WAMSI project reference no: 6.3

Project title*:*	Deployment of Ocean Gliders as part of the West Australian Integrated Marine Observation System (WAIMOS)
Node Leader:	Prof Greg Ivey
Project Leader:	Prof C Pattiaratchi
Project duration	Project start date is 1 July 2008 and ends on 20 December 2011

Due date for current milestone report: 30 June 2010

Project objectives:

1 Temperature, salinity, dissolved oxygen, fluorescence, turbidity and CDOM data from the West Australian shelf and slope waters between Dampier and Fremantle. Monthly data from the Two Rocks transect and Three monthly data from the Leeuwin current is envisaged

Executive Summary

Ocean gliders are autonomous vehicles designed to operate in water depths up to 1000 m. By changing its buoyancy, the glider is able to descend and ascend. For WAIMOS, two different types of gliders are proposed. Both gliders will have the same suite of sensors to measure conductivity (for salinity), temperature, dissolved oxygen, fluorescence, turbidity and CDOM (dissolved organic matter) with depth. The first Slocum glider was deployed to the north of Rottnest Island on 21 June and was recovered off Geraldton on 5th July after travelling 300 km and performing over 2000 vertical casts during this period. Sustained observations of the Two Rocks transect was initiated in January 2009 and has continued as of 26 June 2010 – there have been a total of 12 missions covering 213 days; 4228 km and 36595 vertical profiles. Identification of dense shelf water cascades off the shelf has been the highlight of the data set. Seagliders, to monitor the Leeuwin current have been deployed – one sampled an eddy off Kalbarri and another (deployed off Perth canyon) is traversing the offshore region between Jurien Bay and Rottnest Island.

Research Activity

Slocum glider data: Two Rocks Transect

Slocum glider transects are providing the most detailed seasonal oceanographic information to date for the shelf region off Perth, WA.

Measurements taken during glider deployments off Perth, WA between January 2009 and June 2010 represent the first set of sustained glider observations in the Southern Hemisphere. Slocum glider deployments along the Two Rocks were aimed to obtain monthly transects although due to availability of gliders and/or weather conditions this was not accomplished, although a total of 12 missions were completed each of duration between 10 and 25 days (Table 1).

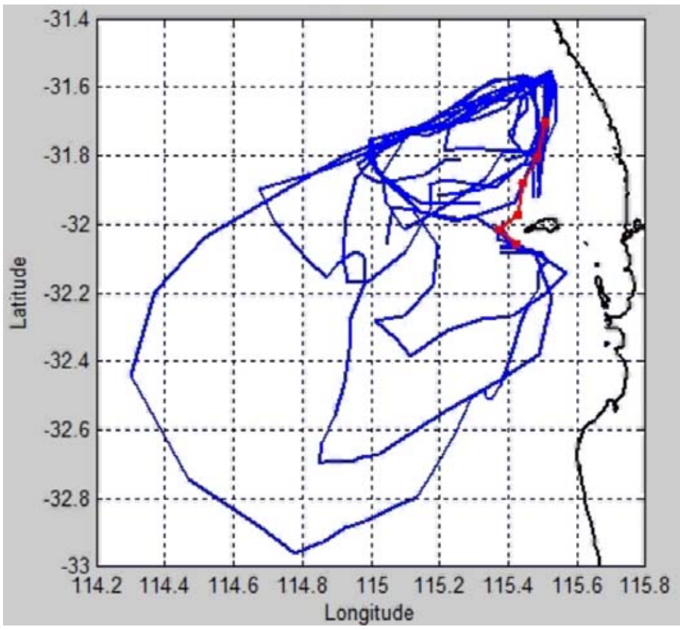

Figure 1 – Slocum glider tracks along the Two Rocks transects over the period January to June 2009.

The highlight of the data collected to date is the identification of dense shelf water cascades (DSWC) along the Two Rocks transect. This was initially identified Perth Coastal Water Study undertaken in 1993/94 through cross shelf transects conducted offshore ocean reef and was reflected in winter data collected from the Slocum gliders in 2008 (see milestone report 1). During winter months, continental shelf waters along south-west Australia are cooler due to the heat loss to the atmosphere and the offshore water is warmer due to the presence of the Leeuwin Current. . These differences between shelf and offshore waters (waters in depths > 30 m) result in the cooler dense waters on the shelf being denser than the offshore waters (Figure 2). As a result, the denser shelf water flows as a gravity current along the sea bed. This process, driven mainly by surface cooling was believed to be a phenomenon which may be found during winter. Data collected during the first half of 2009 from summer (January) to winter (June) have shown that the DSWC is a persistent feature during late summer through to winter. The south west of Australia experiences a Mediterranean climate with hot dry summers and cool winters. The resultant high evaporation during the summer months causes an increase in the salinity of the inner continental shelf waters. As a result the near shore waters become denser than the shelf waters. Slocum glider measurements have shown that in late summer, the higher density water flows off the continental shelf as a gravity current, observed to be up to 20m thick in water depths of 40m (Figure 3). Time-series of transects of salinity obtained between January and April 2009 is shown on Figure 3. In January and February (Figure 3a,b) the inshore water become progressively more saline and by March the initiation of the DSWC may be identified (Figure 3c). By late March the gravity current extends across the shelf and is a persistent feature until end of August (Figures 3d,e,f).

Table 1 – Summary of Slocum glider deployments January 09 to June 2010

Glider	Node	Location	Date Deployed	Date Recovered	Duration (days)	Distance (km)	Casts
UNIT106	WAIMOS	Fremantle, WA	20-Jan-09	10-Feb-09	21	487	2937
UNIT106	WAIMOS	Fremantle, WA	20-Feb-09	13-Mar-09	21	445	3225
UNIT104	WAIMOS	Fremantle, WA	13-Mar-09	27-Mar-09	14	348	2232
UNIT104	WAIMOS	Fremantle, WA	02-Apr-09	27-Apr-09	25	517	3939
UNIT109	WAIMOS	Fremantle, WA	15-May-09	03-Jun-09	19	380	4300
UNIT130	WAIMOS	Fremantle, WA	03-Jun-09	25-Jun-09	22	459	3914
UNIT106	WAIMOS	Fremantle, WA	29-Jul-09	11-Aug-09	13	195	2083
UNIT106	WAIMOS	Fremantle, WA	21-Aug-09	31-Aug-09	10	202	2015
UNIT106	WAIMOS	Two Rocks, WA	08-Dec-09	24-Dec-09	16	221	1980
UNIT106	WAIMOS	Two Rocks, WA	22-Jan-10	15-Feb-10	23	395	4448
UNIT130	WAIMOS	Two Rocks, WA	18-Feb-10	09-Mar-09	19	340	3420
UNIT130	WAIMOS	Two Rocks, WA	07-May-10	17-May-10	10	239	2102
				TOTAL	**213**	**4228**	**36595**

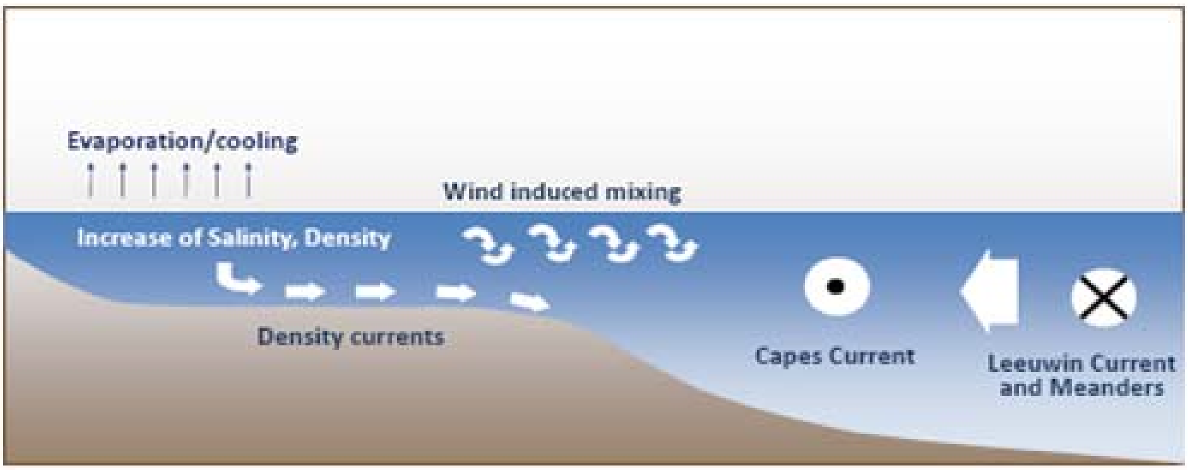

Figure 2 - Schematic of dense shelf water cascade along the Two Rocks Transect.

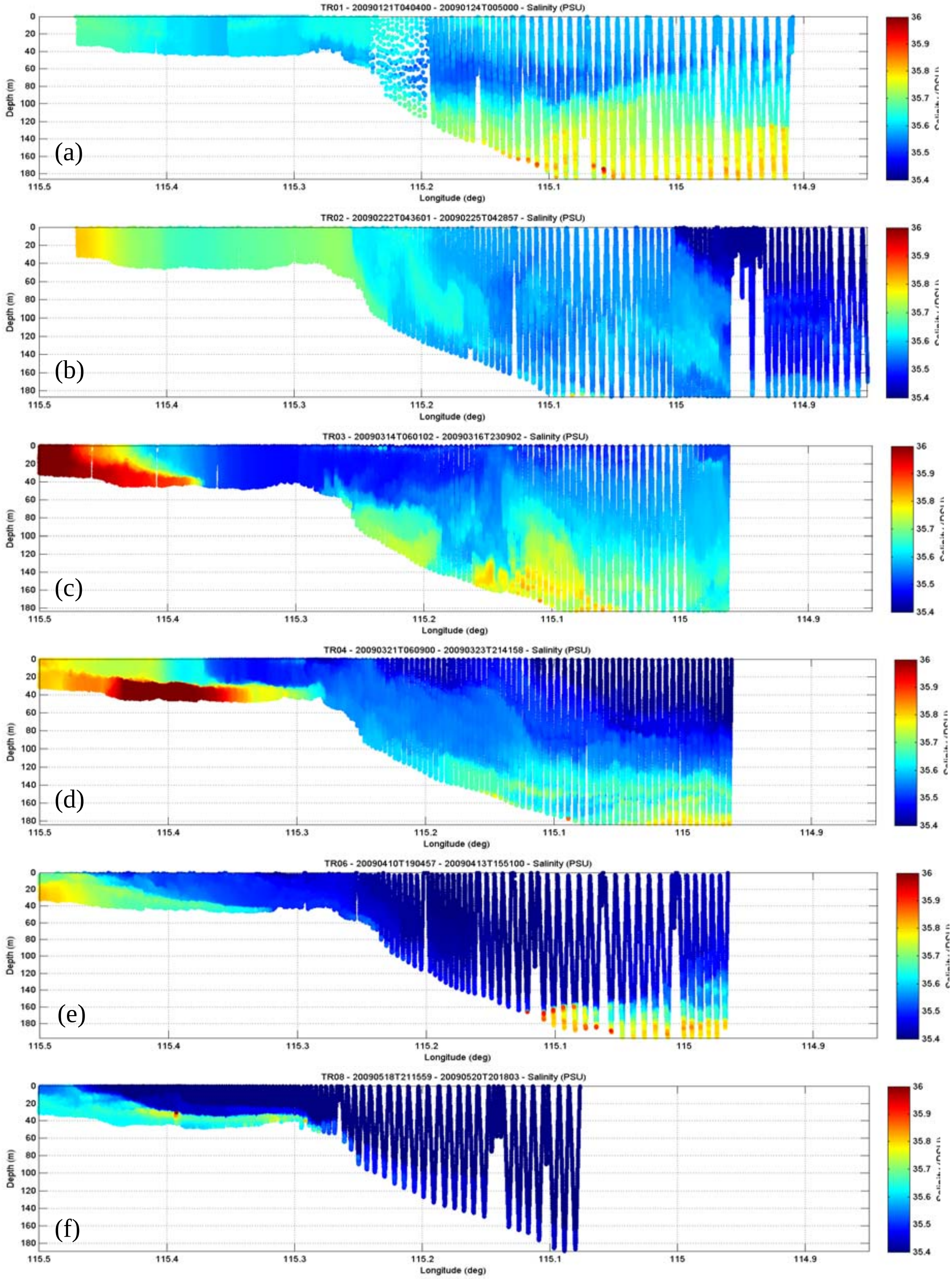

Figure 3 – Slocum glider tracks showing the salinity variation along the Two Rocks transects over the period January to April 2009. (a) 24/01/09; (b) 22/02/09; (c) 14/03/09; (d) 21/03/09; (e) 10/04/09; (f) 20/04/09

In addition to the potential transport properties of DSWC, the glider surveys have indicated that the formation of these dense water masses may have important impacts on nearshore phytoplankton production. Of particular note is the shift in DSWC forcing from a salinity-driven phenomenon in autumn to a more temperature-driven phenomenon in winter (Figure 4). In these two scenarios, the response of the phytoplankton community (as indicated by chlorophyll fluorescence, a proxy for biomass) is quite different – in the former, there is a bloom at the DSWC frontal zone (Figure 4a), whilst in the latter, phytoplankton biomass is maximal adjacent to the seabed and within the DSWC itself (Figure 4b). Such responses may be related to temperature, salinity, nutrient dynamics and/or shifts in phytoplankton species composition or productivity rates. These aspects are currently under investigation.

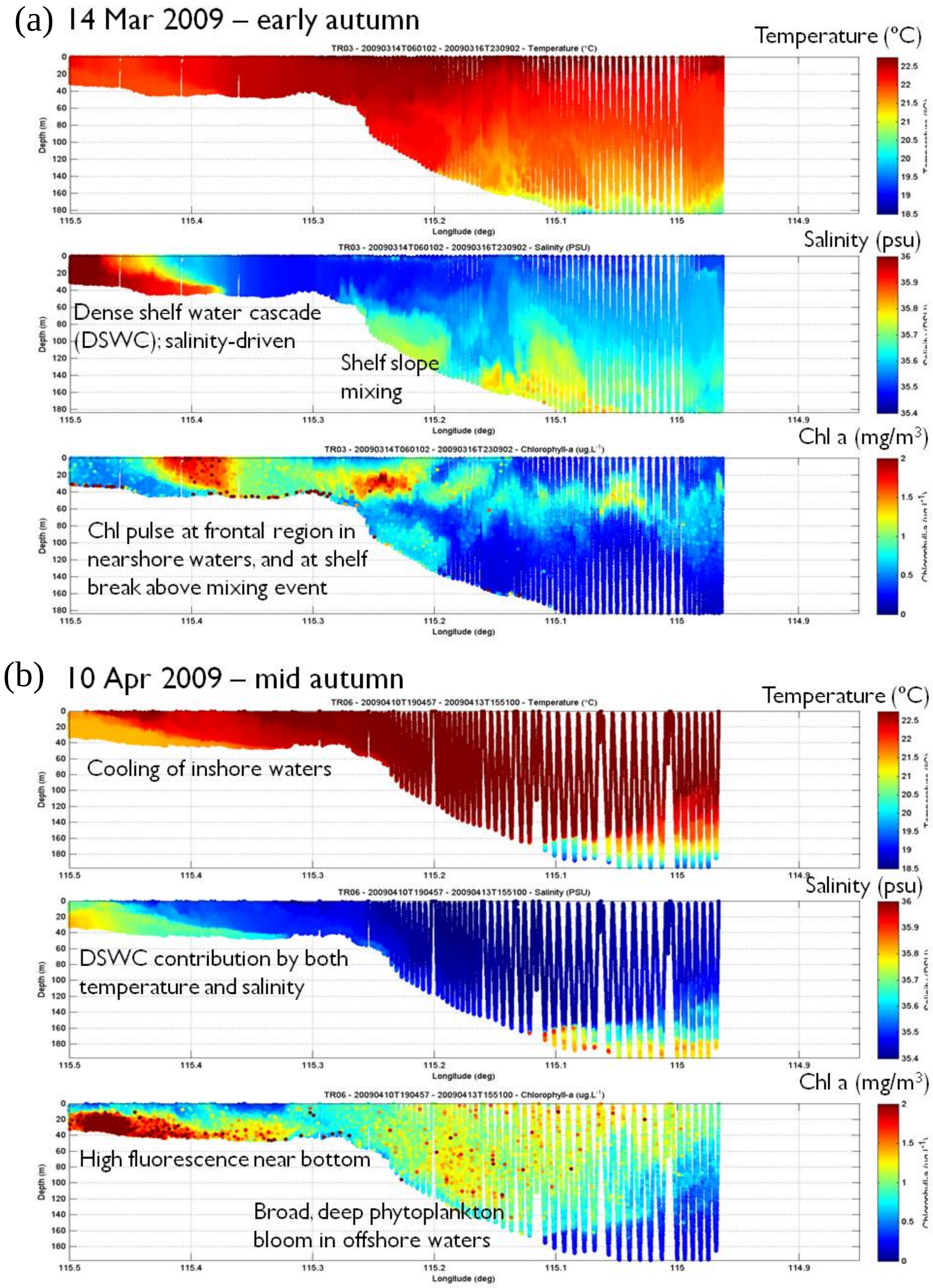

Figure 4 - Cross-shelf profiles, temperature, salinity, and phytoplankton chlorophyll fluorescence along the Two Rocks transect: (a) March 2009, and (b) April 2009.

Cross-shore transects along the Two Rocks transect showing the temperature, salinity and fluorescence distribution between January and June (9 transects) are shown on Figures 5 to 12. In January, the upper layer was stratified in temperature with colder water (~21^o Celsius) in the mid-shelf region, which was associated with higher fluorescence most likely due to the Capes current (Figure 5). A prominent sub-surface chlorophyll maximum is observed offshore associated with the halocline (Figure 5). In February, both the temperature (~22.5^o Celsius) and salinity (~ 35.8) in the shallow waters have increased and there are no other prominent features in either temperature or fluorescence although there appears to be a dense water cascade event at the shelf break (Figure 6). In March the salinity of the near shore zone has increased (from < 35.8 to > 36.0) and initiation of the DSWC may be identified. There is a high fluorescence along the frontal zone between the higher and lower salinity (Figure 7). Transect taken on 21 March (1 week after the previous) indicate that the whole of the shelf is stratified in both temperature and salinity with the bottom layer ~20m thick. Higher fluorescence is associated with the higher salinity (Figure 8). On 10 April, the DSWC is still present but the thickness of the bottom layer was reduced from that on 21 March, most likely due to wind mixing events. The fluorescence values have increased in the higher salinity water (Figure 9). Ten days later (20 April), the DSWC still extends across the whole shelf but well mixed water extends further offshore (compared to the previous transect) and a thin layer of higher salinity colder water may is present just before the shelf break. The fluorescence values are generally uniform and are slightly higher in the frontal zone (Figure 10). In May, the DSWC extends across the whole shelf and is prominent in both temperature and salinity. Although the salinity of the near shore water have decreased (to < 35.7), the offshore waters are lower in salinity (~ 35.4) due to the Leeuwin Current, but now the temperature has decreased to < 20.5^o Celsius). Higher fluorescence water is present closer to the shore and is associated with higher salinity/colder water (Figure 11). By June the salinity has decreased further (< 35.4) and a smaller DSWC can be identified in the temperature at the mid-shelf region ((Figure 12). These transects indicate the dynamic nature of DSWC which is influenced by the local meteorological conditions (evaporation, cooling and wind mixing) as well as the oceanographic processes such as the Leeuwin and Capes Currents, as shown schematically in Figure 2).

All of the Two Rocks Slocum glider data are available through the IMOS eMII data portal at http://imos.aodn.org.au/webportal/.

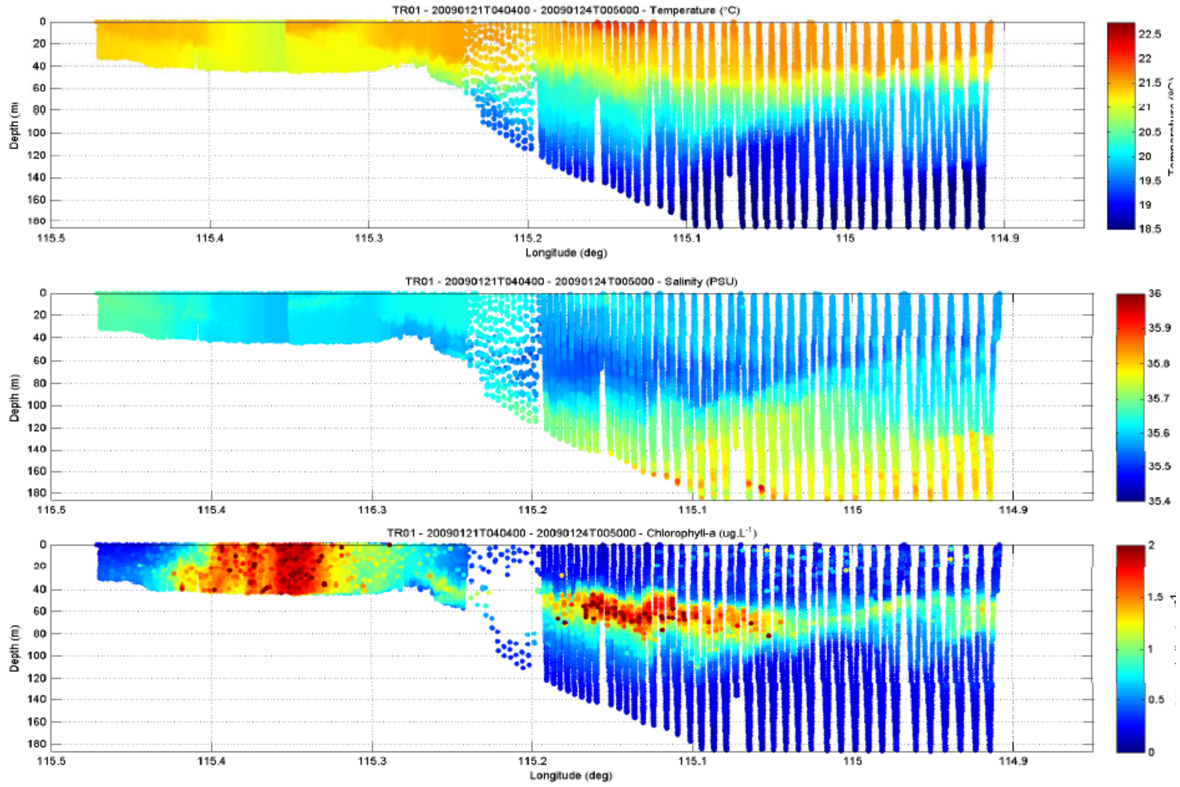

Figure 5 - Cross-shelf profiles, temperature, salinity, and phytoplankton chlorophyll fluorescence along the Two Rocks transect: 24 January 2009.

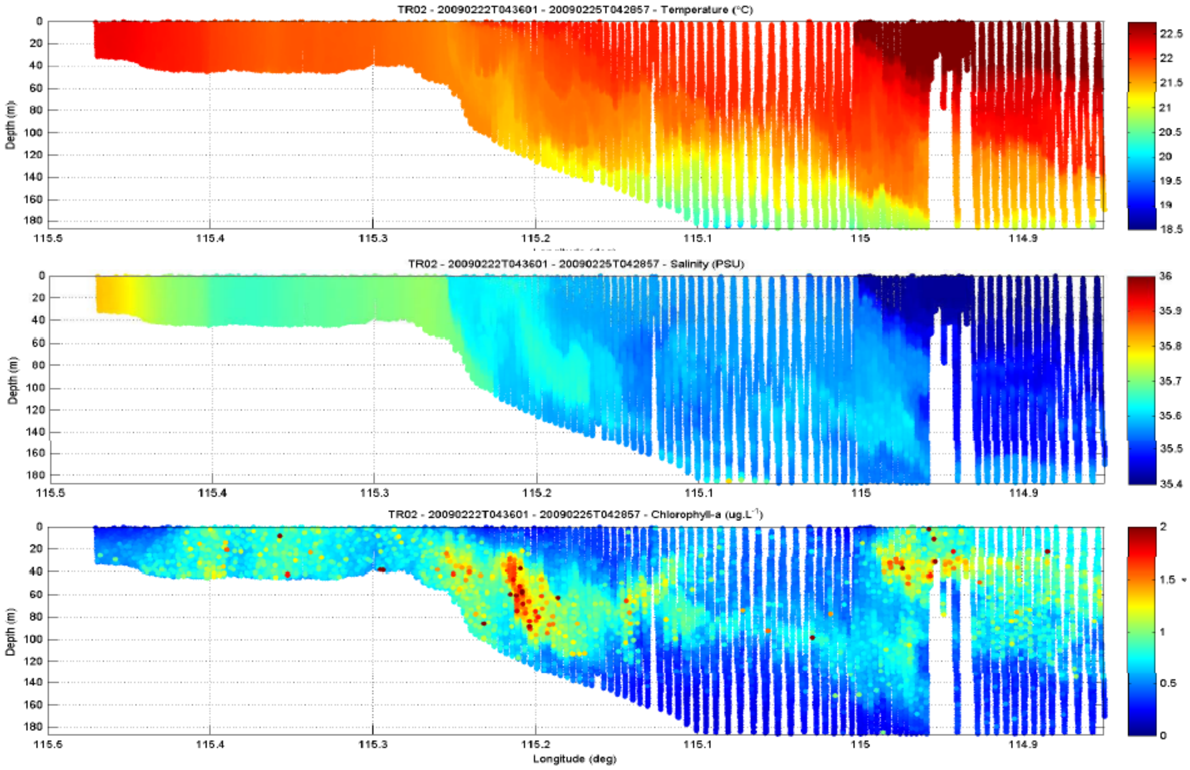

Figure 6 - Cross-shelf profiles, temperature, salinity, and phytoplankton chlorophyll fluorescence along the Two Rocks transect: 22 February 2009.

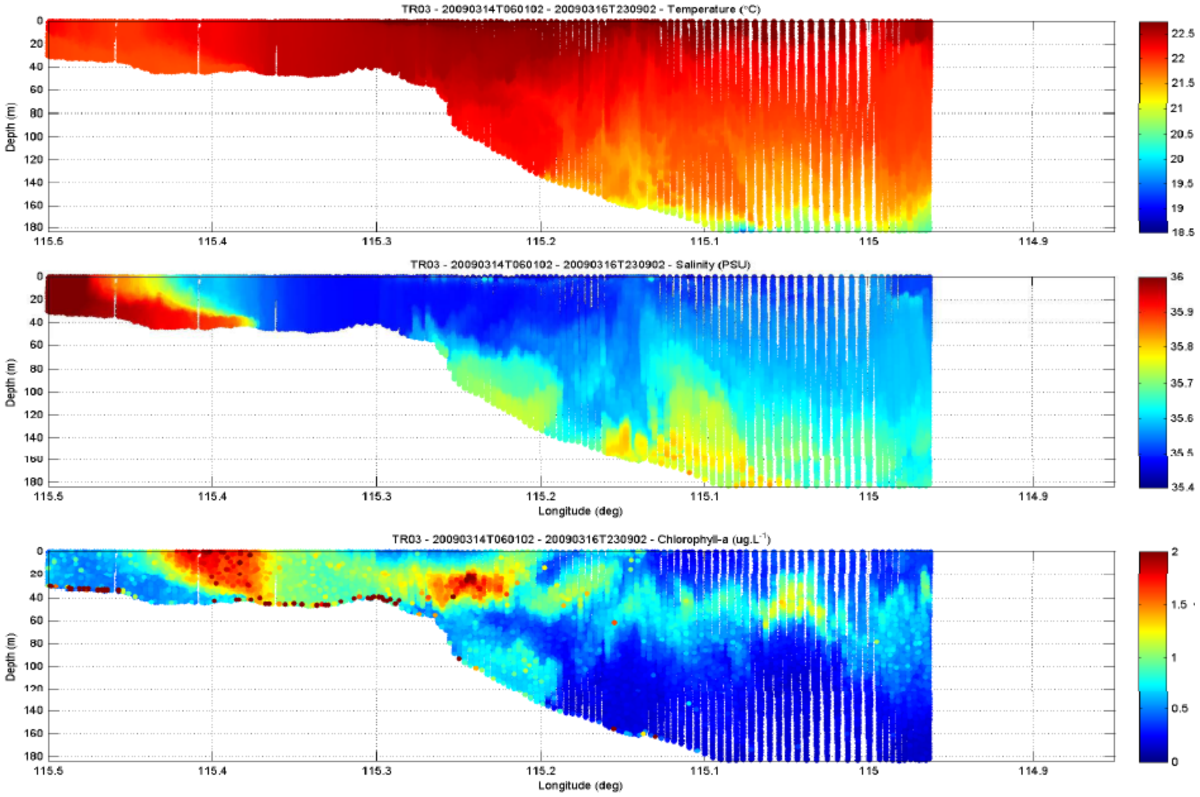

Figure 7 - Cross-shelf profiles, temperature, salinity, and phytoplankton chlorophyll fluorescence along the Two Rocks transect: 14 March 2009.

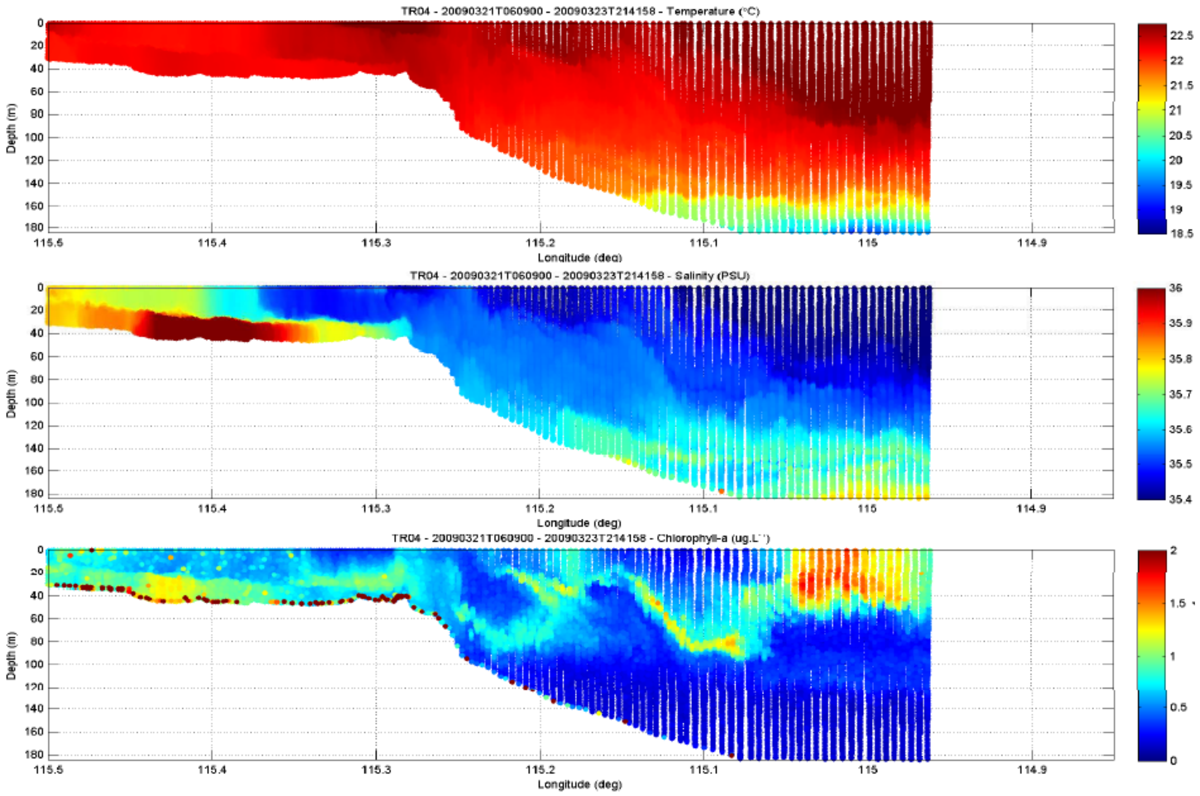

Figure 8 - Cross-shelf profiles, temperature, salinity, and phytoplankton chlorophyll fluorescence along the Two Rocks transect: 21 March 2009.

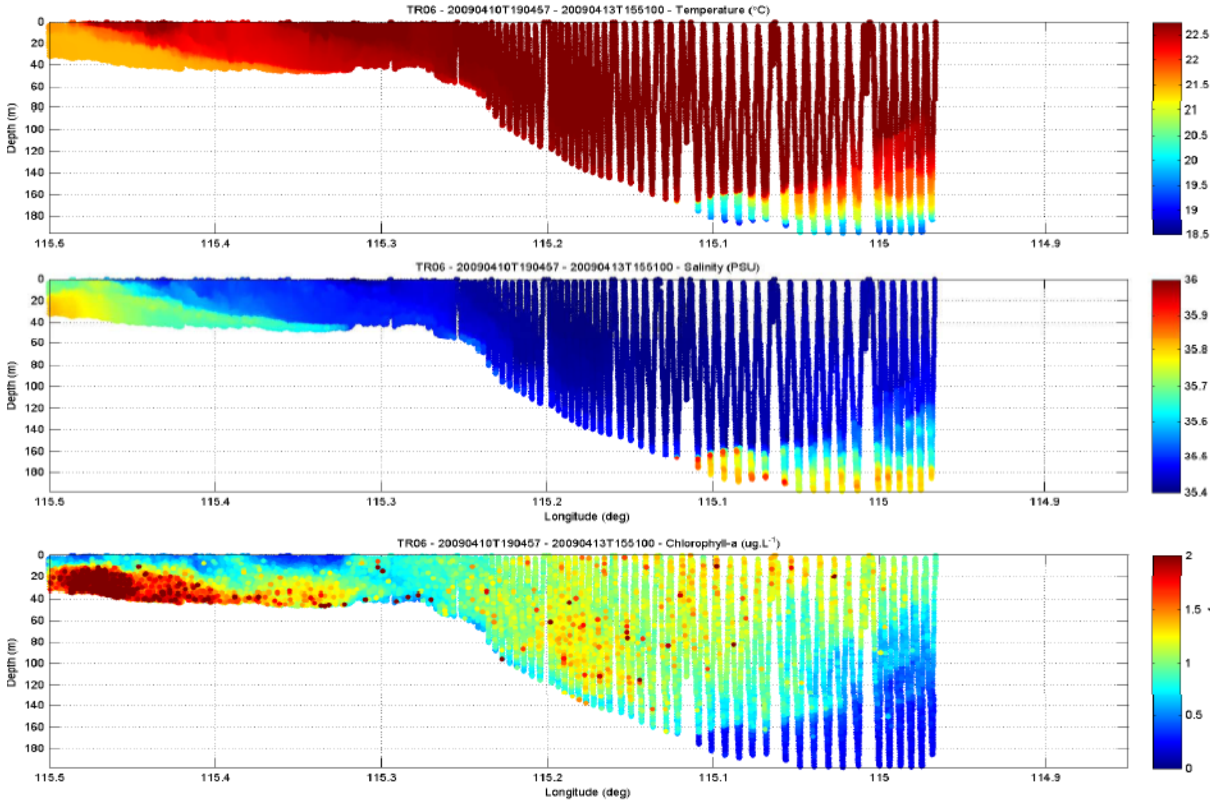

Figure 9 - Cross-shelf profiles, temperature, salinity, and phytoplankton chlorophyll fluorescence along the Two Rocks transect: 10 April 2009.

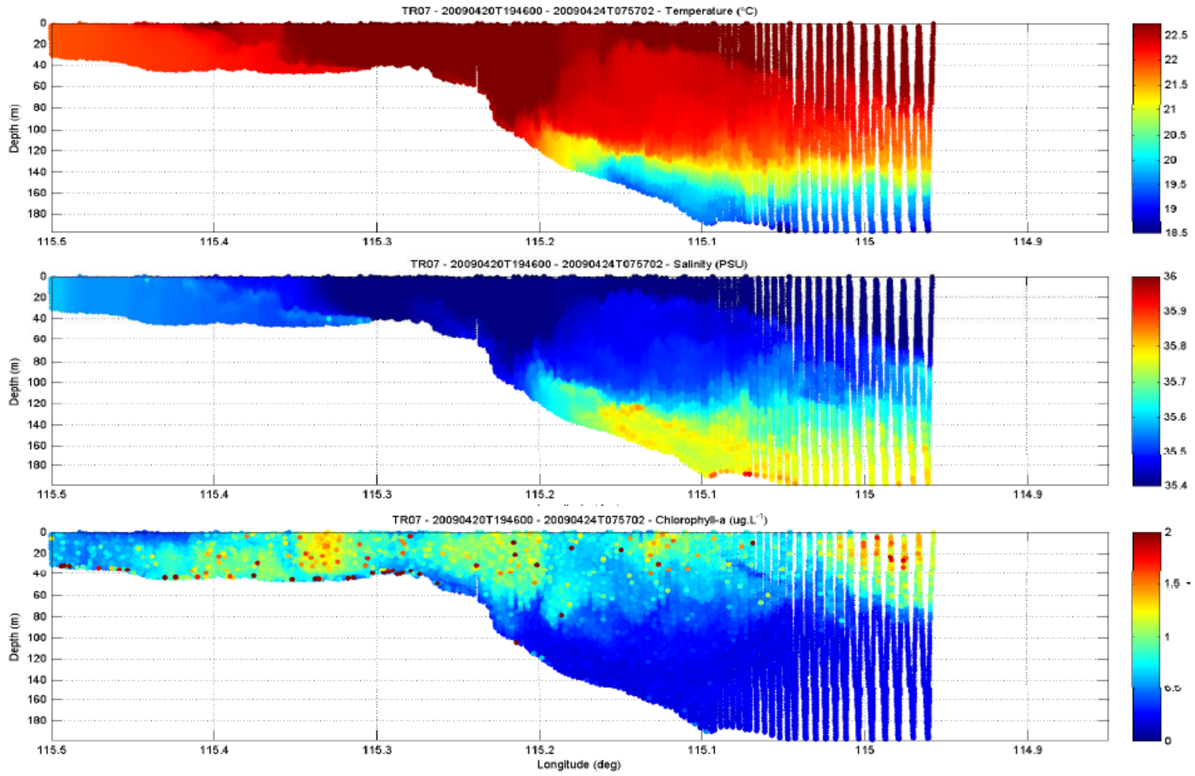

Figure 10 - Cross-shelf profiles, temperature, salinity, and phytoplankton chlorophyll fluorescence along the Two Rocks transect: 20 April 2009.

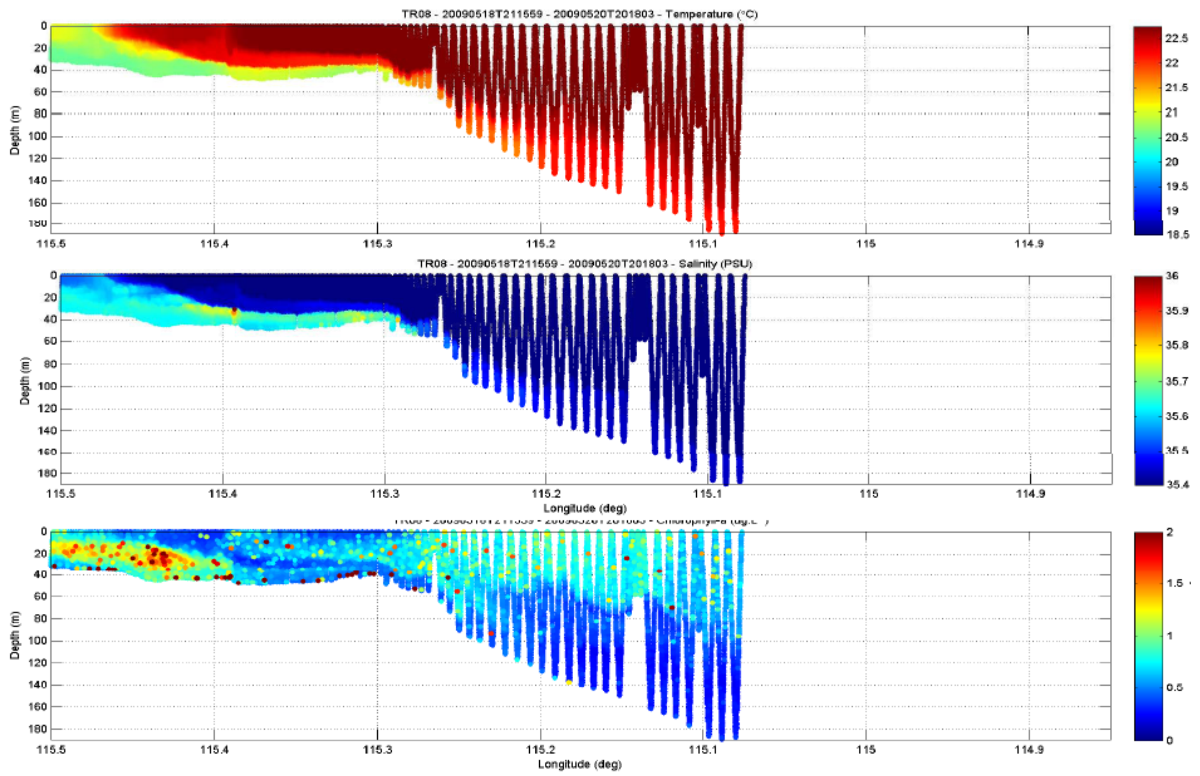

Figure 11 - Cross-shelf profiles, temperature, salinity, and phytoplankton chlorophyll fluorescence along the Two Rocks transect: 18 May 2009.

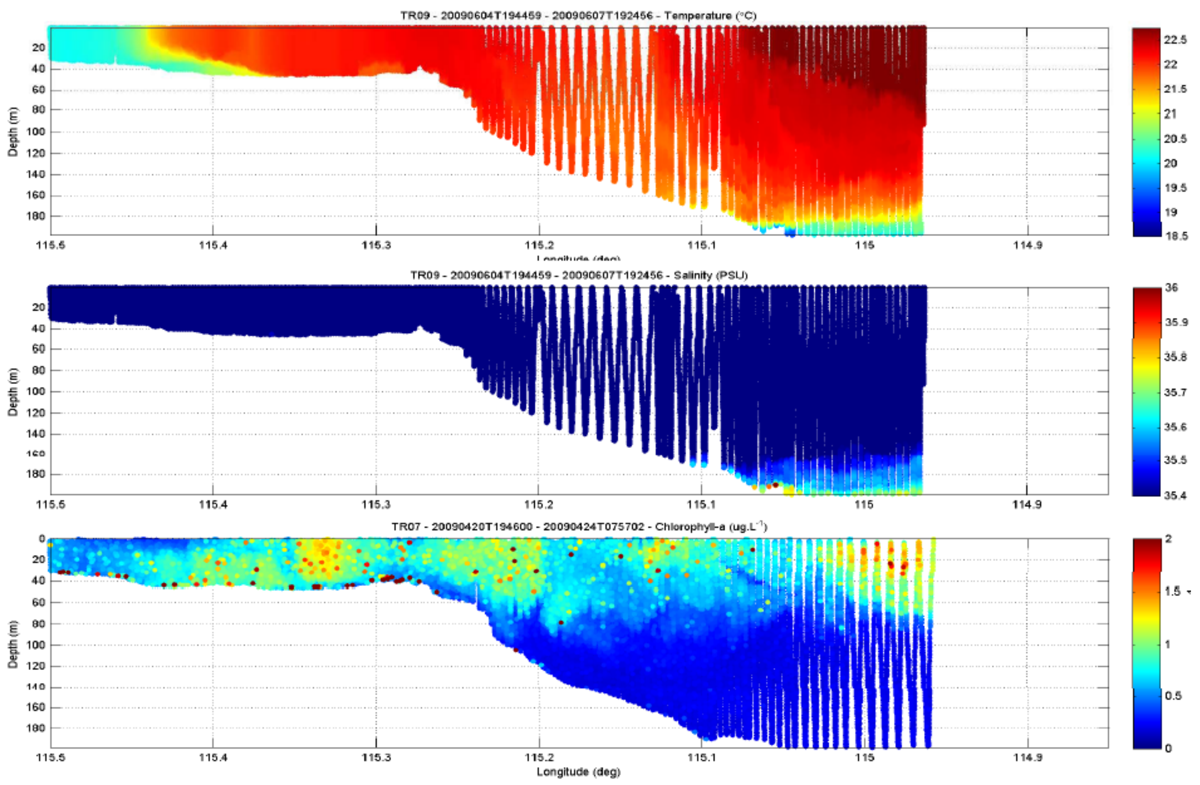

Figure 12 - Cross-shelf profiles, temperature, salinity, and phytoplankton chlorophyll fluorescence along the Two Rocks transect: 4 June 2009.

Seaglider data

There have been 3 missions of Seagliders in Western Australia, including the current deployment (Table 2). The first deployment, on remained on the continental shelf it it was not possible to navigate the glider to offshore waters. The second deployment was entrained into a Leeuwin Current eddy and remained within the eddy for the duration of the mission (a total of 66 days). These two missions were hampered by bad communication between the Seagliders and the glider control making it harder to pilot the gliders. ANFOG has solved these problems and the current deployment between Perth canyon and Jurien Bay is very good example of transects in and out of the Leeuwin Current.

Table 2 – Summary of Seaglider deployments in Western Australia from May 09 to June 2010

Glider	Node	Location	Date Deployed	Date Recovered	Duration (days)	Distance (km)	Casts
sg152	WAIMOS	Kalbarri, WA	20/05/2009	8/06/2009	19	480	1210
sg153	WAIMOS	Kalbarri, WA	11/11/2009	16/01/2010	66	1185	914
Sg520	WAIMOS	Perth Canyon, WA	17/05/2010	*	41*	910*	244*
				TOTAL	**126**	**2575**	**2368**

*Ongoing as of 26 June 2010

Time series data collected by the Seaglider deployment in Kalbarri within a Leeuwin Current eddy is shown on Figure 13. The Seaglider made 6 revolutions of the eddy (Figure 13a) and are reflected in all of the oceanographic parameters measured by the glider. The undulating nature of the temperature, salinity, dissolved oxygen and fluorescence in the time series indicate the position of the glider in different sections of the eddy (Figure 13). The higher salinity core of water undulating between the surface and 200m is associated with the south Indian Central water whilst the higher dissolved oxygen values recorded between 200 and 700m is associated with the Leeuwin Undercurrent transporting sub-Antarctic mode water northwards. This data will form the thesis of a honours student in the School of Environmental Systems Engineering at UWA in 2010.

Time series data collected by the Seaglider deployment between Perth Canyon and Jurien Bay is shown on Figure 14. During its voyage, the Seaglider make 6 encounters with the Leeuwin Current as identified through the warmer, lower salinity (therefore lower density) water. The Leeuwin current was also higher in fluorescence. The higher dissolved oxygen values are again associated with the Leeuwin Current. This mission is currently ongoing it is planned to recover the Seaglider in September/October 2010.

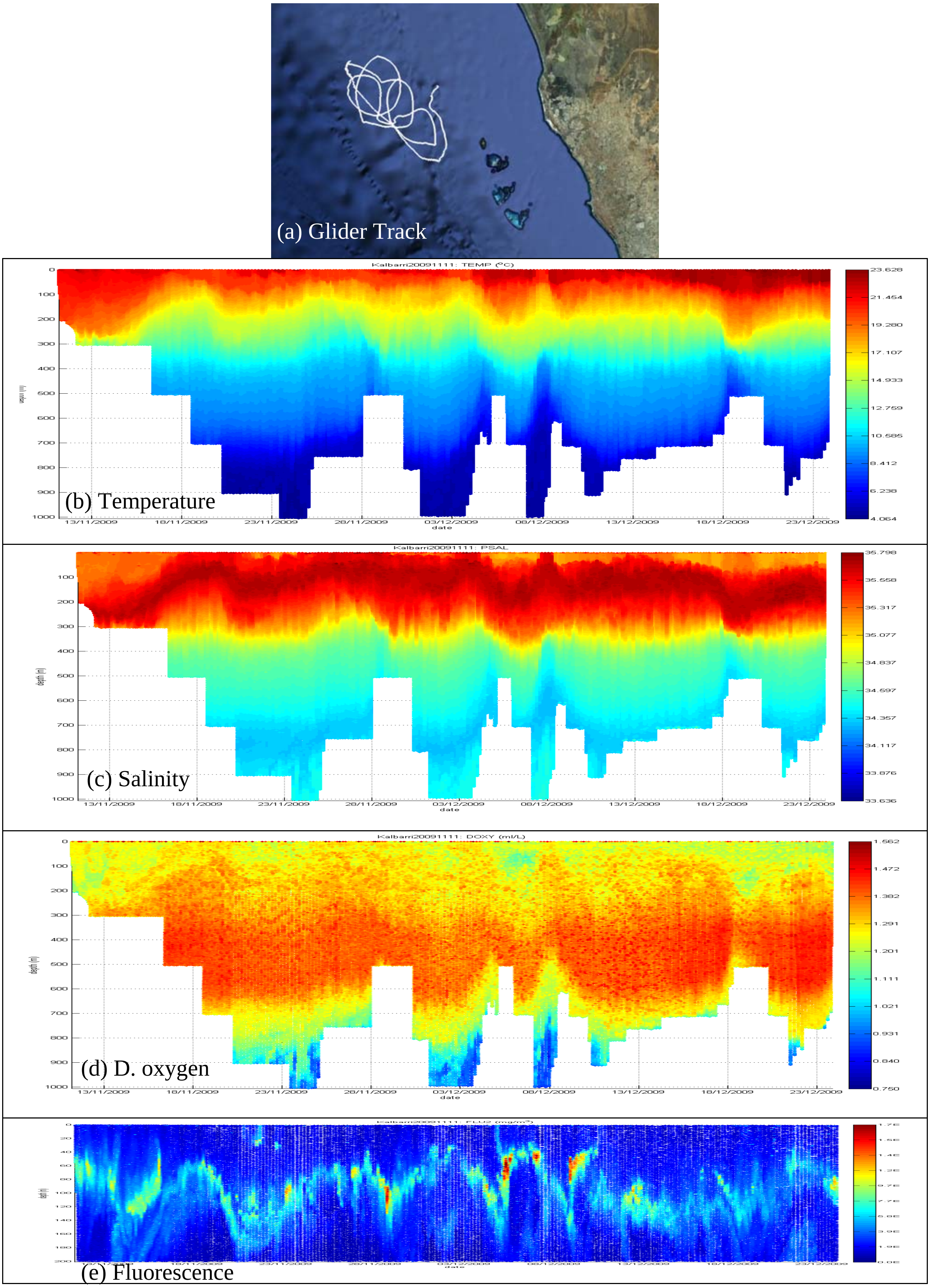

Figure 13 – Time series of Seaglider (a) location; (b) temperature; (c) salinity; (d) dissolved oxygen; and, (e) chlorophyll fluorescence obtained offshore Kalbarri within a Leeuwin Current eddy.

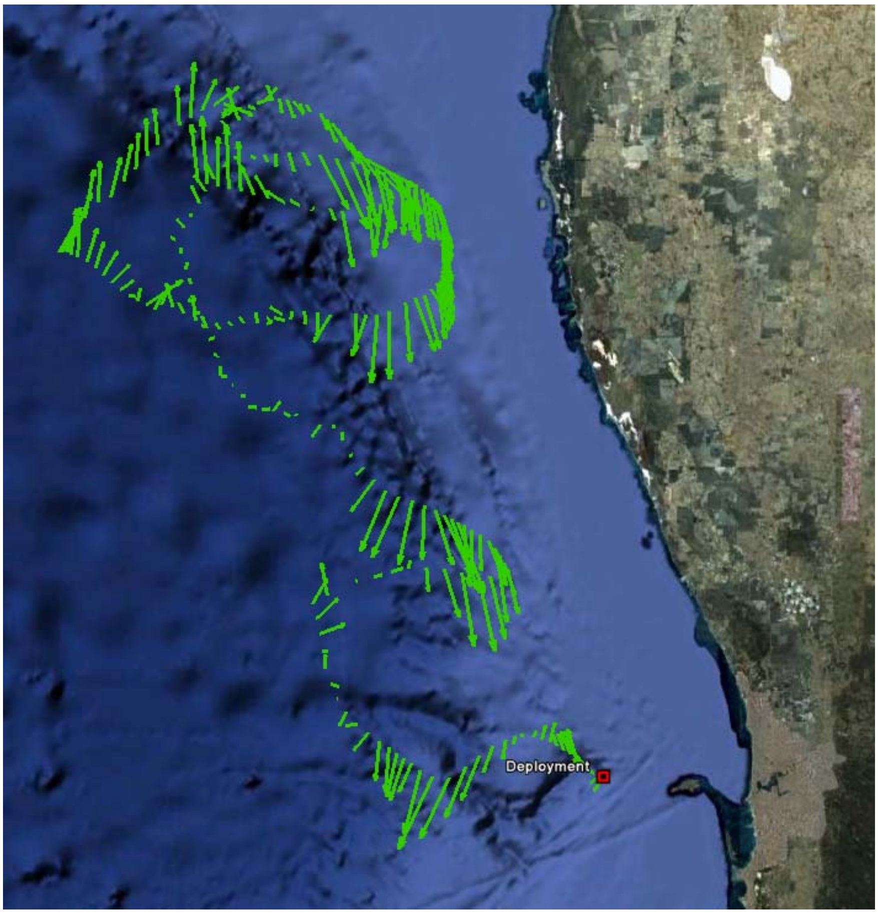

Figure 14 – Track of the Seaglider and surface currents.

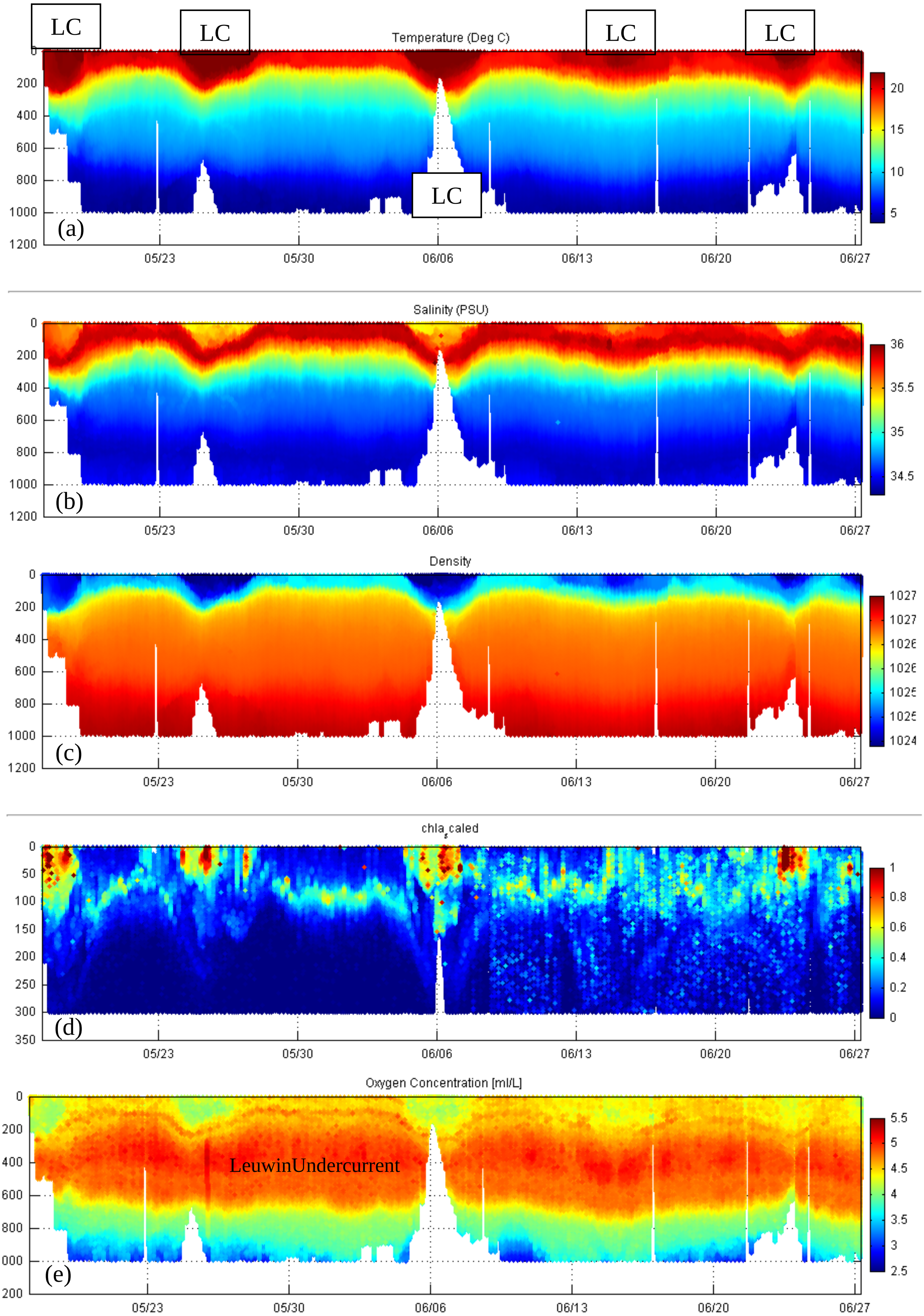

Figure 15 – Time series of Seaglider data: (a) temperature; (b) salinity; (c) density; (d) chlorophyll fluorescence; and, (e) dissolved oxygen obtained between Perth Canyon and Jurien Bay (see glider track in Figure 14).

Issues –

Ocean gliders may be classified as emerging technology as such some delays in the deployment schedule of the gliders are expected. The Australian National Facility for Ocean Gliders (ANFOG), the operator of ocean gliders on behalf of IMOS has made significant progress.

Communication Achievements –

The following presentations were made:

Ninth international conference on southern hemisphere meteorology and oceanography (9ICSHMO)	Melbourne, Australia	February 2009	*Ocean Observations using autonomous ocean gliders* C. Pattiaratchi
Global Ocean Observing System scientific steering committee workshop	Perth, Australia	February 2009	*Ocean observations off Western Australia* C Pattiaratchi
Institute of Marine Engineering, Science and Technology seminar	Fremantle, Australia	May 2009	*Ocean Observations using autonomous ocean gliders* CPattiaratchi
Australian Marine Science Conference	Adelaide, Australia	July 2009	*Western Australian Integrated Ocean Observation System (WAIMOS)* CPattiaratchi
Oceanobs'09 Conference	Venice, Italy	September 2009	*Oceanographic Observations of the Australian Continental Shelf and Slope Waters Using Autonomous Ocean Gliders* CPattiaratchi (poster)
Oceanobs'09 Conference	Venice, Italy	September 2009	*The West Australian Integrated Marine Observation System (WAIMOS)* CPattiaratchi (poster)
European glider observatories	Cyprus	October 2009	*Australian National Facility for Ocean Gliders* B. Hollings
CSIRO Marine and Atmospheric Research,	Hobart, Australia	December 2009	*Coastal Physical Oceanography off South-West Australia* CPattiaratchi
Oceans Sciences meeting	Portland, USA	February 2010	*Sustained bio-optical measurements across the Leeuwin Current system via ocean gliders: spatio-temporal patterns and links to physical forcing* Christine Hanson
IEEE Oceans conference	Sydney, Australia	May 2010	*Sustained oceanographic observations around Australia using autonomous ocean gliders* Ben Hollings

Other comments –

The project has been successful in recruiting a PhD student, Thisara Welhena, based at the School of Environmental Systems Engineering to work on the data obtained from the ocean gliders and HF Radar. Mr Welhena started in July 2009 with top-up scholarship support from this project and from Node 2. In 2010, an honours student Ping Jie Teo from the School of Environmental Systems Engineering at UWA will be doing his research project based on the data obtained from the Seaglider deployed off Kalbarri and entrained into a Leeuwin Current eddy.

Attachments –

Paper from IEEE Oceans conference

Proceedings of the IEEE Oceans 2010 Conference, Sydney, May 2010

Sustained oceanographic observations around Australia using autonomous ocean gliders

B. Hollings[1], C. B. Pattiaratchi[1], M. Woo[1] & C. E. Hanson[1]
[1]School of Environmental Systems Engineering, The University of Western Australia
35 Stirling Hwy.
Crawley, WA 6009 Australia

Abstract - **Ocean gliders are autonomous sensor platforms designed to operate in water depths of up to 1000m. By varying their buoyancy, gliders are able to efficiently ascend and descend through the water column. The Australian National Facility for Ocean Gliders (ANFOG) has been established as part of the Australian Integrated Marine Observing system to develop and operate a fleet of ocean gliders in shelf and shelf slope waters around Australia. In this paper several glider operations around Australia will be discussed including deployments at the mouth of the Spencer Gulf in South Australia, the continental shelf and shelf slope off Western Australia and the shelf, and East Australian Current eddies off New South Wales. Discussion will focus on WA deployments which represent the first sustained measurements taken in the Southern Hemisphere using ocean gliders.**

I. INTRODUCTION

Traditionally, oceanographic sampling has been undertaken from ships; however due to the significant costs of operating an ocean research vessel (of the order of $50,000 per day) and limitations of working in poor weather conditions this has resulted in difficulties in data collection, particularly where sustained, long term, observations are required to examine long term variability. Ocean gliders, autonomous instrument platforms designed to efficiently operate throughout the water column in water depths of up to 1000m, provide an excellent alternative measurement tool. Due to their relatively low cost and extended deployment durations, gliders will allow for the collection of sustained long term observations, even during periods of extreme weather conditions. The resulting long term data sets will enable researchers to better document the variability of the ocean and of coastal ecosystems.

Gliders descend and ascend through the water column by changing their volume and hence their buoyancy; this momentum is converted to forward motion by wings resulting in an average horizontal velocity of 0.25 - 0.40ms^{-1}. Dive pitch is controlled by moving an internal mass (battery pack) and steering is achieved through the use of an active rudder (Slocum) or by the rotation of an off-centre internal mass (Seaglider). Using GPS, internal dead reckoning and altimeter measurements the glider autonomously navigates its way to a series of waypoints. Near real-time data can be uploaded to a base computer via two way Iridium satellite communication, which also allows for remote updating of glider control parameters and waypoints.

The Australian National Facility for Ocean Gliders (ANFOG) has been established as a facility within the Australian Integrated Marine Observation System (IMOS) to develop and operate a fleet of gliders and to provide a near real-time data stream from the continental shelf and slope waters of Australia.

TABLE I
GLIDER SPECIFICATIONS

	Slocum glider	Seaglider
Type	Coastal	Open ocean
Depth Range	20-200m	75-1000m
Length	1.8m (2.15m inc antenna)	1.8m (2.8m inc antenna)
Mass	52 kg	52 kg
Batteries	230 Alkaline C-cells Energy: 8MJ Mass: 18kg	81 Lithium D-cells Energy: 10 MJ Mass: 9.4kg
Max. Volume Change	460 cc	840 cc
Communications	Iridium GPS Navigation Freewave RF-modem ARGOS Transmitter	Iridium GPS Navigation
Steering	Active Rudder	Rotating internal mass
Endurance	30 days	6 months
Range	500 km	4600 km
Speed	40 cm s^{-1}	25 cm s^{-1}

Currently the ANFOG glider fleet consists of 3 Slocum gliders and 5 Seagliders with another 3 Slocum gliders and 6 Seagliders on order. Slocum gliders, manufactured by Teledyne Webb Research are designed to operate to a maximum depth of 200m and have a maximum endurance of 30 days while Seagliders are made by University of Washington and iRobot; these operate to 1000m and have maximum duration of 6 months (Table 1).

All ANFOG gliders have a similar suite of sensors to measure temperature, conductivity, dissolved oxygen (DO), turbidity, coloured dissolved organic matter (CDOM) and chlorophyll-a fluorescence. Currently both Slocum gliders and Seagliders are equipped with a Seabird-CTD & WETLabs BBFL2S three parameter optical sensor (measuring chlorophyll-a fluorescence, CDOM fluorescence and optical backscatter at 660nm). Slocum gliders are equipped with an Aanderra Oxygen optode to measure DO while Seagliders have a Seabird oxygen sensor.

Over the period November 2008 to March 2010 ANFOG has completed 19 successful Slocum glider deployments (Table 2). During this time the Slocum gliders traversed more than 9,000 km and collected over 55,000 vertical profiles of oceanographic data.

TABLE II
SLOCUM GLIDER DEPLOYMENT STATISTICS (MARCH 2010)

#	Node	Deployed	Recovered	Distance (km)	Duration (days)	Raw Casts
1	NSWIMOS	25-Nov-08	11-Dec-08	1002.8	16	1484
2	SAIMOS	15-Jan-09	05-Feb-09	518.39	21	3594
3	WAIMOS	20-Jan-09	10-Feb-09	486.9	21	2937
4	WAIMOS	20-Feb-09	13-Mar-09	445.0	21	3225
5	WAIMOS	13-Mar-09	27-Mar-09	347.6	14	2232
6	NSWIMOS	17-Mar-09	09-Apr-09	705.6	23	1721
7	WAIMOS	02-Apr-09	27-Apr-09	517.28	25	3939
8	WAIMOS	15-May-09	03-Jun-09	380.0	19	4300
9	SAIMOS	28-May-09	24-Jun-09	599.7	27	3721
10	WAIMOS	03-Jun-09	25-Jun-09	459.34	22	3914
11	WAIMOS	29-Jul-09	11-Aug-09	194.8	13	2083
12	WAIMOS	21-Aug-09	31-Aug-09	202.0	10	2015
13	NSWIMOS	02-Oct-09	29-Oct-09	705.4	27	1765
14	NSWIMOS	28-Oct-09	19-Nov-09	659.6	22	1612
15	SAIMOS	04-Nov-09	26-Nov-09	587.8	22	3731
16	WAIMOS	08-Dec-09	24-Dec-09	220.6	16	1980
17	WAIMOS	22-Jan-10	15-Feb-10	396.1	24	4008
18	SAIMOS	10-Feb-10	04-Mar-10	538.5	22	3440
19	WAIMOS	18-Feb-10	09-Mar-10		19	
			TOTAL	**9366**	**384**	**55,665**

**WAIMOS deployments – Perth, WA, SAIMOS deployments – Spencer Gulf, SA, NSWIMOS deployments – NSW mid-coast*

Over the same period 7 Seaglider deployments were completed (Table 3), 3 off Tasmania, 1 off South Australia, 2 off Western Australia and 1 off New South Wales. A total of 9,769 km was covered during 428 days at sea, while collecting over 6548 vertical profiles.

TABLE III
SEAGLIDER DEPLOYMENT STATISTICS (MARCH 2010)

#	Node	Deployed	Recovered	Distance (km)	Duration (days)	Casts
1	BW	13-Feb-09	14-Apr-09	1200	60	860
2	BW	22-Apr-09	24-Jun-09	875	63	1060
3	WAIMOS	20-May-09	08-Jun-09	480	19	1210
4	SAIMOS	26-May-09	07-Aug-09	1860	73	830
5	NSWIMOS	19-Oct-09	12-Jan-10	2382	85	834
6	WAIMOS	11-Nov-09	16-Jan-10	1185	66	914
7	BW	26-Nov-09	27-Jan-10	1787	62	840
			TOTAL	**9769**	**428**	**6548**

***Bluewater (BW) deployments off eastern Tasmania, WAIMOS deployments – Kalbarri, WA, NSWIMOS deployments – NSW mid-coast & SAIMOS Deployment – Portland, VIC*

II. GLIDER DEPLOYMENTS

A. *Western Australia*

Measurements taken during glider deployments off Perth, WA between January 2009 and February 2010 represent the first set of sustained glider observations in the Southern Hemisphere. Slocum gliders were deployed on monthly intervals on a cross shore transect from Two Rocks, north of Perth.

This region exhibits circulation unlike other western continental margins where the surface flow is usually equatorward and highly productive due to upwelling [8]. Off WA the Leeuwin Current (LC), a shallow (< 300- m-deep), narrow (< 100-km-wide) band of warm, low salinity, nutrient-depleted water of tropical origin, flows poleward from Exmouth to Cape Leeuwin continuing into the Great Australian Bight [7][8]. The LC is accepted to be the longest boundary current in the world with a signature that extends from North West Cape to Tasmania [7].

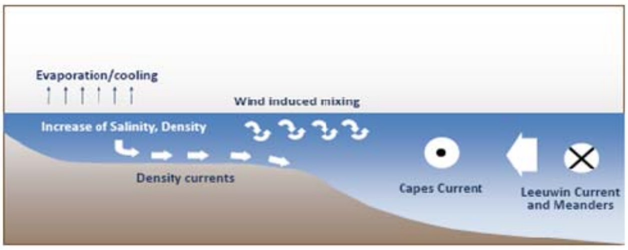

Figure 1. Schematic of circulation off Perth, WA

The continental shelf waters off Perth, WA are influenced by the LC which is generally located along the 200m isobaths and during the summer months by the Capes current (CC), a colder wind driven current, originating between Cape Leeuwin and Cape Naturaliste [6]. The Capes current is generally located inshore of the 50m isobath and has a higher productivity due to upwelling [6]. Previous ship based measurements have shown the existence of a deep chlorophyll maximum off the western Australian coast during the summer months [2]. Data from Slocum deployments has measured the interaction and seasonal variation of the CC and LC.

The south west of Australia experiences a Mediterranean climate with hot dry summers and cool winters. The resultant high evaporation during the summer months causes an increase in the salinity of the inner continental shelf waters. As a result the nearshore waters become more dense that the shelf waters. Slocum glider measurements have shown that in late summer, the higher density water flows off the continental shelf as a gravity current, observed to be up to 20m thick in water depths of 40m (Figure 2 & 3).

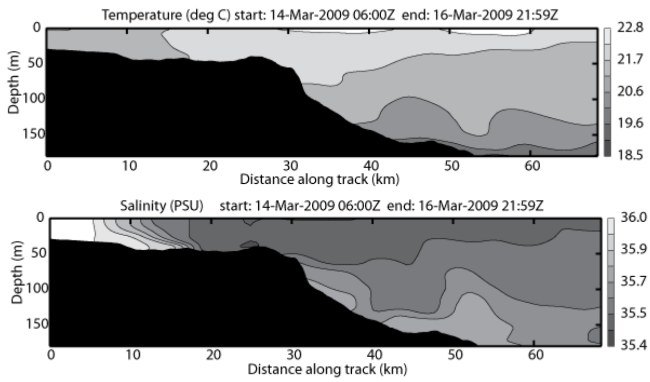

Figure 2. Offshore cross section of Temperature and Salinity off Perth, WA (March 2009)

Subsequent cooling during late autumn and winter results in higher density waters being maintained along the shelf and the dense shelf water cascade (DWSC) persists well into the winter (Figures 4 & 5). In measurements from the end of June 2009 the gravity current appeared to be driven solely by temperature rather than in conjunction with salinity (Figure. 5)

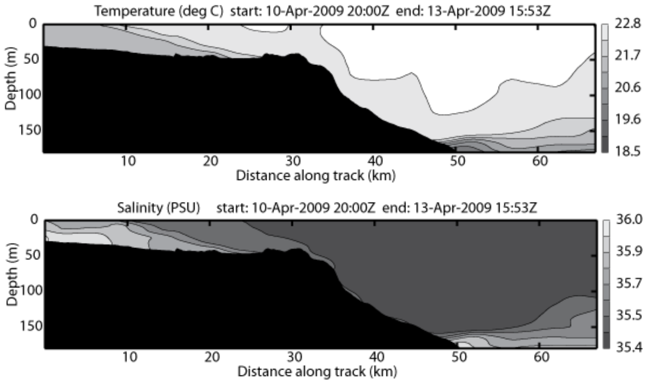

Figure 3. Offshore cross section of Temperature and Salinity off Perth, WA (April 2009)

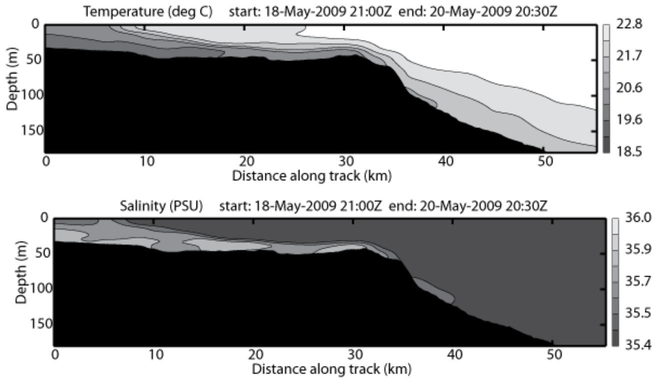

Figure 4. Offshore cross section of Temperature and Salinity off Perth, WA (May 2009)

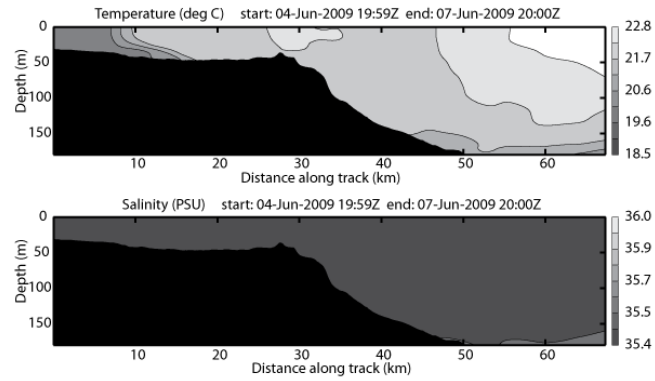

Figure 5. Offshore cross section of Temperature and Salinity off Perth, WA (June 2009)

Increased chlorophyll fluorescence was observed in the frontal region between the CC and LC as well as in the DSWC (Figure 6). The DSWC was found to penetrate up to 150 m water depth and may be an important mechanism for exchange between the shelf and slope waters.

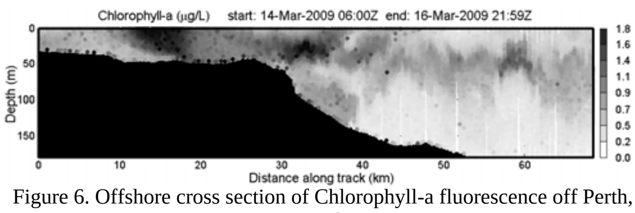

Figure 6. Offshore cross section of Chlorophyll-a fluorescence off Perth, WA (March 2009)

Slocum glider transects are providing the most detailed seasonal oceanographic information to date for the shelf region off Perth, WA.

B. *Spencer Gulf*

The Spencer Gulf is an inverse estuary located on the south coast of Australia. High evaporation in the Gulf leads to a strong salinity gradient which decreases toward the open boundary [4]. During winter, cooling in the upper reaches of the gulf results the water becoming more dense than the adjacent shelf waters which causes the high salinity water to exit the Gulf as a gravity current [4]. Due to the effects of Coriolis this outflow is concentrated to the eastern side of the gulf and shelf waters flow in to replace it along the western boundary [5]. The outflow is modulated by the spring-neap tidal cycle [3]. Glider deployments in this region aim to monitor seasonal and long term variability in continental shelf – Spencer Gulf exchange.

Glider observations from June 2009 clearly show a cool high salinity water mass on the eastern side of the Gulf entrance characteristic of the winter Gulf-continental shelf exchange (Figure 7).

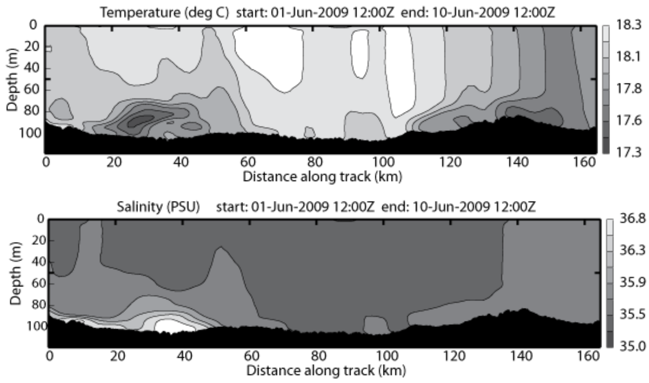

Figure 7. East to west temperature and salinity cross sections across the mouth of the Spencer Gulf, SA (June 2009)

Consistent with past observations, measurements taken during glider deployments during the summer months show strong temperature and salinity stratification across the mouth of the Gulf and do not indicate a near bottom saline outflow (Figure 8).

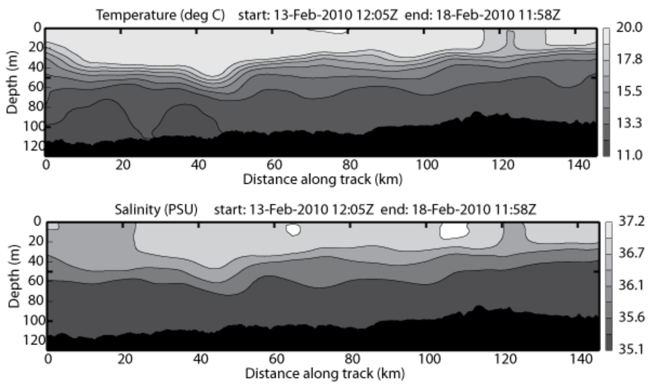

Figure 8. East to west temperature and salinity cross sections across the mouth of the Spencer Gulf, SA (February 2010)

C. New South Wales

The shelf waters of Sydney are influenced by the East Australian current (EAC), the western boundary current of the South Pacific subtropical gyre that affects the flow along much of the eastern coasts of Australia and New Zealand. Extending from the Coral Sea to the Tasman Sea, the EAC system generates numerous eddies [1]. EAC transport (southward flow) varies between a minimum of 7 Sv in winter (July) to a maximum of 16 Sv in summer.

A Slocum glider was used to monitor the physical and biological processes within a warm core eddy in November 2008 and revealed strong physical/biological interaction. After deployment off Port Stephens, the glider was transported by the EAC southwards parallel to the coast before entering the eddy. The glider was then flown into the centre of the eddy, and then back out again while undertaking one rotation of the eddy (Figure 9).

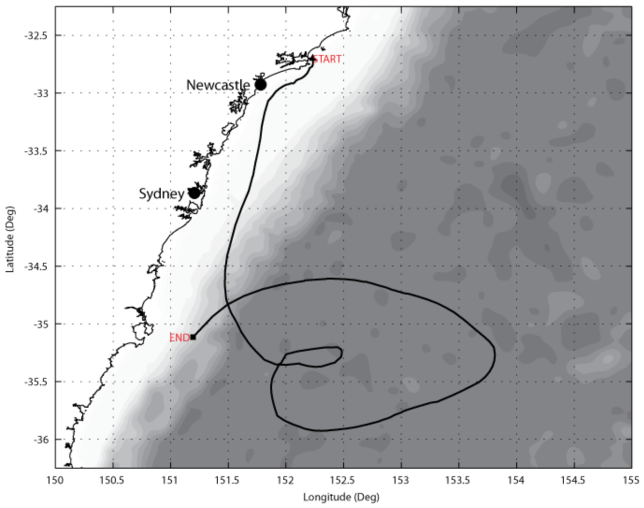

Figure 9. Slocum glider path during deployment (Nov-Dec 2008)

Observations of the eddy showed a complex vertical structure with a well mixed surface layer of 50-70 m depth and a subsurface chlorophyll maximum (SCM) below the thermocline. Chlorophyll fluorescence within the SCM was approximately an order of magnitude greater than observed in the rest of the water column (Figure 10).

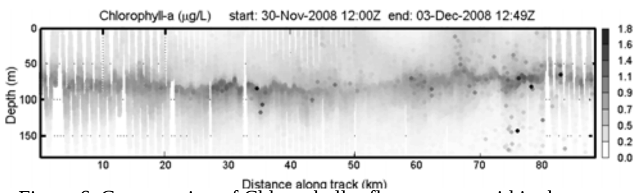

Figure 6. Cross section of Chlorophyll-a fluorescence within the centre of the warm core eddy (Nov-Dec 2009)

D. Tasmania

Three Seaglider deployments have been completed off eastern Tasmania, monitoring the East Australian current in this region. The Seaglider deployments off eastern Tasmania monitored the East Australian current in this region – the glider was entrained into an eddy and revealed very strong currents within the region (Figure 11).

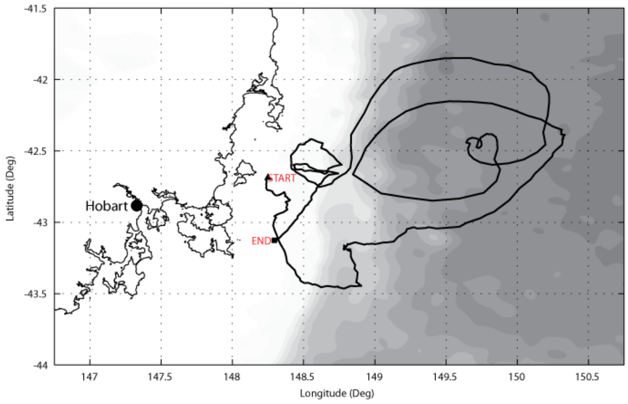

Figure 11. Seaglider glider path during deployment (Feb-Apr 2009)

ACKNOWLEDGMENT

IMOS is supported by the Australian Government through the National Collaborative Research Infrastructure Strategy and the Super Science Initiative.

REFERENCES

[1] F. M. Boland, and J. A. Church, "The East Australian Current 1978," *Deep-Sea Research*, vol. 28, pp. 937–957, 1981.

[2] C. E. Hanson, S. Pesant, A. M. Waite, and C. B. Pattiaratchi, "Assessing the magnitude and significance of deep chlorophyll maxima of the coastal eastern Indian Ocean," *Deep-Sea Research Part II*, vol. 54, iss.8-10, pp. 884-901, 2007.

[3] G. W. Lennon et al., "Gravity currents and the release of salt from an inverse estuary," *Nature*, vol. 327, pp. 695–697, 1987.

[4] R. A. Nunes, and G. W. Lennon, "Physical property distributions and seasonal trends in Spencer Gulf, South Australia: an inverse estuary," *Australian Journal of Marine and Freshwater Research*, vol. 37, pp. 39–53, 1986.

[5] R. A. Nunes Vaz, G. W. Lennon, and D. G. Bowers, "Physical behaviour of a large, negative or inverse estuary," *Continental Shelf Research*, vol. 10, pp. 277–304, 1990.

[6] A. Pearce, and C. B. Pattiaratchi, "The Capes Current: a summer counter-current flowing past Cape Leeuwin and Cape Naturaliste, Western Australia," *Continental Shelf Research*, vol. 19, pp. 401-420, 1999.

[7] K. R. Ridgway, and S. A. Condie, "The 5500-kmlong boundary flow off western and southern Australia," *Journal of Geophysical Research* vol. 109, no. C04017, 2004.

[8] R. Smith, A. Huyer, S. Godfrey, and J. Church, "The Leeuwin Current off Western Australia 1986-1987," *Journal of Physical Oceanography*, vol. 21, pp. 323-345, 1991.

WAIMOS

Western Australian Integrated Marine Observing system

IMOS Integrated **Marine Observing** System
www.imos.org.au

Charitha Pattiaratchi[1] • Ben Hollings[1] • Ming Feng[2] • Rob McCauley[3] • Merv Lynch[4] • Nick D'Adamo[5]

[1]School of Environmental Systems Engineering, The University of Western Australia, Nedlands, 6009, Australia
[2]CSIRO Division of Marine and Atmospheric Research, Wembley, WA6012, Australia
[3]Centre for Marine Science and Technology, Curtin University of Technology, Bentley, WA6102, Australia
[4]Remote Sensing and Satellite Research Group, Curtin University of Technology, Bentley, WA6102, Australia
[5]Intergovernmental Oceanographic Commission (IOC), Perth Office, West Perth, WA6005, Australia

The Western Australian Integrated Marine Observing System (WAIMOS) covers the continental shelf and slope region between Fremantle and Jurien Bay (Figure 1). Within this region there are major topographic features such as Rottnest Island and the Perth Canyon and the circulation is dominated by the Leeuwin Current (LC), Leeuwin Undercurrent (LU) and the seasonal, wind driven Capes Current (CC).

The Leeuwin Current

The major oceanic scale forcing along the west Australian coast is due to the Leeuwin Current, a poleward eastern boundary current. The LC is a shallow (< 300 m) narrow band (< 100 km wide) of relatively warm, lower salinity water of tropical origin that flows southward, mainly above the continental slope from Exmouth to Cape Leeuwin. The maximum flow of the current is located at the 200m isobath. The source of the Leeuwin Current water is from the Indian Ocean from the west and a component from the North West continental shelf which originates from the Pacific Ocean. The LC is weaker (~1.5 Sv) as it flows against the southerly (opposing) winds during October–March (summer) and stronger (7 Sv) when the southerly winds are weaker during April–September (winter). The mean volume transport is estimated to be 3.4 Sv.

The Leeuwin Undercurrent

The Leeuwin Undercurrent (LU) is located beneath the LC between the 250 m and 450 m depth contours, adjacent to the continental slope. The LU transports 5 Sv of higher salinity (> 35.8), oxygen rich, nutrient-depleted water northwards and is closely associated with the subantarctic mode water (SAMW) formed in the region to the south of Australia. A feature of this water mass, resulting from convection, is high, dissolved oxygen concentration.

The Capes Current

The Capes Current (CC) is a cool inner shelf current, originating from the region between Cape Leeuwin and Cape Naturaliste, which moves equatorward along the south-western Australian coast in summer. In the summer, the alongshore wind stress overwhelms the alongshore pressure gradient on the inner shelf (depths < 50 m), moving surface layers offshore, upwelling colder water onto the continental shelf, and pushing the Leeuwin Current offshore.

The Perth Canyon

The interaction between the LU and the canyon generates clockwise eddies within the canyon resulting in upwelling at their centre. As a result of these circulation patterns within the canyon, the canyon supports a high primary and secondary production resulting in pygmy blue whale aggregation during the summer months

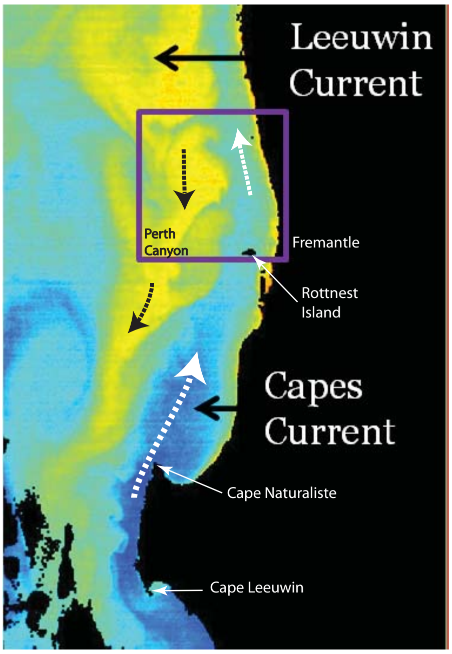

Figure 1 - Location of the main observation region (shown by square) overlain on a SST image showing major surface currents during the summer.

The Observation System

The infrastructure located in this region includes: HF Radar (CODAR and WERA systems) for surface current measurements at 2 different scales; ocean gliders (Slocum and Seagliders) for subsurface water properties (Figure 2); continental shelf moorings (ADCP, thermistor and water quality loggers); passive acoustic sensors for whale monitoring; and, remotely sensed data products (SST and ocean colour). The system has been set up to capture the variability of the LC, CC transport, cross-shelf processes and the key drivers of biogeochemical processes.

An example of the CODAR data of the Leeuwin Current (max current = 0.8 m/s) is shown on Figure 3.

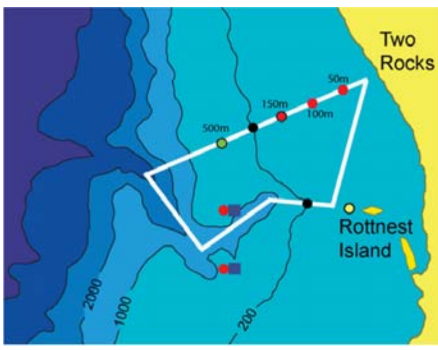

Figure 2 - Location of shelf moorings with a combination of ADCP, water quality and thermistor chains (circles). The squares are passive acoustic sensors. The white line shows the Slocum glider tracks.

An Australian Government Initiative
National Collaborative Research Infrastructure Strategy

HF Radar Data

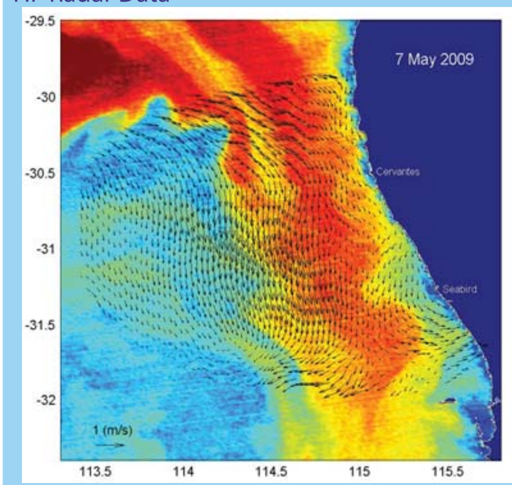

Figure 3 - HF Radar surface currents on 7 May 2009 overlain on a SST image of the same date (HF Radar provided by Mal Heron and Greg AtwaterAustralian Coastal Ocean Radar Network).

Slocum glider tracks along theTwo Rocks transect (Figure 4) shows the evolution of gravity currents on the shelf. In February, the evaporation is at a maximum and the shallow waters increase in salinity. By March, with additional evaporation, the salinity has increased significantly and the higher salinity water begins to exit the shelf. On 14th March the plume is at mid-shelf and by 21 March the plume extends across the entire shelf. By April the salinity on the shelf has decreased but the plume is still present across the shelf. In May the overall salinity of the shelf has decreased, however, the higher salinity plume is still present along the entire continental shelf.

Slocum Glider Data

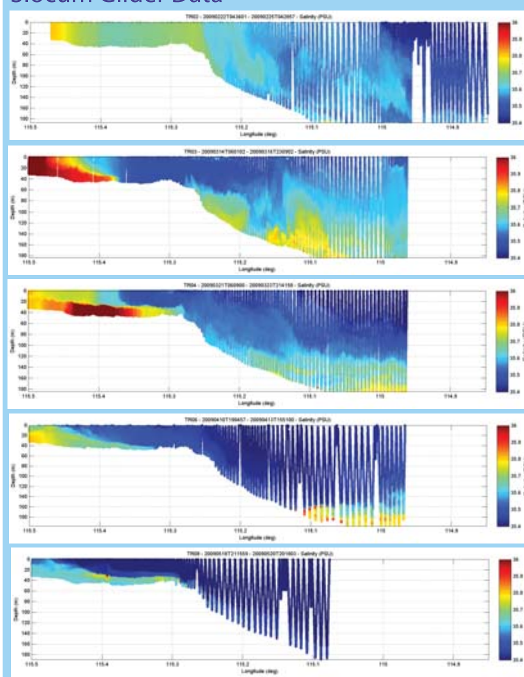

Figure 4 - Cross-shore transects of salinity along the Two Rocks transect showing higher salinity plumes exiting the shelf.
(a) 22 February 2009; (b) 14 March 2009; (c) 21 March 2009 and (d) 10 April 2009; and (e) 18 May 2009

ANFOG

Australian National Facility for Ocean Gliders

IMOS Integrated **Marine Observing** System

www.imos.org.au

• Ben Hollings • Charitha Pattiaratchi • Mun Woo •

School of Environmental Systems Engineering
The University of Western Australia
35 Stirling Highway, Nedlands, 6009, AUSTRALIA

Traditionally oceanographic sampling has been carried out from ships; however the high costs involved have limited data collection. Ocean gliders provide an alternative measurement platform and, due to their low cost and extended deployment durations, will allow the collection of sustained long term observations, even during periods of extreme weather conditions which would have prevented ship based sampling. This will allow researchers to document the natural variability of the ocean and better understand the effects of climate change on coastal ecosystems. The Australian National Facility for Ocean Gliders maintains and operates a fleet of ocean gliders as part of IMOS and provides a near-real-time data stream to researchers around Australia.

Instrumentation

Ocean gliders are autonomous vehicles designed to operate in water depths up to 1000 m. By changing their volume which in turn alters their buoyancy, gliders are able to descend and ascend through the water column. This momentum is converted to forward motion by wings. Pitch adjustments are made by moving an internal mass (battery pack) fore or aft and steering is done using a rudder or by rotating an internal mass.

Moving at an average horizontal velocity of 25 - 40 cm/s gliders navigate their way to a series of pre-programmed waypoints using GPS, internal dead reckoning and altimeter measurements.
The gliders are programmed to provide data through satellite communication when they are at the surface and it is also possible to remotely update the waypoints or other parameters during its mission. Depending on the type of glider and the number of vertical 'dives', the endurance of a glider ranges between 1 and 6 months. Weighing only 52 kg, gliders are able to be easily deployed and recovered by two people from a small boat.

Table 1: Glider specifications

	Slocum	Seaglider
Type	Coastal	Open Ocean
Depth Range	20-200m	Up to 1000m
Length	1.8 m (2.15 m inc. antenna)	1.8 m (2.85 m inc. antenna)
Mass	52 kg	52 kg
Batteries	250 Alkaline C-Cells Energy:8 MJ Mass: 18kg	81 Lithium D-Cells (in 2 packs) Energy: 10 MJ Mass: 9.4kg
Volume Change	Max 460 cc	Max 840 cc
Communication	Iridium GPS Navigation Freewave RF-modem (30km range) ARGOS transmitter	Iridium GPS Navigation
Steering	Active rudder	Rotating internal mass
Endurance	30 days	6 months (650 dives to 1000m)
Range	500 km	4600 km
Speed	40 cm/sec	25 cm/sec

The ANFOG glider fleet currently consists of 4 Slocum gliders and 5 Seagliders.

Figure 1: Inside a Seaglider

The Seaglider, designed and built by The University of Washington is designed to operate in the open ocean region. With a maximum dive depth of 1000m the Seaglider is an effective tool for monitoring the shelf slope & open ocean region. Powered by LiSoCl2 batteries the Seaglider is capable of missions of up to 6 months duration.

The Slocum glider, designed and built by Teledyne Webb Research, is designed to operate in the coastal region to a maximum depth of 200m and powered by alkaline batteries has a maximum endurance of 30 days.

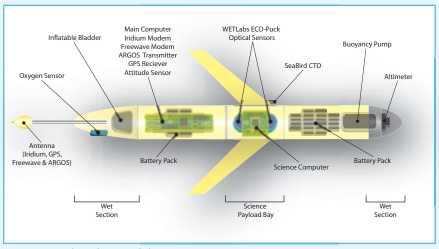

Figure 2: Inside a Slocum Glider

Sensors

The sensor payload can be changed according to specific needs and is only limited by power consumption and space requirements.
All ANFOG gliders are instrumented with a similar suite of sensors to measure conductivity (for salinity), temperature, dissolved oxygen, chlorophyll-a fluorescence, turbidity and CDOM (dissolved organic matter) with depth.

Data

The glider's saw tooth dive profile allows it to sample the ocean both vertically and horizontally. Core data parameters of temperature, salinity, fluorescence, oxygen & turbidity are collected as the glider moves through the water column. Depth averaged currents are also estimated based on the variation between dead reckoned position and GPS position.

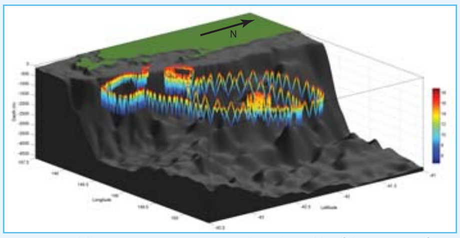

Figure 3: Seaglider temperature measurements through an eddy off the east coast of Tasmania (Feb-Apr 2009)

A subset of this data is transmitted during the deployment and is available in near real-time, a complete data set is saved within the glider and downloaded upon retrieval.

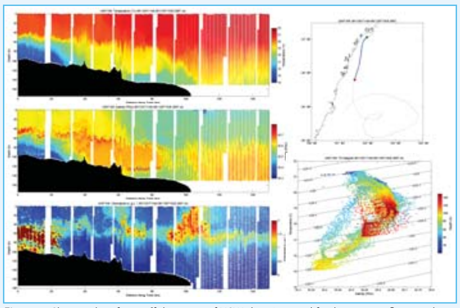

Figure 4: Slocum data from off the coast of NSW showing cool freshwater outflow on the continental shelf (Nov 2008)
a) Temperature; b) Salinity; c) Chlorophyll-a; d) Glider path; e) T-S Diagram

The data retrieved from the glider fleet will contribute to the study of the major boundary current systems surrounding Australia and their link to coastal ecosystems.

Plots of near-real-time glider data and positions are available from the ANFOG website at: www.anfog.uwa.edu.au

www.anfog.uwa.edu.au

An Australian Government Initiative
National Collaborative Research Infrastructure Strategy

ANFOG Glider Deployments

Over the past 6 months ANFOG has successfully completed glider deployments in New South Wales, South Australia, Western Australia and Tasmania.

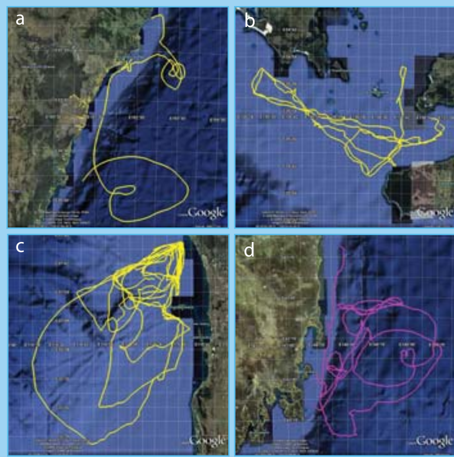

Figure 5:
a) NSW Slocum Glider Tracks; b) SA Slocum Glider tracks;
c) WA Slocum Glider Tracks; d) TAS Seaglider Tracks

Between November 2008 and June 2009 ANFOG has completed 10 successful Slocum glider deployments.
Traversing 5463 km over 209 days of deployments the Slocum fleet has collected over 31,000 vertical profiles of oceanographic data.

Table 2: Slocum deployment summary (June 2009)

Glider	Project	Location	Date Deployed	Date recovered	Duration	Distance	Casts
unit109	NSWIMOS	Port Stephens, NSW	25-Nov-08	11-Dec-08	16 days	1002.8 km	1484
unit104	SAIMOS	Marion Bay, SA	15-Jan-09	05-Feb-09	21 days	518.4 km	3594
unit106	WAIMOS	Fremantle, WA	20-Jan-09	10-Feb-09	21 days	486.9 km	2937
unit106	WAIMOS	Fremantle, WA	20-Feb-09	13-Mar-09	21 days	445.0 km	3225
unit104	WAIMOS	Fremantle, WA	13-Mar-09	27-Mar-09	14 days	347.6 km	2232
unit109	NSWIMOS	Harrington, NSW	17-Mar-09	09-Apr-09	23 days	705.6 km	1721
unit104	WAIMOS	Fremantle, WA	02-Apr-09	27-Apr-09	25 days	517.3 km	3939
unit109	WAIMOS	Fremantle, WA	15-May-09	03-Jun-09	19 days	380.0 km	4300
unit104	SAIMOS	Marion Bay, SA	28-May-09	24-Jun-09	27 days	600.0 km	3712
unit130	WAIMOS	Fremantle, WA	03-Jun-09	25-Jun-09	22 days	459.4 km	3914
				TOTAL	**209 days**	**5463 km**	**31058**

Two Seaglider deployments have been completed, both off the east coast of Tasmania. During these deployments the gliders covered a total of 2075 km during their 123 days at sea and collected 1920 vertical profiles, many of which to 1000m.

Table 3: Seagldier deployment summary (June 2009)

Glider	Project	Location	Date Deployed	Date recovered	Duration	Distance	Casts
SG154	BLUEWATER	Maria Island, TAS	13-Feb-09	14-Apr-09	60 days	1200 km	860
SG151	BLUEWATER	Bicheno, TAS	22-Apr-09	24-Jun-09	63 days	875 km	1060
SG155	SAIMOS	Portland, VIC	26-May-09	*	30 days*	410 km*	450*
				TOTAL	**213 days**	**2485 km**	**2350**

* Deployment in progress