AUV observations of surface mixing and bubble entrainment in the Clyde estuary, Scotland.

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Abstract* — Most of the mixing throughout the world ocean is driven by wind forcing of the ocean surface, which also exerts a controlling influence of the rate of exchange of gases between the atmosphere and the ocean. As part of the UK NERC-funded surface boundary layer consortium "OSMOSIS" we conducted AUV-based observations of near-surface turbulent mixing and bubble entrainment in the Clyde estuary, Scotland, in conjunction with a program of ship-, mooring, and glider-based measurements. A Hydroid REMUS 600m AUV equipped with a forward-mounted microstructure sensing package designed by Rockland Scientific was instrumented for this experiment with an upward-looking 1.1 MHz echo sounder, in order to measure bubbles that are injected into the near surface by breaking waves and often organized into quasi-linear vertical curtains by Langmuir circulation cells. The AUV-based observations reported here were conducted over a seven day period in September, 2011, in a two-day window leading up to, and subsequent three-day window recovering from, a period of force 12 winds. As the wind speed reduced a thin layer of fresher water, previously pinned to the coast by the gale-force winds, rapidly slumped over the survey area. Measurements revealed that wind-generated turbulence was largely confined to this brackish surface layer, a layer too thin to be sampled by conventional means. In this paper we describe the vehicle configuration during this pilot study, the resulting data, and further vehicle modifications that will enable both more robust measurements and more flexible use of the AUV as a test-bed sampling platform.

I. INTRODUCTION

The Clyde Sea is the largest fjord on the west coast of Scotland (Figure 1). Water depths within the region reach 180 m, and the connection to the North Channel of the Irish Sea is over a sill of depth 40 m. The Clyde Sea remains stratified for most of the year, due to freshwater inflow throughout the year and buoyancy input at the surface from heating in the summer [1]. As a result, the seasonal cycle of stratification follows a well-defined pattern with higher levels in the summer than in the winter[2]. There are only very occasional periods when the system mixes completely, and these occur in the late autumn driven by storms[3]. Stratification within the Clyde Sea basin has previously been assumed to be uniform in the horizontal[1,2], with a well-defined front in temperature and salinity at the entrance sill that separates the stratified Clyde Sea water from the permanently well-mixed North Channel water at the seaward boundary of the fjord[4]. The experiment reported here was conducted from the *RV Prince Madog* in September 2011 in the upper part of the fjord to the north of Isle of Arran and west of the Isle Bute in a water depth of 100m. The objective of the experiment was to quantify the effects of wind driven mixing on the upper layers of the sea. In particular the experiment aimed to focus on the role played by Langmuir cells in sustaining turbulence in the surface mixed layer.

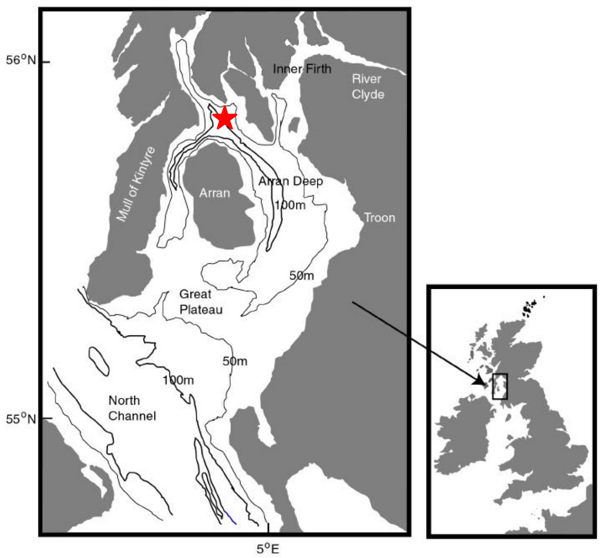

Fig 1: Clyde Sea location map with the study area indicated by a red star.

II. METHODS

Horizontal variability in the water properties was measured with a Remus 600 AUV, which we typically operate with a nose-mounted conductivity-temperature (C-T) sensor, upward and downward looking 600kHz Acoustic Doppler Current Profilers (ADCPs) and a Rockland Scientific International (RSI) shear microstructure package[5]. We additionally equipped the AUV for this experiment with an upward-looking Marine Electronics (ME) 1.1 MHz Multi-return Altimeter (model 11001). Shear microstructure measurements quantify the level of small scale turbulent velocity fluctuations (characterized by ε, the rate of dissipation of turbulent kinetic energy, TKE). Acoustic backscatter at 1.1 MHz is dominated by micro-air bubbles that are injected into the near surface by breaking waves and, under certain conditions, organized into quasi-linear vertical curtains by Langmuir circulation cells[6]. The AUV sampling objective was to characterize the spacing and depth penetration of the Langmuir cells through simultaneous measurement of the along-track vertical/horizontal field of bubbles and the distribution of ε.

Independent measurements of TKE dissipation rate were collected by a more conventional ship-based vertical profiler (RSI VMP system), which was operated on repeated transects through the sampling region. Vertical profilers yield transects of ε which are more highly resolved in the vertical, but less highly resolved in the horizontal, and they typically yield profiles that are contaminated in the upper 0-15m while the platform achieves a stable drop speed and orientation. These results will not be discussed here. Time series of water properties were obtained from moorings that included a surface meteorological package (Figure 2), subsurface ADCPs (Acoustic Doppler Current Profilers), and temperature and salinity loggers located at various depths.

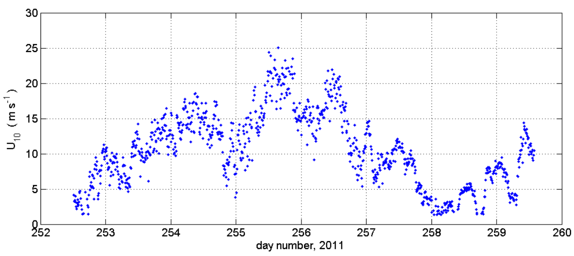

Fig 2: Wind record from the moored Met package, adjusted to 10 m height.

The moorings were deployed for the period of 9th-16th September (year-day numbers 252 to 259), during which time the remnants of hurricane Katia (http://www.nasa.gov/ mission_pages/hurricanes/archives/2011/h2011_Katia.html) swept the Scottish West coast, with sustained 10 m winds of 23 m/s for several hours on 12th September (day number 255, Figure 2). These winds dramatically affected the thermal and salinity structure of the upper water column, with rapid homogenization of the upper 60 m during the strong winds and rapid restratification (thermal and haline) immediately thereafter (Figure 3). AUV missions were run on 10th – 11th, and 14th – 16th September, but were suspended for the period of highest winds on 12th – 13th September. Acoustic bubble data were successfully returned only for the missions of 14th and 15th September.

III. Results

The discussion here will focus on AUV observations from September 14th, during the recovery of the system from the period of strongest winds. On that day the AUV mission consisted of 18 roughly across-shore legs of 1 km in length alternating at depths of 5 m, 10 m and 15 m (Figure 4). A well-defined fresh layer was seen, which appeared at the site in the early hours of September 14th (year-day 257, Figure 3). The base of the fresh layer was generally at about 4 m, but with occasional vertical excursions extending down to ~6 m. Between 3 m and 5 m the buoyancy frequency was very high, typically greater than 30 cycles per hour. The thin fresh layer

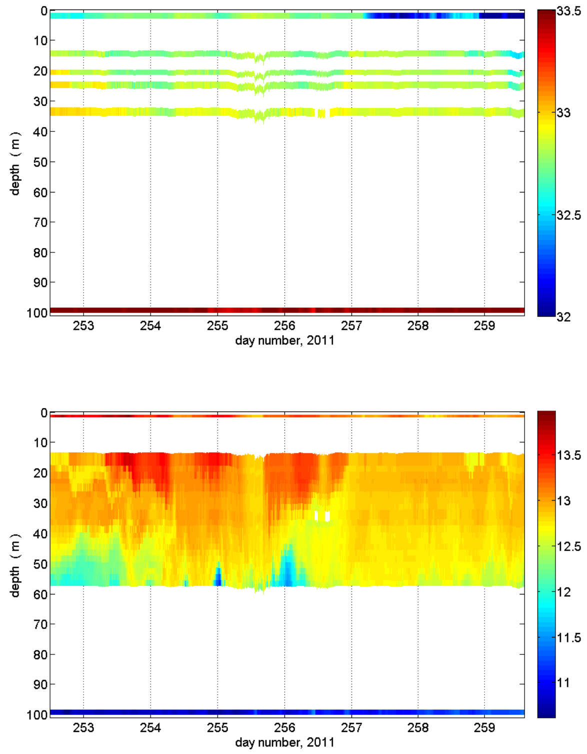

Fig 3: Salinity (top) and temperature (bottom) time series from a mooring in 100 m of water.

was highly sheared (~0.1 s^{-1}), with an average velocity of 0.25 m/s southward, as measured by the AUV ADCPs (not shown). During the strong wind forcing of 11th – 13th September (year-days 254 – 256, Figure 2) the surface fresh water supply from the Clyde Sea estuary was held back by strong southerly winds. As the wind dropped the accumulated fresh pool was free to relax and flowed southward as a shallow surface layer which was highly stratified and highly sheared across the lower interface. Moored surface salinity measurements suggest the thin layer arrived at the study area at approximately 04:00UTC on 14th September, about 20 hours after the sustained strong winds of the previous day, and just a few hours after a shorter wind burst of 15m/s (Figure 2).

The shallowest AUV legs (5 m depth) were, on average, beneath the base of the thin fresh layer, however occasional downward vertical excursions in the base of the layer brought the surface layer down to the depth of the AUV. During these events the AUV encountered the highly turbulent water within the thin layer, and the measured TKE dissipation rate increased by a factor of ~100 (from 10^{-9} to 10^{-7} Wkg^{-1}, see Figure 5). Five meters deeper, at 10 m beneath the surface, the environment was remarkably quiescent throughout the mission, with TKE dissipation rate rarely rising above 10^{-9} Wkg^{-1}, indicating that the TKE was not sufficient to overcome the near-surface stratification and thus confined the shear-generated turbulence to within the 4–5m thick surface layer.

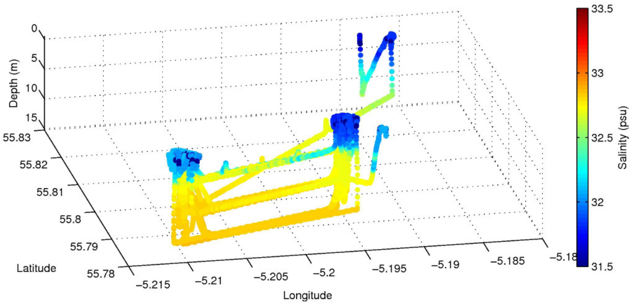

Fig 4: Salinity at the location (latitude, longitude, depth) of the AUV during the mission on 14th September. The longitudinal transects are oriented nearly across isobaths (i.e., in nearly the across-shore direction)

There was mixed success with the acoustic bubble detector. The detector clearly worked, with significant backscatter returns confined to the upper 4 m (Figure 6), and the dominant surface reflection visible. The periodic oscillation in the range to the surface corresponds to the AUV depth control feedback loop. However, no evidence of coherent spatial organization of the bubble clouds was found, and the wavenumber spectrum (not shown) of the depth integrated backscatter (Figure 6, middle panel) showed no dominant horizontal spacing of bubble clouds. We therefore did not achieve our objective to characterize the spacing and depth penetration of the Langmuir cells. In contrast to previous studies which did see coherent bubble clouds related to Langmuir cells[6], it is likely that the thin fresh layer of the present study either interfered with the formation of coherent Langmuir cells, or that the cells were confined to the thin layer, and that their narrow horizontal separation, likely on the order of the thickness of the surface layer, was not resolved with the upward-looking sonar as implemented.

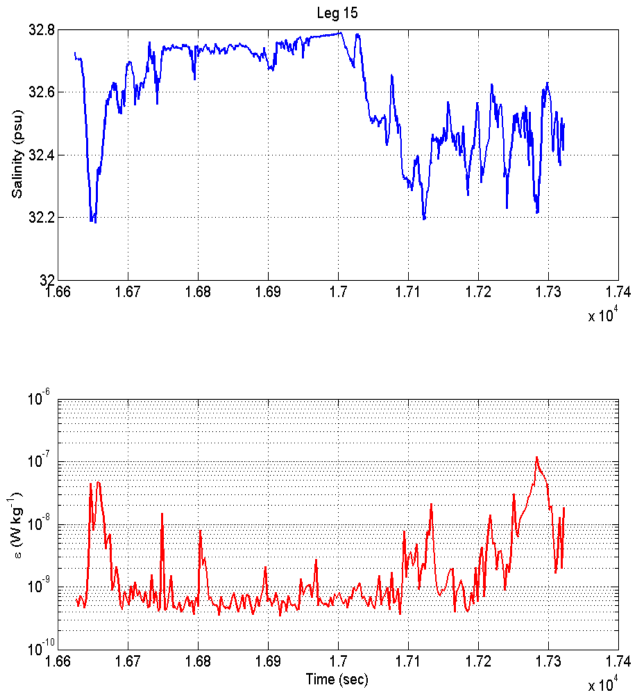

Fig 5: Salinity and TKE dissipation rate (ε) from a 5m leg on 14 September. The alongtrack drop in salinity is at the shoreward end of the transect.

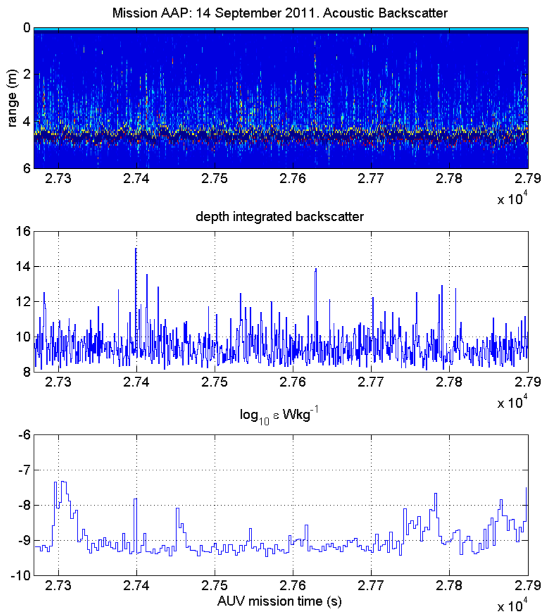

Fig 6: Acoustic backscatter from upward looking 1.1MHz transducer (upper panel), depth integrated backscatter excluding the surface return (middle panel) and TKE dissipation (lower panel).

III. VEHICLE DEVELOPMENT

The bubble measurements shown in Figure 6 were conducted with the ME 1.1 MHz Multi-return Altimeter strapped upward-looking to the aft end of the AUV lift bale, and a rudimentary pressure case with data-logger and batteries strapped along the centerline of the AUV keel. This configuration was destabilizing at the surface, and created intermittent difficulties with respect to initial vehicle dives from the surface. In order to both minimize similar stability complications in future sampling and enable a wider scope of scientific sampling from this vehicle, SAMS is developing, in conjunction with Hydroid, a wet payload section for rapid integration of sensors. The wet payload section (shown in Figure 7 outfitted with the altimeter) is expected to be used first in spring 2013, and should subsequently enable wider use of the vehicle by the UK marine science community.

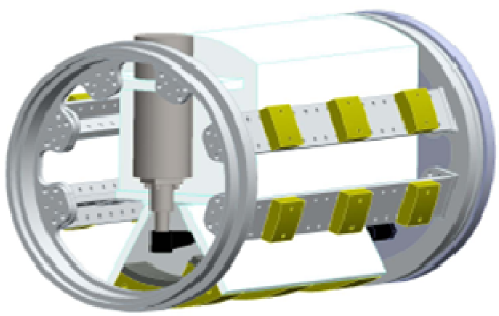

Fig 7: Diagrams of new payload section which will sit directly aft of the nose section. Dimensions are approximately 0.3 m diameter by 0.46 m long.

IV. ACKNOWLEDGMENT

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