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NSW-IMOS: An Integrated Marine Observing System for Southeastern Australia.

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Abstract.
The East Australian Current (EAC) and its eddy field dominate the shelf circulation along the coast of SE Australia. It impacts the climate, weather and fisheries along the most populated part of the Australian coastline. Yet there is much we don't know about the EAC and its role in the transport of heat, generation of eddies, its role in upwelling and the associated biological processes. In this paper we introduce the New South Wales node of the Integrated Marine Observing System (NSW-IMOS). The observing system is designed to complement extant observations in the region and capture key continental shelf processes such as slope water intrusions and encroachments of the EAC, the generation of eddies and the biological response to such events.

1. Introduction

The East Australian Current (EAC) flows poleward from the Coral Sea to the Tasman Sea. It impacts the coastal ocean along its path, particularly along the coast of southeastern Australia where the EAC and its eddy field dominate the shelf circulation [1]. It is in this region that the ocean has warmed more than 2°C/100yr in the past century [2]. The effect of increased ocean temperatures will impact on our climate, weather and marine ecosystems, where some species will prosper and others will decline [3]. This region is also where that the majority of the Australian population live (`http://www.censusdata.abs.gov.au`). In 2007 the Australian government commenced funding implementation of the Australian Integrated Marine Observing System (IMOS, `http://imos.org.au/`, [4]).

The goal of NSW-IMOS is to devise an observing system which will comprehensively examine the physical and ecological interactions of the East Australian Current and its eddy field with coastal waters and to assess the impacts of climate change. More specifically:

- To investigate the EAC, its separation and resultant eddy field along the coast of SE Australia: Determine seasonal and spatial variability in the separation of the EAC from central NSW; Determine the formation, frequency, and evolution of EAC eddies; Understand air sea interactions, particularly to determine the ontogeny of East Coast Lows and severe winter storms in relation to warm core eddies.

- To quantify key continental shelf processes along the coast of SE Australia: Quantify the impact of key processes such as onshore encroachment of the EAC, slopewater intrusions, upwelling, downwelling and internal waves; Quantify the seasonal and decadal variation in the EAC and its southward extension; Examine the coastal wind and wave climate in driving nearshore currents and the northward sediment transport.
- To determine the biological response to oceanographic and climate effects.

We will achieve these goals through an integrated monitoring program along the NSW continental shelf which includes: a network of oceanographic mooring arrays, high frequency coastal radar to enhance spatial coverage, monthly biogeochemical sampling, regular coastal and bluewater surveys by autonomous ocean gliders and an underwater vehicle, and deployment of acoustic receivers for the tracking of tagged fish. The full NSW-IMOS plan can be obtained from `http://imos.org.au/nswimos.html` [5].

The *in situ* data when combined with satellite observations, enable the modelling required to explain the role of the oceans in seasonal prediction and climate change. Sustaining the project will allow identification and management of climate change in the coastal marine environment. It will also provide the observations necessary to better understand and predict the fundamental connections between coastal biological processes and regional/oceanic phenomena that influence biodiversity. A review of the current literature on the East Australian Current is outlined in [6] which sets the framework under which this ocean observing system was designed. The observing system presented here represents a new way forward for integrated observations of the waters of southeastern Australia and goes some way towards filling some of the knowledge gaps that exist in our understanding of the EAC.

2. NSW-IMOS Instrumentation Plan

2.1. Sydney National Reference Transect

To build on our long history (since 1942) of hydrographic observations at the 50 m and 100 m Port Hacking stations, we devised a National Reference Transect (NRT) off Sydney. This transect consists of three moorings shore normal off Bondi, a fourth mooring and four hydrographic sampling locations off Port Hacking (Table 1). This area is typically downstream of the EAC separation and is often influenced by EAC eddies.

2.1.1. Moored Observations The Ocean Reference Station (ORS) is the only site of sustained moored observations along the coast of NSW, operating since Nov 1989 [7]. The ORS is located 3 km off Bondi Beach, in 65 m of water (Table 1). Seven wave-rider buoys have been maintained (for up to 30 years) by the Manly Hydraulics Laboratory (MHL, NSW Department of Commerce) [8]. The buoys are typically in 70 m water depth and between 6−12 km from the coast (Figure 1).

Presently the SYD100 and SYD140 moorings (Table 1) consist of a bottom mounted TRDI 300 kHz acoustic Doppler current profiler (ADCP) housed in a rigid frame with gimbal mount, which measures velocity through the water column in 8 m bins with a 5 min sampling interval. Temperature is recorded at 5 min intervals using a series of Aquatech 520T, and 520PT Aqualoggers at 8 m intervals throughout the water column (co-inciding with the middle of each ADCP bin) to within 20 m of the surface. Additional pressure/temperature loggers are placed at 4 depths (bottom, sub-surface and 2 mid-water column) so as to estimate mooring lay-over. These moorings were initially deployed in June 2008 and apart from some data losses due to instrument failure a comprehensive data set has been returned. In time the PH100 site will be instrumented with two Wetlabs water quality meters (WQM) near bottom and sub-surface, that consists of a SeaBird CTD, as well as measurements of fluorescence, dissolved oxygen and turbidity. It is our intention that as the program progresses these data will be telemetred back to land and made available in near real-time.

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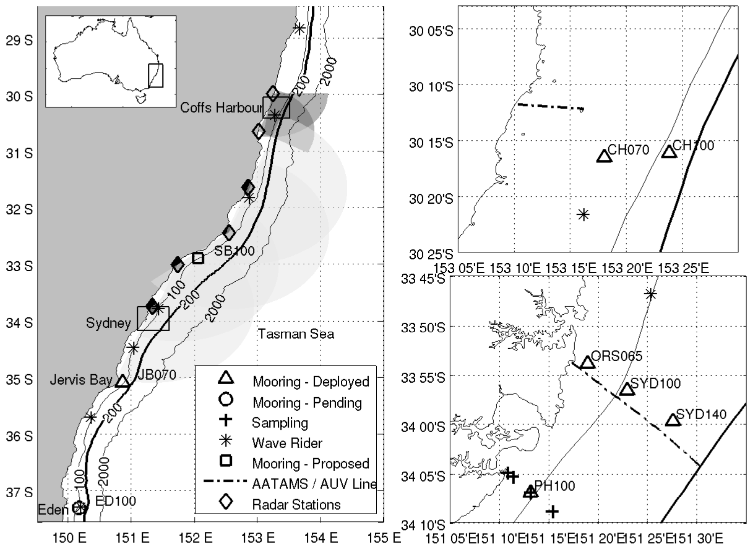

Figure 1. Map showing locations of the present (deployed), pending and proposed moorings as well as the hydrographic sampling locations and the wave-rider buoys. Subpanels (right) show expansions of the Coffs Harbour (top) and Sydney (bottom) regions. Dashed lines show the listening post transects. Diamonds show the locations of the HF Radar stations. Dark shading shows the coverage of the pending WERA HF Radar array at Coffs Harbour and light shading shows the coverage of the proposed CODAR array in Stockton Bight.

2.1.2. Biogeochemical Sampling In addition to the historic biogeochemical sampling, monthly sampling along the NSW-IMOS NRT (Table 1) includes hydrographic measurements, Conductivity, Temperature and Depth (CTD) profiles, water quality, chlorophyll sampling at PH050 and PH100 plus a plankton net sample and a water sample for genetic analysis at PH100. Monthly sampling along the NSW-IMOS NRT off Port Hacking also serves to calibrate fluorometric observations obtained from the instrumented moorings and ocean colour estimates of chlorophyll obtained from satellites (e.g. MODIS), chlorophyll, total suspended solids and coloured dissolved organic material (CDOM).

Table 1. Details of NSW-IMOS mooring sites and biogeochemical sampling sites (PH). * CSIRO funded sampling for temperature and nutrients. @ IMOS funded sampling for chlorophyll-a, pigments (HPLC) CDOM, PAR, phytoplankton and zooplankton. #The exact location is still to be finalised.

Platform Code	Latitude °S	Longitude °E	Depth (m)	Dist (km)	Principal Axis (°T)	Local Isobath (°)	Maintained Since
CH070	30°17.00′	153°17.91′	70	15			August 2009
CH100	30°16.07′	153°23.80′	100	22.2			August 2009
ORS065	33°53.88′	151°18.9′	65	2.1	13.4	16	1989
SYD100	33°56.63′	151°23.03′	100	9.9	18.3	26	June 2008
SYD140	34°00.08′	151°27.92′	140	19	25.0	28	June 2008
PH100	34°06.98′	151°13.14′	100	6.1	-	-	December 2009
JB070	35°05′	150°51′	70	1.85	-	-	July–Oct 2009
ED100#	37°18.96′	150°19.50′	100	25	-	-	N/A
PH025	34°04.94′	151°10.79′	25	0.9	-	-	April 1997
PH050*	34°05.35′	151°11.35′	50	2.1	-	-	December 1942
PH100*@	34°06.98′	151°13.14′	100	6.1	-	-	May 1953
PH125	34°08.88′	151°15.37′	125	11.1	-	-	April 1997

2.2. Additional moorings along the NSW Coast
Additional moorings will be deployed along the NSW coastline to complement the arrays beyond the NSW borders.

Coffs Harbour, 30° ***S:*** Oceanographically this area is typically upstream of the separation point of the EAC, (downstream of the Great Barrier Reef (GBR)) and biologically this area has already been recognised nationally with the designation of the Solitary Island Marine Park. Coral species found there are highly diverse with unique associations of tropical species near their southern latitudinal range as well as subtropical species that are absent or rare in the GBR. This region (and further north to Cape Byron) is exemplified by strong warm currents and a complex wave climate opposing the mean flow. Two moorings similar in configuration to the Sydney moorings have been deployed at the 70 m (CH070) and the 100 m (CH100) isobaths (Table 1) since late 2009.

Stockton Bight, 33° ***S:*** The Stockton Bight-Myall Shore region is known for its biological productivity. It is typically downstream of the EAC separation area and is on the receiving end of a seemingly persistent nutrient supply associated with the separation of the EAC. We plan to deploy a mooring equipped with CTD, ADCP and thermistor string (Figure 1), pending further funding.

Eden, 37° ***S:*** The mooring will again be similar to the SYD140 mooring consisting of a bottom mounted ADCP and a thermistor string throughout the water column (Figure 1), to be deployed in 2010. This will give a record of the predicted extension of the EAC into southern waters.

2.3. HF Radar
A medium range WERA HF Radar system will be deployed off Coffs Harbour in mid 2010 (Figure 1). The system provides spatial maps of surface currents ($\sim$ 1 m depth), as well as wave height, period and direction, and possibly wind direction at hourly intervals. We anticipate coverage out to $\sim$ 70 km offshore with a resolution of $1 - 1.5$ km. As the shelf is very narrow this range should see well out beyond the 2000 m isobath and generally cover the width of the narrow EAC jet. This will provide information on shelf edge processes, flow topography interactions and the generation of EAC instabilities. We intend to deploy a long range CODAR array in the Stockton Bight region when further funding becomes available (Figure 1). This will enable monitoring of the EAC separation and eddy field.

2.4. Autonomous Ocean Gliders
Ocean gliders will be deployed on a regular basis (4 per year, since late 2008) to map the 3-D structure of the EAC and its eddy field. To date five successful Slocum glider deployments have been undertaken in the EAC eddy field. The continuous sub-surface optical measurements obtained by the glider represent a significant advance on the occasional vertical light profiles from ship-based CTDs [9].

3. Preliminary Results from the Sydney Mooring Array: June 2008−June 2009
The 5 minute velocity data from the 3 Sydney moorings (Table 1, Figure 1) have been subsampled to hourly and lowpass filtered with a 36 h cut off frequency and a cosine taper applied to the last 5%. The data were rotated to alongshore (v) and across-shore (u) as per the calculation of the principal axis after consideration of the local isobath direction (Table 2). At all three sites across the shelf, mean alongshore velocities ($-0.1, -0.16, -0.1$ ms^{-1}, at ORS, SYD100, SYD140 respectively) are typically an order of magnitude larger than across-shore velocities. Mean magnitudes ($0.18, 0.23, 0.17$ ms^{-1}) are directed poleward ($184°, 175°, 179°$ respectively). Inshore (ORS) velocities are typically variable with a range of $v = -1.19$ to 0.78 ms$^{-1}, u = -0.19$ to 0.19 ms^{-1} where negative indicates poleward (onshore) transport. Midshelf (SYD100) velocities

Table 2. Mooring data statistics calculated from the hourly, depth-averaged, lowpass filtered data for the mooring array off Sydney (Figure 1, Table 1). Note: due to instrument failure at SYD140 maximum velocities recorded were anomalously lower than at SYD100.

	u (ms^{-1})			v (ms^{-1})			T (°C)		
	ORS	SYD100	SYD140	ORS	SYD100	SYD140	ORS	SYD100	SYD140
Mean	-0.01	0.01	0.00	-0.09	-0.19	-0.10	17.5	17.0	17.0
Std	0.03	0.05	0.06	0.22	0.26	0.17	1.87	1.93	2.25
Skewness	-0.35	-0.10	0.02	-0.34	-0.84	-0.42	0.64	0.78	0.61
Max	0.19	0.25	0.33	0.78	0.89	0.50	23.8	24.3	24.7
Min	-0.19	-0.24	-0.34	-1.19	-1.39	-1.29	13.8	13.3	12.6

are marginally stronger ranging $v = -1.39$ to 0.89 $ms^{-1}, u = -0.24$ to 0.25 ms^{-1}. At the shelf break velocities are typically greater, however due to instrument failure during an extreme event this is not reflected in the statistics (range $v = -1.29$ to 0.5 $ms^{-1}, u = -0.34$ to 0.33 ms^{-1}). Standard deviation in alongshore velocity is greatest midshelf (0.26) with a skewness of -0.84 indicating the predominance of poleward velocities along the shelf. Maximum poleward velocities off Sydney typically occur with EAC eddy intrusion events where the eddy moves across the continental shelf. Currents are generally baroclinic, however at times during strong equatorward flow barotropic currents exist (Figure 2). Vertical velocity shear is greatest during strong poleward current events, and at the inner shelf.

As with velocity, maximum temperatures co-incide with EAC eddy intrusions where mooring knockdowns of up to 30 m vertically have been recorded. At all three sites maximum water temperatures occurred during May 2009 (end of Autumn) of $23.8 - 24.7$°C across the shelf. Temperature exhibits strong stratification throughout the water column. The vertical temperature range is similar across all three sites ranging $\sim 12 - 24$°C. Standard deviation in temperature ranges $1.8 - 2.2$°C across the shelf with positive skewness. The onshore encroachment of eddies significantly alters the temperature field and mixed layer depth.

4. Discussion: National Context and Future Directions

The IMOS array described here gives for the first time simultaneous measurements of the EAC along the NSW coastline. It also provides timeseries of parameters not previously recorded (such as fluorescence, dissolved oxygen and pH). The data sheds new light on EAC interactions with the continental shelf and cross shelf processes including frequency, intensity and duration of events. With time the biological response to such events will also be quantified. The spatial and temporal coverage allowed for by the array will provide context for the more patchy historical data. It will also contribute to improved model parameterisation and prediction capability

An advantage of IMOS when compared to some international counterparts is that there is a level of federal co-ordination, particularly with regards to the distribution of new funding for the extension of IMOS through to 2013. The national backbone that integrates and links all the observations in a national context consists of the data management facility (`http://imos.aodn.org.au`), a satellite remote sensing facility and a network of nine national reference stations where identical measurements of physical and biogeochemical parameters are undertaken on a regular (nominally monthly) basis.

The development of a complete system from observations to hindcasts, nowcasts and forecasts will likely take decades. What we present here is the initial implementation over the first seven years and the vision for the future. While the initial focus has been on the physical environment

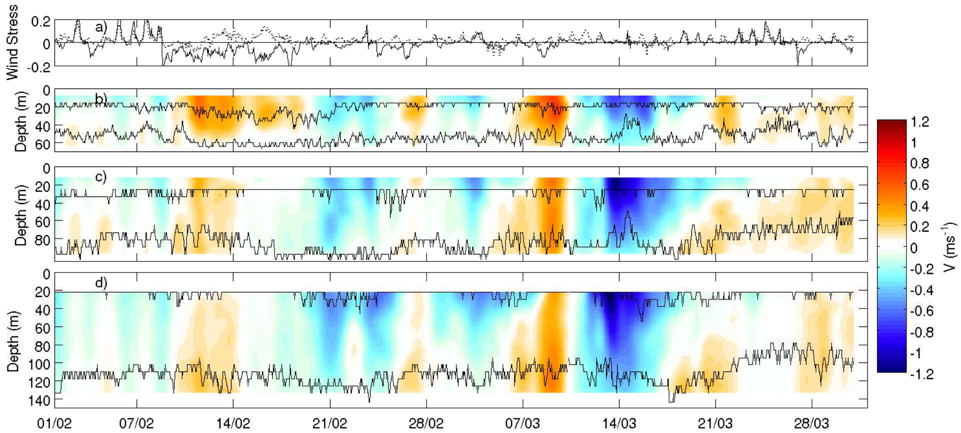

Figure 2. a) Surface wind stress (Pa), alongshore (-), across-shore (...), b–d) Alongshore velocity (v) at b) ORS065, c) SYD100, d) SYD140 for 1 Feb – 31 Mar 2009. Wind stress was calculated from the u and v components of wind velocity measured at Sydney Airport. Solid black lines represent the depth of the surface and bottom mixed layers.

this is by no means setting limitations on future directions. Already the observing system includes a series of shore normal arrays of listening posts for tagged fish, deployed off Sydney and Coffs Harbour to coincide with the locations of our moorings (Figure 1). This will be extended to the south coast in 2011. The data will give a better understanding of relationship between oceanographic conditions and the movement of many species of tagged fish and sharks. Furthermore as more reliable and cost effective biogeochemical sensors become available the system will be augmented to include more parameters.

Acknowledgments

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