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Editorial

The strengthening East Australian Current, its eddies and biological effects — an introduction and overview

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ABSTRACT

The poleward flowing East Australian Current (EAC) is characterised by its separation from the coast, 100–200 nautical miles north of Sydney, to form the eastward flowing Tasman Front and a southward flowing eddy field. The separation zone greatly influences coastal ecosystems for the relatively narrow continental shelf (only 15–50 km wide), particularly between 32–34°S. In this region the continental shelf has a marked shift in the seasonal temperature-salinity relationship and elevated surface nitrate concentrations. This current parallels the portion of the coast where Australia's population is concentrated and has a long history of scientific research. However, understanding of physical and biological processes driven by the EAC, particularly in linking circulation to ecosystems, is limited. In this special issue of 16 papers on the EAC, we examine the effects of climatic wind-stress forced ocean dynamics on EAC transport variability and coastal sea level, from ENSO to multi-decadal time scales; eddy formation and structure; fine scale connectivity and larval retention. Comparisons with the poleward-flowing Leeuwin Current on Australia's west coast show differences in ecosystem productivity that can be attributed to the underlying physics in each region. On average there is double the chlorophyll *a* concentration on the east coast than the west. In comparison to the Leeuwin, the EAC may have less local retention of larvae and act as a partial barrier to onshore transport, which may also be related to the local spawning and early life history of small pelagic fish on each coast. Inter-annual variations in the EAC transport produce a detectable sea-level signal in Sydney Harbour, which could provide a useful fisheries index as does the Fremantle sea level and Leeuwin Current relationship. The EAC's eddy structure and formation by the EAC are examined. A particular cold-core eddy is shown to have a "tilt" towards the coast, and that during a rotation the flow of particles may rise up to the euphotic zone and then down beneath. In a warm-core eddy, surface flooding is shown to produce a new shallower surface mixed layer and promote algal growth. An assessment of plankton data from 1938–1942 showed that the local, synoptic conditions had to be incorporated before any comparison with the present. There are useful relationships of water mass characteristics in the Tasman Sea and separation zone with larval fish diversity and abundance, as well as with long-line fisheries. These fisheries-pelagic habitat relationships are invaluable for fisheries management, as well as for climate change assessments.

There is further need to examine the EAC influence on rainfall, storm activity, dust deposition, and on the movements by fish, sharks and whales. The Australian Integrated Marine Observing System (IMOS) has provided new infrastructure to determine the changing behaviour of the EAC and its bio-physical interaction with the coasts and estuaries. The forecasting and hindcasting capability developed under the Bluelink project has provided a new tool for data synthesis and dynamical analysis. The impact of a strengthening EAC and how it influences the livelihoods of over half the Australian population, from Brisbane to Sydney, Hobart and Melbourne, is just being realised.

1. Introduction

The East Australian Current (EAC) is the major western boundary current of the South Pacific sub-tropical gyre, flowing from the southern Coral Sea and along the coast of northern New South Wales (NSW, Ridgway and Dunn, 2003). It has important connections with the large-scale climate from seasonal (Ridgway and Godfrey, 1997; Holbrook and Bindoff, 1999; Kessler and Gourdeau, 2007) through to El Niño – Southern Oscillation (ENSO) (Holbrook et al., 2005a, b; Holbrook and Maharaj, 2008), and to multi-decadal time scales (Ridgway, 2007). The EAC is typically >30 km wide, 200 m deep and flows up to 4 knots (2 m s^{-1}), with a variable annual transport estimated as 20–30 Sv (Mata et al., 2000; Ridgway and Dunn, 2003). For comparison, the EAC has $\sim$5 fold greater volume transport than the seasonally flowing Leeuwin Current on the west coast. The core of the EAC is centred

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over the continental slope, although its coastal presence is felt during eddy encroachment and by isotherm uplift where the shelf narrows. Its source water in the south Coral Sea is derived from the South Equatorial Current which has spent 1–2 years flowing across the Pacific (~15°S), producing a tropical, nutrient-poor water mass.

The last compendium of research on the EAC published in 1983 had a focus on meso-scale processes. It included five papers on warm-core eddies (Airey, 1983; Cresswell, 1983; Mulhearn, 1983; Rochford, 1983; Tranter et al., 1983a) and four papers on the associated zooplankton and biota of warm-core eddies (Brandt, 1983; Griffiths and Brandt, 1983; McWilliam and Phillips, 1983; Tranter et al., 1983b). This mesoscale focus was in keeping with oceanographic interests of the time (Mullin, 1993). Before 1983 it was evident that the EAC off the coast of New South Wales (NSW, 28-38°S) was dominated by a series of eddies, slowly propagating poleward along the coast. The zooplankton papers confirmed that warm-core eddies were distinctive compared to the surrounding Tasman Sea (Brandt, 1983), retaining the assemblage of their origin (Tranter et al., 1983b), and had the potential for mesozooplankton to increase and evolve over time (Griffiths and Brandt, 1983). While not entirely isolated from the Tasman Sea, nor isolated from each other, these eddies functioned rather like an incubator of plankton. For example phyllosoma (lobster larvae) were relatively rare compared to the surrounding waters of the Tasman Sea (McWilliam and Phillips, 1983); a warm-core (downwelling during formation) eddy has the capacity to become enriched in phytoplankton biomass (Tranter et al., 1980, 1983a).

In a number of ways, the 1983 volume was ahead of its time as evidenced by the routine use of satellites, drifters and even remote sensing (Cresswell, 1983; Cresswell et al., 1983), by the multidisciplinary studies (Griffiths and Brandt, 1983; Tranter et al., 1983b), and by four papers on the physics and biology of warm-core "rings" of another western boundary current - the Gulf Stream - as well as one study on warm-core rings in the recently described Leeuwin Current (Andrews, 1983). After 1983 there was an apparent decline in publications on the EAC that persisted for over a decade. Today, there are over 190 publications that mention the EAC in the title and abstract, but knowledge gaps are evident in the paucity of studies on cyclonic (cold-core) eddies compared to anticyclonic eddies, and particularly on the biological and fisheries responses in the EAC (Fig. 1). There are few comparisons of the EAC with other western boundary currents or with the poleward-flowing Leeuwin Current or its eddies (Waite et al., 2007). It is timely therefore to address these gaps in our knowledge of the EAC, particularly given that ocean warming has led to an increase in its strength and influence along eastern Australia (Ridgway, 2007; Ling et al., 2009). Climate change will have wide ranging effects on the coastal and marine environment of NSW, eastern Victoria and Tasmania. The EAC is predicted to both strengthen and warm significantly (Cai et al., 2005), which will have many diverse effects from changing weather patterns to shifts in marine species distribution (Hobday et al., 2011).

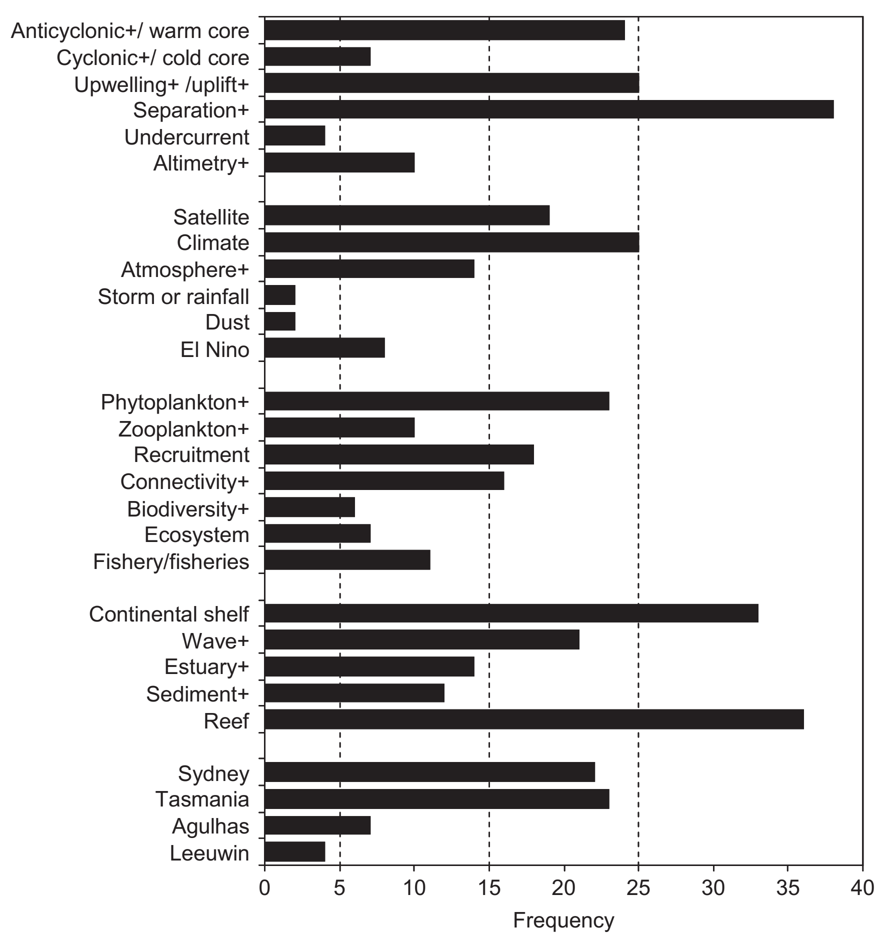

Fig. 1. Key word search in the primary literature in 192 papers including "East Australian Current" in the topic found on Web-of-Science. +, including various derivations of the word.

The EAC transports tropical reef fish well outside their normal range to almost 6° latitude farther south (Booth et al., 2007; Figueira and Booth, 2010) with flow-on effects for biodiversity, invasive species and fisheries. It is also timely for this special issue with the recent investment in ocean observing by Australia - the Integrated Marine Observing System (IMOS) and its implementation in NSW (Roughan et al., 2010).

The contributions to this special issue focus on the knowledge gaps noted above (Fig. 1). Two papers take advantage of Australia's unusual situation with poleward boundary currents on both east and west coasts, and make specific comparisons between the EAC and the Leeuwin Current (Condie et al., 2011; Thompson et al., 2011). The 16 papers in this issue are placed in five sections, ordered from ''physics to fish'', and include:

(1) broad-scale climate-induced effects (Holbrook et al., 2011);
(2) eddy frequency and dynamics (Brassington et al., 2011; Oke and Griffin, 2011; Baird et al., 2011-a);
(3) boundary current transport, cross-shelf flows and the influence on connectivity and life history strategies (Condie et al., 2011; Malcolm et al., 2011; Roughan et al., 2011);
(4) plankton distribution, including phytoplankton diversity, zooplankton and ichthyoplankton, and the response to ocean warming (Baird et al., 2011b; Hassler et al., 2011; Thompson et al., 2011; Syahailatua et al., 2011a; b); and
(5) fisheries habitats of the Tasman Sea and the effects of climate change (Bryne et al., 2011; Hartog et al., 2011; Hobday et al., 2011; Young et al., 2011).

2. Results and discussion

2.1. Broad scale EAC processes

Ridgway and Dunn (2003) describe four stages to the EAC: the formation in the south Coral Sea (15-24°S); the intensification of the current and flow along the coast of SE Queensland and northern NSW (22-35°S); the separation stage from the coast (31-33°S); and then declining to eddies off southern NSW and coastal fingers off Tasmania. During intensification the current strengthens, especially off Smoky Cape (31°S) where the shelf is its narrowest (~15 km). Thereafter most of the current separates from the coast, forming the Tasman Front, which flows eastward towards Lord Howe Island and New Zealand, leaving behind a coastal southward flow and a series of large warm core and cold core eddies. The strength of the poleward extension of the EAC has an approximately 10–15 year oscillation (Hill et al., 2008). Building on recent work (Holbrook, 2010), Holbrook et al. (2011) demonstrate, using baroclinic shallow-water dynamics, that interannual to multi-decadal changes in model-hindcast EAC transports, calculated along a zonal transect extending eastwards from Sydney, are significantly affected by incoming oceanic Rossby waves forced offshore. Holbrook et al. (2011) further show that ENSO to multi-decadal time scale sea-level changes recorded at the Fort Denison tide-gauge in Sydney Harbour are strongly and highly significantly related to these modulated EAC transports by oceanic Rossby waves – whereby Tasman Sea forced Rossby waves account for a substantial proportion of the interannual to multi-annual variability and remotely-forced Rossby waves (from east of New Zealand) explain the ocean-adjusted multi-decadal trend in EAC transports and sea level at the western boundary.

2.2. The poleward extension of the EAC – a current of warm-core eddies

South of the separation point (~32°S), the EAC becomes unstable and develops into a series of meanders. Meanders pinch off the main eastward flow 1-4 times a year (Marchesiello and Middleton, 2000; Bowen et al., 2005; Mata et al., 2006) developing into large, warm-core (anti-cyclonic) eddies. The warm-core eddies propagate southwest and can last for over a year. The mesoscale variability is so large that very often a single continuous current cannot be identified, which distinguishes the EAC from other western boundary currents (Godfrey et al., 1980; Wilkin and Zhang, 2007; Brassington et al., 2011). The separation has variously been ascribed to wind stress, coastal geometry (i.e. the westward retraction of the coast), bottom topography, or baroclinic instabilities in the flow: the reality is complex (Ridgway and Dunn, 2003). After separation the EAC retroflects northward and can feed back into the EAC, as an anticyclonic eddy or transport heat into the Tasman Sea. Further separations and retroflections are evident along the NSW coast around 34 and 37°S (Ridgway and Dunn, 2003).

Sometimes cyclonic (clockwise, cold-core) coastal eddies are generated as the EAC meanders and separates from the coast in the vicinity of Port Stephens and the Stockton Bight, entraining coastal water from this enriched separation area (Oke and Griffin, 2011; Brassington et al., 2011). Such eddies are reported to hold the key to survival and recruitment of fish larvae in the Kuroshio system (Kasai et al., 2002). The vertical movement undertaken as water circulates the eddy, as demonstrated by Oke and Griffin (2011), hints at another mechanism of producing high phytoplankton biomass. A further complication is introduced by the leaning of eddies, which in the case of the January 2007 cold-core eddy studied by Oke and Griffin (2011) consisted of a shoreward tilt of 60 km horizontal displacement in a water depth of 4.5 km. Clearly, the location and processes leading to the formation of these cyclonic coastal eddies is critical to the biological properties that develop. Brassington et al. (2011) provide insight into this relatively fast process through a combination of SST and surface drifter analysis that traces the formation of a cyclonic eddy from the interaction of coastally-upwelled water and EAC frontal dynamics over a period of one week.

Like other eddies created by western boundary currents (Chapman and Nof, 1988), EAC eddies are vulnerable to surface flooding. The density of the EAC decreases in summer due to warming and freshening, just as the maximum southward flow is approached. Commonly this buoyant water flows over the top of existing eddies. In the case of large warm-core eddies, the flooding current encircles the eddy, trapping denser water in the centre which is then submerged (Tranter et al., 1982). The depth of the surface mixed layer of the eddy prior to flooding, and the depth to which the original mixed layer is submerged, determines the vertical distribution of phytoplankton biomass in the core of the eddy (Baird et al., 2011a).

2.3. Numerical modelling of the EAC: Insights into transport, cross-shelf flow and biological connectivity

In the last decade, there have been a number of studies undertaken on the dynamics of coastal ocean processes along the coast of southeastern Australia associated with the EAC (references in Roughan et al., 2011). Much work has focused on measurement and modelling of regional and coastal circulation together with the hydrographic structure. Objectives have included understanding the effects of the forcings (current driven and wind) on the response in surface, midwater and bottom boundary layer regions of the continental shelf waters. Modelling studies have been complemented by extensive observational studies focused on slope water intrusion dynamics on the continental shelf.

Recent advances in ocean hindcasting and forecasting of the global ocean such as Bluelink (Oke et al., 2005, 2007, 2009; Schiller et al., 2008) are promising. The present ~10 km resolution allows the modelling of the effect of ocean scale processes on regional seas, and captures much of the mesoscale variability of the EAC system. The resolution of Bluelink models does limit its ability to resolve processes along the continental shelf, particularly for the narrow (15–50 km) continental shelf region of southeastern Australia.

The Bluelink Analysis and Reanalysis products (BODAS and BRAN) provides forcing for higher-resolution shelf models such as the EAC implementation (SEAPOM, Roughan et al., 2011). There are still limitations in the accuracy of such models. They may for example under-represent the number of cyclonic cold-core eddies, or show persistent deviation between observations and forecasts such as in the Tasman Sea (Oke et al., 2008). Roughan et al. (2011) investigate physical processes in the ocean along the coast of southeastern Australia. A high resolution hindcast of ocean state from 1992 – 2006 using a Bluelink assimilation product (BODAS) is used to investigate connectivity of non-swimming particles such as planktonic larvae, eggs and spores. Upstream of the EAC separation, the poleward flow of the EAC determines the particle trajectory length scales. Downstream of the separation point where the eddy field is most active, particle trajectories are dictated by the presence or absence of EAC eddies.

Southeastern Australian waters have experienced a multi-decadal warming over recent decades at a rate of between three and four times the global average (Holbrook and Bindoff, 1997; Ridgway, 2007) - the global average warming rate being about 0.5-0.6 °C century^{-1}. The SE Australian region is a global hot-spot for ocean temperature change. Climate change projections indicate a further strengthening (Cai et al., 2005) and southward migration of the EAC throughout the century. Consequently, marine ecosystems in this region are expected to be significantly affected by these long-term projected changes in the EAC. The net effect of these changes on the biological connectivity of coastal populations is a critical concern for coastal management. Malcolm et al. (2011) investigate links between EAC processes and ocean temperature at a number of northern NSW shelf sites inshore of the core of the EAC. For the period 2001–2008, offshore sites had temperatures ~1 °C higher than nearshore sites, with the EAC having the greatest impact during late spring/summer. The high spatial and temporal sampling revealed interesting local effects. Nonetheless, gradients in the distribution of tropical species in this nearshore region were dominated by time-averaged location of the EAC.

The EAC may aid the coastal connectivity of populations, but it can also act as a barrier to connectivity as it separates from the coast (Condie et al., 2011; Roughan et al., 2011). The degree of local retention and cross-shelf exchanges of propagules is intriguingly related to the spatial variation in spawning and life histories of small pelagic fishes around Australia (Condie et al., 2011).

At the regional scale, flow disturbance around headlands and islands is also evident and has great potential to structure plankton and influence larval transport (Suthers et al., 2004, 2006). Cresswell et al. (1983) noted the presence of weak clockwise cells in the embayments of northern New South Wales (such as between Smoky Cape and Korogoro Point, between Hat Head and Crescent Head; and between Crescent Head and Point Plomer). These local circulations could have significant importance for genetic structuring of marine populations (i.e. sub-stocks). The most recent example is how the local variation in genetic structure of the sea urchin *Centrostephanus rogersii* is correlated with the variation in SST throughout the EAC separation zone (Banks et al., 2007).

2.4. Separation from the coast, and formation of planktonic habitats

There are distinctive water types and pelagic habitats over the shelf, generated by the EAC as it separates from the coast (Fig. 2, Baird et al., 2011-b). The EAC accelerates off northern New South Wales where the continental shelf off Smoky Cape (~31°S) narrows by half in less than 0.5° latitude, to just 16 km wide. The acceleration lifts up cool nutrient-rich slope water onto the shelf generating marked upwelling signatures in Sea Surface Temperature (SST, Fig. 3A) and chlorophyll *a*, typically between 30–33°S (Fig. 3A, Oke and Middleton, 2000; 2001; Roughan et al., 2003; Roughan and Middleton, 2004). Further uplifting is also facilitated by eddies, by topography and by summer north-easterly winds (Roughan and Middleton, 2002), all of which can stimulate phytoplankton blooms and red tides. Typically the red tides found off Sydney originate in the EAC separation zone north of Port Stephens (Dela-Cruz et al., 2002, 2003). On the larger scale, the separated EAC and Tasman Front are source regions for southwest Pacific subtropical mode water (Holbrook and Maharaj, 2008).

The increased productivity of the waters south of the separation zone and offshore of the Stockton Bight (Fig. 3) is consistently observed in remote sensing products (e.g. MODIS, cover image) and coupled bio-physical models of the region (Baird et al., 2006a, b; Macdonald et al., 2009). In particular, the climatological nitrate concentrations in the upper 100 m over the continental shelf between 32–34°S is persistently elevated (> 4 μM, Fig. 3B). This nutrient load delivered by the separation and upwelling events outweighs that delivered by river discharge or sewage discharge (Pritchard et al., 2003) by an order of magnitude.

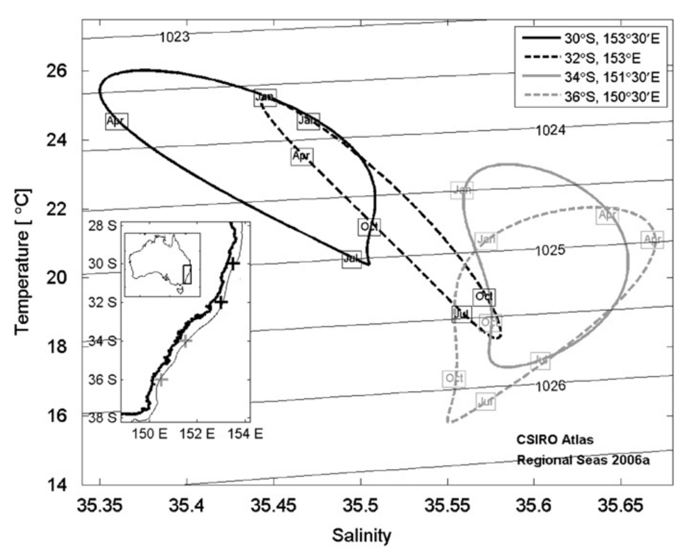

Fig. 2. A summary of the climatological temperature-salinity properties of the southeast Australian continental shelf (after Baird et al., 2011-b), showing the seasonal cycle of surface T-S properties in the CSIRO Atlas of Regional Seas version 2006a near the 200 m isobath at 28°S, 32°S, 34°S and 36°S. The change in seasonal T-S properties south of 32°S and the separation zone is evident. The background lines are density [kg.m^{-3}].

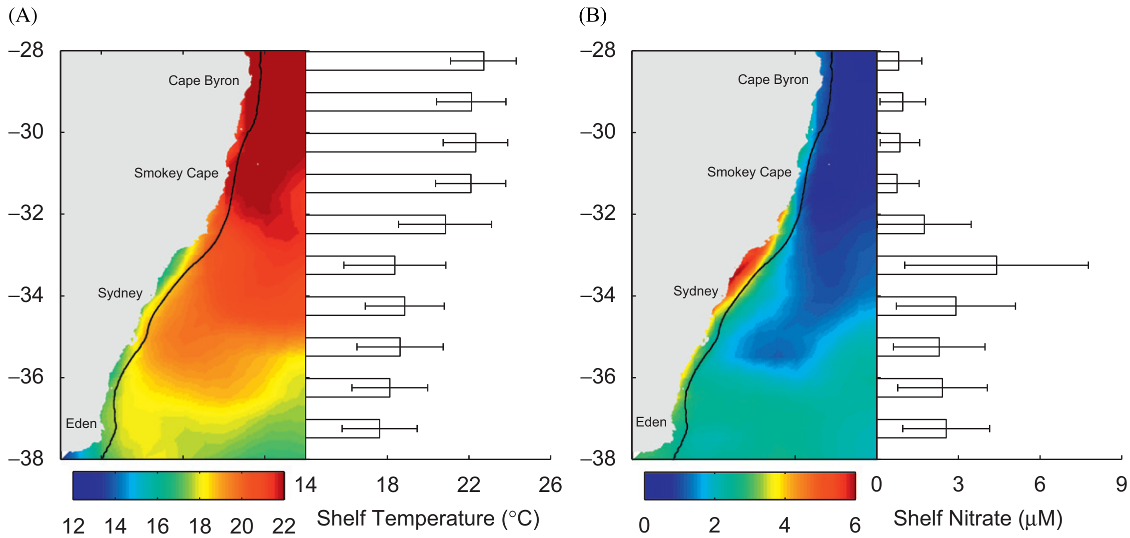

Fig. 3. Climatological temperature (A) and nitrate (B) concentration from the 2006 CSIRO Atlas of Regional Seas (CARS), derived from a quality-controlled archive of all available measurements. The contour plots (left) show depth- and seasonal-averaged values for 0–100 m at the CARS grid resolution of 0.5° × 0.5°. The bar plots show the corresponding latitudinal averages for the 2 closest data points to the coast. See Ridgeway et al. (2002) and Dunn & Ridgeway (2002) for further information regarding the CARS dataset.

The inner shelf waters are cooler and sometimes less saline than the EAC, generated by coastal upwelling and sporadic land runoff. In turn, the EAC is warmer and less saline than the Tasman Sea (Fig. 2, Baird et al., 2011a). These water types can explain much of the spatial distribution of larval fish, at a relatively fine-scale (10's km, Syahailatua et al., 2011a). The pelagic habitat of deep water fishes such as myctophid larvae is expected, but the contrasting distributions of larval trevally and larval herring is intriguing. It suggests a fine scale separation over the shelf of spawning and nursery habitats of these two abundant species and their responses to climate change may be reflected in the dynamic area of their pelagic habitats. These habitats are also related to the growth rates of larval trevally (faster in inner-shelf water) and larval *Sardinops* (slower in inner-shelf water, Syahailatua et al., 2011b).

The paucity of pigment biomarkers of phytoplankton in the region was addressed by two papers (Hassler et al., 2011; Thompson et al., 2011). The spatial patterns of the phytoplankton along the east and west coasts of Australia were compared by Thompson et al. (2011) via an extensive analysis of in situ pigment and remotely-sensed SeaWiFS data. On average there is double the Chlorophyll *a* concentration on the east coast. The south east coast had relatively more Prochlorophytes, Euglenophytes and diatoms than the southwest, and southern waters are dominated by *Synechococcus*. Using biomarker pigments to indicate similarities in phytoplankton communities, Hassler et al. (2011) show that the phytoplankton communities within an offshore, cold-core eddy more closely resembled communities within inner-shelf waters, supporting previous hypotheses that cold core eddies represent an important mechanism to disperse phytoplankton offshore (Moore et al., 2007). A vertical supply (doming) of nutrients occurred within the sampled eddies and high maximum quantum yield values were observed, suggesting well-adapted, non-limited (nutrient or light) phytoplankton communities (Hassler et al., 2011).

2.5. Climate change impacts on marine ecosystems in the Tasman Sea

The recognition of distinctive pelagic habitats in the Coral Sea and Tasman Sea (Hobday and Hartmann, 2006) was a significant advance for fisheries management and quota allocation, by providing dynamic, real-time permits to regions for fishing. These broad-scale habitats were pragmatically based on SST and climatological stratification to provide real-time management. This benchmark study is extended in this issue (Hobday et al., 2011) to 5 variables to recognise 7 broad habitats off eastern Australia: bathymetry, SST, T250m, surface chlorophyll (SeaWiFS) and nitrate climatology. Not surprisingly, these dynamic habitats provide more precise measurements of fish catch, or diet (smaller CVs), compared to static or traditional boundaries (Hobday et al., 2011). The ecosystem basis to these pelagic habitats can be inferred from stable isotope analysis (Revill et al., 2009). These habitats have little seasonality, but vary in size and location over almost 2 decades (Hobday et al., 2011; Hartog et al., 2011).

For the purpose of a broad marine ecosystem understanding, the waters along the coast of southeastern Australia are best characterised by the warmer Coral Sea waters as biologically unproductive while the cooler Tasman Sea waters are more productive (Baird et al., 2008). Under this simplified view, warm-core eddies represent regions of pinched-off meanders of Coral Sea (EAC) water surrounded by Tasman Sea water. Any shift in Coral Sea waters southward, or in the characteristics of eddies produced by the EAC may change biological productivity and alter the species of fish caught – and therefore the economics of southeast Australian fisheries. One study has revealed that the increase in water temperature of the Tasman Sea has increased the growth rates of juvenile commercial fish such as redfish and jackass morwong, which generally reside in the upper 250 m (Thresher et al., 2007). Conversely, they found the juvenile growth rates of deep water fish (orange roughy and oreos, >1000 m) decreased, although under climate change this could eventually reverse. The cause of this decreased growth was also related to cooler temperatures, possibly as a result of increasing flow by the enigmatic EAC undercurrent (Cresswell, 1994). Similarly Ling et al. (2009) have shown the impacts of the extension of the EAC over the past 30 years and the penetration of the EAC into Tasmanian waters. Where previously kelp forests were plentiful, sea urchin barrens now abound. Byrne et al. (2011) establish the thermal tolerance of the larval sea urchin *Heliocidaris erythrogramma* – another kelp dependent species in this region.

The strong variability of the both the main flow of the EAC, and the eddy field downstream of the separation point, may hide shifts associated with climate change. For example, Baird et al. (2011b) found that week-time scale synoptic oceanographic and meteorological features provided the best explanation of zooplankton observations from the Warreen cruises of 1938-42. Seasonal and inter-annual signals in zooplankton data were more difficult to identify. This raises the question as to whether the biological data available along the NSW coast is sufficient to provide a 'baseline' state of marine ecosystems before the 20th century warming.

Perhaps the greatest expression of the influence of the East Australian Current (EAC) is demonstrated by its relationship with the top end of the food web and from there to the fisheries that exist within and outside the EAC (Campbell, 2008; Young et al., 2001, 2011). The EAC is the focus for a range of top predator tuna and billfish, either as a thermal refuge, a feeding environment or as a spawning ground (Campbell, 2008; Young et al., 2001, 2003; Young et al., 2011). In particular, yellowfin tuna, *Thunnus albacares*, are closely associated with the EAC as catch data over many years have highlighted (e.g. Ward, 1996). The higher temperature of surface waters relative to the adjacent Tasman Sea has enabled these typically subtropical species to extend their range as far south as Tasmania (Young et al., 2001). Predicted ocean warming suggests that these and other tropical tuna and billfish species are likely to be an increasingly important component of pelagic ecosystems within Australian waters in years to come (Hartog et al., 2011). However, it is unlikely that temperature alone will explain whether increased warming will be the only factor. Understanding the food webs that underpin these predators will also be needed (Baird and Suthers, 2007). For example, large diatoms apparently play an important role in the concentration of yellowfin tuna within the EAC off Fraser Island (Young et al., 2010). Intermediate predators and their prey are linked via zooplankton such as crab megalopae feeding on large diatoms (e.g. *Dactyliosolen* spp.) to top predators such as the tunas. How these lower orders will respond to ocean warming is not well understood. Monitoring the seasonal and interannual variability of phyto- and zooplankton in the EAC and their relationship to pelagic food webs will be vital to understanding how predicted ocean warming will enhance or otherwise top predator fish communities within the EAC.

3. Conclusions – some remaining unknowns

Holbrook and Bindoff (1997) calculated a depth-averaged warming to 100-m depth of 1.5 °C century^{-1} off Tasmania based on objectively-mapped historical vertical temperature profiles over 34 years (1955-1988). More recently, using the Maria Island long term quasi-monthly monitoring station (1944–2002, almost 60 y), Ridgway (2007) reports a SST warming rate of 2.3 °C per century and increasing salinity of 0.34 per century. Ridgway (2007) and others have noted the remarkable impact of the EAC's southward penetration off Tasmania. The Tasman Sea region, and particularly the poleward extension of the EAC are predicted to be strongly impacted under climate change scenarios (Cai et al., 2005). The strengthening of the EAC is predicted to warm Australian waters by 1-2 °C by 2030 and 2-3 °C by 2070s, particularly off Tasmania (Poloczanska et al., 2007). The temperature in the Tasman Sea will have great impacts, particularly on temperature-dependent crops (i.e. frost sensitive) and those crops that depend on autumn rainfall. Murphy and Timbal (2007) investigated the relationship between rainfall, maximum and minimum temperature of continental southeastern Australia and three SST indices. Of the indices investigated, the Tasman Sea Index was more strongly correlated with rainfall, and maximum and minimum temperatures in southeastern Australia in autumn than the other SST indices. It was also the best overall predictor of temperature throughout the year.

This collection of papers has filled significant gaps in our knowledge of EAC and sea-level response in Sydney Harbour, the form and function of eddies off the coast and the biological significance of shelf transport and pelagic habitats. There is evidence for the temperature effects on larval urchins, and of changing distribution of pelagic habitats, but the challenge of comparing old plankton data sets with new, requires a firm understanding of the local weather at the time of collection.

The effects of the annual and seasonal variability of the EAC (Hill et al., 2008) on coastal ecology are diverse and largely unknown. The EAC interaction with the shelf is difficult to quantify, as the EAC is notoriously "leaky" to the east. Consequently EAC activity and the transport of heat from the Coral Sea to the Tasman Sea is derived from a long-term XBT transect between Brisbane, New Caledonia and Fiji (Ridgway et al., 2008). Until now (Holbrook et al., 2011), there had been no clear connection between large-scale ocean dynamics on ENSO time-scales or EAC transport changes, and sea level observed on Australia's east coast. The Fremantle sea level index is particularly useful to fisheries management for Western Australia in the absence of fisheries data (Caputi et al., 1996). Use of estuarine sea level at the long term Fort Denison tide-gauge in Sydney Harbour (Holbrook et al., 2011) may now provide the analogous tool for Australia's southeast. We do not understand the relationship of the EAC and/or eddies with the northward, coastal counter-current(s), which is likely of great importance to understanding the effects of climate change, connectivity and even northward sediment transport (Goodwin et al., 2006).

An eddy census needs to be conducted to determine if the EAC's eddy climate is changing with the current strengthening. The biological and fisheries effects of an eddy should be considered, especially aspects such as entrainment of shelf water. The final large-scale question concerns the air-sea interaction over a warm-core eddy, particularly during winter. The link with warm-core eddies and east coast low events (particularly winter storms) needs to be further explored (Hopkins and Holland, 1997). Many of these questions will be addressed with the new marine infrastructure by IMOS (Roughan et al., 2010, 2011), and its implementation along the coast of NSW.

A surprising unknown is the relationship of the EAC with its megafauna. The relationship between the movement of sharks or whales and the EAC and water types is a complete mystery (e.g. Rowling, 2001; Bruce et al., 2006). An IMOS passive acoustics mooring on the shelf (33°S) will go some way to addressing these dynamics. At the finer scale, we still do not know the biological responses to the EAC's transport of heat, particularly for kelp distribution on rocky reefs. It will be useful to use the shelf circulation models of Roughan et al. (2011) and relate them to interannual variability in estuarine and rocky reef communities. We do not know the ecology of temperate krill and many of the copepods off our coast, let alone the nanoplankton and bacterioplankton diversity. The effects of temperature on zooplankton (salps and krill), and the effects of acidification on local plankton remains to be explored.

A significant advance will be to compare processes between the Leeuwin Current and EAC, as now being encouraged by the national IMOS program. Two papers in this issue make some comparisons of fundamental oceanographic variables (Condie et al., 2011; Thompson et al., 2011) and provide the basis for other comparisons. The Leeuwin Undercurrent has a significant role in the production of eddies (Feng et al., 2007), yet there has been no systematic study of the EAC Undercurrent since Cresswell (1994).

Studies have been made of large anticyclonic eddies (> 100 km diameter), but we have no understanding or index of smaller-scale features (< 50 km diameter). The frequency and duration of upwelling in the separation zone is an important question. The mesoscale variability is difficult to replicate in eddy-resolving models such as Bluelink and the dynamics of eddy formation, growth, and decay remains uncertain, as highlighted by Oke and Griffin (2011) and Brassington et al. (2011). While modelling capabilities have advanced significantly in recent years, the end goal is to achieve sufficiently dense observations in real time that we can implement a co-ordinated approach to numerical ocean prediction and forecasts of quantifiable accuracy at relevant spatial scales (Seim et al., 2009).

Our collective challenge will be to continue the tradition of EAC-interdisciplinary studies demonstrated in 1983. The development of new molecular, modelling or sensor methods may tempt us towards specialist and potentially isolated research, yet the scientific rewards for collaboration and interdisciplinary science are worth the extra effort.

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