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Methods in Oceanography

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Full length article

Assessing the potential of autonomous submarine gliders for ecosystem monitoring across multiple trophic levels (plankton to cetaceans) and pollutants in shallow shelf seas



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ARTICLE INFO

Article history:

Received 7 March 2014

Received in revised form

13 June 2014

Accepted 17 June 2014

Available online 22 July 2014

ABSTRACT

A combination of scientific, economic, technological and policy drivers is behind a recent upsurge in the use of marine autonomous systems (and accompanying miniaturized sensors) for environmental mapping and monitoring. Increased spatial–temporal resolution and coverage of data, at reduced cost, is particularly vital for effective spatial management of highly dynamic and heterogeneous shelf environments. This proof-of-concept study involves

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Keywords:

Autonomous underwater vehicles
Submarine glider
Slocum
Ecosystem monitoring
Multiple trophic levels

integration of a novel combination of sensors onto buoyancy-driven submarine gliders, in order to assess their suitability for ecosystem monitoring in shelf waters at a variety of trophic levels. Two shallow-water *Slocum* gliders were equipped with CTD and fluorometer to measure physical properties and chlorophyll, respectively. One glider was also equipped with a single-frequency echosounder to collect information on zooplankton and fish distribution. The other glider carried a Passive Acoustic Monitoring system to detect and record cetacean vocalizations, and a passive sampler to detect chemical contaminants in the water column. The two gliders were deployed together off southwest UK in autumn 2013, and targeted a known tidal-mixing front west of the Isles of Scilly. The gliders' mission took about 40 days, with each glider travelling distances of >1000 km and undertaking >2500 dives to depths of up to 100 m. Controlling glider flight and alignment of the two glider trajectories proved to be particularly challenging due to strong tidal flows. However, the gliders continued to collect data in poor weather when an accompanying research vessel was unable to operate. In addition, all glider sensors generated useful data, with particularly interesting initial results relating to subsurface chlorophyll maxima and numerous fish/cetacean detections within the water column. The broader implications of this study for marine ecosystem monitoring with submarine gliders are discussed.

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1. Introduction

Shelf and adjacent coastal seas host highly productive ecosystems and are shared by an increasing variety of stakeholders utilizing limited space, e.g. shipping, fishing, aquaculture, recreation, hydrocarbon and aggregate extraction, and renewable energy (Collie and Adamowicz et al., 2013; Sharples and Ellis et al., 2013). These potentially conflicting demands require appropriate management, e.g. through Marine Spatial Planning, a complex task that is dependent upon high quality data and evidence (Gilman, 2002; Douvere and Ehler, 2011).

In addition to the management of multiple stakeholders to ensure that ecosystem health and services are maintained, additional data from shelf seas are required to meet international statutory obligations such as establishment of Marine Protected Areas (MPAs) and implementation of the EU Marine Strategy Framework Directive (MSFD) (European Union, 2008; Brennan and Fitzsimmons et al., 2013). However, marine mapping and monitoring using dedicated research and survey vessels is expensive, and offshore operations can be hindered due to weather constraints (Schofield and Glenn et al., 2013). In addition, the spatial and temporal resolution of vessel-based data are often insufficient to fully capture ecosystem dynamics, including the linkage of physical and biological processes, predator–prey interactions, community structure, and the spatio-temporal variability of different ecosystem components (Day, 2008). Satellite remote sensing of the oceans can provide useful supporting data at large spatial scales, but is restricted to the uppermost layers of the sea surface. Fixed moorings and profiling floats may provide long time series, but the former only collects data at a single point and the latter are difficult to spatially control (L'Heveder and Mortier et al., 2013).

Submarine (buoyancy-driven) gliders are a type of Autonomous Underwater Vehicle (AUV) that oscillates through the water column and can remain unattended at sea for several weeks to months (Rudnick and Crowley et al., 2012). Gliders carrying appropriate sensors can simultaneously monitor a range of physical and biological parameters, and regular surface communications with satellite allow their movement to be controlled and data to be uploaded in near real-time. However, gliders

are relatively slow moving (20–40 cm/s horizontally), making them prone to drift in areas of strong currents (Leonard et al., 2007; Davis and Leonard et al., 2009). Their sensor load is limited and each mission necessitates a balance between battery life, mission duration, sampling frequency, and data quality (Willcox and Bellingham et al., 2001). Despite these limitations, the scientific research community is increasingly focusing on gliders as a tool for monitoring of features at the meso- and sub-mesoscale, including highly variable and dynamic phenomena such as oceanic fronts, eddies and upwelling regions (Davis and Ohman et al., 2008).

Traditionally, gliders have been deployed with a basic set of sensors that enable measurement of physical oceanographic parameters such as temperature, salinity or currents (e.g. Perry and Sackmann et al., 2008; Ruiz and Pascual et al., 2009; Bouffard and Pascual et al., 2010; Merckelbach and Smeed et al., 2010; Todd and Gawarkiewicz et al., 2013) and lower trophic levels of the ecosystem (i.e. phytoplankton and zooplankton, e.g. Baumgartner and Fratantoni, 2008; Niewiadomska and Claustre et al., 2008; Fox and Gower et al., 2009; Frajka-Williams and Rhines et al., 2009; Guihen et al., 2014). More recently, new sensors have been integrated onto gliders that can measure abundance of higher trophic level organisms, e.g. fish and cetaceans (e.g. Baumgartner and Fratantoni, 2008; Ferguson and Lo et al., 2010; Klinck and Mellinger et al., 2012; Meyer-Gutbrod and Greene et al., 2012; Baumgartner and Fratantoni et al., 2013; Send and Regier et al., 2013). In addition, glider ‘fleets’ are increasingly used to establish ocean monitoring networks rather than single platform deployments (e.g. English and Chuanmin et al., 2009; Alvarez and Mourre, 2012; Bouffard and Renault et al., 2012; Alvarez and Chiggiato et al., 2013). However, until now, there has been limited effort devoted to the simultaneous measurement of physical parameters and multiple biological components of the ecosystem using gliders.

This contribution describes a deployment of gliders carrying sensor loads capable of simultaneously monitoring multiple marine ecosystem components, from physical parameters and chlorophyll *a* fluorescence (CTD and fluorometer) to zooplankton and fish (echosounder), and cetaceans (hydrophone). This ‘proof-of-concept’ study involved the deployment of two shallow-water gliders off southwest UK in autumn 2013, targeting a known tidal-mixing front in a productive inner-shelf environment. By targeting a frontal area, the gliders were expected to encounter steep vertical and horizontal gradients in physical parameters and potentially elevated levels of biomass. In addition, fronts in UK shelf waters are considered as potential targets for spatial protection measures (e.g. MPAs; (Miller and Christodoulou, 2014)) and are therefore a particular target for multi-trophic-level monitoring.

The aims of the paper are therefore to: (1) describe the various sensors that were deployed on the gliders, (2) provide an overview of glider and sensor operations during the autumn 2013 deployment, (3) present some initial scientific results and examples of collected data, and (4) discuss some of the benefits and issues that arose from the glider missions. The intention is that this study will aid future assessment of submarine gliders as a suitable platform for cost-effective, long-term monitoring of shelf sea ecosystems.

2. Survey area

The survey was conducted west of the Isles of Scilly, off southwest UK (Fig. 1), where shelf waters are <100 m deep. Here, tidal flows to the northeast and southwest peak at ~75 cm/s during spring tides, and are weakest towards the northwest and southeast. Residual currents flow northwest and northwards with speeds of up to 5 cm/s (Pingree and Lecann, 1989). Shelf waters to the west of the Isles of Scilly are seasonally stratified (typically from late spring to late autumn), whereas inshore waters around the islands themselves remain mixed as a result of tidal–topographic interactions; a series of seasonal bottom and surface tidal-mixing fronts occur at the boundary between these stratified and mixed water masses (Simpson, 1981). Frontal dynamics lead to cooler, nutrient-rich waters being transferred into the photic zone and thus enhancing primary production (Pingree and Holligan et al., 1976; Simpson and Tett et al., 1982), which can in turn lead to fronts (including the Isles of Scilly fronts) becoming hotspots for higher trophic levels such as marine mammals (Beaumont and Austen et al., 2007; Leeney and Witt et al., 2012). The recognition of a wide variety of important marine habitats around the Isles of Scilly has led to the designation of the Isles of Scilly Marine Conservation Zone

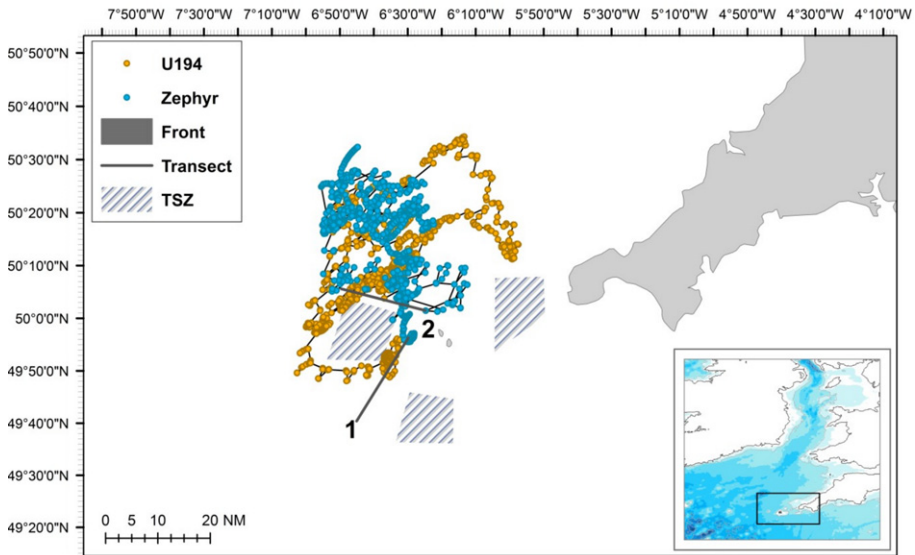


Fig. 1. Map of survey area and glider positions. Inset shows geographic overview of the survey area and depth contours (dark blue = deeper water; white = land). Enlarged map shows land in grey (Isles of Scilly and west Cornwall). Dots represent glider GPS positions (blue: *Zephyr*; orange: *U194*); thin black lines indicate glider tracks between positions, based on linear interpolation. Large grey arrows indicate the approximate location of the Isles of Scilly tidal mixing front determined by remote sensing Fig. A.1. Numbered dark grey lines indicate the initial (1) and revised (2) transects. Shaded areas represent traffic separation zones (TSZ). Note that *U194* locations are only based upon GPS fixes received following re-deployment on 04 October 2013 (cf. Table 1 and Fig. 2). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Key events in chronological order.

Date	Event
12/09/2013	Deployment
14/09/2013	<i>Zephyr</i> d-tag memory card full (no data stored hereafter) until re-deployment
17/09/2013	<i>U194</i> "beached"
21/09–03/10/2013	Recovery and repairs <i>U194</i>
04/10/2013	Re-deployment <i>U194</i> ; exchange <i>Zephyr</i> d-tag
10/10/2013	<i>Zephyr</i> d-tag stops recording: no power supply due to damaged cable
21/10/2013	Retrieval of <i>Zephyr</i>
13/11/2013	Retrieval of <i>U194</i>

(MCZ) in 2013 (Defra, 2013). In addition, the waters around the Isles of Scilly are valuable for marine recreation and tourism (Beaumont and Austen et al., 2007). There is also significant commercial fishing activity in the area, including a nearshore industry for shellfish and crustaceans (Beaumont and Austen et al., 2007). There are three traffic separation zones (TSZ) surrounding the islands due to high levels of shipping traffic (Fig. 1).

3. Methods

3.1. Gliders

We used two shallow-water *Slocum* gliders, *Zephyr* and *U194* (Fig. 2), developed by Teledyne Webb Research Corporation, which are specifically designed for shallow-water operations (<200 m). A detailed description of the glider can be found in Webb and Simonetti et al. (2001), but here we

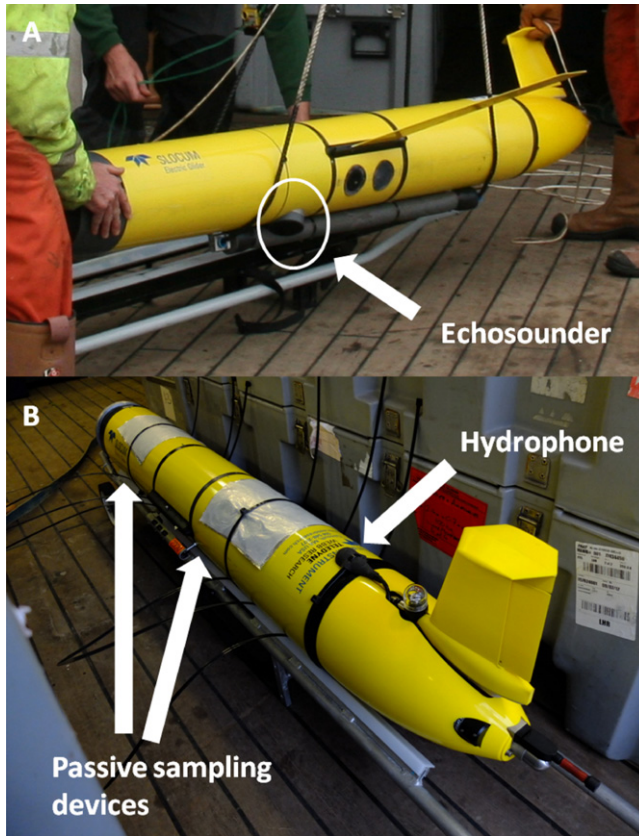


Fig. 2. (A) Picture of *U194* showing ES853 echosounder on the underside of the glider and (B) picture of *Zephyr* (wings not yet attached), showing the d-tag hydrophone and silicone rubber passive sampling sheets attached to the glider body.

focus on aspects relevant to this paper. *Slocums* move through the water column in a saw-tooth motion induced by changes in their buoyancy. A pump transfers seawater in and out of a holding chamber, which results in a change to the vehicle's density; this leads to a sequence of sinking and rising, which is translated into a forward motion by the attached wings. The average horizontal speed is 20–40 cm/s and vertical motion is 10–20 cm/s. Dive depth can be regulated by either a pressure sensor or an altimeter. Due to the shallow depth and varying bathymetry, we used the altimeter with an inflexion height of 10 m above the bottom to maximize dive depth. Forward and backward shifting of the battery packs controls dive angle; a rudder in the tail fin controls the yaw. When at the surface for communication, an air bladder at the tail is filled for additional buoyancy. Two-way communication is via Iridium satellite connection, allowing for near real-time transfer of subsets of data and manipulation of mission settings. Navigation is by Global Positioning System (GPS) when the vehicle is at the surface, and via dead reckoning during dives.

3.2. Glider sensors

3.2.1. Oceanographic sensors

Both gliders were equipped with the standard *Slocum* science package, which includes a non-pumped, low-drag, continuous profile Sea-bird SBE-41 CTD (temperature, conductivity and pressure) and WET Labs ECO pucks (BB2FLS, *Zephyr*; F1bbCD-SLK, *U194*), providing combined measurements of

chlorophyll *a* fluorescence, coloured dissolved organic matter (CDOM), and backscatter. The excitation wavelengths were 470, 370 and 700 nm, the emission wavelengths 695, 460 nm. The ECO pucks were mounted in the science bay, facing downwards. Also included are an Aanderaa Oxygen Optode 4835 and an altimeter. CDOM and backscatter provide information on organic and inorganic material in the water-column, which would be useful for an in-depth examination on ecosystem dynamics along a tidal mixing front. However, in this study, only temperature and chlorophyll *a* fluorescence measurements are considered for demonstration purposes, which were obtained on a 1 Hz sampling frequency. All acquired data were stored internally and a subset transmitted via Iridium each time the glider surfaced.

Ensuring data quality from autonomous vehicles is an important, but potentially difficult task. The issues can be reduced by using stable instruments (such as ship-borne CTD rosettes) with calibrations pre- and post-deployment. Therefore, we used two ship-based CTD casts, one taken directly after *Zephyr* retrieval (21st October 2013) and one taken at day 38 (19th October 2013) of the *U194* mission to correct the glider data (temperature and chlorophyll *a*) where necessary. Due to the problems of “in-mission” calibration (e.g. aligning the ship and glider position), we were unable to take CTD casts at the same time and location as *U194*. Therefore, we present the ship-based profile with the nearest spatio-temporal *U194* match (Δ time: 27 min; distance: 7.65 km). Additional water samples at surface and bottom were taken for chlorophyll *a* measurement verification. A subset of oceanographic data was stored on the National Oceanography Centre (NOC) sftp server and made available to the Met Office via the British Oceanographic Data Centre (BODC), for inclusion in their Forecasting Ocean Assimilation Models (FOAM).

3.2.2. Echosounder

In addition to the standard science payload, glider *U194* was equipped with an Imagenex ES853: a self-contained, single-beam 120 kHz echosounder (Fig. 2A). The ES853 was mounted in a science bay, aligned centrally along the short axis of the glider and at an angle of 64° from the long axis (towards the nose). This ensured that when the glider was in a downward glide (typical dive angle of -26°), the transducer pointed directly downwards, analogous with the downward-looking orientation of a ship's echosounder. The echosounder operates with a pulse length of 100 μ s, beam angle of 10° , range of 100 m, configurable gain of either 20 or 40 dB, and measures mean volume backscattering (S_v , dB re 1 m^{-1}) per range bin interval of 0.5 m. It requires power of 0.25 W, drawn from a 24 V DC supply, and can output values to a PC or record data to internal storage. The ES853 has a dynamic range of 120 dB and records signals as integer values, thus the resolution in signal strength is reduced compared with typical floating-point recording of larger, ship-based echosounders.

The glider-integrated ES853 was controlled via serial port and polled at a frequency of 0.25 Hz, with data stored on the glider's internal memory. Upon retrieval of the glider the data were downloaded and processed following Guihen et al. (2014), where raw echo-intensity data were converted to mean volume backscattering strength (S_v), using the active version of the SONAR equation (Urlick, 1983) and calibration and manufacturers' constants for echosounder receiving response and source level. Glider position data are used to locate individual pings in time, depth and aspect. These data were then processed using Myriax Echoview software (version 4.80), including subtraction of time-varied gain amplified background noise (after Watkins and Brierley, 1996), and accounting for variability in aspect of the transducer (after Dunford, 2005) and depth of the echosounder. Due to operational difficulties, the ES853 was not calibrated using standard sphere methods (Foote et al., 1987), so data shown here are relative. However, Guihen et al. (2014) showed that a calibrated ES853, mounted on a glider, provided quantitative estimates of zooplankton distribution comparable to a ship-borne echosounder, providing a suitable sampling strategy is employed. As a result we are confident that the ES853 data provide a relative index of zooplankton distribution.

3.2.3. Passive acoustic monitoring

Glider *Zephyr* was equipped with a Passive Acoustic Monitoring (PAM) system based on a modified d-tag sensor (Johnson and Tyack, 2003). The d-tag was mounted in the glider's aft wet space close to the buoyancy bladder, with the hydrophone on top of the glider just in front of the rudder (Fig. 2B).

Power was taken from the glider's main batteries. The sensor was configured to sample at 480 kHz, and an automatic detector was implemented to detect the narrow-band high-frequency clicks of harbour porpoise *Phocoena phocoena* (Villadsgaard et al., 2007). A 2 ms waveform clip of detected clicks was stored to flash memory. Recordings were also made of acoustic data decimated to a sample rate of 96 kHz for offline detection of other cetacean species and the measurement of noise. Although recordings were made using a lossless compression format which typically gives a compression ratio of 4:1 (Johnson et al., 2013), continuous recording would have filled available storage in approximately two weeks. The recorder was therefore programmed to operate for 10 out of every 40 s and only at water depths >40 m.

Recovered data were processed offline with PAMGuard software (Gillespie et al., 2008) to detect cetacean clicks and whistles and to measure noise in third octave bands between 22 Hz and 45 kHz. An operator (KG) viewed all detections manually, viewing click waveforms and whistle time frequency contours, and listening to sections of data to confirm detections and classify groups of transient sounds as either 'cetacean clicks' or as 'pump noise'.

3.2.4. Passive sampling devices for trace organic contaminant monitoring

Passive sampling devices made of a thin layer of polymer were deployed on *Zephyr* (Fig. 2B). These polymer sheets are made of AlteSil[®] silicone rubber (24 cm × 28 cm × 0.5 mm thick), and were Soxhlet extracted with ethyl acetate before further soaking in methanol. Performance reference compounds (PRC; perdeuterated polycyclic aromatic hydrocarbons and fluorinated polychlorinated biphenyls) were then uniformly spiked into the batch of samplers according to a method similar to that described by Booij et al. (2002). Samplers were kept in closed containers at –20 °C until deployment. Control samplers were used to assess possible contamination during transport, deployment and retrieval operations, and to measure initial PRC concentrations. Two sampling sheets were placed on top of the glider and fastened using cable ties (Fig. 2B). A thin sheet of aluminium foil (muffle furnace prior to exposure) was placed between the samplers and the glider body to minimize possible contamination of the samplers by direct diffusion from the glider hull itself.

After retrieval, the surface of the samplers was thoroughly cleaned in the laboratory to remove any bio-fouling before static batch extraction with pentane (three times 300 mL over 72 h). Extracts were combined and reduced in volume. The solvent was changed to dichloromethane before clean-up by gel permeation chromatography. The extracts were then reduced in volume and analysed by gas chromatography–mass spectrometry for polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs) and other chlorinated organic compounds. Field and laboratory procedures have been described elsewhere in more detail (e.g. Allan et al., 2010, 2013).

3.3. Glider mission

Both gliders were deployed southwest of the Isles of Scilly from the RVCEFAS *Endeavour* on 12 September 2013, in order to conduct repeated transects over the targeted tidal-mixing front (Fig. 1, 'transect 1'). The approximate location of the front was monitored prior to the survey via satellite-derived front maps (Miller, 2009). A ship-based pre-deployment transect was performed in order to ensure the area was free of static fishing gear (which is common in this area and represents a potential hazard to any glider) and to take repeated CTD and water samples to affirm the transect was located over the target front. A ship-based transect was performed on 21 October 2013 along the glider survey line (Fig. 1, 'transect 2'), in order to (1) compare the ES853 echosounder data with those collected using the calibrated multi-frequency (38, 120 and 200 kHz) split-beam Simrad EK60 on the RV CEFAS *Endeavour*, and (2) to collect CTD and water samples for *U194* calibration purposes. Due to glider control problems encountered during the mission, the initial glider transect (Fig. 1, 'transect 1') was shifted to the north of the Isles of Scilly on 24 September 2013 (Fig. 1, 'transect 2'). *Zephyr* was recovered from the RV CEFAS *Endeavour* on 21 October 2013 and on this occasion, a CTD cast was conducted for glider-sensor calibration. Due to quickly deteriorating weather, retrieval of *U194* had to be abandoned and the glider was picked up via fast-boat three weeks later on 13 November 2013.

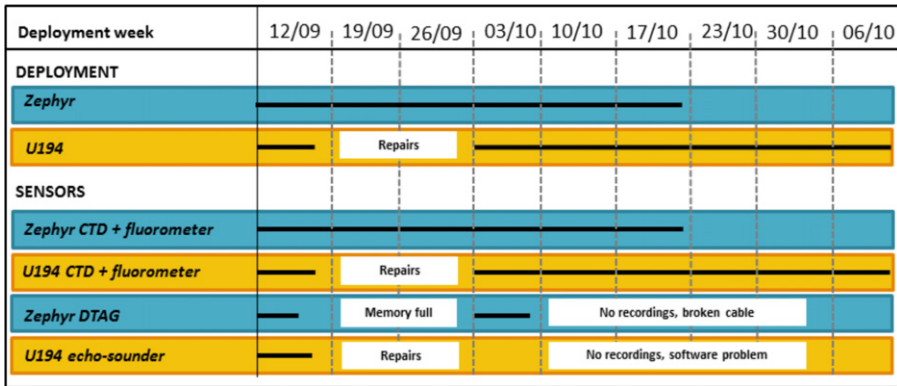


Fig. 3. Timeline glider deployments (blue shading: *Zephyr*; yellow: *U194*) and sensor activity, represented by black lines. Dates indicate the beginning of each week of the deployment, white boxes provide information on sensor malfunctions. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4. Results

4.1. Mission summary

Strong tidal flows and northwards density currents deflected both gliders to the northwest of the Isles of Scilly soon after deployment on 12 September 2013 (Hill et al., 2008). Unable to counteract these currents, *U194* was pushed into very shallow waters West of the islands on 17 September 2013, where manoeuvring was impossible and the glider needed to be recovered. Emergency recovery and subsequent repairs were carried out between 20 September and 04 October 2013 (Table 1).

U194 was redeployed on 04 October 2013 via fast-boat northwest of the Isles of Scilly. This also provided an opportunity to update faulty software on the *Zephyr* d-tag; both gliders then resumed their mission. The planned glider transect was repositioned to the north of the western TSZ (Fig. 1), where tidal flows and currents were weaker and where *Zephyr* had been located for most of the previous three weeks. Using a more dynamic piloting approach (e.g. regularly adjusting waypoints according to tidal flows, changing current correction setting), control of the flight path of *U194* was much improved. In contrast, piloting of *Zephyr* became increasingly challenging following redeployment, possibly due to the hydrocarbon sensor sheets loosening and adding extra drag to the vehicle (making it more susceptible to current drift). Nevertheless, both gliders executed the mission without any further problems until retrieval. A summary of key events and a timeline of sensor activity is given in Table 1 and Fig. 3, respectively.

Over the six-week deployment, the two gliders performed a total of 5474 dives (each dive comprising one up and downcast, based on dives of ≥ 10 m) to a maximum depth of 101 m (*Zephyr*) and 104 m (*U194*) (Table 2). The total horizontal distance covered was 2389 km, with an average distance of ~ 0.9 km between GPS fixes.

4.2. Physical environment

Fig. 4 shows the glider data is in good agreement with measurements obtained from ship-based CTD-casts. However, *U194* chlorophyll *a* displayed a significant offset (Fig. A.2) and data shown here are corrected based on the vessel-profile by applying an ordinary linear model and adjusting the *U194* chlorophyll *a* data by the slope and offset ($U194_{corrected} = U194_{raw} \times 1.33 + 0.084$). Although there is a slight offset between *Zephyr* and ship chlorophyll *a*, no correction was applied, because the water samples suggest that the glider fluorometer gives a better reflection of the true chlorophyll than the vessel data. No correction of temperature measurements was necessary.

Glider *Zephyr* predominantly sampled thermally stratified waters during its mission, although it crossed the targeted tidal-mixing front several times in the first 500 h (Fig. 5A, Fig. A.3). A strong

Table 2

Mission statistics. Statistics only considers dives of ≥ 10 m (to exclude non-mission dives) and GPS fixes of ≥ 100 m apart. *U194* statistics based on post-redeployment dives only.

Statistic	<i>Zephyr</i>	<i>U194</i>
Total deployment days	38	39
Total number of dives	2654	2821
Total horizontal distance (km)	1080	1309
Mean horizontal distance b/w GPS fixes (km)	0.9	0.85
Max distance b/w GPS fixes (km)	13.7	10.3
Mean dive depth (m)	44.55	40
Max dive depth (m)	101.49	103.89

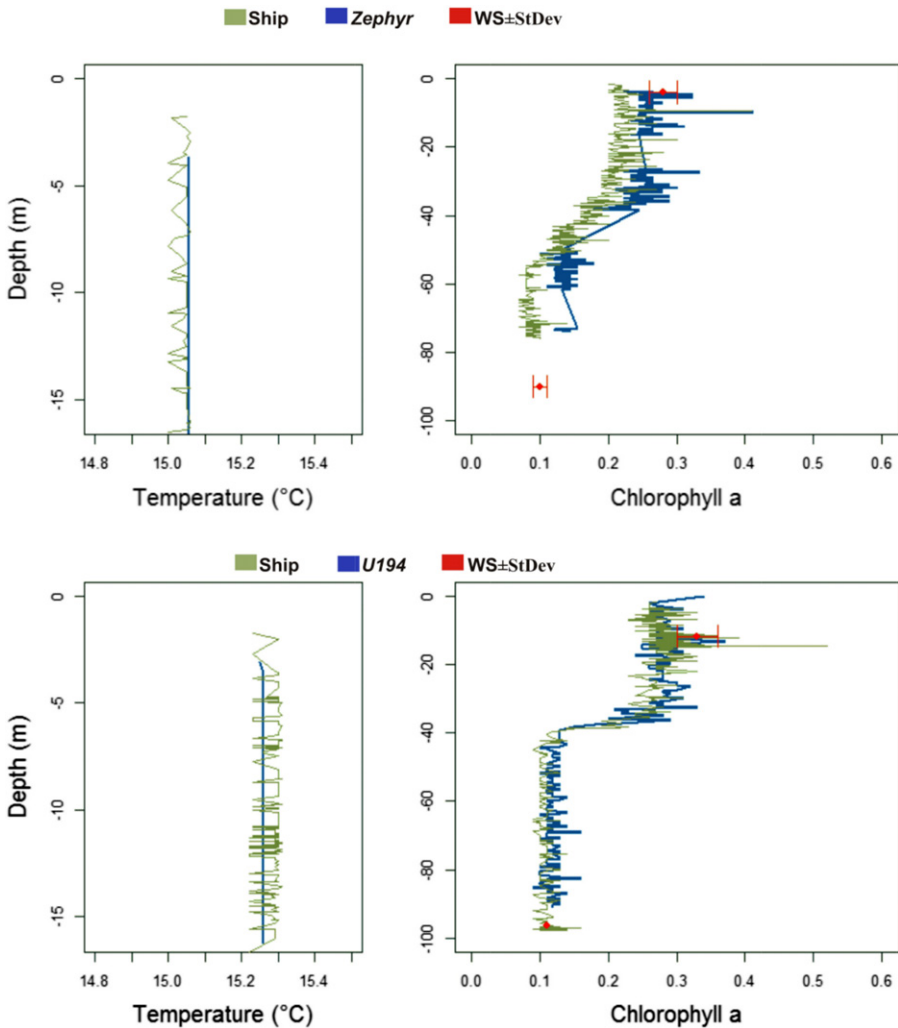


Fig. 4. Comparison between ship and glider derived temperature and chlorophyll for *Zephyr* (upper panel) and *U194* (lower panel). Green: Ship; blue: glider; red points show chlorophyll *a* from water samples \pm standard deviation ($N = 3$). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

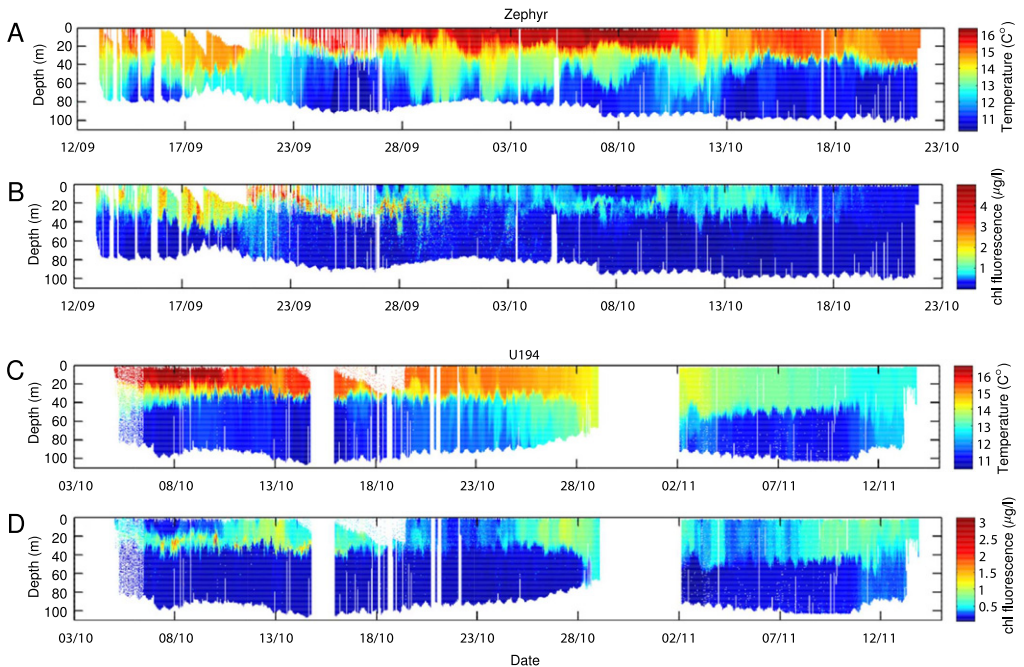


Fig. 5. Time series plots of temperature and chlorophyll concentration of both gliders against depth (panels A–B, *Zephyr*; panels C–D, *U194*). Time refers to hours since the mission start on 12 September 2013 at 1200 h. Note shifted time axis for *U194*, which only considers data since re-deployment from 04 October 2013.

thermocline at 20–40 m depth is particularly evident after ~500 h (Fig. 5A). Elevated levels of chlorophyll *a* fluorescence are visible in the water column towards the base of the thermocline, particularly around 300 h (Fig. 5B). Fluorescence increases notably where the thermocline crops towards the surface in the frontal region, e.g. during a frontal crossing at ~200 h (Fig. 5B). High levels of chlorophyll *a* fluorescence remain visible even after the equinox (21 September 2013; ~200 h), which is usually taken as the end of the primary production period elsewhere on the UK shelf (Weston et al., 2005).

Glider *U194* also predominantly sampled thermally stratified waters throughout its mission, but spent less time in frontal regions (Figs. 1 and 5C). Subsurface chlorophyll maxima at ~30 m depth, associated with the thermocline, are clearly visible in *U194* profiles until ~800 h into the mission (Fig. 5D). The deployment of *U194* was substantially longer than that of *Zephyr* (Fig. 3), and included a major storm event on 27 October 2013 (1080 h into the mission, Fig. 5C). Interestingly, the water mass remained stratified (although much weaker) after this storm event, although surface waters had cooled significantly and the thermocline depth increased to ~50 m (Fig. 5C).

An interesting feature visible on the *Zephyr* temperature profile is the lack of an obvious relationship between bottom temperature gradients and surface gradients, particularly around 400–600 h (Fig. 5A). Consistently high surface temperatures were experienced throughout this period (> 15 °C), whereas the bottom temperature alternated between ~11–13 °C. In general, the transition zone along the bottom appears wider than at the surface (Fig. 5A, Fig. A.3). In addition, clear bottom front crossings occurred on nine occasions, whereas the surface front was intersected six times only (Fig. 5A, Fig. A.3).

4.3. Echosounder

The ES853 120 kHz echosounder, integrated onto *U194* (Fig. 2A), successfully recorded acoustic data from the water column during the first five-day deployment (Figs. 3 and 6). Unfortunately,

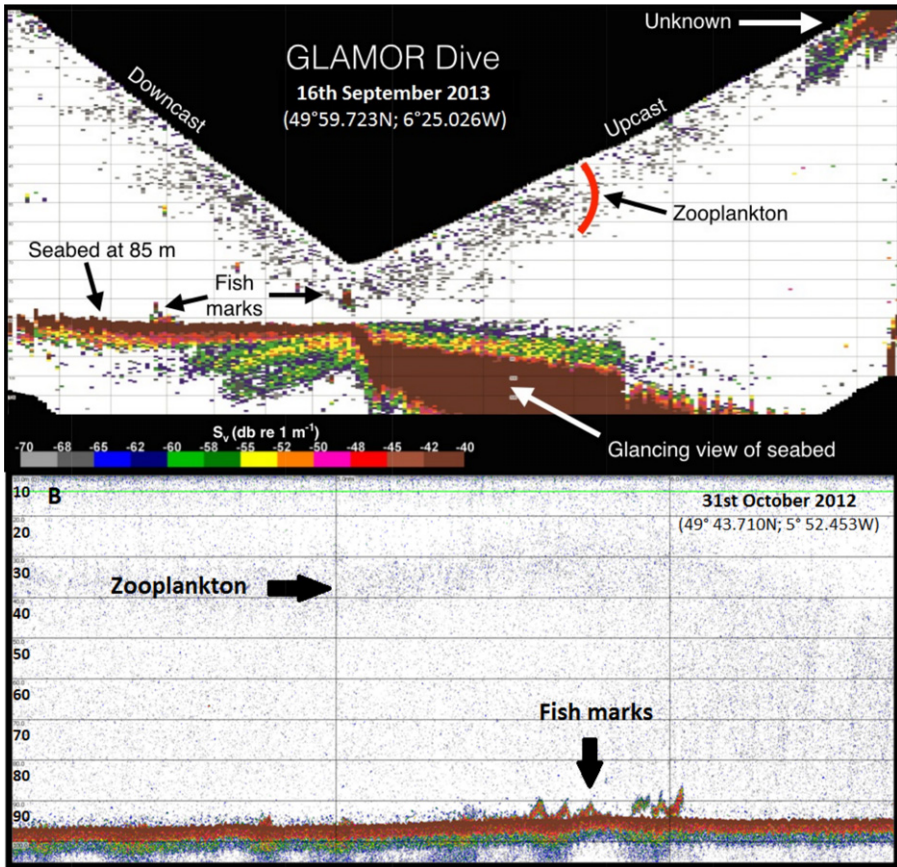


Fig. 6. Echograms of glider-integrated ES853 at 120 kHz (A) and equivalent vessel based EK60 120 kHz (B). Distance between the two sites 43.3 km. Features such as the seabed, fish shoals and zooplankton scattering have been indicated. Gain thresholds for both echograms were set to -70 dB.

after redeployment a technical error prevented communication between the echosounder and the glider and, as a consequence, acoustic data for the rest of the mission were not stored on the internal memory of glider and echosounder. Focusing on the downcast, when the echosounder is vertically orientated and most comparable to a ship-based echosounder, typical features observed in echograms include the seabed and fish shoals (Fig. 6A). Similar acoustic features were observed in an echogram derived from the ship-based echosounder in the same area at the same time of year (Fig. 6B).

A band of scattered targets, consistently present within 20–25 m of the glider echosounder during both down- and up-casts (Fig. 6A), was interpreted to represent small organisms such as zooplankton. The vessel-based echogram at 120 kHz revealed similar scattered targets throughout the water column, with some evidence for elevated concentrations at ~ 30 –40 m depth associated with the thermocline (Fig. 6B). Due to the reduced signal-to-noise ratio of the glider echosounder, these small targets were only observed within a limited range of the transducer. In contrast, the stronger water column targets related to fish shoals were recorded throughout the water column on glider data (Fig. 6A). These targets appeared similar to those recorded from RV *CEFAS Endeavour* during its annual pelagic fish survey in the area (Fig. 6B), and were thought to consist of boarfish (*Capros aper*). Due to differing ping rates (4 vs 0.25 s^{-1}) and vehicle speeds (5 ms^{-1} vs. 0.3 ms^{-1}), the horizontal resolution of acoustic data obtained from the glider was nearly twice as high compared to the vessel (1.2 m vs.

2.5 m per ping), which suggests that the fish shoals imaged on the glider echogram are possibly small examples of these boarfish shoals.

A noticeable feature on glider acoustic profiles is the presence of high backscatter patches in the uppermost water column, observed down to ~ 20 m water depth during upcasts (Fig. 6A). Adverse weather conditions, with large waves or swell, are known to introduce bubbles into surface waters; however, weather conditions were favourable during the period that these features were observed so this cause is doubtful. Technical issues, such as side-lobe detection of the sea surface, are also thought to be unlikely as these patches were not always present, absent during previous trial deployments, and no changes had been applied to the echosounder settings. Vessel-derived echograms did not show the same features, although the transducer depth of the vessel-based echosounders was 8.2 m below the surface and so did not cover the surface layer. It is therefore possible that these high backscatter patches have a biological origin, representing organisms restricted to surface layers. However, their unusually high backscatter, widespread occurrence, and consistent appearance throughout the deployment, also make this an unlikely source. Therefore, further investigation is required to determine the true origin.

4.4. Passive acoustic monitoring

The power cable to the d-tag acoustic sensor was damaged during or soon after installation, so PAM data were only collected between 04 and 10 October (Fig. 3). These data included 2413 10s recordings over 291 separate dive cycles, with an average of eight recordings per dive. Harbour porpoise clicks were detected during two separate dives, although one of these consisted of only a single click. Dolphin clicks and whistles were detected during 194 dives: 145 of these were clicks only, 49 whistles only, and 42 both (for map of locations of recordings see Fig. A.4). Fig. 7 shows the waveforms and power spectra of a typical dolphin and porpoise click. No other obvious noise sources, such as the pitch battery motor were apparent in the data.

Noise attributable to the glider pump was recorded on 169 occasions. The times of these noises corresponded to the times when the pump was 'on' in the glider log files, typically occurring for only a few seconds at the bottom of each dive. Fig. 8 shows the distribution of noise in third octave bands with the pump on and the pump off. Median noise levels with the pump off are generally low indicating that the system can be used to make accurate measurements of ambient noise. Noise levels at all frequencies are considerably higher when the pump is in operation. However since the duration of these noisy periods is relatively short, it will have little effect on overall survey effort.

4.5. Passive sampling devices

Recovered silicone rubber sample sheets were visually inspected for bio-fouling before analysis (as this can affect the uptake of contaminants into passive samplers); bio-fouling levels were found to be very low compared to static exposures. Significant dissipation of performance reference compounds (PRC) was observed from sample sheets. PRC dissipation was used to estimate sampling rates using a published procedure (Booij and Smedes, 2010). These rates were in the range of 3–7 L d⁻¹ depending on the chemical. Sampling rates were normalized to a standard surface area (Huckins et al., 1993) and compared with those observed during static or other mobile deployments of passive samplers e.g. Booij et al., 2007; Allan and Harman, 2011; Lohmann et al., 2012); Table 3). Sampling rates for the glider-mounted passive samplers used here are in a similar range to those commonly observed for static deployments, whereas mobile exposures with high velocities tend to achieve high sampling rates (Table 3). The PRC data from this passive sampler exposure (i.e. 50% dissipation for d₁₀-phenanthrene) indicate that sampling was time-integrative for substances with octanol–water partition coefficient (log K_{ow}) above 4.5. Since gliders are launched for periods of weeks to months, these exposures can still detect polycyclic aromatic hydrocarbons (PAH) and polychlorinated biphenyls (PCB) in the low pg L⁻¹ range, i.e. levels at which these compounds typically occur in oceanic waters.

Freely dissolved concentrations of PAHs ranged from just over 1 ng L⁻¹ for phenanthrene down to below 10 pg L⁻¹ for higher molecular weight PAHs. Polychlorinated biphenyls (PCBs) were found

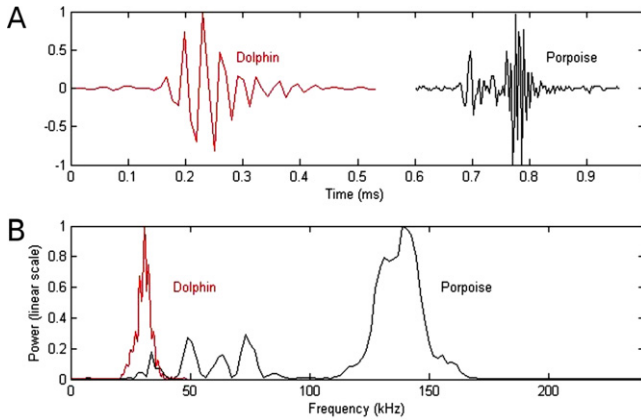


Fig. 7. (A) waveforms and (B) power spectra of detected dolphin and porpoise clicks using the d-tag hydrophone on *Zephyr*.

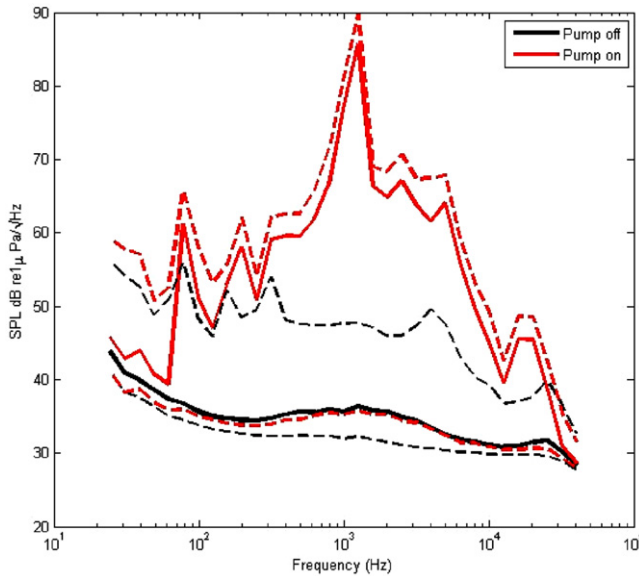


Fig. 8. Spectrum-level noise measurements at third octave intervals for times when the *Zephyr* pump was on and when the pump was off. The three lines for each situation represent the median values and the lower and upper 90% intervals.

at levels below 10 pg L^{-1} (except for PCB congener 28 with a concentration of 32 pg L^{-1}). The freely dissolved concentration of hexachlorobenzene was 45 pg L^{-1} . These concentrations were not corrected for temperature or salinity, but are generally in the range of those measured in open waters of the North Atlantic.

5. Discussion

In this ‘proof-of-concept’ study, two submarine gliders were equipped with sensors capable of simultaneously measuring physical properties of the water column and multiple trophic levels, in order to test their potential for ecosystem monitoring. The results highlight the advantages and current limitations of utilizing gliders as autonomous platforms for the outlined purpose. The key

Table 3

Passive sampling rates, typical exposure times, and limits of detection for various passive sampler deployment modes.

Deployment mode	Sampling R_s ($L d^{-1}$) ^a	Exposure time	Limits of detection ($pg L^{-1}$) ^b	Refs.
Static	1–20	0.5–3 months	0.3–30	(Vrana and Schuurmann, 2002; Allan et al., 2010; Prokes et al., 2012; Allan et al., 2013)
Mobile ^c	18–27	4–6 days	3.0–7.0	(Booij et al., 2007)
Mobile ^d	70–200	5 h and 48 h	1.0–30	(Allan and Harman, 2011; Allan et al., 2011; Lohmann et al., 2012)
Calibration ^e	60–200	15 days	0.2–0.6	(Booij et al., 2003)
Glider ^f	3–7 ^g	39 days	2.0–4.0	Present study

^a For a standard semipermeable membrane device sampling surface area of 460 cm².

^b Limits of detection in water for PAHs/PCBs in the linear phase of uptake ($C_{w,lim} = m_{lim}/[R_s t]$) with a arbitrarily set m_{lim} of 0.5 ng per sample.

^c Ship-based measurement using the ship's continuous water supply (water velocity in the pipe of 15 cm s⁻¹).

^d Samplers towed behind a benthic trawl net (1.2–1.4 knot); towed behind a research vessel.

^e During sampler calibration with water velocity of 90 cm s⁻¹ and water temperature of 30 °C.

^f Average glider velocity through water of 20–40 cm s⁻¹ (horizontal velocity).

^g Sampling rates corrected to a surface area of 460 cm².

outcomes relate to operational aspects, current sensor technology, instrument calibration and data validation.

5.1. Glider operations

The two gliders successfully completed their missions, which lasted for just under 40 days and which each comprised >2500 dives to depths of up to 100 m over total horizontal travel distances of 1000–1300 km. The gliders continued to collect data in weather conditions that stopped research vessel activity in the region, including a particularly severe storm on 27 October 2013 (Fig. 5C).

The two major operational challenges were flight control and alignment of the two glider trajectories in space and time. Although previous deployments have demonstrated that gliders are capable of following a proposed transect in areas of strong tidal flow (e.g. Leonard et al., 2007), this proved extremely challenging in the present study (Fig. 1). This is likely due to the combination of strong tidal and non-tidal residuals acting on the vehicles together. In order to fully understand the effect of hydrodynamics on our gliders, a detailed analysis is required including currents, tides and meteorological forcing in relation to the glider tracks and flight settings, which is beyond the scope of this paper.

The flight of *U194* was significantly improved by applying a more dynamic piloting approach, including e.g. increased monitoring, modifying dive angle and current correction settings, and adjusting waypoints depending on currents and tidal state. Hybrid *Slocums* equipped with a thruster are also now commercially available (Jones, 2012), which should further aid future deployments in tidally dominated environments. Furthermore, ongoing modelling and simulation research, dealing with optimal path planning and influences on glider trajectories, can be used to aid the survey design (e.g. Fernandez-Perdomo and Hernandez-Sosa et al., 2011; Ting and Mujeebu et al., 2012).

Aligning the flight of multiple gliders is a key requirement in whole-ecosystem monitoring, as the sensors required to simultaneously measure multiple ecosystem components cannot currently be integrated onto a single vehicle due to limited payload capacity and energy constraints. In addition, certain instruments need to go onto different platforms due to acoustic interference problems (e.g. active echosounder and passive hydrophone). In order to obtain meaningful data on multiple parameters simultaneously, the vehicles should be aligned in time and space; ideally the maximum distance between the vehicles should not exceed the scale on which the variables change. This is a challenging task, because gliders equipped with different sensors will display specific flight behaviours, e.g. due to different ballasting and external sensor configurations. For example, the hydrocarbon sheets used on *Zephyr* in this study are likely to have added extra drag to the vehicle resulting in different flight behaviour compared to *U194* (cf. Fig. 1). If time and budget allow, extended

trials focusing on simultaneous flight prior to a mission could improve piloting for individual gliders and, therefore, trajectory alignment.

5.2. Sensors

Throughout the mission, CTD and fluorometer sensors on both gliders provided water-column data at a spatio-temporal resolution and frequency not attainable through ship-based surveys or satellite imagery. For example, *Zephyr* crossed the Isles of Scilly tidal-mixing front several times (Fig. 5A), with collected data highlighting the spatial offset of the surface and bottom fronts (Fig. 5) as well as chlorophyll maxima associated with the thermocline (Fig. 5B); these features would not be detected using remote sensing data. Glider *U194* dominantly sampled stratified waters, and monitored change in the water column from seasonally stratified to mixed over a period of six weeks (Fig. 5C); within this period the glider continued collecting data during the severe storm event on 27 October 2013. Despite the high resolution and amount of information collected, file sizes were small enough for a subset of data to be transmitted via Iridium during the mission.

The newly integrated ES853 echosounder and d-tag passive acoustic monitoring system provided promising data on the spatial distribution of higher trophic-level organisms. The hydrophone recorded numerous cetacean clicks and whistles from different species during the six days of operation (Figs. 7 and A.4). The echosounder was capable of detecting targets, including fish and zooplankton, similar to targets detected by vessel-based data echosounders (Fig. 6).

The novel hydrocarbon sheets trialed here can easily be attached to gliders and AUVs, and collect supplementary information on water quality. This has particular application for regulatory monitoring, e.g. in response to European legislation such as the Water Framework Directive and the Marine Strategy Framework Directive. The sampling scheme can be extended from hydrophobic compounds (as used in this study) to samplers specifically designed to sample hydrophilic substances and metals.

Limitations of glider-integrated instrumentation include the need for data calibration and validation, particularly over long-term surveys. CTD and fluorometer calibration procedures are generally undertaken during glider deployment and retrieval using calibrated ship-based CTDs and by taking water samples. However, depending on survey area and season, a considerable amount of bio-fouling can affect the glider-integrated instruments; this causes sensor drift in a non-linear fashion, which is difficult to account for with calibration procedures at the beginning and end of a mission. In addition, collection of water samples remains essential for phytoplankton biomass estimations or species identification.

Although the echosounder and PAM system are capable of collecting data on the distribution of higher trophic level organisms over large spatio-temporal scales, they are significantly harder to calibrate compared with the physical sensors. Single-beam single-frequency echosounders provide a limited capability for target identification, which are normally undertaken using multi-frequency discrimination methods (e.g. Korneliusson and Ona, 2003). However, these instruments are currently too large and powerful to be integrated into underwater gliders. To establish fish species with absolute certainty, verification via net sampling also remains essential. Size-length relationships needed for target strength model parameterization for conversion to biomass and information on age-class distribution are additional parameters that can only be acquired with dedicated net sampling from vessel-based surveys. There has been some success at classifying cetacean whistles collected by PAM systems to species level (Gillespie et al., 2013), although considerable problems remain in estimating absolute animal abundance from glider-based data. Critical data for the estimation of abundance are the range at which animals are detected and either the rate of vocalization or the ability to isolate and count individuals (Marques et al., 2013). Gliders are too slow moving to use target motion analysis to localize animals in the water columns, as is commonly done for sperm whales (e.g. Lewis et al., 2007) and vocalization rate is poorly known for most species. Finally, echosounder and PAM system development should focus on methods for summarizing the complex data to enable transmission of a subset of collected data, rather than after retrieval. This would enable the glider to target, on the fly, hotspots of animals.

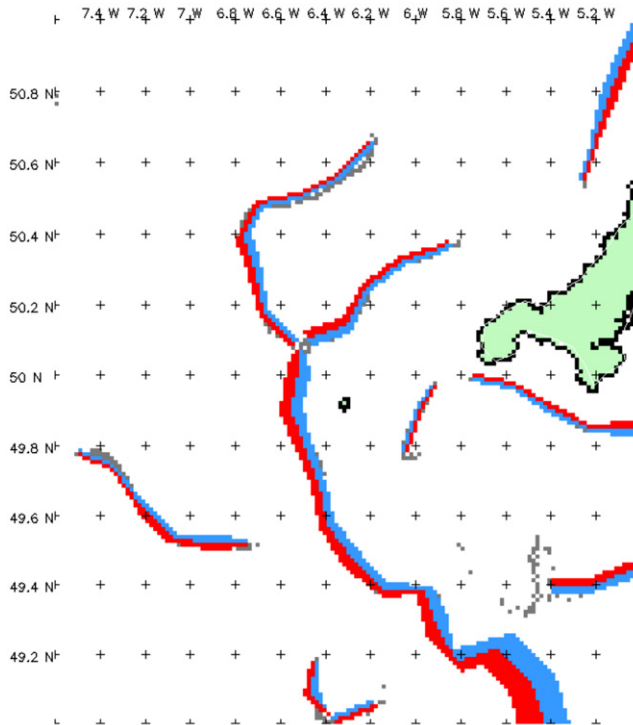


Fig. A.1. Composite satellite-derived front map of the survey area off southwest UK, based on data from 12 September–17 October 2013. Red indicates warm-water (stratified) side of tidal-mixing fronts, blue the cold-water (mixed) side. Line thickness equates to the strength of the front (the thicker the line, the stronger the front). Note the strong tidal-mixing front west of the Isles of Scilly, separating stratified waters to the west from tidally mixed waters to the east (*cf.* Fig. 1). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

6. Conclusions and recommendations

This proof-of-concept study has highlighted some of the advantages and current limitations of utilizing submarine gliders for the purpose of ecosystem monitoring. Advantages include cost efficiency, capability of working in adverse weather, and collection of 3D water-column data at high spatio-temporal resolution over periods of weeks to months. This is not achievable with other single platforms, but is essential in order to detect change and its effect on an ecosystem, e.g. breakdown of seasonal stratification, impact of short-duration storm events. All of the novel glider-integrated sensors used in this study delivered useable data, although they could only provide information on distribution of biological indicators rather than accurate estimates of abundance or biomass. More broadly, glider sensor calibration and data validation remain challenging and dependent upon supporting infrastructure (ships, moorings), so acquired data are often only suitable for qualitative analysis. In addition, for the purpose of multi-vehicle surveys, aligning glider trajectories and flight control are significant issues that require further improvement (especially in dynamic tidally-dominated environments). Nevertheless, the promising results achieved in this study have led to a further deployment targeting oceanic fronts off southwest UK (planned for autumn 2014) using unmanned surface vehicles (USVs) as an in addition to submarine gliders.

For effective whole-ecosystem monitoring in the future, a range of autonomous platforms will need to be deployed within a marine monitoring network, including USVs, AUVs and gliders. Successful implementation of an autonomous monitoring network has already been demonstrated in the

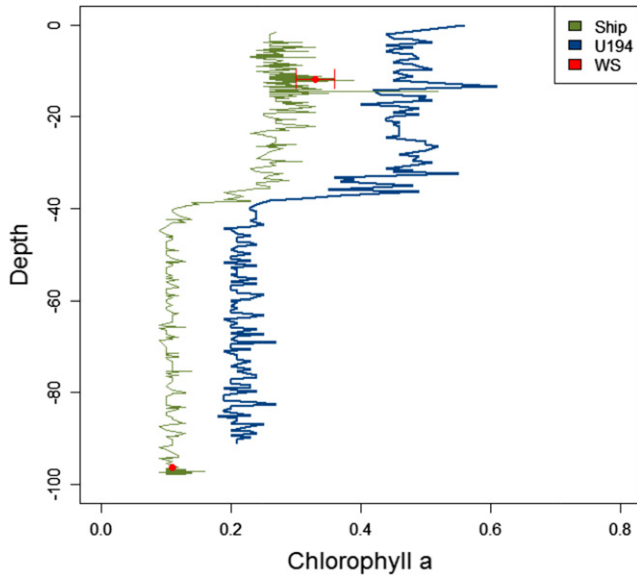


Fig. A.2. Calibration profiles between ship (green) and U194 (blue), showing uncorrected chlorophyll *a* data. Red points show values from water samples \pm standard deviation ($N = 3$). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

California Current Ecosystem, where satellite imagery, vessel surveys, gliders, floats and moorings are used in combination to provide compatible data on ecosystem dynamics at various spatio-temporal scales (Ohman et al., 2013). Satellite remote sensing provides information on large-scale surface processes, which is supplemented by submarine gliders measuring water column properties. Moorings and targeted vessel surveys utilize more powerful sensors working at high frequency, and are used to calibrate satellite and glider data; vessels are also used to run structured experimental surveys, which require ship-based equipment. Together, the sampling network efficiently provides a synoptic view of an ecosystem at multiple scales, which can significantly advance our understanding of marine ecosystem functioning and drivers of change.

Acknowledgements

This project would not have been possible without the hard work and professionalism of the Marine Autonomous and Robotic Systems (MARS) staff at NOC, particularly David White, James Burris and Sam Ward. We also thank to the ship staff of the RV *CEFAS Endeavour* and the Scilly Inshore Fisheries and Conservation Authority for their support in glider deployment, recovery and calibration activities.

The Gliders and AUVs for Marine Observation and Research (GLAMOR) project was primarily funded by UK Department for the Environment, Food and Rural Affairs (Defra), through their Strategic Evidence and Partnerships Fund. Damien Guihen was funded by Natural Environment Research Council (NERC) grant NE/H014756/1. Additional financial support came through Defra project MF1112 (POSEIDON), Ian Allan (NIVA) and Branislav Vrana (RECETOX) acknowledge funding from the European Union Seventh Framework Programme (FP7/2007–2013) under grant agreement no. 262584, JERICO (TNA project GLISS). Passive sampler analyses were also carried out through the JERICO project (Work Package 10). We thank James Bowcott (PML) for providing the satellite front bulletins throughout the cruise.

The authors thank the two anonymous reviewers and guest editor Gwyn Griffiths for their detailed and helpful comments, which substantially improved the manuscript.

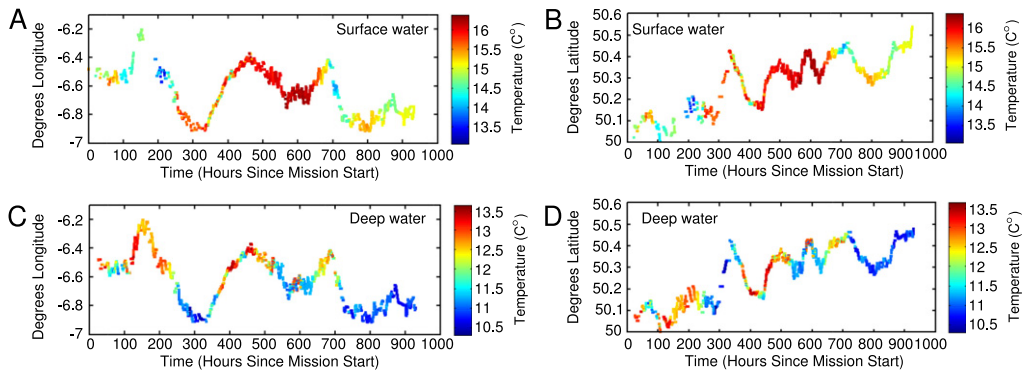


Fig. A.3. Temperature of surface waters (A and B, between 5–10 m depth) and deeper waters (C and D, between 60–70 m depth) as a function of time and longitude (A and C) and latitude (B and D).

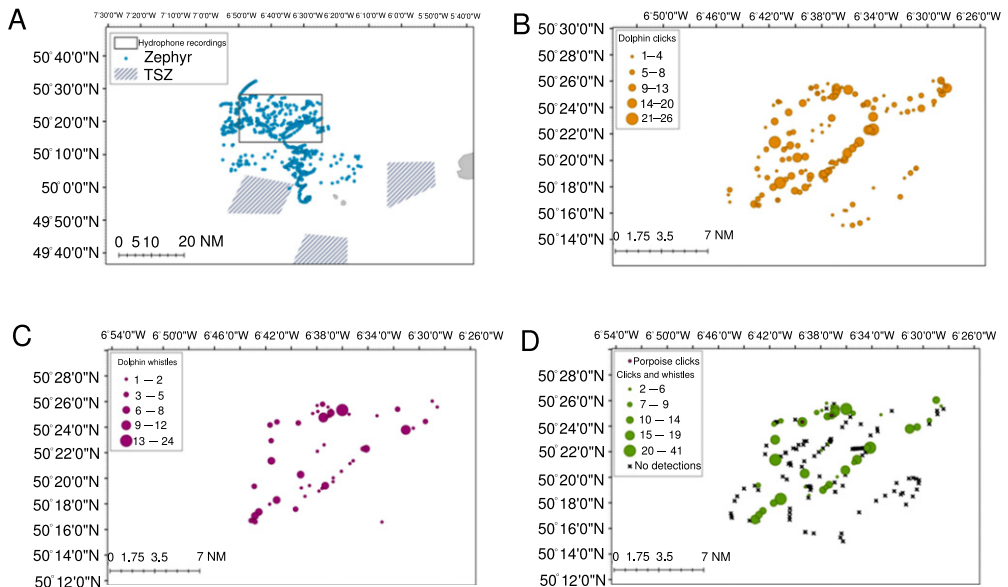


Fig. A.4. Maps showing the area where the d-tag hydrophone on *Zephyr* was active (A) and recorded dolphin clicks (B), whistles (C), and dives with both and porpoise clicks (D). Black crosses refer to locations of dives without recordings.

Appendix

See Figs. A.1–A.4.

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