Coastal Oceanography Using a Small AUV

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ABSTRACT

Bathymetry, current, temperature, and depth (CTD) measurements using a small, mobile, autonomous underwater vehicle (AUV) platform are described. Autonomous surveys of a shallow water column off the east coast of Florida during December 1997 were carried out using a 2.13-m long, 0.53-m maximum diameter Ocean Explorer series AUV, equipped with a 1200-kHz acoustic Doppler current profiler (ADCP) and a CDT package. At a speed of 1–2 m s\(^{-1}\), this AUV can perform preprogrammed missions over a period of several hours, collecting in situ oceanographic data and storing it on an onboard datalogger. The vehicle may also carry sidescan sonar or a custom small-scale turbulence measurement package or other instruments for subsidiary measurements. The versatility of the AUV allows measurement of oceanographic data over a substantial region, the motion of the platform being largely decoupled from that of any surface mother ship.

In the missions of 5 and 11 December 1997, “lawn mower pattern” AUV surveys were conducted over 1 km\(^2\) regions on the east coast of Florida, north of Fort Lauderdale, at depths of 7 and 3 m, respectively, in a water column where the depth ranged from 10 to 32 m. During 5 December, the region was subjected to a cold front from the northwest. Local wind measurements show presence of up to 10 m s\(^{-1}\) winds at temperatures of up to 10–15\(^\circ\)C below normal for the time of the year. The fixed ADCP indicates occurrence of significant internal wave activity in the region. The data collected using the mobile AUV are utilized to develop a map of the bottom topography and examine current, temperature, and density variations in the context of the background information from a fixed bottom-mounted ADCP and Coastal-Marine Automated Network buoys. The work described here is a significant step in the development of an autonomous oceanographic sampling network, illustrating the versatility of an AUV platform. The data collected during the missions described will form part of a bank for information on the impact of a cold front on shallow subtropical waters. The authors expect to repeat the missions during other such fronts.

1. Introduction

The variability of currents in the coastal ocean contains a broad spectrum of temporal and spatial scales that are driven by winds, tides, and the intrusion of boundary currents such as the Florida Current. To examine this variability, a rational approach requires a suite of instruments capable of resolving turbulent and fine scales to mesoscale variations in the current field. Given these inherent sampling issues, combinations of platforms are required to resolve the variability in an adaptive sampling strategy based upon existing ocean and atmospheric forcing conditions.

Conductivity and temperature at fixed locations may be monitored using moored chains of sensors (e.g., Luther et al. 1999). For current measurement, acoustic Doppler current profilers (ADCP) are commonly used in various configurations. Thus, an upward-looking
ADCP may be mounted on a fixed platform on the seabed (Prandle 1995; Lueck and Lu 1997) or be suspended from moorings at an intermediate depth (see Stramma et al. 1995) to remotely measure local current velocities in the water column. Several ADCPs may be employed in an array or grid pattern to provide synoptic spatial variations of currents in the region.

Alternately, downward-looking ADCPs have been mounted on the hull of a moving ship (Joyce 1989; Saunders and King 1995) to provide current velocity information over the region. In this configuration, the ship’s gyrocompass measurements and its ground speed are required to determine the current velocities (Marmorino and Trump 1994; Chapman et al. 1997). However, the ADCP must be calibrated to determine the absolute velocity profile (sum of the barotropic and baroclinic components). Potential sources of errors in the resulting current profiles are instrument sensitivity or resolution, its alignment (Joyce 1989) and accuracy in bottom tracking. The seawater properties, such as the conductivity and temperature variations with depth, are characterized through periodic CTD casts from ships (see, e.g., Fratantoni and Johns 1996).

Expendable Current Profilers (XCP) are used to measure the upper-ocean current and temperature structure to 1500-m water depth (Sanford 1986). These are typically deployed from an aircraft (AXCP) and provide three-dimensional synoptic snapshots of the upper-ocean variability. They can be particularly useful in storms (see, e.g., Shay et al. 1992, 1998c).

Synoptic information of the upper mixed layer, such as the surface seawater temperature, can be measured from a remote satellite. Surface currents may be measured using a HF Doppler radar. The latter is based on utilizing the fact that the backscatter from ocean surface waves has a wavelength of one-half the radar wavelength (Crombie 1955; Shay et al. 1995, 1998a,b, 2000). Use of HF radar to provide real-time surface currents in a coastal environment is becoming increasingly common.

Platforms in the form of towed bodies have also been used for CTD and small-scale turbulence measurements (e.g., Fleury and Lueck 1991). Long tether lines are required to ensure that the platforms are free from vibrations associated with the motion of the surface ships; such vibrations lie in the frequency range of interest of finescale measurements and can significantly corrupt the latter.

Small, mobile, autonomous underwater vehicles (AUVs) have recently become available as stable and reliable platforms for oceanographic measurement instruments and for conducting continuous surveys of the water column in a region. A number of efforts are underway in developing such mobile measurement platforms with the ultimate aim of establishing them as basic elements in an oceanographic sampling network (Curtin et al. 1993). Notable recent oceanographic applications of the AUVs include ones involving Massachusetts Institute of Technology’s Odyssey (Bellingham and Williams 1996; Schmidt et al. 1996), Woods Hole Oceanographic Institution’s Autonomous Benthic Explorer (Yoerger et al. 1997, 1999) and the REMUS (Glenn et al. 1998), the large diameter Naval Surface Warfare Center (NSWC) vehicle (Levine and Lueck, 1996, 1999), the Southampton Oceanographic Center’s Autosub (Griffiths et al. 1998), Naval Postgraduate School’s Phoenix (Riedel and Healy 1999), and Florida Atlantic University’s Ocean Explorer (Dhanak and Holla 1999). Of these, the NSWC vehicle and the Autosub are fairly large vehicles. The others may be classed as small AUVs, which are fairly versatile and can be low cost both in terms of hardware and operations, the latter being partly due to the fact that the vehicles can be launched from small research vessels. An AUV has an advantage over a tethered vehicle in that it is uncoupled from the motion of a surface mother ship so that (i) it is free from low frequency vibrations transmitted down tether lines, which can influence certain in situ measurements; and (ii) operations are possible in storms when surface ships may not be able to operate. Using such mobile platforms, the submesoscale [O(10 km)] distributions of currents, temperature, salinity, and water density can be determined. In particular, if used in conjunction with other measurement systems outlined above, the small AUV’s offer the possibility of making four-dimensional space–time measurements in an affordable way, potentially during a storm when processes such as sediment transport and turbulent mixing occur with great intensity and are expected to induce major changes to the bed form and the water column.

The AUV platforms provide an attractive autonomous means of making bathymetric and hydrographic surveys of a water column. Traditionally these have been carried out with fixed, ship-mounted or tethered platforms (see Fratantoni and Johns 1996). For example, echo sounder systems from ships (see, e.g., Bourillet et al. 1996) are used to develop bathymetry maps of the region. While measurements from an ADCP mounted on an AUV have to contend with sources of error similar to those from a moving surface ship described above, they may be less prone to alignment problems in the relatively calmer underwater conditions and may allow bottom-tracking at good resolution in water columns whose full depth is out of range of a surface-ship mounted ADCP. Typically, in the absence of these errors, high-resolution current profiles can be acquired using presently available ADCPs over relatively short horizontal scales to examine finescale variability across coastal fronts and eddies where considerable shears may occur due to differing water masses. Ideally, AUV based measurements complement the fixed, surface-ship based and AXCP measurements. In particular, they would work best if synoptic background information were available.

Here, the use of the Ocean Explorer (OEX) series
autonomous underwater vehicles, built at Florida Atlantic University, as a platform for ADCP and CTD measurements is described. The platform was used to survey two adjacent regions off the east coast of Florida during winter of 1997. The OEX and its instrument payload are described in section 2. Experimental missions of 5 and 11 December 1997 on the east coast of Florida and measurements from a fixed upward-looking ADCP in the vicinity as well as prevailing atmospheric conditions from two National Oceanic and Atmospheric Administration (NOAA) C-MAN buoys are described in section 3.

2. The Ocean Explorer (OEX) series vehicle

An OEX series AUV (Smith et al. 1995), is typically 2.13 m long (Fig. 1) with a modified Gertler Series 58 Model 4154 fiberglass hull of 0.53-m maximum diameter and an interior framework made of high-density polyethylene and 6061-T6 aluminum. The OEX is designed to support multiple in situ sensor payloads for performing search and mapping operations in coastal shallow-water environments. Its unique feature is a modular bayonet-mount interface between its payload and tail section, allowing easy switching between pay-
loads. The 1.1-m tail section houses navigation, control, and propulsion components whereas a nominal 1-m payload section, which may be extended to 2.4 m, is dedicated to house mission-specific instruments. In air, the OEX weighs approximately 180 kg, and is designed to be neutrally buoyant. Its maximum depth rating is 300 m, although to date, most of the operations have been carried out in less than 150-m water depths. The control surfaces are aft-mounted with a cruciform shape, and are replaceable with different fin sizes for different vehicle lengths and propulsion requirements. Each of these fins is driven by a brushless DC motor via a worm gear. In addition to the fins, the three-blade, 18-in. propeller is based on a modified National Advisory Committee for Aeronautics (NACA) 4412 section, and is driven by a brushless DC motor via a spur gear; in a recent development, the latter has been upgraded to a fully flooded motor with no gears. Using its onboard rechargeable NiCad batteries, which can provide up to approximately 2 k W h total energy, the OEX can maintain a cruising speed of 1.5 m s\(^{-1}\) (a speed range of 1–2.5 m s\(^{-1}\)) for approximately 10 hours continuously between the recharge cycles. Longer missions are possible using more batteries.

For navigation and control, the aft section (see Fig. 1) of the OEX houses 1) an ADCP (1200-kHz Navigator from RD Instruments), which measures altitude and vehicle velocity with respect to either the water column or ground as well as providing in situ current profiles; 2) a Watson Block self-motion package, which provides attitude and heading information, including Euler angles, tri-axial body rates and acceleration; 3) a differential GPS receiver unit; 4) RF Ethernet; 5) a Falmouth Scientific Instrument’s micro CTD, which provides conductivity, temperature and depth measurement; and 6) a Motorola 68060 CPU with a VX Works operating system and 1 Gbyte disk storage capacity for logging a significant amount of navigation and environmental data. The presence of the motors and the batteries in the tail section can contaminate compass measurement. Therefore, an auxiliary TCM2 Precision Navigation flux-gate compass mounted in the payload section, instead of the Watson Block, is utilized to provide heading information. The accuracy of vehicle positioning and navigation underwater depends primarily on the TCM2 flux-gate compass (Table 1) and the onboard ADCP that provide heading and speed measurements, respectively. For small AUVs, the interior magnetic signatures are usually significant and such errors must be characterized and compensated for. Typical procedures involve spinning the compass together with the vehicle, and building a deviation table for the compass given the existence of a compass rose or another independent heading reference that is more accurate. Prior to the experiments described here, a compass rose was used to build the deviation table, from which a maximum of approximately 3° overall heading error was inferred. That is, over a 1 km long leg transect, an overall positioning error of approximately less than 50 m is expected.

The OEX carries out pre-programmed missions defined using ASCII text files that can be downloaded to it underwater via an Ethernet cable or remotely while at surface via a RF connection, thereby increasing the operational efficiency. The AUV has several safety features that allow it to surface if unexpected difficulties arise during periods of active sampling.

**Instrumentation**

During the missions described herein, the AUV carried the downward-looking 1200 kHz ADCP and a Falmouth Scientific Instruments (FSI) micro-CTD (see specifications in Table 1), rated at a maximum depth of 500 m; since the missions described here, the CTD package has been replaced with a FSI micro-CTD2. The CTD sensors were calibrated by FSI with the instrument mounted on a model of the hull section of the AUV. The locations of these instruments on the bottom of the AUV are shown in Fig. 1. On the mission of 5 December, the ADCP operated in a mode that allowed measurement of local water velocity at the first ADCP bin 2 m beneath the ADCP at 2 Hz and the AUV ground
Fig. 2. (a)–(d) Meteorological and (e) water temperature data recorded by C-MAN buoys LKWF1 (thick line) and FWYF11 (thin line), located about 50 miles north and south of the site, respectively, for 1–12 Dec 1997. (f)–(g) Raw current data from a fixed ADCP (HSCP) located 5 km south of the region are also shown. The vertical bars mark times of AUV operations.

velocity at the same rate, the two measurements being taken in an interleaving sequence. On the mission of 11 December, the ADCP operated in a current profiling mode, measuring the velocity in the water column beneath it at 16 bins with a vertical resolution of 1m. Again, the current measurements were interleaved with bottom tracking measurements, both at a sampling rate of 2 Hz as before.

To allow for GPS fixes, the OEX was programmed to surface periodically during its mission. The AUV location was also continuously tracked acoustically via an USBL transponder from the research vessel, the FAU Oceaneer R/V; the latter was also used to launch and recover the AUV. During the missions, 113 different variables were recorded on the onboard computer, including instantaneous vehicle position in latitude and longitude, vehicle depth and altitude, current magnitude, and direction at the vehicle location, and in situ conductivity and temperature.

3. ADCP–CTD measurement missions along the east coast of Florida

a. Site and flow description

In the Florida Straits, the Florida Current has maximum speeds of 1.5–1.7 m s\(^{-1}\) that intermittently intrudes over the shelf break along the Florida Keys. Lee et al. (1992) found a gyre circulation along the inshore edge of the Florida Current with scales of O(50 to 100 km) and a seasonal signal modulating biological activity. Submesoscale ocean features have also been observed with scales of 5–15 km and lifetimes of about 12–24 h in this coastal ocean regime (Shay et al. 1998a). As the
current exits the Florida Straits and joins the Antilles Current, its transport increases to about 40 Sv (Schott et al. 1988). The Florida Current turns northward and follows the continental slope that eventually forms the Gulf Stream core off Cape Hatteras.

These larger mesoscale flows have been observed with various techniques over the previous few decades, yet little is known about the upper-ocean variability between the submesoscale to mesoscale. Submesoscale ocean flows interact with mesoscale features as well as with the tides, winds, and waves, and are accentuated by large eddies, which spin off the Gulf Stream. During the mission is shown in Fig. 2. Station LKWF1 is at Lake Worth (26°37’N, 80°2’W) about 52 km north, while station FWYF1 is at Fowey Rocks (25°35’N, 80°6’W), about 63 km south of the surveyed regions. The wind speed, air temperature, the atmospheric pressure, and the water temperature at the two stations during the period 1–12 December 1997 are shown in Figs. 2a–d respectively; the air temperature, wind speed, and barometric pressure were monitored respectively at heights 13.4, 13.7, and 6 m above mean sea level at LKWF1 and at 11, 43.9, and 29.3 m above sea level at FWYF1. The water temperature recorded at the two sites over the period is shown in Fig. 2e. The arrows in Figs. 2a,b point in the direction the wind is blowing to, positive values implying blowing northward.

The prevailing winds in the region are generally from the south. However, as we can see from Fig. 2, during the cold front of 5–9 December 1997 [Julian Days (JD) 339–343], the region was subjected to cold northwest winds at maximum speeds varying between 6 and 10 m s⁻¹, higher speeds occurring at FWYF1. It may be noted that the variation in wind direction is fairly consistent between the two stations even though approximately 115 km separate them. The air temperatures dropped by as much as 10°C at FWYF1 and by 15°C at LKWF1 during the spell. As may be expected, the water temperature at the northern station was generally cooler. During the cold front, it dropped by about 2°C at LKWF1 and by about 1°C at FWYF1. The variation in air pressure at the two sites was markedly similar, both featuring a small depression preceding the cold front.

### Background ocean conditions

Background current profiles were recorded by a moored, bottom-mounted, 150-kHz EDO Acoustics...
Harbor Surveillance Current Profiler (HSCP) located at 26°5.7355'N, 80°5.2263'W near Port Everglades in Fort Lauderdale (see Fig. 1b), about 5 km from the survey regions. The HSCP records velocity at a time interval of 7.5 min in 35 0.5-m bins. A subset of these measurements, encompassing 23 days of observations, were used here to document the background ocean conditions for the AUV missions of 5 December 1997 (JD 339) and 11 December 1997 (JD 345); unfortunately, the HSCP malfunctioned on the latter date so that moored current profile data are not available for that date. In the analysis of the HSCP data, measurements above a water depth of 2 m were not used since the transducer angles may not have been optimal to resolve near-surface currents. The time series of the north and east components of the current at the 8.8-m bin are respectively shown in Figs. 2f,g for comparison with the currents measured by the AUV at a depth of 9 m. Along-shelf currents in the range 0–0.8 m s\(^{-1}\) are apparent in the figure over the range of the time series shown. Backscattered acoustic signals were ensemble-averaged to form a profiler time series at 0.5 m vertical intervals every 7.5 min starting at 2 m and ending at 18-m depth. Around JD 331 and 344, large amplitude tidal fluctuations are apparent in the north (along-shelf) component of velocity. These are, however, suppressed between Julian Days 337 and 341 and are replaced by more rapid oscillations of apparently periodic nature ranging from 3–4 h. Similar fluctuations are observed in the east (cross-shelf) component of velocity. The time series for other neighboring bins all collapse fairly well onto the one shown in the figures. The HSCP measurements are described in detail below.

1) LOW-FREQUENCY FLOWS

To illustrate the observed current structure variability at the HSCP mooring, the profiler time series was low-pass filtered using a Lanczos window (see, e.g., Emery and Thompson 1998) with half power (6 db) at 48 h (hereafter referred to as subinertial flows). The half-power width of the filter was 201. Inertial period at 26°N is 27.4 h. While a Lanczos window may pass or leak diurnal tidal energy into the near-inertial signals, digital filtering was performed on detided currents where the \(K_1\) and \(M_2\) components were removed. These time series captured an episode of the Florida Current moving over the shallow water HSCP mooring (Fig. 3a). During this period, the northward current approached 40 cm s\(^{-1}\), which occurred during the 5 December AUV trial. As observed during the OPiRC-2 experiment along the Florida Keys (Shay et al. 1998b), the core of Florida Current has a maximum of 150–160 cm s\(^{-1}\). However, most of the record indicates a coastal current with maximum speeds of about 20 cm s\(^{-1}\) directed toward the south. These low frequency flow events were barotropic, consistent with the notion that the shallow coastal ocean circulation is well mixed.

2) TIDAL CURRENTS

The 23 days of ADCP measurements allow for the analysis of the tidal currents in the semidiurnal band (\(M_2\)) and the diurnal band (\(K_1\)). These two constituents seemingly dominate the current records inshore of the Florida Current, and are well resolved by the HSCP. From the HSCP data, the magnitude of the near-surface (4 m) tidal current speeds \(\sqrt{u^2 + v^2}\), where \(u\) and \(v\) respectively refer to north (along-shelf) and east (cross-shelf) components of the current velocity, for the semidiurnal \(M_2\) and diurnal \(K_1\) constituents were about 4–6 cm s\(^{-1}\), respectively. In the cross-shelf direction, the phases for the current reversed direction below 6 m for the \(K_1\) constituent, whereas the phase for the \(M_2\) constituent was nearly constant. However, the amplitudes of the tidal currents in the cross-shelf directions were relatively weak, of about 1 cm s\(^{-1}\). Clearly the more energetic velocity components were in the along-shelf direction with amplitudes of 4 to 6 cm s\(^{-1}\). In these components, the phases remained relatively constant with depth, ranging from 32° to 64° and −28° to −36° for the diurnal and semidiurnal constituents, respectively. Notice that the variance in the cross-shelf direction was a factor of 10 to 20 times less than in the along-shelf direction. The maximum current variance occurred at a depth of 6 m with an along-shelf variance of 731 cm\(^2\) s\(^{-2}\). The explained variance of the observed tidal current variations \(u_i\) by the \(m\) tidal components \((\sum_{p=1}^{m} u_p)^2\) was determined from the expression

\[
1 - \frac{\sum_{i=1}^{n} \left( u_i - \sum_{p=1}^{m} u_p \right)^2}{\sum_{i=1}^{n} u_i^2},
\]

where \(n\) is the number of data points (4407) and \(m\) represents the number of tidal constituents (2) as per Table 2. Tidal currents explained 3% to 7% of the observed current variance, which is consistent with upper ocean tidal currents found at the ADCP mooring along the Florida Keys (Shay et al. 1998b).

Other flows that are apparent in the records are 3–4-h period oscillations (see Figs. 2f,g); these were isolated through high-pass filtering of the detided current records at 8 hr using a Lanczos-squared window (Fig. 3b). In the along-shelf current component, these oscillations ranged from ±25 cm s\(^{-1}\) and on JD 339, these currents decreased to about 10 cm s\(^{-1}\). By contrast, the cross-shelf component was considerably weaker with amplitudes ranging from ±10 cm s\(^{-1}\). Further, these oscillations were depth-independent as in the low frequency and tidal flows. While it has been shown that barotropic signals can exist within the internal wave band, it is unclear whether these oscillations were due to the surface boundary layer dynamics (Shay and Chang 1997). The wind records shown in Figs. 2a,b indicate the passage of an atmospheric front over a few hours at both
sites on JD 335. However, the tidal time series indicated a general decrease starting on JD 334 and by the time of the AUV measurements, tidal currents were 5 cm s$^{-1}$. By contrast, these higher-frequency motions of about 15–20 cm s$^{-1}$ were excited by the winds on JD 335 and gradually decreased to about 10 cm s$^{-1}$ during the AUV mission. Thus, the wind rather than the tide played an important role in the excitation of these motions that had periods significantly less than the local inertial period of 27 h.

4. AUV-based measurements

a. Mission of 5 December 1997

The period of operation of this mission is marked on Fig. 2 by the first set of vertical bars. The wind speed of 5–9 m s$^{-1}$ recorded at the C-MAN stations is consistent with the observation of a cold wind from the northwest in the region during the mission. In order to survey the area, the AUV traveled repeatedly along an east–west “lawn mower pattern” path at a prepro-
grammed depth of 7 m, surfacing twice to obtain GPS fixes. The path comprised a total of seven east–west legs traversed in about 3 h at an average speed of 1 m s$^{-1}$.

The instantaneous position of the vehicle in terms of its latitude, longitude, and depth is shown in Figs. 4a–d. The AUV started out at the northern boundary of the region, moved south and then traveled repeatedly along an east–west lawn-mower-pattern path at a preprogrammed depth of 7 m, surfacing twice to obtain GPS fixes. The lengths of the long and the short legs of the pattern were chosen to be 1 km and 200 m, respectively. The seven legs of the AUV path can be discerned from Figs. 4b,d and the times when the AUV surfaces are clearly apparent from Fig. 4c. During part of the sixth leg, approximately during 2152–2201 h GMT, the AUV got caught in an abandoned line and strayed from its programmed path. This section of the sixth leg is therefore excluded from the analysis below.

The instantaneous water depth as a function of latitude and longitude during the seven legs is shown in Fig. 5. The bathymetry shown is obtained through measurement of vehicle depth using the pressure sensor in the onboard CTD package (see Table 1 for accuracy) and the measurement of the vehicle altitude using the 1200 kHz ADCP. The latter measures this as well as the vehicle speed over ground. The information from the four beams of the ADCP is processed internally in the unit to provide the velocity and altitude data. In this mode of ADCP operation, the bathymetry resolution is
Fig. 4. (a)–(c) AUV mission of 5 Dec 1997. Squares and circles respectively mark the starting and finishing times of each of the seven legs. (d) AUV path and measured current at a depth of 9 m on 5 Dec 1997. (e) Comparison between north and east components of velocity on 5 Dec, as recorded by the AUV (○) and by the fixed ADCP (*) located about 5 km south of the site. Raw fixed ADCP data are shown.
limited by the accuracy in measurement of the vehicle’s altitude, depth and position over the traversed path and density of the vehicle track line in a given coverage area. Throughout the two missions, bottom track in the shallow water was maintained. At a given point along the vehicle path, the inferred water depth is estimated to be accurate within 1 m while the geographical location of the point is estimated to be within 50 m, taking into account navigational errors described in section 2. The information in Fig. 5 has been interpolated in Fig. 6a to develop a bathymetry map of the surveyed region. While a bathymetry survey using a single ADCP does not quite meet the International Hydrographic Office’s standard, it does provide a low-cost means to characterize fairly accurate bathymetry maps in shallow water (see Table 1 for sensor specification). From Fig. 6a, the fairly flat, meandering “channel” between the reefs is clearly apparent and is consistent with the available bathymetry map from a 1962 U.S. Coast and Geodetic Survey (USCG) shown in Fig. 6e (top box). The accuracy in bathymetry measurement cannot be inferred through detailed comparison between Figs. 6a,e as significant storm-related changes to bathymetry are possible since the USCG survey was conducted. However, the range of variation in bathymetry and the prominent features are clearly evident in both maps.

The recorded water temperature and salinity data from the onboard CTD package for the seven legs are plotted in Figs. 7 and 8 against the instantaneous longitudinal position of the AUV. The specifications of the CTD package are given in Table 1, from which we can infer an error of less than 0.01 psu in salinity. The water
Fig. 6. Regional maps of (a) bathymetry, inferred from Fig. 5, (b) water temperature, (c) salinity, and (d) density. (e) Bathymetry of the two surveyed regions (boxed) according to U.S. Geological Survey of 1962.
temperature and salinity depicted in the figures exhibit greater variability between legs in the deeper (easterly) waters than in the shallower waters nearer the shore. The approximate mean temperature of 24.5°C at the near-shore position is consistent with the C-MAN buoy data shown in Fig. 2e. The difference between the minimum and maximum measured temperature is about 0.8°C. The data in Figure 8 suggest occurrence of horizontal salt intrusions at around 7-m depth along the legs at intermediate longitudes. The mean value of salinity is 35.7 psu, the difference between the minimum and maximum values being about 0.45 psu. The associated density variations along the legs are shown in Fig. 9 and the measurements are plotted on the temperature–salinity (TS) diagram in Fig. 10. The data are generally aligned with the 1024 kg m$^{-3}$ pycnocline, suggesting a region of instability and significant small-scale activity. The difference between maximum and minimum values of density is about 0.23 kg m$^{-3}$. The information is used to generate, through interpolation, regional maps of the distribution of temperature, salinity and water density (Figs. 6b–d) at 7-m depth. It may be noted that these are not synoptic maps; rather they characterize the spatial distribution of the in situ measurements during the mission. Temporal variations on the scale of mission duration or smaller cannot be resolved in such a survey. However, multiple AUVs may be utilized to minimize the influence of temporal variability. The maps suggest that warmer, more saline waters generally lie in the eastern part of the region that is closest to the Florida Current. A region of cold, relatively less saline and less dense water, protrudes into the surveyed region from the south. The corresponding variations in density are clearly apparent in Fig. 6d.

For this mission, the ADCP was programmed to measure and record its velocity relative to ground and its velocity through the ambient water, but not to profile the velocity in the water column. The velocity through
the water is measured at the first ADCP bin, 2 m beneath the vehicle. Thus, with a vehicle depth of 7 m, we can only determine local currents at a 9-m depth. The variation in the horizontal components of the current over each leg, about the mean for each leg, is shown in Fig. 11 and the data has been interpolated to show the regional current distribution in Fig. 4d. Taking account of the navigational accuracy discussed in section 2, the length of the legs and the bilinear interpolation used in developing Fig. 4d, it is estimated that the error in the position of the current vector is less than 50 m and the error in current velocities are of the order indicated in Table 1. Please note that as in the case of the other maps (Figs. 6b–d), Fig. 4d does not represent a synoptic view. Temporal variations in the current of the order of variations of $O(3 \text{ h})$ or smaller are not properly resolved. Use of multiple AUVs is expected to improve the resolution. The magnitude and direction of the current is consistent with that measured by the moored HSCP (Figs. 2f,g). A detailed comparison between the AUV current measurements and the HSCP is given in Fig. 4e. The AUV measurements shown in this figure have been averaged over 7.5-min intervals, consistent with the available HSCP data. The magnitudes of the current, particularly the cross-shelf component, are of the right order, considering that the HSCP is located around 5 km south of the surveyed region. While the mean current is generally northward, the cross-shelf variations seen in Fig. 11 suggest presence of large-scale eddies or horizontal shear layers.


The period of operation of this mission is marked on Fig. 2 by the second set of vertical bars. The southerly wind of around 5–7 m s$^{-1}$ speed recorded at the C-MAN stations is consistent with the observation of a 10–15 kt wind from the south-southeast in the surveyed area.

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**Fig. 8.** Salinity variations about the mean value of $S_M$ for each leg at mean latitude $\text{Lat}_M$ plotted against instantaneous longitudinal position of AUV on 5 Dec 1997.
Waves of around 0.5 m were observed in the area. The relation of the chosen site (B) for this mission to the mission of 5 December 1997 (A) is shown in Fig. 1b, and the mode of survey is shown in Fig. 12. Site B lies southwest of site A, which was surveyed on 5 December 1997, the longitudinal position of the two sites overlapping somewhat. Site B is generally shallower than site A and the area covered is smaller than at site A. This time the AUV traveled back and forth along a north–south lawn-mower-pattern path at a programmed depth of 3 m, surfacing twice to obtain GPS fixes. The path comprised several north–south legs, around 1 km in length and separated by around 200 m from neighboring legs, traversed in about 2.5 h at an average speed of 1.5 m s$^{-1}$. The recorded CTD data was interpolated as before to obtain the local bathymetry and the distribution of temperature, salinity and density at a depth of 3 m (Fig. 13). The water depth generally increases from 10 to 15 m with distance from the shore, although some cross-shelf ridges are apparent in the figure; the water depth is consistent with that at site A (Fig. 6a). The bathymetry is consistent with the U.S. Geological Survey of 1962 (Fig. 6e) as before. The temperature distribution at the 3-m depth had a mean of 24.71°C and a range of 0.1°C, the temperature increasing with distance from the shore while the salinity distribution at 3 m had a mean of 36.1 psu and a range of 0.14 psu, the salinity generally decreasing with distance from the shore. The corresponding water density distribution had a mean of 1024.27 kg m$^{-3}$ and a range of 0.12 kg m$^{-3}$, the density decreasing with distance from the shore. The measurements imply that near-shore waters were cooler, more saline, and therefore denser, than offshore waters although the differences are rather small. The water temperature is typical for the region during winter. It is not possible to make direct comparison of the temperature and salinity distributions between the two surveys in view of the differences in...
locations relative to the shore as well as in the survey depths. It may be noted, however, that in the region where the longitudinal positions overlap, although the mean water temperature at 3-m depth on 11 December 1997 was generally the same as at 7-m depth during the passage of the cold front on 5 December 1997, the water was more saline and therefore denser in the former case. Also evident from Figs. 6 and 13 are the reduction in the range of variations in temperature, salinity and density.

For this mission, the on-board 1200-kHz ADCP was programmed to record the velocity profile of the flow beneath the vehicle at a bin spacing of 1 m. The local current field at depth 5 m, as interpolated from the ADCP measurement, is shown in Fig. 12. The ADCP data from 8–14 bins, covering water depth of 5–17 m, was interpolated to obtain current velocity transects along five north–south legs. Only bins that were free from any apparent contaminations from bottom reflections were utilized. The data for each bin was low-pass filtered with a cutoff at ~40 m in along-shelf direction and resampled on an equally spaced grid. The east–west (cross-shelf), north–south (along-shelf), and downward velocity components are respectively plotted against instantaneous latitude position of the vehicle in Figs. 14a–c. We note from Fig. 14a that the cross shelf component was generally shoreward, varying in magnitude between 0 and 10 cm s$^{-1}$. From Fig. 14b, the magnitude of the northward, along-shelf component varied from a value of around 20 cm s$^{-1}$ at the easternmost locations to ~5 cm s$^{-1}$ at the shallower, near shore locations. Thus the current direction apparently varied during the mission from northwest to southwest on approach to shore. It may be noted that the survey over the six consecutive legs shown in Fig. 14 was carried out over a period of 86 min and the results are subject to time aliasing issues discussed below. The characteristics of the depth profiles for the locations away from the shore suggest that the flow there was driven by the presence of significant northbound winds depicted in Figs. 2a,b.

The mean value of the vertical component for each bin in Fig. 14c has upward values below 2 cm s$^{-1}$.

5. Discussion

A small AUV platform provides a tether free, low operational cost method of surveying substantial regions of the water column, potentially during storms. The OEX series AUV appears to be a good mobile platform in this category. Significant information about the bathymetry and spatial variability in the water column in a region can be identified with a few passes as in the missions described here. Refined information can be obtained through use of more, tighter, passes in a “lawnmower pattern.” Temporal variations on the scale of mission duration or smaller cannot be resolved in such a survey. The problem can, however, be reduced through use of multiple vehicles and conducting the survey in
the presence of other fixed synoptic systems which can provide subsidiary background information about the temporal variability.

Recent studies (Shay et al. 2000) off the east coast of Florida utilized a shore-mounted Ocean Surface Current Reader (OSCR) HF radar to provide surface current measurements while the OEX AUV made detailed measurements of current profiles, temperature, and conductivity in the water column under the OSCR grid. CTD and current measurements were also made from a ship. This latest work will result in significant new information about the mixed layer in waters influenced by the presence of the Florida Current.

The bathymetry data collected during the missions described here are consistent with the available hydrographic surveys of the region, illustrating the usefulness of the AUV. The currents measured by the onboard ADCP 5 December 1997 were also consistent with that measured by a nearby moored ADCP. Further missions using the AUVs, in conjunction with other fixed systems, are planned in shallow waters off the east coast of Florida in order to further develop a comprehensive dataset to study active processes in the mixed layer during the passage of cold fronts over tropical waters. The coastal circulation in the area is dominated by the movement of the Florida Current over the shelf, by tidal currents, and by wind events, of the type described here, which may generate barotropic internal waves. While it is unclear whether the higher frequency motions observed in the moored HSCP data are solely internal waves, examining their behavior relative to the AUV measurements represents an important first step. Moreover, since the currents observed at the HSCP were generally barotropic, the comparisons with the AUV

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**Figure 11.** Current variation at 9-m depth over the seven legs about the mean value, plotted against the instantaneous longitudinal position of the AUV on 5 Dec 1997. The magnitudes of the east, north components \((u_m, v_m)\) of the mean current are shown in each subplot.
FIG. 12. AUV paths and current distributions at 9 m on 5 Dec 1997 (marked A) and at 5 m on 11 Dec 1997 (marked B) mapped on latitude–longitude plane. Arrow sizes are scaled to represent speed in the range $\text{(0–31 cm s)}^{-1}$.

FIG. 13. Regional maps of (upper left) bathymetry, (upper right) water temperature, (lower left) salinity, and (lower right) density at 7-m depth on 11 Dec 1997.
measurements on 5 December at the 8–9-m level reflect the variability throughout the column, especially during vertically well-mixed conditions. In addition, vortices and spinoff eddies are often present in this area. Thus, subsequent experiments will have to be of sufficient duration to resolve the low-frequency flows associated with these processes. In particular, AUV systems will work best in conjunction with fixed, ideally synoptic measurements.

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