

Sustained Ocean Observing along the Coast of Southeastern Australia: NSW-IMOS 2007–2014

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1. INTRODUCTION

The East Australian Current (EAC) flows poleward along the coast of southeastern Australia forming the western boundary current of the South Pacific subtropical gyre. This is the most populated region of Australia; hence, the warm current influences the climate and marine economies of nearly half the Australian population. The current transports heat and biota poleward, as well as driving cross-shelf exchange as it flows from the tropics to the Tasman Sea. As the EAC has strengthened in recent decades, the waters off the coast of southeastern Australia have warmed significantly, at a rate of three to four times the global average.¹ Off the coast of New South Wales (NSW),² studies have showed that surface waters have warmed at a rate of 0.75 °C per century (~34°S), whereas further to the south (~42.5°S), the surface waters have warmed at a rate of 2.02 °C per century². Increasingly, we are seeing the associated impacts of tropicalization on marine ecosystems, particularly in western boundary currents such as the EAC.³

Since 2006, the Australian Federal government has invested over \$120 M in Australia's Integrated Marine Observing System (IMOS, www.imos.org.au), which has had matching co-investment from industry, universities, stakeholders, and state and federal agencies. The main goal is to provide a multidisciplinary, multi-institutional approach to enhance the observation and understanding of the oceans around Australia. The funding flows through 10 centrally coordinated "infrastructure" facilities that have the responsibility of deploying ocean observing equipment in the oceans around the Australian continent, covering physical, chemical, and biological variables. (See Ref. 4 this book for an in-depth description of the one such facility, ACORN—the Australian Coastal Ocean Radar Network.) These facilities are supported by the National IMOS office and an eleventh data facility responsible for data management.

Nationally, the scientific community has self-organized into a number of broadly state-based scientific nodes, covering the coastal oceans around Australia. These being NSW-IMOS (southeast coast), Q-IMOS: Queensland (northeast coast and northern Australia), WAIMOS (west coast), SAIMOS (south coast), and Tas-IMOS (Tasmania). In addition, an all-encompassing Blue Water and Climate Node focuses on the deep water and long time scale processes. The IMOS infrastructure is deployed in accordance with the scientific plans (developed by each node) that have each undergone international peer review. In addition to the individual node plans, the national IMOS steering committee has developed a national science plan that encompasses the overarching science themes and objectives of IMOS. Each of these science plans is available on the IMOS Website. IMOS has been remarkably successful to date, and all data collected through IMOS are freely available to the research community (<http://imos.aodn.org.au/imos123/home>). Here, we focus on the IMOS implementation along the coast of southeastern Australia, as guided by the New South Wales node of IMOS (NSW-IMOS).^{5,6}

2. NSW-IMOS IN THE NATIONAL CONTEXT

2.1 SCIENCE OBJECTIVES

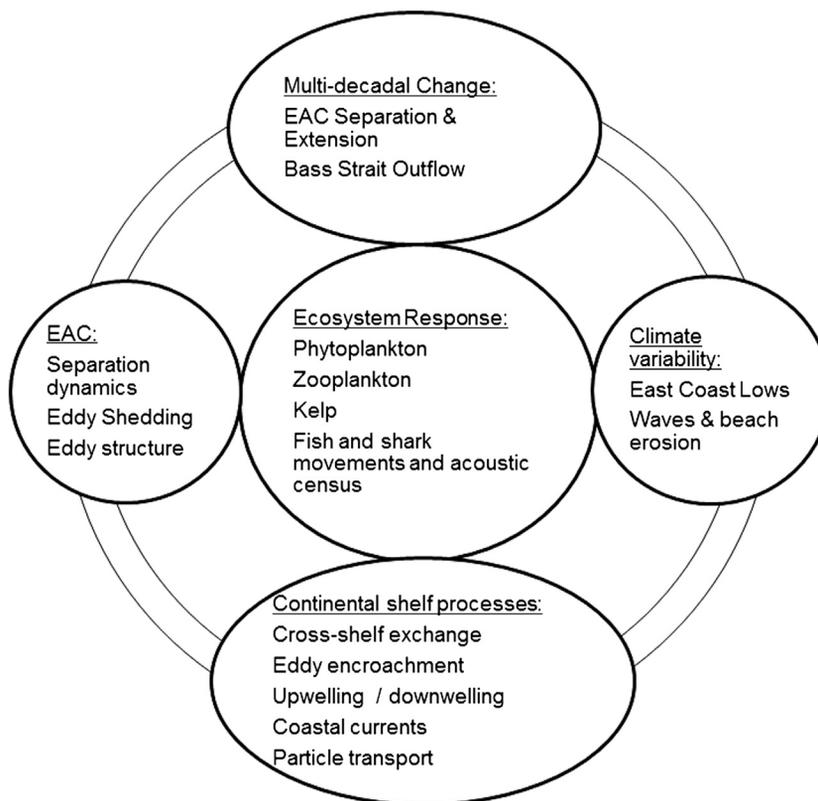
Through the evolution of the IMOS program, a set of national science plans has been developed, one for each of the regional science nodes. This process has allowed the marine and climate science community to come together and provide the scientific rationale for a national-scale Integrated Marine Observing System (IMOS). Through this, a number of unifying national overarching goals were identified: (1) multidecadal ocean change, (2) climate variability and weather extremes, (3) major boundary currents and inter-basin flows, (4) continental shelf and coastal processes, and (5) the ecosystem response.⁷

Each of the coastal nodes then formulated their science themes in the context of the national objectives (<http://imos.org.au/plans.html>); for example, each of the regional nodes is working to understand the dynamics of their respective boundary current and inter-basin flows. In the case of NSW-IMOS, the science themes revolve around the East Australian Current and its role in each of the 5 themes (see Figure 1). For example, under theme 1, multidecadal change, we are addressing questions such as how is the heat transport of the EAC changing, including the offshore recirculation and the poleward eddy transport. As another example, in the context of theme 4, continental shelf processes, we wish to understand the frequency, magnitude, and drivers of upwelling and downwelling processes and slope water intrusions in the coastal waters off NSW and how they influence cross-shelf exchange of properties.

2.2 SOCIO-ECONOMIC DRIVERS

Australia is a vast continent about the size of the mainland United States, with a small population (less than 23 M). More than half these people live within 50 km of the coast that stretches from Brisbane to Melbourne, making this the most populated region of the country. In addition, more than 80% of the population live in coastal regions. Thus, despite the size of the continent, we are primarily a marine nation. Therefore, major coastal issues affect a vast number of the population. These issues include urbanization, water quality, freshwater supply, beach erosion, and severe storms. Severe storms such as East Coast Lows are generally formed over the ocean, bringing high rainfall, high winds, and significant wave height, often causing widespread destruction and coastal erosion. The defense sector collaborates with the research community on operational generation of ocean forecasts, but in general, defense activities are currently not as significant a driver of ocean research in Australia as in other countries, such as the United States.

More than 3500 km² of coastal waters along the NSW coastline (to the three-nautical-mile limit) have been designated as multiple use Marine Estates, to conserve marine biodiversity, maintain ecological processes, and provide for

**FIGURE 1**

Conceptual model of the science goals of NSW-IMOS in the framework of the five national IMOS science themes.

Adapted from Ref. 7.

ecologically sustainable use, public appreciation, and education. In this respect, science needs are associated with a need to understand habitat distributions and connectivity of populations in the context of marine park planning.

Though there are presently no major mining activities off our coastline, the ports associated with the international export of coal are areas of major coastal activities. Along the coast of southeastern Australia, although the fishing effort is modest (the EAC, a western boundary current, is oligotrophic by nature), marine tourism is a major economic driver. Perhaps the biggest threats to the region are associated with the warming and strengthening of the EAC and implications for tropicalization of temperate regions (including habitat loss and invasive species), changes to ocean productivity, and increased storm activity.^{7,8}

3. THE NSW-IMOS INFRASTRUCTURE—DESIGN OF THE ARRAY

As with any observing system, the design of the NSW-IMOS array needed to serve a number of competing needs (both scientific and societal as previously mentioned), while working within the constraints imposed by financial and human resources. The advantage to the top-down approach implemented in Australia is that the science needs were articulated first, and the array was then designed to try to meet those objectives in a structured way. This is in contrast to some of the more bottom-up approaches taken elsewhere, where observing systems grew upward from individual efforts at combining process studies and sustained observations. NSW-IMOS covers more than 2000 km of coastline. Hence, we identified three key areas to concentrate observational efforts: upstream of the EAC separation (30°S), downstream of the EAC separation point (34°S), and in the EAC extension (36°S). Complementary observational platforms were colocated to derive maximum benefit in terms of spatial (vertical and horizontal) and temporal coverage. Each of the pieces of the observing system are described briefly in the next sections, along with how they integrate to the whole.

3.1 EAC TRANSPORT ARRAY

The East Australian Current forms the western boundary current of the South Pacific subtropical gyre. It is the main pathway for heat transport along the coast of south-east Australia, and it redistributes heat between the ocean and atmosphere on its journey poleward. Little is known about its deep subsurface structure, undercurrent, and the time variability of the flow. To address these issues, a full transport resolving mooring array was deployed for an 18-month period from April 2012 to August 2013. The array consists of five moorings extending eastward along a line at approximately 26°S , from 154 to 155.5°E , in depths between 1500 and 4750 m (Figure 2(a)). The deep water array is augmented by three shelf moorings, extending the line inshore onto the continental shelf. This data will provide the upstream boundary condition for future modeling studies of the EAC. A data assimilation project is ongoing to assess the utility of this array in predicting EAC separation and eddy shedding.

3.2 HF RADAR

The Coffs Harbour region in northern NSW ($\sim 30^{\circ}\text{S}$) was chosen as the location of the only high-frequency surface radar pair along the continental shelf of south-eastern Australia (Figure 2(a)).⁴ The location was chosen for a number of reasons: Coffs Harbour is generally upstream of the EAC separation point, and in this region, submesoscale frontal eddies are frequently formed on the inside edge of the EAC. In addition, both state and federal marine reserves have been designated in the

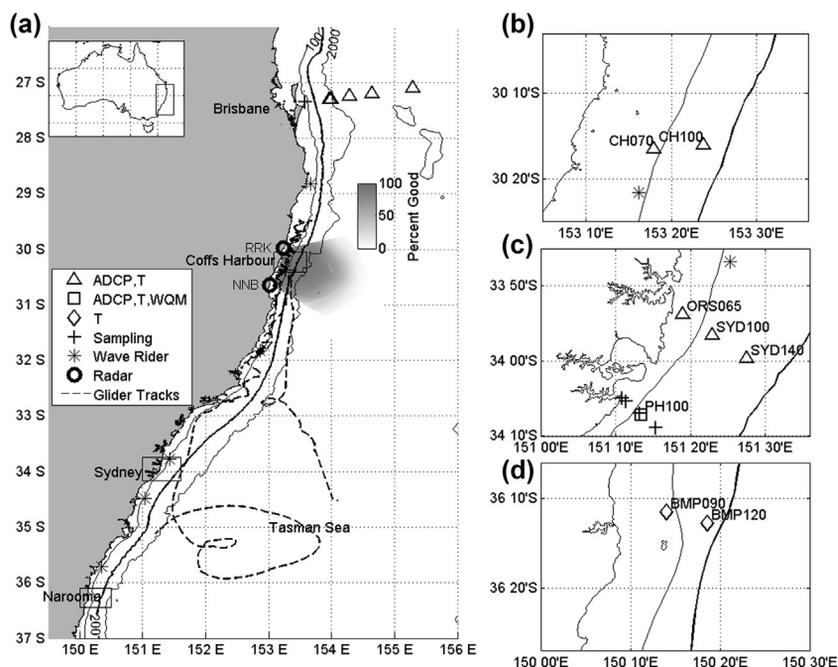


FIGURE 2

(a) Map showing the location of the NSW-IMOS study sites along the east coast of Australia and collocation of equipment. HF radar coverage from the two sites at RRK (Red Rock) and NNB (North Nambucca) is indicated by the shading, with the circles showing the land-based wave ride buoys. Dashed lines indicate representative glider paths, a star shows the location of wave ride buoys. Right panels show a zoom of the location of the oceanographic moorings at (b) Coffs Harbour, (c) Sydney, and (d) Narooma. Instrumentation is as per the legend—ADCP measures velocity through the water column, T is temperature through the water column, WQM indicates biogeochemical sampling at a fixed depth, and sampling (+) indicates where physical biogeochemical samples are taken.

region, which is known for its biological significance, at the intersection between the northern extent of kelp and southern extent of coral.

Land-based WERA systems were deployed at Red Rock (30°S, [Figure 2](#)) and North Nambucca (30.6°S, [Figure 2\(a\)](#)). Each site consists of a transmitter (13.92 initially, now 13.5 MHz, 100 kHz bandwidth) and an array of 12 receivers. This measures surface current velocities at a spatial resolution of 1.5 to 2 km with a maximum range of 100 km offshore.^{4,9}

Due to the high spatial resolution of the data, for the first time, we have resolved the surface velocity structure of a number of submesoscale coherent flow structures, including eddies, fronts, and filaments. Increasingly, processes such as coastal cold core eddies are being recognized for their impact in entrainment of shelf waters,

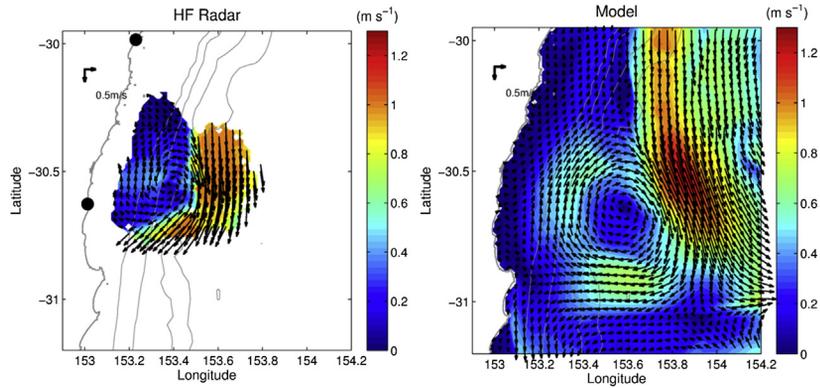


FIGURE 3

Snapshot of surface current vectors and intensity (color) from HF radar observations (left) and ROMS modeling (right) on July 9, 2012. The coastline and 100-, 200-, 1000-, and 2000-m isobaths are shown in gray.¹¹ Black dots (left) indicate the location of the two HF radar sites.

which are likely enriched with nutrients and seed populations (see Ref. 10 this book). Surface velocity fields captured by the radar allow for an investigation into the evolution of such features, and when combined with numerical modeling, can resolve the dynamical drivers. One such example of a submesoscale cold core eddy is given in Figure 3, where an attempt has been made to reproduce the flow field in a numerical simulation.¹¹

3.3 GLIDERS

Under the IMOS arrangement, gliders are managed by a centrally coordinated facility (ANFOG, www.anfog.ecm.uwa.edu.au). This results in a nationally consistent approach to QA/QC, calibration, and data processing, and it reduces maintenance and management costs. There are down sides to this strategy, such as the availability of gliders and limited human resources to manage multiple deployments around a continent the size of Australia; however, these shortcomings are manageable. ANFOG presently maintains a fleet of both Seagliders (deep) and Slocum gliders (shallow).

Gliders have been deployed into the EAC as part of the NSW-IMOS program since 2009. Initially, the program was fairly exploratory in nature while we ascertained what could (and could not) be achieved in a western boundary current (WBC) regime. We deployed a combination of Seagliders and Slocum gliders into EAC eddies to understand the temporal evolution of these mesoscale features that dominate the circulation downstream of the EAC separation point ($\sim 31\text{--}32^\circ\text{S}$, more than 50% of the time¹²). This approach resulted in mixed success—some missions proved very successful for understanding eddy dynamics,¹³ watermass properties,¹⁴ and entrainment of shelf waters.¹⁵ But, the logistics and

cost associated with retrieval of a wayward glider swept offshore in a mesoscale eddy (Figure 2(a)) on top of a number of gear failures (particularly with the Seagliders) resulted in a change of strategy.

Sustained endurance lines that are common in other regions are not feasible in a dynamic WBC—at least not extending onto the shelf and into shallow water where alongshore surface velocities frequently exceed 2 m/s.^{16–18} Thus, a strategy was adopted that resulted in gliders being deployed off Yamba (29.5°S) with a zig-zag mission definition extending poleward along the continental shelf. In this manner, the glider is advected poleward with the alongshore currents, and we maximize cross-shelf coverage. The transects generally start at the 25-m isobath, extending to just inshore of the shelf break (~100 m) with a spatial extent of 300 to 400 km (approximately 29–32°S, Figure 2(a)). The final retrieval location (and hence, along-shelf distance) is dependent upon the balance between battery life and weather conditions. From 2009 to 2014, 22 glider missions have been conducted off southeast Australia, and as of May 2014, 13 of these have been repeat cross-shelf (zig-zag) deployments along the continental shelf inshore of the EAC, resulting in a new high-resolution climatology of the shelf waters.¹⁹ This climatology has been used to show the role of along-shelf advection in the momentum balance²⁰ and the importance of the EAC in driving upwelling as it separates from the coast.^{17,18}

3.4 THE SHELF MOORING ARRAY

The longest moored time series on the east coast of Australia is the Ocean Reference Station (ORS065, Figure 2(c), Table 1). It has been maintained (under contract for Sydney Water Corporation) since 1989 and has been included as an IMOS data stream since May 2008. To build on this long history of observations, we created an array of moorings shore normal off Bondi with the addition of two moorings in 100 and 140 m of water (SYD100 and SYD140, respectively), complemented by another mooring ~20 km to the south off Port Hacking (PH100, Figure 2(c)). Presently, these three moorings (Table 1) consist of a bottom-mounted TRDI 300 kHz ADCP housed in a rigid frame with gimbal mount and a line of thermistors extending from the bottom to 15–20 m below the surface (string of Aquatech 520 temperature and temperature/pressure loggers at 8-m intervals through the water column) that is supported by a sub-surface float. In addition, the PH100 mooring is augmented with a Wetlabs water quality meter (WQM) consisting of a SeaBird CTD and measurements of fluorescence, turbidity (Wetlabs FLNTU), and dissolved oxygen, collectively referred to as BGC in Figure 2, Table 1. At various times, this mooring has also had a separate surface float to serve as a warning, but it also allows for measurement of sea surface temperature and to act as a real-time testbed.

Whereas the parameters measured at the CH070 and CH100 moorings (Figure 2(b)) are the same as off Sydney, the ADCP mooring design differs, with the ADCPs suspended 1–2 m above the bottom in floating frame with two acoustic releases hanging directly below the moorings. The final two moorings in the array

Table 1 NSW-IMOS Mooring Deployment Metadata

Name	Latitude (°S)	Water Depth (m)	Distance Offshore (km)	Date Deployed	Parameter Measured	Major Axis	V Bin Depths (m)	T Sensor Depths (m)
CH070	30.27	74	16	August 2009	T, V	20°	10–65	16–72
CH100	30.27	98	25	August 2009	T, V	20°	13–89	11–96
ORS065	33.90	67	2	1989/May 2008	T, V	16°	11–61	16–66
SYD100	33.94	104	10	June 2008	T, V, BGC	19°	12–96	24–102
SYD140	33.99	138	19	June 2008	T, V	24°	23–127	21–137
PH100	34.12	115	6	October 2009	T, V, BGC	33°	14–104	15–111
BMP090	36.19	94	9	March 2011	T	15°		28–92
BMP120	36.21	119	16	March 2011	T	15°		20–116

Parameters measured are T: temperature at 8 m through the water column (4 m at ORS065), V: velocity at 4 m through the water column (8 m at SYD140), BGC: Wetlabs Water quality meter (WQM) consisting of Seabird CTD temperature, salinity, dissolved oxygen, and fluorescence. The ORS065 was first deployed in 1989, with data incorporated into IMOS since May 2008. The major axis orientation is calculated from depth averaged velocity data over a period of Four years from January 2010 to December 2014, except for BMP, where orientations are estimated from bathymetry.

Table adapted from Refs [17](#), [18](#), [23](#), [29](#).

BMP090 and BMP120 (Figure 2(d)) consist solely of a subsurface temperature/pressure string at 8-m intervals to ~20 m below the surface (Table 1).

Temperature and velocity data are recorded at 5-min intervals, while the WQM records 60 burst samples at a rate of 1 Hz every 15 min. Initial deployment dates are indicated in Table 1, and to date, each mooring continues to return excellent data with a return rate generally between 70 and 90%. An example data set is shown in Figure 4, and additional data can be visualized at www.oceanography.unsw.edu.au.

In general, the NSW-IMOS moored array is fairly low cost by ocean observing standards. Despite the strong surface currents (frequently in excess of 1.5 m/s), the subsurface profile of the moorings means we can limit the size of the weight (vessel) needed; thus, we can deploy from local fishing vessels. The trade-off is that we sacrifice real-time data and surface parameters.

3.5 IN SITU BIOGEOCHEMICAL SAMPLING

The Port Hacking site (Figure 2, Table 1) is one of a series of nine national reference stations (NRS) located around Australia²¹ that are instrumented in a similar way and are augmented with in situ biogeochemical sampling monthly.^{21,22} Lynch provides a full description of this national network. Each of the national reference stations provides a broad suite of observations that can provide temporal reference for more spatially distributed and intensive shorter term studies.²³ In addition, they provide for the calibration and validation of coastal remote sensing activities. Regionally, individual NRS act as focal points within each of the coastal IMOS nodes.²¹

The two sites at Port Hacking (50 and 100 m) have been occupied nominally monthly since the 1940s, making them some of the longest oceanic temperature records in existence and some of the only long-term records in the southern hemisphere. Initially, temperature was monitored (using reversing thermometers) at PH050 (d = 0, 10, 20, 30, 40, and 50 m) and PH100 (d = 0, 10, 25, 50, 75, and 100 m). Monthly CTD profiles have been taken along a shore normal transect encompassing PH100 since 1997 (Figure 2(c)) at depths of 25, 50, 100, and 125 m. Niskin bottle samples are taken at discrete depths for measurements of total dissolved inorganic carbon, alkalinity, and nutrients. We use combined water column samples from all the Niskin bottles at a site for phytoplankton. Zooplankton measures are taken from a plankton drop net. Zooplankton and phytoplankton samples have also been collected at the 50 and 100 m stations since 1997.

Since the start of IMOS, additional water samples have been included at various times for genetic analyses and investigation of microbial communities. In addition, the monthly sampling off Port Hacking serves to calibrate fluorometric observations obtained from the instrumented moorings and ocean color estimates of chlorophyll obtained from satellites (e.g., MODIS): chlorophyll, total suspended solids, and colored dissolved organic material (CDOM). The methodology is documented in detail in an IMOS operations handbook (http://imos.org.au/facility_manuals.html).

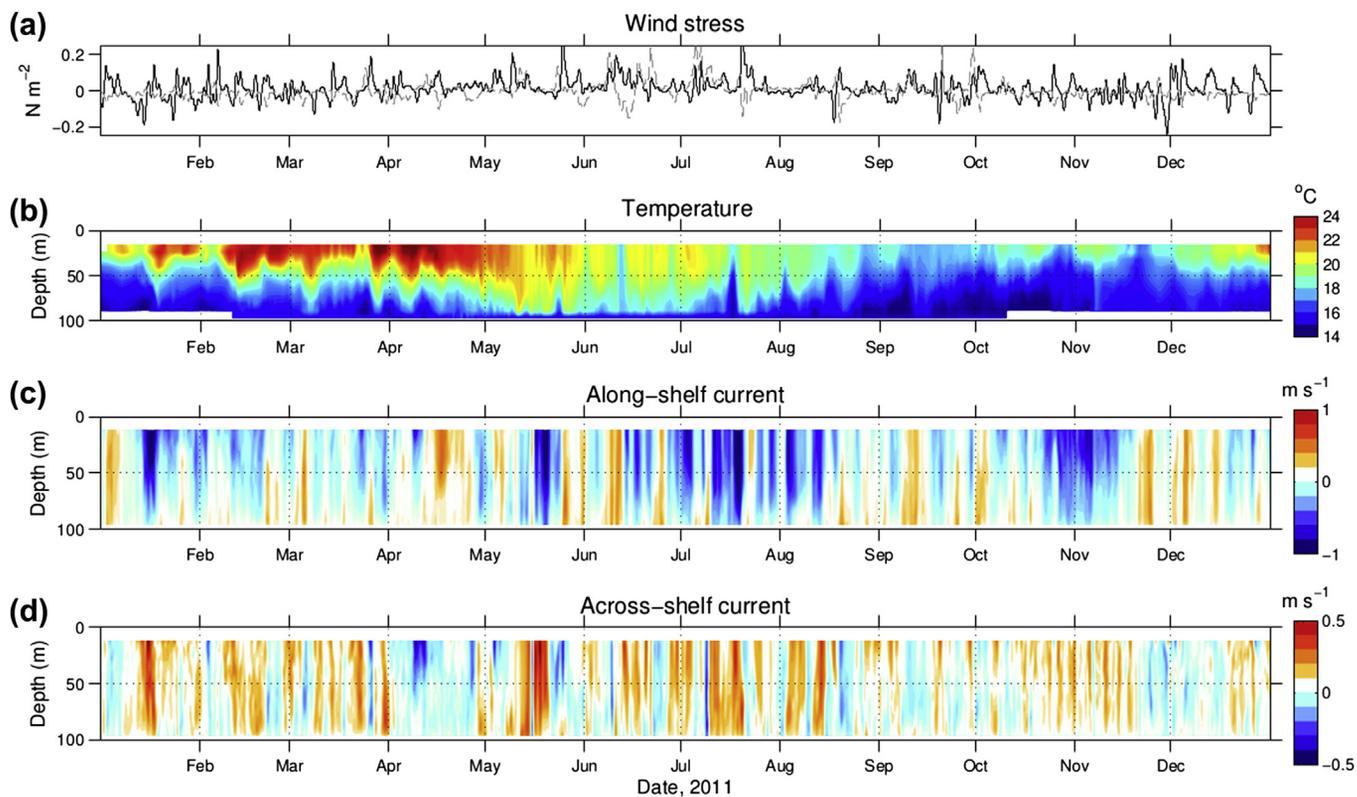


FIGURE 4

Data from the SYD100 mooring during 2011 showing (a) wind stress, where black (gray) is the alongshore (cross-shelf) component, (b) temperature measured at 8-m intervals through the water column, (c) along-shelf current, and (d) across-shelf current. EAC intrusions are exemplified by warmer water temperatures and strong southward currents.

3.6 HIGHER TROPHIC LEVELS

One of the integrating aspects of the IMOS program is the extension of the ocean observing system into plankton and marine animals. Three IMOS facilities, AATAMs, CPR, and AUV, have established a successful long-term observing program of biological responses to oceanographic change. We discuss some of these insights here. AATAMs (Animal Tagging and Monitoring) has two branches, the first focuses on the tagging and tracking of marine mammals (fur seals, sea lion, and elephant seals) and the integration of animal behavior with oceanographic conditions (as measured from CTDs that are glued to the animal's heads, known as bio-logging). This has proved particularly successful in the southern ocean where elephant seals are foraging under ice, thereby collecting new observations of temperature and salinity outside the range of ships and ARGO. This publicly available database provided by IMOS and their French collaborators has approximately 75,000 profiles between the Kerguelen Islands and Pyrdz Bay.²⁴

The second branch of AATAMs is the acoustic tagging of fish and sharks in waters around Australia. AATAMs listening stations have been deployed as either arrays or across-shelf curtains around Australia. Specifically, off NSW, arrays that monitor the movement of tagged fish and sharks have been deployed at Coffs Harbour, Sydney, and Bateman's Bay (Figure 2). A national database is now available through the IMOS portal for registered users to access where their tagged fish have unexpectedly turned up. This innovation has revealed some surprisingly large travel distances, such as great white sharks traveling from New Zealand to eastern Australia and bull sharks traveling from Sydney to Townsville (North Queensland).²⁵ With improved understanding of the actual range of species of interest, we can better incorporate them into biological models and analyses.

Ships of opportunity have been used to deploy a Continuous Plankton Recorder (CPR) between Brisbane, Sydney, and Melbourne, undertaking 33 voyages since 2008 (Figure 5). The CPR is identical to those operated around the world, collecting and preserving plankton on a silk roll, which is converted to abundance. The CPR is complemented by sampling for phyto- and zoo-plankton and microbial diversity at the National Reference Stations, with standardized sampling for larval fish at some NRS commencing in late 2014.

One remarkable discovery by the CPR was the massive abundance of black fungal spores on the CPR silk after the extensive dust storm over eastern Australia in September 2009, after 10 years of drought.²⁶ The spores were able to be grown on agar from the formalin-fixed material, and they were identified as a terrestrial fungus, *Aspergillus sydowii*. Though the fungus is implicated with coral disease, no particular disease outbreak resulted on this occasion. The significance of more conventional marine phytoplankton blooms (such as the dinoflagellate *Noctiluca*²⁷) or swarms of gelatinous zooplankton (such as salps) is starting to be realized.²⁸

The Autonomous Underwater Vehicle (AUV) facility has focused on imaging the benthos and automating the characterization of the habitat. Surveys are repeated at very specific locations along the eastern seaboard (and nationally at a number of key locations spread across large latitudinal ranges on both the east and west coasts of

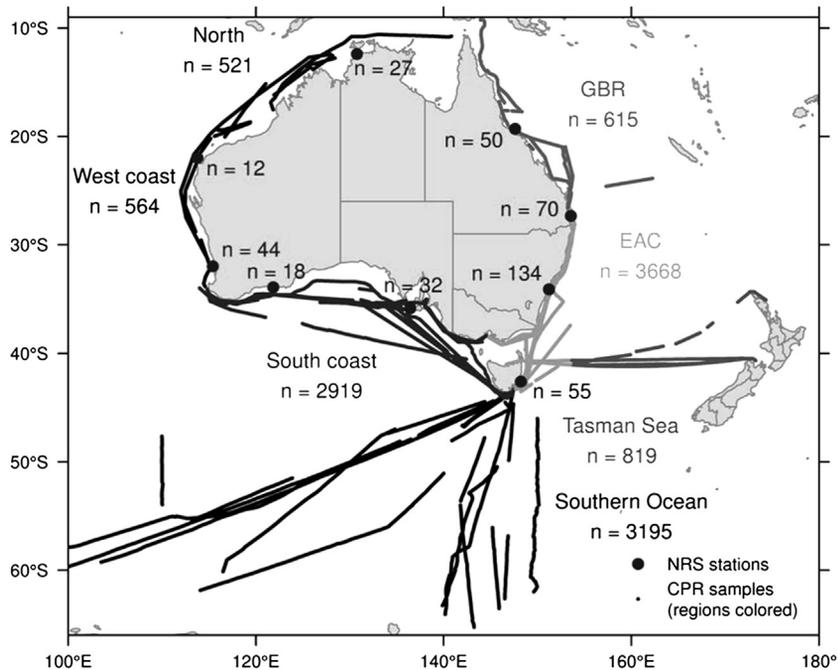


FIGURE 5

The EAC-CPR route is run quarterly from Brisbane to Melbourne on ships of opportunity by the IMOS-SOOP facility, and it is complemented by the quarterly Great Barrier Reef (GBR)-CPR route, the quarterly south coast route from Melbourne to Fremantle, and the annual routes to the Southern Ocean and from New Zealand, as per solid lines.

Adapted from <http://imos.org.au/australiancontinuousplanktonr3.html>.

Australia). Repeat visits to these sites, stretching from the Solitary Islands (29°S) to Batemans Bay (36°S), have shown, for example, the impact of extreme events on coral bleaching and the subsequent recovery and loss of kelp through marine heat waves. One of the main science questions being addressed by the AUV facility is quantifying kelp and other brown algae at the northern (warmer) boundary of their distribution, while also examining their paucity around major urban centers. Kelp is affected not only by sea urchin grazing as a result of a trophic cascade, but it is also affected by environmental change and pollution, which, therefore, has implications for the location of marine sanctuary zones. Observing by the AUV facility helps provide a science-based case for the contentious questions around marine parks zoning.

4. ASSESSING THE DESIGN OF THE SHELF MOORING ARRAY

In recent years, significant time and financial resources have been invested into ocean observing systems internationally. There is no doubt that these systems as a whole are worthwhile, and they are collecting critical baseline data; however,

it is likely that in some instances there is either (1) room for improvement to address data gaps, or (2) room for possible consolidation, where observations are redundant. In the case of NSW-IMOS, the system was designed on the basis of a number of process studies that had been conducted previously, providing a best estimate of a strategy with a view to facilitating as much emerging research in the future as possible. In the case of the shelf mooring array, five years since the deployment of the first moorings, we are now in a position to assess the design of the array and to question if the array is serving our science needs.²⁹ An objective way of assessing the array is to use both the data and models to understand the spatial and temporal correlations in conjunction with the dominant processes.

4.1 HOW CORRELATED ARE THE DATA?

Spatial correlations of the different parameters measured at the mooring sites provide insight into the relevance of the array design and the variability resolved. For adjacent sites, correlations across the shelf for depth-averaged along-shelf velocities and temperature are high, ranging from 0.84 to 0.89 (lags between 0 to 3 h) and 0.87 to 0.93 (lags between 0 to 6 h), respectively (Table 2). In contrast, for across-shelf velocities, the only correlation coefficients that are greater than 0.25 are CH070–CH100 (0.71) and ORS065–SYD100 (0.57, Table 2). These results suggest the need for at least three moorings at regular intervals across the relatively shelf (<30 km) in order to resolve the cross-shelf dynamics.

Along the coast, the along-shelf velocity exhibits similar variability downstream (ORS065, SYD100, SYD140, and PH100) with correlations greater than 0.62 (Table 2). Between upstream and downstream, correlations for along-shelf velocities are still significant, ranging from 0.24 to 0.34 for lags around 22 to 36 h, and they show the different EAC dynamics along the coast and the potential need for an additional array between 30 and 34°S.

The temperature at Port Hacking and Narooma sites (6, 9, and 16 km from the coast, respectively) are most correlated to Sydney inshore moorings (ORS065, 2 km from the coast, Table 3). In contrast, the temperatures at the offshore sites CH100 and SYD140 are the least correlated with moorings at other latitudes, as the dynamics offshore are expected to be mostly driven by the EAC (CH100) and its eddies (SYD140). The temperature variability (Table 3) between inshore and offshore within 25 km of the coastline confirms the relevance of the cross-shelf arrays of two to three moorings.

In terms of temporal variability, the de-correlation time scales at a particular depth are very variable, ranging from 2 to 20 days for temperature, 6 to 50 h and 30 min to 3 h for along- and across-shelf currents, respectively (Table 4). This suggests that high-frequency measurements are necessary to resolve the across-shelf variability, although less so for along-shelf processes. The minimum de-correlation time scales in the water column are driven by local physical processes. Upstream (CH) and in the EAC extension (BMP), the shortest de-correlation time

Table 2 Maximum Correlations and Lags in Hours of the Along- (Black) and Across-Shelf (Gray) Components of the Sub-Inertial Depth-Integrated Velocities

Platform	CH070	CH100	ORS065	SYD100	SYD140	PH100
CH070		0.84 (–1 h)	0.32 (29 h)	0.34 (25 h)	0.30 (28 h)	0.28 (22 h)
CH100	0.71 (3 h)		0.25 (36 h)	0.28 (30 h)	0.29 (31 h)	0.24 (31 h)
ORS065	0.11 (–17 h)	0.11 (214 h)		0.86 (–3 h)	0.71 (–3 h)	0.80 (–2 h)
SYD100	0.11 (55 h)	0.14 (–112 h)	0.29 (1 h)		0.89 (0 h)	0.72 (1 h)
SYD140	0.09 (33 h)	0.04 (–219 h)	0.24 (0 h)	0.57 (–1 h)		0.62 (2 h)
PH100	0.10 (220 h)	0.18 (–203 h)	0.09 (198 h)	0.09 (–102 h)	0.08 (–115 h)	

All correlations are significant at the 95% significance level and are computed using the maximum concomitant time series available for each mooring pair between 2010–2014 (between 564 and 1112 days).

Adapted from Table 2 in Ref. 29.

Table 3 Maximum Correlations and Lags in Hours (h) of the Sub-Inertial Depth-Integrated Temperature

Platform	CH070	CH100	ORS065	SYD100	SYD140	PH100	BMP090	BMP120
CH070		0.88 (6 h)	0.66 (24 h)	0.60 (14 h)	0.44 (2 h)	0.64 (28 h)	0.69 (48 h)	0.71 (36 h)
CH100			0.47 (23 h)	0.43 (13 h)	0.40 (-215 h)	0.44 (-240 h)	0.55 (56 h)	0.59 (81 h)
ORS065				0.89 (2 h)	0.67 (2 h)	0.90 (0 h)	0.76 (11 h)	0.77 (8 h)
SYD100					0.87 (2 h)	0.89 (-1 h)	0.72 (-8 h)	0.58 (240 h)
SYD140						0.72 (-8 h)	0.58 (240 h)	0.51 (226 h)
PH100							0.77 (11 h)	0.66 (151 h)
BMP090								0.93 (0 h)

All correlations are significant at the 95% significance level and are computed using the maximum concomitant time series available for each mooring pair between 2010 and 2014 (between 626 and 1461 days).

Table 4 De-Correlation Time Scales for Each Mooring and Variable Computed as the Maximum Lag Corresponding to Auto-Correlations Greater than a Threshold of 0.7. The Minimum, Maximum, and Their Depths Are Indicated. The Calculations Are Based on 5 min Measurements from 2010 to 2014

Platform	CH070	CH100	ORS065	SYD100	SYD140	PH100	BMP090	BMP120
Temperature	3.3–20 days (bottom–top)	2.3–20 days (bottom–top)	3.3–16 days (44 m–top)	3.6–12.5 days (42 m–top)	3.7–7.4 days (42 m–top)	4.9–15 days (32 m–top)	5.5–10.6 days (92 m–top)	5.8–17 days (114 m–top)
Along-shelf velocity	15–25 h (bottom–17 m)	22–50 h (bottom–16 m)	6–19 h (bottom–19 m)	10–29 h (bottom–24 m)	25–42 h (bottom–31 m)	9–26 h (bottom–20 m)		
Across-shelf velocity	1.2–1.7 h (bottom–17 m)	1.8–3 h (bottom–12 m)	0.6–1 h (bottom–top)	0.8–1.9 h (bottom–16 m)	1.3–2.7 h (bottom–55 m)	0.7–1.3 h (bottom–16 m)		

scale is at the bottom for all variables due to the frequent bottom water uplift driven by the EAC,^{9,17,18} whereas in the eddy region (SYD), the most variable temperature is at mid-depth. The design of the mooring array covering the water column seems appropriate for the investigation of both of these highly variable processes.

4.2 MODELING ASSESSMENT

An eddy-resolving model was used to assess the spatial correlations in sea surface temperature and velocity,³⁰ to understand if the mooring array does an adequate job of resolving inter-annual variability in sea surface temp and velocity along the entire coastline. Results showed that at the inter-annual time scale, temperatures were fairly well correlated along the shelf, and they go some way toward representing the intra-seasonal variability. However, although alongshore correlations were generally high, there was a distinct region of lower correlation at ~ 32 to 33°S (which was more exacerbated in the velocity fields), suggesting that this region must be instrumented if we are to gain a true understanding of the shelf dynamics in this region.

4.3 MANAGEMENT

Data management is an essential, and in many ways, the most important part of the observing system. To this end, significant investment has been made into an open data repository through the Australian Ocean Data Network (AODN, imos.aodn.org.au).

All IMOS data is made freely available, including enhanced data products and web services in a searchable and interoperable framework. A central data facility (eMII) provides the standards, protocols, and systems to integrate the data and related information into a number of conformal frameworks, and it provides the tools to access and utilize the data. In addition, for some types of data, they provide additional derived data products, as well as web services for processing, integration, and visualization of the data (<http://imos.org.au/emii.html>). Some IMOS data are also routinely integrated into international programs and databases.

4.4 DATA UPTAKE

Data uptake is an equally important aspect of the program, and this is supported and promoted through an increasing number of data products being made available in addition to regular outreach opportunities to keep the community informed.

NSW-IMOS is one of the IMOS success stories when it comes to data uptake in an integrated manner. We have a vibrant and active science community who use the data in a multitude of ways, and we have actively sought to ensure that the data is being used to maximum benefit. Since 2007, NSW-IMOS data has been integral to the success of more than 50 externally funded research projects that have used IMOS infrastructure as a backbone. In addition, the core NSW-IMOS data have been used by over 45 postgraduate research projects, including 14 Ph.D. completions to date. The vast numbers of conference presentations that acknowledge

NSW-IMOS (more than 200) are likely to increase the number of forthcoming journals articles (presently more than 50). Each of these science outputs contributes to the success and longevity of the program.

One of the ways we have encouraged data uptake and multidisciplinary science is to bring people together regularly in node science meetings (two per year), with a different emphasis at each meeting. Participant numbers range from 30 to 50, with themes including “Model data integration” and “Integrating up the food chain.” Alternatively, we hold meetings with a specific regional focus, such as a recent two-day workshop on the 70-year time series at Port Hacking.

In addition, we have designed university courses around the data. For example, a new multi-university master’s level subject run through the Sydney Institute of Marine Science (www.sims.org.au) that introduces students to a number of the core NSW-IMOS data streams has proved very successful with up to 40 M.Sc. students enrolling per year. This strategy brings wide exposure to the program as the students come from broad backgrounds nationally and internationally, from industry, nonprofits, and state agencies alike.

5. SHORTCOMINGS AND RECOMMENDATIONS FOR THE FUTURE

5.1 GAPS IN THE ARRAY

The assessment of the array through a combination of models and observations has shown that data gaps exist particularly in the central and southern part of the domain. Unfortunately, due to funding constraints, the mooring array at 36°S has been cut, which leaves a significant gap in monitoring of the EAC extension where the ocean has been shown to be warming rapidly. In addition, this region is a marine protected area, and NSW stakeholders (e.g., NSW Office of Environment and Heritage and Department of Primary Industries) place a priority on understanding coastal processes.

In the short term, these gaps could be filled by an increase in glider coverage. A potentially cost-effective alternative is to run shore normal glider endurance lines in this region, although EAC eddies have proved that this is a difficult environment in which to operate gliders. In addition, an extension of the longshore glider program along the NSW shelf down to the southern part of the domain would provide valuable seasonal and spatial coverage of the shelf hydrography.

The EAC full transport array was removed in Sept 2013 due to funding limitations and problems with shipping schedules. Encouragingly, it is slated to be redeployed in 2015. However, the gap between deployments allows for an important assessment of the array and its utility in predicting EAC dynamics including eddy shedding and separation.

A strategy that has proved cost prohibitive to date is to transition a number of the coastal moorings to real-time data acquisition. This would allow for greater immediate data uptake through the assimilation into coastal circulation models

while providing information that meets societal needs (e.g., the commercial and recreational fishing industries). In addition, this would provide a platform for over-ocean wind observations that are critically lacking.³¹

A major gap exists in the biologically critical Stockton Bight area ($\sim 32\text{--}33.5^\circ\text{S}$), which is recognized as a fisheries nursery area. The most straightforward way of filling the gap would be an increase in the coastal radar coverage combined with increased southward coverage in glider range. This would provide information on the northward coastal counter current and export from the shelf of coastal waters.

Finally, expanding the reach of the biogeochemical sampling through either regular seasonal or opportunistic sampling at the northern and southern moored arrays (30 and 36°S) would allow more opportunities to validate satellite/remotely sensed products such as Chl-*a* and provide baseline data for impacts of ocean warming and environmental change.

5.2 MODEL–DATA INTEGRATION

At present, the Australian IMOS program does not have core funding to support model–data integration. This is in contrast to other programs such as the US-IOOS Coastal and Ocean Modeling Testbed, which is focused on operationalizing models out of the research community. To address this issue without creating a significant financial burden, IMOS has taken the lead in coordinating a new workshop: the Australian Coastal and Oceans Modelling and Observations Workshop (ACOMO). Two workshops were held at the Australian Academy of Science in October 2012 and 2014. The goal of these workshops was to bring the somewhat disparate coastal ocean modeling community together to coordinate activities in order to make significant advances in a unified way. The meeting presented an opportunity to detail the state of play and identify future needs and opportunities. Furthermore, a closely related project, the Marine Virtual Laboratory (MARVL) project (<http://www.nectar.org.au/marine-virtual-laboratory>), is developing software tools to enable model–data integration to happen more efficiently.

Data assimilation techniques are being used increasingly to make assessments of observing systems.³² Within Australia, collaborators within NSW-IMOS have secured additional federal research funds to conduct data assimilation modeling to assess the design of the observational array. Over the coming years, we envisage that this will provide insight into the types and locations of observations needed to understand the dynamics in the region. Thus, it will help to target new deployments and potentially will provide cost savings.

6. CONCLUSIONS

In Summary, NSW-IMOS is an example of a highly successful implementation of a coastal ocean observing system. The observational array has been built around pertinent science questions, leveraging existing data streams and opportunities.

The science questions are integrated into the national and international context and represent the state of the science today.

The operational aspects are streamlined as they are run through a number of centrally coordinated specialized infrastructure facilities. Data return is increasingly consistent, and data dissemination and uptake is broad. The operations are backed by a team of active and highly successful scientists (the “node”) who are using the observing system widely as a backbone to conduct high-quality internationally relevant research.

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REFERENCES

1. Wu L, Cai W, Zhang L, Nakamura H, Timmermann A, Joyce T, et al. Enhanced warming over the global subtropical western boundary currents. *Nat Clim Change* 2012;**2**(3): 161–6.
2. Thompson PA, Baird ME, Ingleton T, Doblin MA. Long-term changes in temperate Australian coastal waters and implications for phytoplankton. *Mar Ecol Prog Ser* 2009;**394**:1–19.
3. Verges A, Steinberg P, Hay M, Poore A, Campbell A, Ballesteros E, et al. The tropicalization of temperate marine ecosystems; climate-mediated changes in herbivory and community phase shifts. *Proc R Soc B* 2014;**281**:20140846. <http://dx.doi.org/10.1098/rspb.2014.0846>.
4. Wyatt LR. *The IMOS ocean radar facility*. ACORN; 2015 [This book].
5. Roughan M, Morris BD, Suthers IM. NSW-IMOS: an integrated Marine observing system for Southeastern Australia. *IOP Conf Ser Earth Environ Sci* 2010;**11**:012030. <http://dx.doi.org/10.1088/1755-1315/11/1/012030>.
6. Roughan M, Suthers I, Meyers G. The Australian integrated Marine observing system (IMOS) and the regional implementation in New South Wales. In: You J, Henderson-Sellers A, editors. *Climate alert: change monitoring and strategy*. Sydney University Press; 2010, ISBN 9781920899363.
7. Roughan M, Suthers IM, Morris B, Armand L, Baird M, Coleman M, et al. *NSW-IMOS node science and implementation plan July 2009–2013. Tech rep Sydney Institute of Marine Science Mosman, Sydney NSW, 2088, Australia*. 2009.
8. Robertson R, Doblin M, Ingleton T, Roughan M, Suthers IM. *NSW-IMOS node science and implementation plan 2015–2020. Tech rep Sydney Institute of Marine Science Mosman, Sydney NSW, 2088, Australia*. 2014.

9. Schaeffer A, Roughan M, Wood JE. Observed bottom boundary layer transport and uplift on the continental shelf adjacent to a western boundary current. *J Geophys Res Oceans* 2014;**119**. <http://dx.doi.org/10.1002/2013JC009735>.
10. Archer MR, Shay LK, Jaimes B, Martinez-Pedraja J. *Observing frontal instabilities of the Florida current using high frequency radar*. 2015.
11. Schaeffer A, Roughan M. *MARine virtual laboratory (MARVL) – high-resolution ROMS test: the east Australian current at 30°S in Solitary Island Marine Park*. 2014.
12. Cetina Heredia P, Roughan M, Van Sebille E, Coleman MA. Long-term trends in the East Australian Current separation latitude and eddy driven transport. *J Geophys Res Oceans* 2014;**119**. <http://dx.doi.org/10.1002/2014JC010071>.
13. Baird ME, Suthers IM, Griffin DA, Hollings B, Pattiaratchi C, Everett JD, et al. Physical-biogeochemical dynamics of a surface flooded warm-core eddy off southeast Australia. *Deep-Sea Res II* 2011;**58**(5):592–605. <http://dx.doi.org/10.1016/j.dsr2.2010.10.002>.
14. Baird ME, Ridgway K. The southward transport of sub-mesoscale lenses of Bass Strait Water in the centre of anti-cyclonic mesoscale eddies. *Geophys Res Letts* 2012;**39**:L02603.
15. Everett JD, Macdonald HS, Baird ME, Humphries J, Roughan M, Suthers IM. Cyclonic entrainment of preconditioned shelf waters into a Frontal Eddy. *J Geophys Res Oceans* 2015;**120**:677–91. <http://dx.doi.org/10.1002/2014JC010301>.
16. Roughan M, Middleton JH. On the east Australian current; variability, encroachment and upwelling. *J Geophys Res Oceans* 2004;**109**:C07003. <http://dx.doi.org/10.1029/2003JC001833>.
17. Schaeffer A, Roughan M, Morris B. Cross-shelf dynamics in a western boundary current. Implications for upwelling. *J Phys Oceanogr* 2013;**43**:1042–59.
18. Schaeffer A, Roughan M, Morris B. Corrigendum: cross-shelf dynamics in a western boundary current. Implications for upwelling. *J Phys Oceanogr* 2014;**44**:2812–3. <http://dx.doi.org/10.1175/JPO-D-14-0091.1>.
19. Schaeffer A, Roughan M. Influence of a western boundary current on shelf dynamics and upwelling from repeat glider deployments. *Geophys Res Lett* 2015;**42**:121–8. <http://dx.doi.org/10.1002/2014GL062260>.
20. Roughan M, Oke PR, Middleton JH. A modeling study of the climatological current field and the trajectories of upwelled particles in the East Australian Current. *J Phys Oceanogr* 2003;**33**(12):2551–64.
21. Lynch TP, Morello EB, Evans K, Richardson AJ, Rochester W, Steinberg CR, et al. IMOS National Reference Stations: a continental-wide physical, chemical and biological coastal observing system. *PLoS One* 2014;**9**:12. <http://dx.doi.org/10.1371/journal.pone.0113652>.
22. Lynch TP, Roughan M, McLaughlan D, Hughes D, Cherry D, Critchley G, et al. A National Reference Station Infrastructure for Australia – using telemetry and central processing to report multidisciplinary data streams for monitoring marine ecosystem response to climate change. In: *MTS/IEEE oceans Canada 2008*; 2008.
23. Roughan M, Morris BD. Using high-resolution ocean timeseries data to give context to long term hydrographic sampling off Port Hacking, NSW, Australia. In: *Proceedings of MTS/IEEE oceans 2011 Kona USA*; 2011.
24. Roquet F, Williams G, Hindell MA, Harcourt R, McMahon C, Guinet C, et al. A Southern Indian Ocean database of hydrographic profiles obtained with instrumented elephant seals. *Sci Data* 2014;**1**:140028. <http://dx.doi.org/10.1038/sdata.2014.28>.

25. Heupel MR, Simpfendorfer CA, Espinoza M, Smoothey AF, Tobin A, Peddemors V. Conservation challenges of sharks with continental scale migrations. *Front Mar Sci* 2015;**2**:12. <http://dx.doi.org/10.3389/fmars.2015.00012>.
26. Hallegraeff GM, Coman F, Davies C, Hayashi A, McLeod D, Slotwinski A, et al. Australian duststorm associated with extensive *Aspergillus sydowii* fungal bloom in coastal waters. *Appl Environ Microbiol* 2014;**80**(11):3315–20. ISSN 0099-2240. <http://dx.doi.org/10.1128/AEM.04118-13>.
27. McLeod DJ, Hallegraeff GM, Hosie GW, Richardson AJ. Climate-driven range expansion of the red-tide dinoflagellate *Noctiluca scintillans* into the Southern Ocean. *J Plankton Res* 2012;**34**(4):332–7.
28. Henschke N, Everett JD, Doblin MA, Pitt KA, Richardson AJ, Suthers IM. Demography and interannual variability of salp swarms (*Thalia democratica*). *Mar Biol* 2014;**161**: 149–63.
29. Roughan M, Schaeffer A, Kioroglou S. Assessing the design of the NSW-IMOS Moored Observation Array from 2008–2013: recommendations for the future. In: *Proceedings of MTS/IEEE oceans 2013, San Diego USA. Sept 2013*; 2013.
30. Oke PR, Sakov P. Assessing the footprint of a regional ocean observing system. *J Mar Syst* 2012;**105–108**:30–51.
31. Wood J, Roughan M, Tate P. Finding a proxy for wind stress over the coastal ocean off Sydney. *Mar Freshw Res* 2012;**63**(6):528–44. <http://dx.doi.org/10.1071/MF11250>.
32. Xue P, Chen C, Beardsley RC, Limeburner R. Observing system simulation experiments with ensemble Kalman filters in Nantucket Sound, Massachusetts. *J Geophys Res* 2011; **116**:C01011.