subsurface currents at 4 m from NA2 mooring. The $u$-component ranged between 10 to -25 cm s$^{-1}$, and were weaker than the $v$-component. The maximum northward surface current observed during TS Henri on YD 247-248 approached 40 cm s$^{-1}$ compared to about 20 cm s$^{-1}$ at 4-m. The southward current was a maximum of about 25 cm s$^{-1}$, suggestive of more background variability in the north-south direction than in the east-west direction. During Henri, this resulted in a bulk current shear of $5 \times 10^{-2}$ s$^{-1}$ (Fig. 11c). These levels of bulk current shears between surface and near-surface current measurements have been documented in other
coastal regimes influenced by the Gulf Stream and Florida Current (Shay et al. 1995; 2002) as more dense, subtropical water may have been subducted underneath the fresher, coastal waters (Marmorino et al. 1998). Subsequent to Henri, the currents oscillated with a frequency close to the local inertial period (26.4 h) in both the surface and subsurface layers. Over the 33-d series, surface and subsurface currents were well correlated with values exceeding 0.80 from (6). On YD 261, the correlation decreased to below 0.7, which may be in part due to weak u components. Complex phases ranged from -17° (anticyclonic veering with depth) to 42° (cyclonic veering with depth) as per (7). Similar trends in the data were observed at the 4-m level at the EC4 mooring.

Current data from 4-m depth were regressed to the surface current measurements (Fig. 12). At EC4, the scatter for the u component revealed a slope of 0.8 with a bias of -2 cm s\(^{-1}\). By contrast, the slope was O(1) in the v component (Fig. 12b) where the bias was -0.1 cm s\(^{-1}\). For the 814 hourly values, the histogram of the differences reflect this average bias in the distributions. At NA2, the trends are similar in the regression, but with slightly higher slopes. That is, surface currents were 20% higher than the 4-m depth currents. Biases ranged from -2.5% to 1.6 cm s\(^{-1}\) in the u and v components, respectively. The distributions of the current differences are also similar to those at NA2, suggesting that measurements in the upper few meters of the column were consistent with surface currents averaged over the 1.44 km\(^2\) area.

Surface velocities at the 25-m mooring (i.e. cell 1816 depicted as a red triangle in Fig. 1) were used to estimate the complex correlation and phase coefficients as per equations 6,7 averaged over the 33-d series at each of the radar cells. As shown in Fig. 13, correlation coefficients tended to follow the isobaths with a maximum of 1 at the mooring location. Correlation coefficients decreased from more than 0.7 to about 0.5 in the northern part of the domain. This observed decrease in their values is due to the far-field returns from the Venice Beach site. By contrast, offshore correlation coefficients remained above 0.6 across the shelf. Phases indicated an anticyclonic current veering relative to 25-m isobath south of NA2 and a cyclonic veering north of the mooring site. The range of the phases was -10 to 10° over most of the domain. Such behavior contrasts with data acquired along the east Florida Shelf where the correlation indices are governed by the FC and coherent submesoscale ocean structures (Shay et al. 2002).
Averaged current differences from 33-d of coincident measurements are listed in Table 3. In terms of current speed, there was a 4.8 cm s\(^{-1}\) difference between the surface and 4-m values at NA2. This difference decreased to about 1.7 cm s\(^{-1}\) at EC4. Directional differences were 8 to 10° in the currents. The \(u\) component ranged from -1.9 to -2.5 cm s\(^{-1}\) at the two moorings compared to 1.6 to -0.1 cm s\(^{-1}\) for the \(v\) component. The complex correlation coefficients for the current vectors were 0.88 and 0.9 with phases of 5 and -3° at NA2 and EC4, respectively. The RMS differences were 0.2 to 1 cm s\(^{-1}\) in the weaker east-west components, compared to 4.2 to 5.2 cm s\(^{-1}\) in the north-south components. Note that the lower values in the \(u\) component are due to the lower dynamic range of 10 cm s\(^{-1}\) compared to 30 cm s\(^{-1}\) in the \(v\) component. Comparisons between the surface and bottom currents revealed larger differences. For example at NA2, the mean current and direction difference was 6 cm s\(^{-1}\) and 2° at 22-m. At EC4, the mean current difference was only 4.5 cm s\(^{-1}\), but the directional difference was 18°. A better indicator of this vertical decorrelation was the correlation indices decreased to 0.5 with phases of -49 to -55°. Based on the RMS difference estimates, this was due to the current in the north-south direction that included the strong accelerations of the surface currents by Henri and the subsequent near-inertial current response. Surface and near-bottom analyses reveal that these flows are predominantly baroclinic. Thus, these differences are reflective of geophysical variability such as tidal and wind-driven flows as observed in previous HF-radar experiments.

5 Physical Forcing Mechanisms:

To examine the physical effects of the tides and winds, tidal currents were determined from the 33-d hourly time series from the measurements following Foreman (1977). Surface and subsurface currents are fit to the dominant semidiurnal and diurnal tidal frequencies. The effects of the surface wind and stress on the detided time series are examined at the NA2 mooring where accurate wind measurements were acquired from the IMET package. Surface stress is estimated using Fairall et al. (1996) with 10-m adjusted winds.

5.1 Tidal Variations

Tides over the WFS are mixed with contributions from both diurnal and semidiurnal components. To
examine this variability in the domain, the dominant tidal constituents are analyzed for the semidiurnal 
\((M_2, S_2)\) and diurnal \((K_1, O_1)\) constituents. For the \(M_2\) constituent, the amplitudes of the currents 
ranged from 4 to 5.2 cm s\(^{-1}\) (Fig. 14a). While weaker \(M_2\) tidal amplitudes contributions were located 
inshore of the NA2 mooring and south of Tampa Bay, they generally increased offshore. Except for the 
relative maxima in the southern part of the domain, the pattern of the \(S_2\) current amplitudes was similar 
to those of the \(M_2\), but they were weaker, ranging from 2 to 3.2 cm s\(^{-1}\). The diurnal tidal currents 
associated with the stronger \(K_1\) constituent were a maximum of 5 cm s\(^{-1}\) in the northern and southern 
parts of the domain with a minimum of about 1 cm s\(^{-1}\) in the south central portion. The \(O_1\) tidal 
amplitudes differed considerably with a minimum oriented in the north-south direction where the \(O_1\) 
amplitude increased offshore to a maximum of 3.5 cm s\(^{-1}\) (Fig. 14d).

By combining these current amplitudes from the various constituents, variances accounted for by 
tidal constituents ranged from a maximum of 40 cm\(^2\) s\(^{-2}\) to a minimum of 15 cm\(^2\) s\(^{-2}\) (Fig. 15a). The 
minimum in tidal variances of 20 cm\(^2\) s\(^{-2}\) is centered in the domain, compared to values exceeding 
25 cm\(^2\) s\(^{-2}\). The explained variance (Fig. 15b), defined here by the relative ratio of predicted versus 
observed variances, indicated values ranging from 18 to 40\% over the domain. The largest values of 
variance explained \(> 30\%\) were located in the northeastern part of the domain, presumably influenced 
by the Tampa Bay port. Over the remainder of the domain, explained tidal variance ranged from 18\% to 25\%. In the southeastern part of the domain, the low values may be somewhat misleading since this 
region is in the far-field of the Coquina Beach radar.

In terms of vertical structure, surface and subsurface tidal currents for the \(M_2\) and \(K_1\) constituents 
for the \(u\) and \(v\) components are listed in Table 3. Surface tidal currents were more energetic than those 
at 4-m depth except for the \(M_2\) component at EC4. However, \(M_2\) current differences were less than 
1 cm s\(^{-1}\) at both NA2 and EC4. By contrast, the differences in the \(u\)-component increased to more 
than 1.5 cm s\(^{-1}\) for the \(K_1\) constituent at EC4. Vertical variations with depth suggest that the \(K_1\) tidal 
currents contained more baroclinic structure than the \(M_2\) constituent which has a barotropic component 
(i.e. phases and amplitudes indicate little vertical variation). The \(v\)-component tidal currents explained 
more of the bottom current variations than those on the surface at both moorings. For the \(u\)-component,
the tides explained 25 to 38% of the observed variance. At the NA2 mooring, tidal current time series for just the $M_2$ and $K_1$ constituents are shown in Fig. 16. The $M_2$ surface current reflects the variability of the depth-averaged current in both components. That is, the depth-integrated values range between ± 4 cm s$^{-1}$. After removing the depth-independent currents in both velocity components, there is little evidence of baroclinic signature in the $M_2$ tidal constituent compared to the $K_1$ tidal component. The surface $K_1$ tidal components range between 2 to 2.5 cm s$^{-1}$ compared to a depth-independent values of ± 1 cm s$^{-1}$ for both $u$ and $v$ components (Fig. 16b,d). Surface and depth-integrated currents are also out of phase. Removing this depth-averaged component, indicates baroclinic current structure of ≈ 2 cm s$^{-1}$. Thus, the $M_2$ tidal current has a large barotropic component, whereas the $K_1$ contains baroclinic structure, consistent with previous WFS studies (He and Weisberg 2002).

5.2 Effects of Wind Forcing

Surface friction velocity ($u_*$) and the difference between the wind (stress) direction and detided surface current ($\Delta \theta$) observed at NA2 mooring are shown in Fig. 17. Over the 33-d time series, $u_*$ ranged between 0.05 m s$^{-1}$ to as high as 0.35 m s$^{-1}$ during Henri. The mean $u_*$ was 0.19 m s$^{-1}$ with a standard deviation of ± 0.06 m s$^{-1}$. The difference between the wind (and stress) direction and surface current ranged between $-\pi$ to $\pi$ with a large fraction of the values between ± $\frac{\pi}{4}$. Approximately 60% of the time series had an average directional difference of 0.2 radians ($\approx 12^\circ$). Here the negative value implies that the mean is offset about $12^\circ$ to the right of the wind and stress direction with a standard deviation of ± 0.42 radians ($\approx 24^\circ$). Theoretically, steady-state Ekman dynamics implies that the time-averaged surface velocity is at an angle of $\frac{\pi}{4}$ radians to the right of the stress. Liu et al. (2005) fully examines this effect, however, in the present context, there is a significant wind-induced surface current in the detided current signals.

To further examine these relationships between 10-m surface winds and currents, these data were regressed to determine the bias and slope (Fig. 18). In the east-west direction, regression slope was 0.02 with a bias of -0.9 cm s$^{-1}$. In the north-south direction, the slope was 0.03 with a bias of 1.1 cm s$^{-1}$. For a surface drift current, the theoretical slope should be 0.036 or 3.6% as suggested by Bye (1967). As this flow is assumed to be irrotational, there is also a logarithmic vertical dependence but
is not explored here given the 4-m separation between the surface and subsurface measurements. For example, using upward-looking ADCP profiles to 2-m from an AUV, Shay et al. (2003) found a log-layer in the downwind directions. Rotating the currents into the wind stress direction following Drennan and Shay (2005) did not reveal any further insights.

These slopes and biases are used to construct a time-dependent wind-drift time series as shown in Fig. 19. The predicted time series associated with the wind-drift follows the detided surface current signals quite closely suggestive of the importance of the time-dependent wind. This wind component obviously includes the diurnal cycling as well as the longer period or synoptic fluctuations. In some cases, the wind-driven component over-predicts the surface current, however, over most of the time series, there seems to be fairly good agreement. Estimates of variance for the wind-driven surface currents are approximately 19-21 cm$^2$ s$^{-1}$ in both directions. However, the wind component explains about 50% of the detided current variance in the east-west direction. By contrast, only 20% of the variance is explained in the north-south detided current component.

These results are regressed to examine differences between the predicted and observed wind-driven currents (Fig. 20). In the east-west direction, the slope is 0.81 with a bias of -0.9 cm s$^{-1}$. The difference in the predicted and observed surface current indicates a normal distribution centered between -2 and 0 cm s$^{-1}$. In the north-south direction, there appears to be a slightly better comparison as the slope is O(1) with a bias of 1.1 cm s$^{-1}$. The normal distribution is skewed about -4 cm s$^{-1}$ with a large fraction of the differences located between ± 6 cm s$^{-1}$. These results suggest that the time-dependent wind and stress explained 20 to 50% of the remaining variance in the detided current signals. Based on previous studies (e.g., Weisberg et al. 2000) and recent studies (Liu et al. 2005), the Ekman-geostrophic is approached as a spin-up of an initial value problem using WFS observations when winds increase rapidly after a period of quiescent winds. Near-surface currents are first oriented to the right of the wind stress and then rotate left to align more in the along shelf direction. As sea-level gradient develop, currents rotate farther left of the stress direction with depth as the bottom Ekman layer develops. As the experiment did not contain cross-shelf T/S arrays or pressure sensors, the geostrophic current could not be resolved from the surface current measurements except in the 48-h low-pass filtered currents (not
Shown).

6 Discussion and Summary:

Over the broad WFS, tides, winds and geostrophic balances all contribute to the circulation. A dual-station High Frequency Wellen Radar (WERA), transmitting at 16.045 MHz, was deployed along the WFS during the summer of 2003. The WERA HF-radar system overlooked a cross-shelf array of ADCPs deployed in support of USF’s COMPS program (Weisberg et al. 2002). WERA-derived surface currents agreed with 4-m currents measured at these moored ADCPs. Given WERA’s performance even during Henri (and more recently in hurricane Jeanne), this radar technology has matured to a point where a coordinated engineering and scientific approach can be used to resolve complex coastal ocean processes from multiple platforms for coastal ocean observing systems such as SEA-COOS (Seim et al. 2003).

A 33-d, nearly continuous vector surface current time series was acquired starting on 23 Aug ending 25 Sept 2003. In a 16-element phased array mode, WERA (configured in phased array mode) mapped coastal ocean currents over a 40 km × 80 km domain with a horizontal resolution of 1.2 km at ≈ 2820 cells. A total of 1628 half-hour snapshots of the 2-dimensional current vectors were acquired during this time series, and of these samples, only 70 samples (4.3%) were missing from the vector time series. Complex surface circulation patterns were observed that included coherent tidal currents, and an along-shelf current response to tropical storm Henri on 5 Sep 2003. Cyclonically rotating surface winds, adjusted to 10-m in the HF radar domain, ranged from 11 to 14 m s\(^{-1}\) and forced surface velocities of more than 35 cm s\(^{-1}\) as Henri made landfall north of Tampa Bay.

Radial and vector comparisons to subsurface measurements at 4-m from moored ADCPs revealed \textit{RMS Differences} of 4 to 6 cm s\(^{-1}\). Regression analyses indicated slopes close to unity with biases ranging from -2 and 1.6 cm s\(^{-1}\) between surface and subsurface measurements in the \(u\) and \(v\) current components, respectively. Tidal amplitudes were 4 to 5 cm s\(^{-1}\) for the \(M_2\) constituents and about 3 to 4 cm s\(^{-1}\) for the \(K_1\) constituent. Vertical structure of the \(M_2\) tidal current indicated that the semidiurnal components were predominantly barotropic with amplitudes exceeding 4 cm s\(^{-1}\). Similar results have been observed off of Duck North Carolina (Cook and Shay 2002) and south of the mouth of
the Chesapeake Bay (Shay et al. 2001). By contrast, diurnal tidal constituents were more baroclinic with a depth-averaged current of about 1 cm s$^{-1}$. Tidal currents explained 25 to 40% of the observed surface current variance. The time-dependent wind-drift currents explained between 20 to 50% of the detided current variance in the north-south and east-west directions, respectively. In the north-south direction, current variability is presumably associated with lower-frequency flows (Liu et al. 2005). Despite the relatively narrow dynamic range, results suggest that the WERA measured the surface velocity well under weak to moderate wind conditions.

WERAs are now deployed along the East Florida Shelf at three sites, and configured to provide near-real time measurements at 10-min intervals at a grid spacing of 1.2 km. Since May 04, we have acquired a nearly continuous surface velocity data set (see http://iwave.rsmas.miami.edu/wera). In this venue, the energetic Florida Current and its submesoscale eddy field occurs over short time and space scales. Compared to the WFS, surface velocities may vary by as much as 2 m s$^{-1}$ over just a few hours, including submesoscale vortices and lobe-like structures with spatial scales of a few kilometers. These kinematical fields support vorticites and divergences that scale as 5 to 7 $f$ (Peters et al. 2002). Such structure has relevance to understanding the coastal ocean’s health in transporting toxins and oil spills that cause closures of Florida’s pristine beaches and impact the ecologically sensitive coral reef track. High-resolution measurements are important for tracking capsized vessels and rafters crossing the treacherous Florida Straits. It is our vision to increase the size of the footprint to address these broad societal issues and improve our understanding of upper ocean processes and the importance of the current and directional wave field field on air-sea interaction processes across the Florida Straits where currents and waves affect the wind stress direction (Haus et al. 2000; Drennan and Shay 2005).

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Tage, Phil Talley, Jay Moles, Charlie Hunsicker, Karen Windom, and Robert Brown from Manatee County provided the real estate at Coquina Beach. Suzi Fox of the Turtle Watch Education Center approved the deployment. The Department of Environmental Protection (Renate Skinner, Steve West) permitted us to use the sites. We also thank Thomas Helzel for his assistance in deploying the radar for this acceptance test. Scott Guhin also assisted in the deployment. We also thank Larry Kanitz and Dave Powell and his staff for assisting with logistical support for the deployment. The continuing support of the Dean Brown of Rosenstiel School of Marine and Atmospheric Science is greatly appreciated.

7 References:


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Table 1: Capabilities of the WERA system. Beam Forming (BF) using a phased array is needed for wind and wave measurements compared to the Direction Finding (DF) where the array is arranged in a square. The more elements in the phased array, the higher the current resolution.
Table 2: Comparison of radial currents between the surface current ($r_o$) and subsurface current ($r_{4m}$) at EC4 and NA2 relative to bearing angles from Venice and Coquina Beach for mean differences, rms differences and the correlation coefficient ($R^2$) based on the 33-day time series (N=814 points).

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Table 3: Averaged difference between the surface and subsurface currents at NA2 (4 m, 22 m) and EC4 (4 m, 17 m) moorings for speed ($V_{o-b}$), direction ($\theta_{o-b}$), u-component ($u_{o-b}$), v-component ($v_{o-b}$) component, complex correlation coefficient ($\gamma$), phase ($\phi$) and the $rms$ differences in the east-west ($u_{o-b_{rms}}$) and north-south ($v_{o-b_{rms}}$) velocity components based on mooring data during the WFS 2003 experiment (N=814 points).
Table 4: Amplitudes (u,v) and relative phases (ϕ_u,ϕ_v) of diurnal (K_1) and semidiurnal (M_2) tidal components derived from a harmonic analysis of the WERA surface currents (ζ=0) and the 4-m and near-bottom ADCP current measurements during the WFS Experiment based on 1628 points over the 33-d time series at NA2 and EC4 moorings. Observed (σ_o^2) and predicted variance (σ_p^2) and variance explained (%) are based on the K_1, and M_2 tidal constituents.

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Figure 1: WERA domain (circles) for vector currents only relative to USF ADCP moorings (EC4, EC5, and NA2 triangles), CMAN Stations (squares) with the master site at the Venice Sewage Treatment Facility and the slave at Coquina Beach during Aug and Sep 2003.
Figure 2: Doppler spectrum from the WERA WFS deployment from a cell located 40 km offshore showing the spectral peaks in power (dB) relative to the frequency (Hz). Bragg frequencies are depicted as $\pm \nu_b$ at 0.408Hz as well as the frequency offset ($\Delta\nu$). Frequency offsets of the spectral peaks for the advancing and receding wave field correspond to the radial current. Second-order returns contains information about the waves.
Figure 3: Intersection angles (°: left panel) and GDOP (right panel) from the master (solid) and slave (dashed) radial beams at the WERA cells. The contour interval for the intersection angles is at 20° intervals and the GDOP is contoured at 0.25 increments.
Figure 4: Percent of time of vector current maps were acquired by WERA during the WFS Experiment in Aug and Sep 03 relative to the ADCP moorings.
Figure 5: Signal to noise ratio over the WERA domain for the vector currents averaged from 33-d of measurements from the master (Venice Beach) and the slave (Coquina Beach) as per the color bar.
Figure 6: 24-h low pass filtered 10-m surface wind (m s$^{-1}$) at NA2, Venice pier and an NDBC Buoy rotated into an oceanographic context during the Aug and Sep 03 experiment over the WFS.
Figure 7: Evolution of surface currents for a) 1700 UTC 29 Aug, b) 1730 UTC 29 Aug, c) 1800 UTC 5 Sept, d) 2000 UTC 5 Sept; e) 0400 UTC 6 Sept; and f) 0200 UTC 8 Sept. Note that Tropical Storm Henri passed west of the radar domain on 5 to 6 Sept and made landfall north of Tampa Bay with maximum surface winds of about 25 m s⁻¹. Color bar depicts current magnitude.
Figure 8: Standard deviations (cm s\(^{-1}\)) in the a) u-component and b) v-component surface currents and c) time-averaged mean current (arrows) superposed on covariance of the observed surface flows (cm\(^2\) s\(^{-2}\)), estimated from the variances in panels a and b with the appropriate color bar for each panel. The v-component standard deviation (panel b) is 2 times larger than that in the cross-shelf direction (panel a).
Figure 9: Surface friction velocity ($u_*$; m s$^{-1}$) and vector current (cm s$^{-1}$) time series at the NA2 ADCP mooring (cell 1816) for the surface, 4-m, 8-m, 14-m and 22-m during the WFS experiment in Aug and Sep 03.
Figure 10: Comparison of radial surface ($r_o$: solid) and 4-m currents ($r_{4m}$: dashed-dotted) for time series for EC4 from a) Coquina Beach and b) Venice components and regression analyses for c) Coquina Beach and d) Venice between surface ($r_o$) and 4-m ($r_{4m}$) in cm s$^{-1}$. 

Bias = -0.9
Slope = 0.83

Bias = -1.1
Slope = 0.88
Figure 11: Comparison of WERA-derived surface (solid) and 4-m subsurface (dotted) current time series from the surface ADCP mooring at NA2 deployed by USF for the a) u-component (cm s$^{-1}$), b) v-component (cm s$^{-1}$), c) bulk current vector shear ($x10^{-2}$ s$^{-1}$) defined as current differences within panels a and b divided by a depth difference of 3.25 m, and d) daily complex correlation coefficients ($\gamma$) and phase angles ($\phi^{(\circ)}$: located at the top of the bars) relative to the surface velocity. A negative phase implies an anticyclonic current veering with depth.
Figure 12: Scatter diagrams (left panel) and histograms (right panel) for the comparisons at EC4 (NA2) for a,c) u-components and b,d) v-components surface ($U_0$) and subsurface currents ($U_{4m}$) along the 20-m (25-m) isobaths, respectively based on 814 hourly data points in Aug and Sep 03.
Figure 13: a) Complex correlation and b) phase (°) relative to the NA2 mooring cell (1816) (triangle in Fig. 1) corresponding to the 25-m USF mooring for the 33-day time series. Values are given on the color bars and note that a positive (negative) phase implies cyclonic (anticyclonic) veering relative to Cell 1816.
Figure 14: Amplitudes (cm s\(^{-1}\)) of the \(M_2\), \(K_1\), \(S_2\), and \(O_1\) tidal constituents based on a tidal analysis of the 33-d of WERA surface velocity measurements in Aug and Sep 03.
Figure 15: Surface current a) variance predicted (cm$^2$ s$^{-2}$) and b) variance explained (%) by the major tidal constituents over the WFS during Aug and Sep 2003.
Figure 16: M₂ (left panels) and K₁ (right panels) tidal currents (cm s⁻¹) at the NA2 mooring for the u (a,b) and v (c,d) components comparing surface (solid) and depth-integrated ADCP (dashed) tidal currents (upper panel) and vertical structure oscillations (observed-depth averaged) from 4 to 20 m (lower panel) contoured at 0.25 cm s⁻¹ intervals.
Figure 17: Time series of a) surface friction velocity ($u_*$: m s$^{-1}$) and b) direction difference between the wind stress and the surface current direction (radians) at NA2 over 33 days. A negative difference implies surface currents to the right of the wind stress.
Figure 18: Regression analysis between wind (m s$^{-1}$) and detided currents (cm s$^{-1}$) for a) u-component and b) v-component with the biases and slopes based on Fig. 17 where directional differences between wind and current of $\pm \frac{\pi}{4}$ ($N=476$ points or approximately 60% of the data series).
Figure 19: Comparison between predicted wind-drift currents based on Fig. 17 and observed detided signals for u-component (top panel) and v-component (bottom panel) in cm s$^{-1}$ for the entire data series.
Figure 20: Regression analysis and histogram differences between predicted wind-drift surface current \((p)\) and observed \((o)\) detided surface currents (cm s\(^{-1}\)) for a) u-component and b) v-component with the biases and slopes.