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Deep-sea, high-resolution, hydrography and current measurements using an autonomous underwater vehicle: The overflow from the Strait of Sicily

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Abstract. AUTOSUB-2, an autonomous underwater vehicle (AUV) developed by the Southampton Oceanography Centre, was used for high resolution hydrographic surveys in the Sicily Strait. A combination of "seasoar" type profiling and terrain following missions were undertaken and velocity and hydrographic measurements taken from AUTOSUB-2 were compared with concurrent shipboard hydrographic and velocity profiles. Even though shipboard stations were separated by just 5 to 8 km along the mission path, data from the AUV showed small scale variability that was missed by the shipboard sampling. In this paper we present the example of an intense jet, with maximum speed greater than 0.50 m s^{-1}, less than 4 km wide.

Introduction

Previous physical oceanographic work with Autonomous Underwater Vehicles (AUVs) includes: shallow hydrographic surveys of Narragansett Bay, Rhode Island, using the U.S. Navy's Large Diameter Unmanned Underwater Vehicle, [*Levine et al.*, 1997], a survey of coastal fronts in Haro Strait, British Columbia, (again in relatively shallow water) using the Massachusetts Institute of Technology's ODYSSEY IIb, [*Nadis*, 1997] and short, shallow, hydrographic surveys off Port Everglades, Florida using a Florida Atlantic University Ocean Explorer series AUV, [*An et al.*, 2001]. Short geophysical surveys of the Juan de Fuca Ridge using the Woods Hole Oceanographic Institution's Autonomous Benthic Explorer in water depths > 2000 m have been reported by *Tivey et al.*, [1998]. The study presented here demonstrates the use of an AUV to obtain high quality hydrographic and current measurements in deep water (up to 900 m) while terrain following.

The Sicily Strait (hereafter SS), forms a natural barrier to the passage of the deep waters from the eastern to the western basins of the Mediterranean. The SS has a complicated bathymetry (Figure 1) with two near-parallel channels separated by a central bank which rises to within 100 m of the sea surface.

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In the top 150 m of the SS there is an eastward flow of Modified Atlantic Water below this, Levantine Intermediate Water (LIW) flows westward. An energetic vein of LIW passes through the narrow eastern channel (sill depth 430 m) and a weaker, slightly cooler and fresher, vein flows through the broader western channel (sill depth 370 m) [*Astraldi et al.*, 1996]. An analysis by *Sparnocchia et al.*, [1999] identifies the region immediately downstream of the sills as a site for mixing between the overflow waters and Tyrrhenian Deep Water.

The objective of the AUV deployments reported here was to study this region of enhanced mixing in greater detail. We present data from mission 239, a 186 km mission across and downstream of the sills, to demonstrate that an AUV can obtain high quality hydrographic observations on a scale which would be difficult to achieve using conventional surveys.

Vehicle and instrumentation

A schematic of the AUTOSUB-2 AUV vehicle showing the location of the major system components and science sensors is shown in Figure 2. AUTOSUB-2 (see e.g. *Millard et al.*, [1998], *McPhail and Pebody* [1998]) is 6.8 m long, 0.9 m in diameter, weighs 2400 kg when dry in air and has a displacement of 3.5 tonnes. In its current configuration AUTOSUB-2 has a maximum depth of 1600 m, a range of 800 km and travels at a speed of 1.2 to 1.6 m s^{-1}.

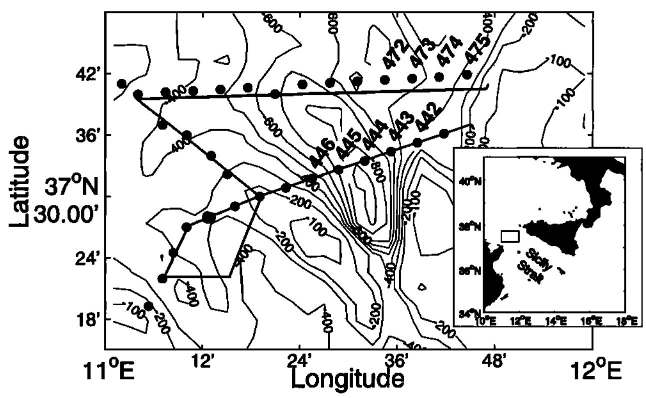

Figure 1. Bathymetry of the survey area (depth contours are at 100 m intervals). The path of AUTOSUB-2 on mission 239 is shown as a thick black line; shipboard CTD and LADCP stations are shown as black circles. The rectangle in the inset map shows the study region.

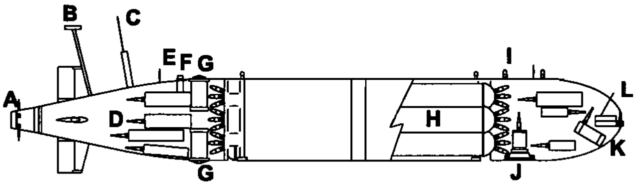

Figure 2. Schematic of AUTOSUB-2 showing the major system components and the science sensors. A - propulsion motor, B - GPS aerial, C - Orbcom aerial, D - pressure cases housing other sub systems, E - Argos aerial, F - acoustic transponder, G - ADCP (upward and downward looking), H - carbon fibre battery pods, I - light beacon, J - emergency abort weight, K - forward looking altimeter, L - CTDs.

Navigation is by global positioning system (GPS) when the AUV is at the surface and by dead-reckoning when submerged. For dead-reckoning AUTOSUB-2 uses information from a 300 kHz, RDI Workhorse Navigator, Acoustic Doppler Current Profiler (ADCP), when within 200 m of the sea floor, and a SEATEX Motion Reference Unit (MRU6) which incorporates a three-axis servo vector fluxgate compass and provides magnetic heading data to the ADCP.

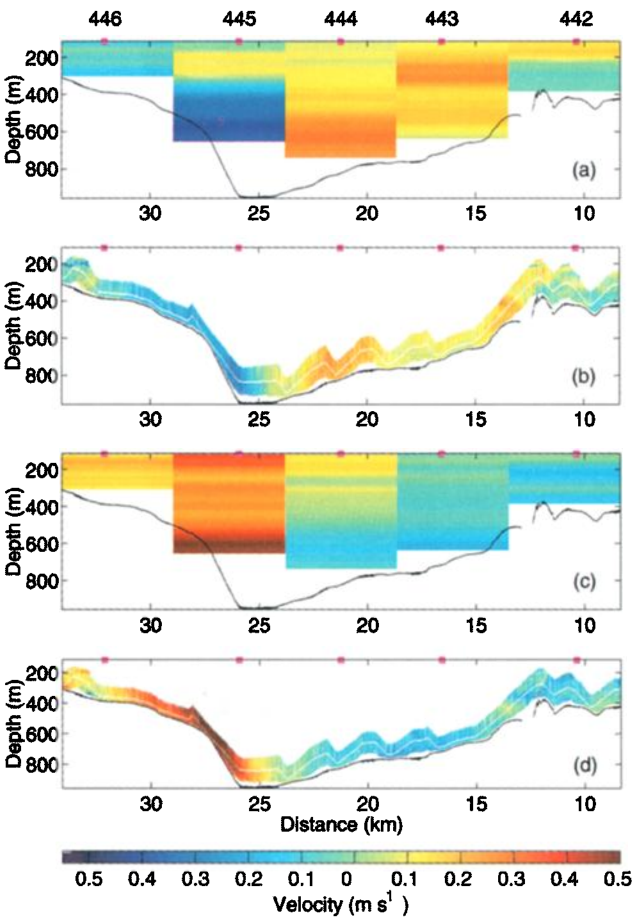

Figure 3. An example of velocity data from the AUTOSUB-2 upward and downward looking ADCPs and the shipboard LADCP. The LADCP data are from stations 442, 443, 444, 445 and 446, the AUV data are from just east of station 442 to just west of station 446, (see Figure 1). The position of each LADCP profile is shown by the magenta square on the top axis of each panel. Northward velocity component of a) the LADCP data, b) the AUV ADCP data. Eastward velocity component of c) the LADCP data d) the AUV ADCP data.

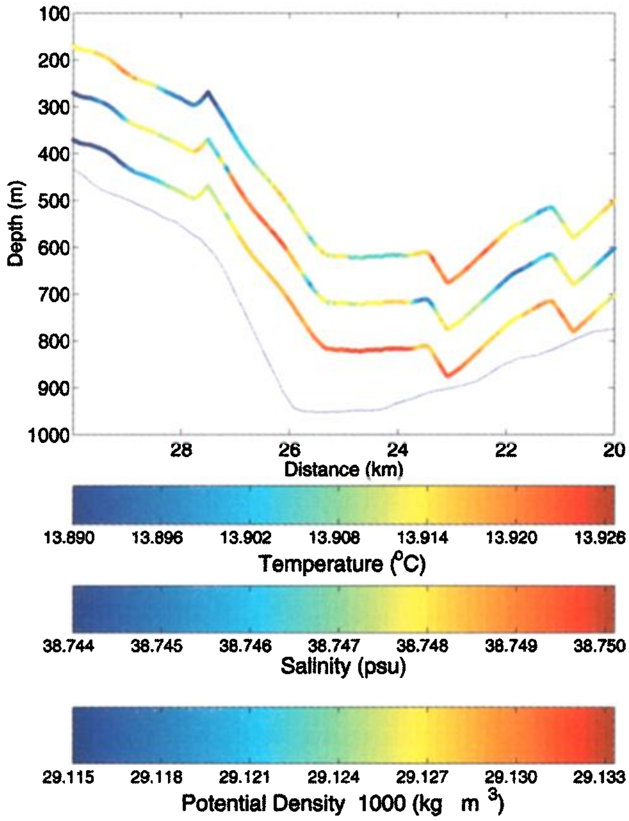

Figure 4. Example of temperature (upper trace), salinity (middle trace) and potential density (lower trace) data from the AUTOSUB-2 primary CTD sensor. The value of the scaler quantity is denoted by the colour of the circle, the potential density data are plotted at the depth of the AUV and at the distance from the start of the mission track. The data are from the part of the ADCP velocity section between 20 and 30 km shown in Figure 3.

The compass was calibrated by AUTOSUB-2 i) steaming in a 1 km square underwater and ii) by surfacing for a GPS fix, then diving and running in a straight line underwater for 2 km (with bottom tracking) then surfacing again for a second GPS fix. The first part of the calibration process corrects for any heading dependent error, the second part corrects for the local magnetic declination.

For our work in the SS, AUTOSUB-2 carried two SBE-9+ Conductivity-Temperature-Depth (CTD) systems mounted in the front of the vehicle, and two 300 kHz RDI ADCPs, one upward and one downward looking (see Figure 2).

Data collection and processing in the Sicily Strait

The data presented here were collected between 19:00 UTC on 14 June and 11:10 UTC on 16 June 2000 on AUTOSUB-2 mission 239. Figure 1 shows the mission track. During this mission, AUTOSUB-2 controlled its altitude above the seafloor while terrain following collecting data between 30 m and 100 m above the sea-bed. The complex bathymetry in the SS forced the AUV to follow significant changes in bottom depth and bottom slope. The AUV found a maximum bottom slope of 25% and an rms slope of 5%, over a horizontal distance of 100 m, during mission 239.

The two ADCPs collected data in 4-m bins at a range of up to 108 m from AUTOSUB-2 with one bottom track and two water track pings every 3 seconds. The two water pings were averaged internally by the ADCP. For an average vehicle speed of 1.4 m s^{-1} this sampling interval gives a horizontal resolution of 70.7 m at 100 m range from the ADCP transducer head, with adjacent samples overlapping by up to 62.3 m. The velocity data were transformed into absolute velocities in earth co-ordinates using the heading information from the AUTOSUB-2 compass and the bottom track velocities from the downward looking ADCP. Where AUTOSUB-2 was out of range of the bottom, or where the bottom track information was missing, a linear interpolation was used to fill in the missing data (only 3% of the total samples) assuming that AUTOSUB-2 did not change its heading during this time.

The CTDs sampled at a rate of 24 samples a second; the data presented here were averaged into 3-second bins. This averaging reduces the horizontal resolution of the CTD data to 4.2 m with a mean vehicle speed of 1.4 m s^{-1} and the vertical resolution to 0.48 m with a typical climb rate of 0.16 m s^{-1}.

A set of shipboard CTD and lowered ADCP (LADCP) profiles were made concurrently with this mission at the stations shown on Figure 1. The CTD was a SBE 911+ CTD and sampled at a rate of 24 Hz, the LADCP was a RDI 150 kHz broadband ADCP which collected data in 16-m bins. Data from the shipboard CTD were subsequently averaged into 1-m bins and the salinity data derived from the CTD were calibrated with water bottle samples. The LADCP data were processed using the method of *Firing and Gordon* [1990].

Results

The average navigation error of the terrain following mission, as measured by GPS surface fixes (at 0 km, 93 km and 186 km), was 1.2% of the distance travelled.

An example of velocity data from the upward and downward looking ADCPs on AUTOSUB-2 along a section from just east of station 442 to just west of station 446 is shown in Figure 3b), d). The position of AUTOSUB-2 in Figure 3 is shown by the white region between the coloured bands. The data shown are the "raw" 3-second, 2 ping, averages from the ADCPs which have been mapped into a depth-distance co-ordinate system. The data are presented as north and east velocity components. For comparison, the north and east velocity components measured by the shipboard LADCP at stations 442, 443, 444, 445 and 446 are also shown, Figure 3a), c), (see Figure 1 for the station positions). AUTOSUB-2 passed station 442 54 minutes before the LADCP cast and passed station 446 13 minutes after the LADCP cast. Data from the two types of sensor agree to within ± 10° and ± 10 cm s^{-1}, however these differences could result from the temporal and spatial variability of the flow, and not just differences between the instruments and the data processing.

During this section AUTOSUB-2 crossed a deep basin downstream of the eastern sill. The ADCP data from AUTOSUB-2 and the shipboard LADCP data show strong (up to 55 cm s^{-1}) east-southeasterly flow on the western side of the basin, between 400 and 900 m depth over a distance of 4 km[1] with a weaker north-northwesterly return flow (about 22 cm s^{-1}) on the eastern side of the basin, and a region of almost stationary water in the center of the basin. The recirculation in this basin appears to be part of the overflow from the western sill. The overflow is steered by the topography northwards around the central bank then back southwards toward the eastern sill before turning north once more.

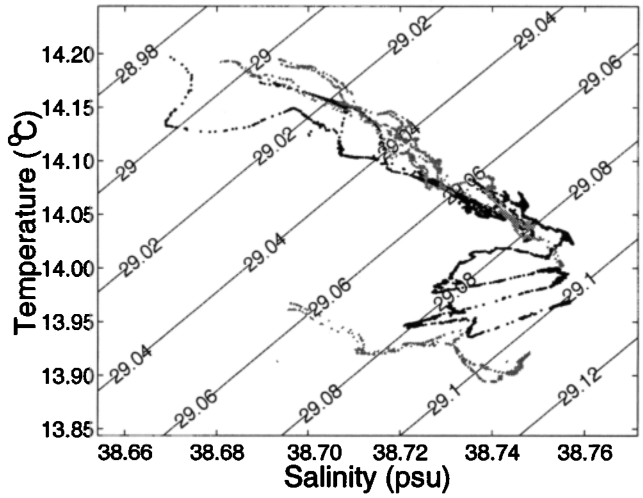

Figure 5. A comparison of T-S data from the AUTOSUB-2 primary CTD sensors (black dots) and the shipboard CTD (grey dots). The shipboard CTD data are from stations 472, 473, 474 and 475, the AUTOSUB-2 data are from between stations 472 and 475, (see Figure 1). In each case the data are from 237 m depth, the shallowest depth of the AUV between these stations, to the maximum depth measured by the AUV.

Figure 4 shows temperature, salinity and potential density data, along the part of the section from 20 to 30 km in Figure 3. The data were derived from the AUTOSUB-2 CTD sensors. There is good agreement between the two sensor pairs, the rms differences for the 3-s averages being less than the sensor accuracy specified by the manufacturer for 24 Hz sampling. The data show very small scale variability, especially on the western slope of the basin that may be indicative of active mixing in the jet observed in the ADCP data. In contrast there are only two shipboard CTD stations for this section, one at the deepest part of the basin at 25.9 km and one on the eastern side at 21.2 km (stations 444 and 445 on Figure 1).

As a check on the data quality, AUTOSUB-2 CTD data were compared with the shipboard CTD data along a part of the mission where the water mass characteristics were relatively constant. The results are presented in Figure 5 which is a T-S plot of data below 237 m from CTD stations 472, 473, 474 and 475 and the corresponding AUTOSUB-2 CTD data between these stations (AUTOSUB-2 was always deeper than 237 m). Although intended to lie close to, or along, the AUTOSUB-2 track in fact these CTD stations lay between 2.2 and 2.6 km north of the track, due to the 1% navigation error of the AUV. Shipboard CTD profiles reached to within 6 or 7 m of the bottom whereas

[1]The track of AUTOSUB-2 crossed the current at an angle of about 45°.

AUTOSUB-2 was never closer than 30 m to the bottom. As a consequence of the northward offset and the deeper profiling depth, the shipboard CTD sensors reached slightly colder water. Otherwise both data sets generally showed the same T-S ranges and variability, although the AUTOSUB-2 data also clearly shows mixing between the two different types of profile captured by the CTD.

Conclusions

We have shown that it is possible to make high quality, deep-sea, hydrographic and velocity measurements with an AUV in a region of complex bathymetry. In particular, AUTOSUB-2 is a good platform for ADCPs. It can operate below the depth-range of conventional shipboard, hull-mounted, ADCP systems (300 to 400 m with a 150 kHz ADCP) and, due to its stable motion, less temporal/spatial averaging of the data is required resulting in greater horizontal resolution. The example presented here shows that the fine horizontal resolution of an AUV hydrographic survey can provide information on small scale features that could not be measured by conventional shipboard sampling.

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