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ScienceDirect
Deep-Sea Research II 54 (2007) 789–796
DEEP-SEA RESEARCH PART II
www.elsevier.com/locate/dsr2

The Leeuwin Current and its eddies: An introductory overview

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Received 22 December 2005; received in revised form 18 December 2006; accepted 24 December 2006
Available online 21 June 2007

Abstract

The Leeuwin Current (LC) is an anomalous poleward-flowing eastern boundary current that carries warm, low-salinity water southward along the coast of Western Australia. We present an introduction to a new body of work on the physical and biological dynamics of the LC and its eddies, collected in this Special Issue of Deep-Sea Research II, including (1) several modelling efforts aimed at understanding LC dynamics and eddy generation, (2) papers from regional surveys of primary productivity and nitrogen uptake patterns in the LC, and (3) the first detailed field investigations of the biological oceanography of LC mesoscale eddies. Key results in papers collected here include insight into the source regions of the LC and the Leeuwin Undercurrent (LUC), the energetic interactions of the LC and LUC, and their roles in the generation of warm-core (WC) and cold-core (CC) eddies, respectively. In near-shore waters, the dynamics of upwelling were found to control the spatio-temporal variability of primary production, and important latitudinal differences were found in the fraction of production driven by nitrate (the *f*-ratio). The ubiquitous deep chlorophyll maximum within LC was found to be a significant contributor to total water column production within the region. WC eddies including a single large eddy studied in 2000 contained relatively elevated chlorophyll *a* concentrations thought to originate at least in part from the continental shelf/shelf break region and to have been incorporated during eddy formation. During the Eddies 2003 voyage, a more detailed study comparing the WC and CC eddies illuminated more mechanistic details of the unusual dynamics and ecology of the eddies. Food web analysis suggested that the WC eddy had an enhanced "classic" food web, with more

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0967-0645/$ - see front matter
doi:10.1016/j.dsr2.2006.12.008

concentrated mesozooplankton and larger diatom populations than in the CC eddy. Finally, implications for fisheries management are addressed.

Keywords: Mesoscale eddy; Leeuwin Current; Leeuwin Undercurrent; Primary production; *f*-ratio; Chlorophyll *a*

1. Introduction

The Leeuwin Current (LC) off Western Australia is anomalous in that it is the only poleward-flowing eastern boundary current globally. It therefore carries warm, low-salinity water southward along the coast of Western Australia (Cresswell and Golding, 1980; Pearce, 1991) in contrast to other eastern boundary currents where strong upwelling is typical. The physical dynamics of the LC have been studied over the past two decades (e.g., Godfrey and Ridgway, 1985; Thompson, 1987; Feng et al., 2005). Although the dynamics of the LC are critical to regional fisheries such as the economically important Western Rock Lobster, *Panulirus cygnus* (Caputi et al., 2003), the biological impact of the LC has only recently been studied (Griffin et al., 2001; Hanson et al., 2005a, b). In general, the interaction between ocean physics and biology in the LC region is understudied in comparison with other boundary current systems.

The strength of the LC varies seasonally, flowing strongly in the austral winter when southerly winds are weakest (e.g., Cresswell, 1991; Fieux et al., 2005) and the alongshore pressure gradient strengthens (Potemra, 2001; Godfrey and Ridgway, 1985). Interannual variation in LC strength is related to the El Niño Southern Oscillation: stronger flow occurs during La Niña years and weaker during El Niño years (Pearce and Phillips, 1988; Feng et al., 2003; Li and Clarke, 2004). As the current strengthens both annually and interannually, a significant portion of LC water feeds into the mesoscale anticyclonic eddies that spin up from the current and propagate westward away from the coast (Pearce and Griffiths, 1991; Morrow et al., 2004). Interannual variation in LC strength influences the local marine ecosystem, and is positively correlated with settlement of western rock lobster, *P. cygnus*, to juvenile habitat (Pearce and Phillips, 1994; Caputi et al., 2003), though the mechanism is unknown.

Globally, mesoscale eddies (50–200 km diameter) have been seen to generate large productivity pulses in many nutrient-poor regions of the world ocean (Letelier et al., 2000; Garcon et al., 2001) by two primary mechanisms, "eddy pumping" of nutrients upwards from deep to shallow waters by cyclonic eddies (McGillicuddy and Robinson, 1997; Brzezinski et al., 1998; Siegel et al., 1999) and transport of nutrients and productivity offshore from coastal, frontal or upwelling areas by either cyclonic or anticyclonic eddies (Garcia-Gorriz and Carr, 2001; Lima et al., 2002; Whitney and Robert, 2002). Productivity enhancement due to eddy pumping is generally seen in the centre of upwelling cyclonic eddies and at the periphery of convergent anticyclonic eddies (Oschlies and Garcon, 1998; Mordasova et al., 2002).

Very few LC eddies have been sampled and studied by field-going oceanographers, so before the investigations presented here, relatively little was known about their influence on the regional biogeochemistry and ecology. SeaWiFS ocean-colour imagery suggested that anticyclonic eddies of the LC had higher near-surface concentrations of chlorophyll *a* than adjacent waters, and that the time of maximum concentration was mid-winter, when the LC is most intense (Griffin et al., 2001). Cresswell and Griffin (2004), however, found that fluorescence was a local minimum in the center of an anticyclonic LC eddy south of our study region.

Papers in this volume represent the first collection of intensive multidisciplinary investigations of the LC and its associated mesoscale eddies. Our aim is to characterize the dynamics and productivity of the LC in some detail, with special emphasis on biophysical coupling and the mesoscale eddies. A number of modeling papers (Domingues et al., 2007; Rennie et al., 2007; Mueleners et al., 2007; Batteen et al., 2007) document various mechanistic aspects of the LC including its sources, structure, and eddy generation. Hanson et al. (2007a) then examine the magnitude and significance of the ubiquitous deep chlorophyll maximum layer found within LC and offshore waters, while Hanson et al. (2007b) and Twomey and co-workers (2007) investigate the nitrogen uptake dynamics of phytoplankton in broad geographic regions north and south of the Abrolhos islands from field efforts in

2000 and 2003, respectively. Moore et al. (2007) report the first measurements of chlorophyll *a* in the very large WC eddy of 2000.

The rest of the papers in this volume form part of the Waite et al. study of two counter-rotating LC eddies in 2003 (Eddies 2003): Feng and co-workers (2007) detail the physical structure of the eddies studied. These are followed by a discussion of vertical mixing within the warm WC eddy in particular (Thompson et al., 2007) and fluxes of nitrogen into the eddy (Greenwood et al., 2007). Phytoplankton productivity and nutrient uptake are discussed by Waite and co-workers (2007a) with a special effort devoted to nutrient dynamics and nitrogen fixation (Holl et al., 2007). Microzooplankton grazing and picoplankton abundances are investigated by Paterson et al. (2007a, b), followed by enumeration of the mesozooplankton by Strzelecki et al. (2007). Larval fish abundances and distributions are discussed in detail by Muhling et al. (2007). Waite et al. (2007b) investigate food web structure within the eddies as elucidated by the N and C isotope signature of the organisms, in combination with all other data. And finally, Gaughan (2007) discusses implications of mesoscale eddy formation for fisheries management of coastal species. In the present paper, we provide a brief context for, and introduction to, the ~20 papers contained in this volume.

2. Results and discussion

2.1. Physical oceanographic modelling

New model results using a Lagrangian approach have indicated that the warm, low-salinity tropical water transported by the LC along the coast sources contributions from waters as remote as the western tropical Pacific Ocean to the east (via the Indonesian throughflow) and the Somali Basin to the west (via the South Java Current) (Domingues et al., 2007). One novel finding is that eastward movement of Subtropical Gyre water can move directly into the Leeuwin Undercurrent (LUC) (Domingues et al., 2007). Overall, it is clear that there are significant exchanges between the LC and the LUC and the adjacent Subtropical Gyre, such that the Gyre is probably both a source and a sink for both boundary currents (Fig. 1).

Using a process-oriented numerical study, Batteen et al. (2007) found that the north–south thermohaline gradient is the primary force generating both the poleward LC and the equatorward LUC beneath it. The major role of the wind is to slow the poleward surface flow, and wind also

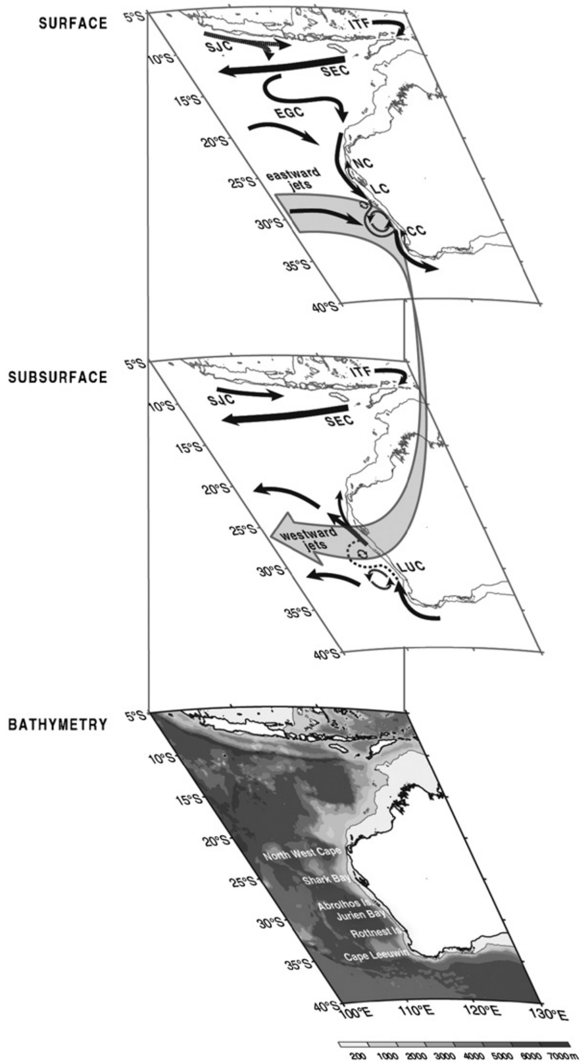

Fig. 1. Simplified schematic of surface currents off Western Australia emphasizing the connection between the Leeuwin Current (LC) and Leeuwin Undercurrent (LUC) as a curved vertical arrow. Indicated is (1) the bathymetry and key coastal landmarks (bottom), (2) the subsurface (200–400 m) northward-flowing LUC, showing westward jets offshore, (3) the LC at the surface, fed by the eastward jets transporting Subtropical Water / South Indian Central Water into the LC and then the LUC. The relative position of other regional currents is referred to in the text. Papers in this volume address key questions regarding the origin of the Leeuwin Current from both the Indonesian Throughflow (ITF) and the South Java Current (SJC) and its interaction with adjacent water masses including the wind-driven counter-currents, the Capes Current (CC) and the Ningaloo Current (NC). Thanks to Sue Wijffels (CSIRO, Hobart) for helpful discussions on this figure.

enhances eddy spin up (see below) and creates localized upwelling regions.

As the LC intensifies south of the Abrolhos Islands (Meuleners et al., 2007) it becomes cooler and saltier along its trajectory, and most of the heat loss is due to offshore fluxes of mesoscale eddies (Domingues et al., 2006). The mean flow itself may, however, play a key role in controlling the migratory paths and speed of the mesoscale eddies (Meuleners et al., 2007). In fact, LC/LUC interactions may trigger initial perturbations causing mesoscale eddies to form a key process of interest in the LC (Fig. 2). The LC/LUC interactions result in eddy pairs where cyclonic eddies form in the LUC and anticyclonic eddies in the LC (Rennie et al., 2007; see Fig. 3).

The interaction of the LUC with the bathymetry of the continental shelf, such as the Perth Canyon, can act as a catalyst for eddy formation (Rennie et al., 2007), resulting in at least two regions with topographic triggers for eddy formation, the Abrolhos Islands and Shark Bay (Fig. 1), and another possible region off Rottnest Island. Bottom topography is also important for intensifying and trapping currents near the coast, weakening subsurface currents and intensifying eddies off the Capes region to the south (Batteen et al., 2007). Why the LC primarily remains anchored to the shelf break when rounding Cape Leeuwin is another question of key physical oceanographic interest (Fig. 1). Both the regional dynamics influencing the mean flow, and the triggers and controls of mesoscale eddies are potentially of importance in determining the biology of the LC system overall.

2.2. Regional production patterns

In the LC and offshore waters of the Gascoyne region south of Northwest Cape (Fig. 1), the ubiquitous deep chlorophyll maximum (DCM) was found to be a true biomass maximum (Hanson et al., 2007a), as opposed to merely a physiological adaptation of the cellular carbon: chlorophyll *a* ratio, which can occur at low light levels (Cullen, 1982; Geider, 1987). This is of interest for regional production estimates, since the DCM layer can contribute 30–70% of total water-column production depending on light attenuation levels, which should be accounted for in regional primary production models. Modeling such processes would be complicated by the fact that the DCM is too deep (50–120 m) to be assessed using ocean-colour satellite imagery (Hanson et al., 2007a). Because of the low concentrations of dissolved nutrients (especially nitrogen) in the upper mixed-layer of the LC, patterns of primary production are strongly affected by the dynamics moving more nutrient-rich waters from the base of the LC (which can be up to 300 m deep) toward the surface (Hanson et al., 2005a, b); pulses of upwelled nutrients are incorporated into, and then regenerated within, the plankton community (Twomey et al., 2007). Because such injections of nutrients into an already nutrient-poor euphotic zone are both relatively weak and sporadic, the frequency, duration and intensity of seasonal and localized upwelling events along the west coast of Australia play key roles in determining the ecological structure of the planktonic community (Twomey et al., 2007; Hanson et al., 2007b). Interestingly, while regenerated nutrient sources appear to dominate primary production north of the Abrolhos Islands within the LC proper (Hanson et al., 2007b); nitrate becomes equally important to the south (Twomey et al., 2007), suggesting latitudinal gradients in new production whose exact causes remain unclear. Nitrogen fixation was not a significant source of nitrogen (N) to the region in the latter study, with diazotrophs contributing less than 1% of the total measured N uptake (Twomey et al., 2007).

Interaction between the deep chlorophyll maximum (DCM) typical of LC waters, and the intensification LC flow, can cause fluctuations in primary productivity due to deepening and shallowing of the nutricline (Hanson et al., 2007a). These studies illuminate the key role of LC dynamics in controlling productivity in the core region of LC mean flow, and the importance for productivity of wind-driven upwelling regions such as the Ningaloo Current and Capes Current shoreward of the main body of the LC, primarily in summer. Clearly, the LC eddy system has a dynamic impact on near-shelf productivity, both temporally and spatially. It is worth noting that while upwelling tends to be a summer phenomenon in the LC because of persistent southerly winds, the formation and activity of mesoscale eddies tends to peak through the winter months, making the primary oceanographic drivers strongly seasonal.

2.3. Eddies

Mesoscale eddies form from mixed barotropic and baroclinic instability of the LC (e.g., Batteen

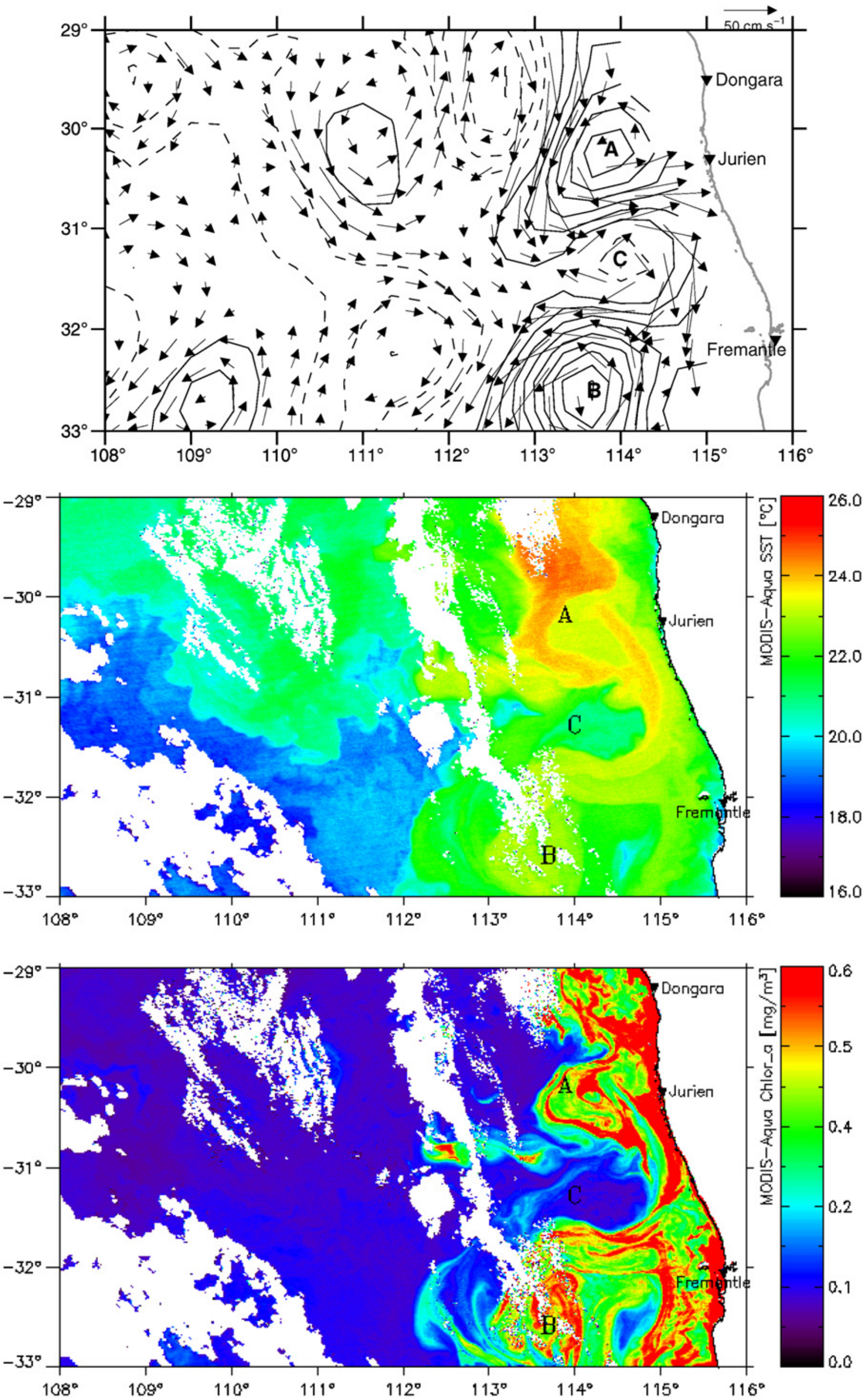

Fig. 2. Typical structure of forming LC eddies. (a) Sea surface height anomaly and surface geostrophic current anomaly (arrows) in the southeast Indian Ocean on 28 May 2003. (b) SST and (c) SSC concentration from MODIS satellite in the same region as (a) on 25 May 2003. Note the formation of a WC–CC–WC triplet. Figure from Feng et al. (2007) with permission.

and Butler, 1998; Feng et al., 2005; Figs. 2 and 3). In 2000 (Moore et al., 2007) and 2003 (Waite et al., 2007a, and references therein) field programs sampled slightly rarer WC eddies that were both large and long-lived, classical examples of large, mature WC eddies of LC origin (Waite et al., 2007a).

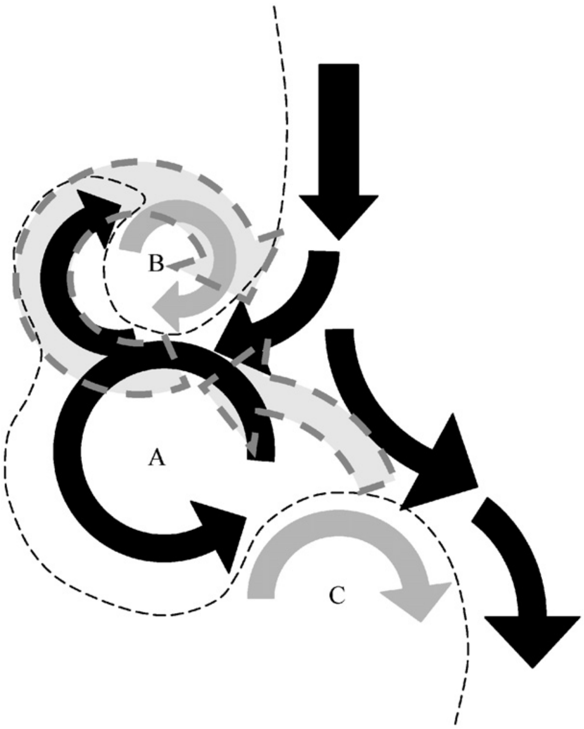

Fig. 3. Schematic of formation of eddy pairs in the Leeuwin Current and Undercurrent. The black arrows represent the Leeuwin Current heading southward along the coast and the thin dashed line represents the warm water boundary. The solid grey arrows represent cooler offshore water and the grey dashed arrows represent the Leeuwin Undercurrent. (A) Leeuwin Current anticyclonic eddy. (B) Undercurrent cyclonic eddy which at the surface appears as a cyclonic eddy enclosing oceanic water, and paired with surface LC eddy. (C) New eddy forming from ocean water drawn between the Leeuwin Current and the anticyclonic eddy. Figure from Rennie et al. (2007) with permission.

The WC eddies were both shown to contain locally enhanced chlorophyll *a* concentrations (Moore et al., 2007; Feng et al., 2007) consistent with limited exchange between the eddies and surrounding waters (Mackas and Galbraith, 2002). The 2003 eddy had measurably enhanced production rates (Waite et al., 2007a), likely due to the mixed layer dynamics favouring a strong diatom population (Thompson et al., 2007) and extensive recycling of available nutrients (Greenwood et al., 2007), mostly by the abundant microheterotroph grazers (Paterson et al., 2007a). The microheterotroph population was diverse and included a rare Phaeodarian species with only a handful of documented occurrences globally (Paterson et al., 2007b). N fixation rates were low (Holl et al., 2007), about 1% of total N uptake. Mesozooplankton abundance and biomass were twice as high in the WC eddy as in the CC eddy, consistent with the higher phytoplankton and microzooplankton biomass and higher primary production in the WC (Strzelecki et al., 2007), while impacts on larval fish were limited by the physical dynamics of the WC eddy (Waite et al., 2007b; Muhling et al., 2007).

The structure of the cold-core (CC) eddy studied in 2003 was somewhat atypical of such features globally, which are known to be potentially a significant source of deep water to the surface (Vaillancourt et al., 2003). The LC CC eddy had a cap of warm Indian Ocean water that seems to have limited upwelling to depths between 1000 and 500 m (Feng et al., 2007). It is possible that this structure is typical of LC CC eddies generally. Rennie et al. (2007) show model results that suggest the CC eddies may be sourced generally from the deeper LC undercurrent. The CC eddy sampled in 2003 seemed representative of intense CC eddies that form seaward of the LC, upstream of a developing LC meander (Rennie et al., 2007).

Finally, Gaughan (2007) discusses how the LC system has the potential to exert direct negative influences on recruitment of bony fish on south-western Australia' s continental shelf through a combination of offshore entrainment (i.e. removal) of larval fish, and through dilution of plankton concentrations on the continental shelf. In the end, it is unclear whether the enhanced production within the WC eddies (Waite et al., 2007a), or the fisheries losses from offshore entrainment (Gaughan, 2007) will dominate the impact of the LC's mesoscale eddy field on fisheries. However, the answer is likely to differ for fish with different larval ecologies, so it is clear that this interaction of the LC with larval fish is one key area for future work.

Overall, then, this new body of work clarifies some of the key physical interactions between the LC, the LUC and the adjacent subtropical gyre. The biological surveys of the LC's north and south regions demonstrate a spatially and temporally dynamic ecological system whose productivity hinges on interactions between the LC, and the continental shelf, as well as on the intense seasonal winds. The LC eddies had significant impact on regional production patterns. In addition to the key questions regarding the interaction of LC flow with regional fisheries, a number of questions remain to be addressed in terms of how the physical dynamics control the biology and biogeochemistry of the LC ecosystem. These include the dynamics of nutrient injection on to the continental shelf, especially to the south of the Abrolhos Islands (Twomey et al., 2007), the mechanism of incorporation of new nutrients into forming LC eddies (Waite et al., 2007a), the potential role of iron in controlling productivity (Holl et al., 2007), and the overall links between these processes and climatically driven changes in LC flow.

Acknowledgements

We thank the captain and crew of the SS Southern Surveyor (Eddies 2003) without whose support we could not have tracked the eddies, and extend special thanks to L. Pender and M. Underwood for ship-board technical support. Eddies 2003 was supported by the University of Western Australia, the Faculty of Engineering, Computing and Mathematics (UWA) Strategic Fund, and the Waite et al. (2007) Collaborative Project from the Strategic Research Fund for the Marine Environment (SRFME). Sue Wijffels assisted greatly with discussions regarding Fig. 1 and Figs. 2 and 3 are sourced from Feng et al. (2007) and Rennie et al. (2007), respectively.

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