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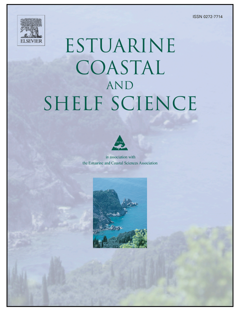

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A Western Boundary Current Eddy Characterisation Study

by

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Key Points:

- 497 short-lived eddies detected in a coastal corridor off eastern Australia.
- About 23 individual short-lived eddies traced per year.
- 43% of cyclonic eddies (4-5 per year) found off southeast Queensland.
- Cyclonic eddies displaced shelf water by about 110-120 km.
- Cyclonic eddies postulated to establish quasi-permanent northward flow.

Abstract

The analysis of an eddy census for the East Australian Current (EAC) region yielded a total of 497 individual short-lived (7-28 days) cyclonic and anticyclonic eddies for the period 1993 to 2015. This was an average of about 23 eddies per year. 41% of the tracked individual cyclonic and anticyclonic eddies were detected off southeast Queensland between about 25 ^{o}S and 29 ^{o}S. This is the region where the flow of the EAC intensifies forming a swift western boundary current that impinges near Fraser Island on the continental shelf. This zone was also identified as having a maximum in detected short-lived cyclonic eddies. A total of 94 (43%) individual cyclonic eddies or about 4-5 per year were tracked in this region. The census found that these potentially displaced entrained water by about 115 km with an average displacement speed of about 4 km per day. Cyclonic eddies were likely to contribute to establishing an on-shelf longshore northerly flow forming the western branch of the Fraser Island Gyre and possibly presented an important cross-shelf transport process in the life cycle of temperate fish species of the EAC domain. In-situ observations near western boundary currents previously documented the entrainment, off-shelf transport and export of near shore water, nutrients, sediments, fish larvae and the renewal of inner shelf water due to short-lived eddies. This study found that these cyclonic eddies potentially play an important off-shelf transport process off the central east Australian coast.

Keywords: Western boundary currents; fisheries; eddies; transport; shelf dynamics; East Australian Current.

1. Introduction

In-situ observations from Western Boundary Current (WBC) regions indicate that cyclonic eddies (CEs) are important for fisheries (Kasai et al. 2002, Govoni et al. 2009, Suthers et al. 2011, Matis et al. 2014, Mullaney et al. 2014, and Everett et al. 2015). Forming on the near-coast side of WBC regions, CEs become enriched in fish larvae and primary productivity stimulating nutrients due to the entrainment of near-shore coastal water. The East Australian Current (EAC) CEs observed to the south of the EAC intensification zone (Ridgway and Dunn 2003) where found to be usually short-lived (2-4 weeks). The eddies were more frequent and of smaller scale than anticyclonic eddies (ACEs) and ranged in size from about 10 km to 100 km (Mullaney and Suthers 2013; Everett et al. 2015). Observed CEs propagated close to the coastal zone, often generated a near-shore northward flow (e.g. Huyer et al. 1988, Roughen et al. 2011, Everett et al. 2011) and were located at the coastal side of the EAC. CEs were also usually cold-core eddies, i.e. characterised by a negative sea surface temperature anomaly (SSTa), and Chlorophyll-a (Chl-a) concentrations were about twice than those observed for ACEs (e.g. Govoni et al., 2009, Suthers et al. 2011, Everett et al. 2011, Everett et al. 2014, Mullaney et al. 2014, Everett et al. 2015). Studies of EAC CEs are few and limited to the southern regions of the EAC (e.g. Oke and Griffin 2010; Macdonald et al. 2016), which is referred to as the EAC separation zone (Ridgway and Dunn 2003). This study aimed to provide a census for short-lived eddies (7-28 days) along the east Australian coast with a particular focus on CE off the coast of southeast Queensland. This region is part of the EAC intensification region (Figure 1).

Everett et al. (2012) and Pilo et al. (2015) performed the only two eddy characterisation studies of long-lived eddies (>28 days) for the EAC. Both studies utilised data from the same global eddy census conducted by Chelton et al. (2011). Pilo et al. (2015) compared the eddy statistics for three WBC regions, i.e. the Agulhas Current, the Brazil Current and the EAC region. The study expanded on Everett et al.'s (2012) analysis by estimating also average lifetime, propagation speed and distance travelled. A census of short-lived CEs (7-28 days) propagating within close proximity to the shelf, which appear to be more important for primary productivity and fisheries due to the entrainment of near coast shelf water, recruitment and retention is lacking for the EAC and other WBCs (Mullaney and Suthers 2013). The analysis presented in this paper aimed to expand on these previous studies (Everett et al. 2012, Pilo et al. 2015). Its focus was on the analysis of eddy characteristics detected in a coastal corridor of about 100 km width, i.e. eddies that were wedged between the coast line and the EAC. We quantified the occurrences of short-lived cyclonic eddies important to fisheries and provided the first assessment of the role of these eddies for the coastal ocean off southeast Queensland.

The east Australian continental shelf is at its widest (80-90 km) off the coast of southeast Queensland between about 25-27 ^{o}S and to the south of Fraser Island (Figure 1). The EAC forms to the north of this region from the South Equatorial Current and Coral Sea outflows. It intensifies forming a swift, albeit seasonally varying in strength, southward flowing current hugging the continental shelf (Ridgway and Dunn, 2003). A prominent oceanographic feature of the region is the EAC-driven Southeast Fraser Upwelling System (Brieva et al. 2015).

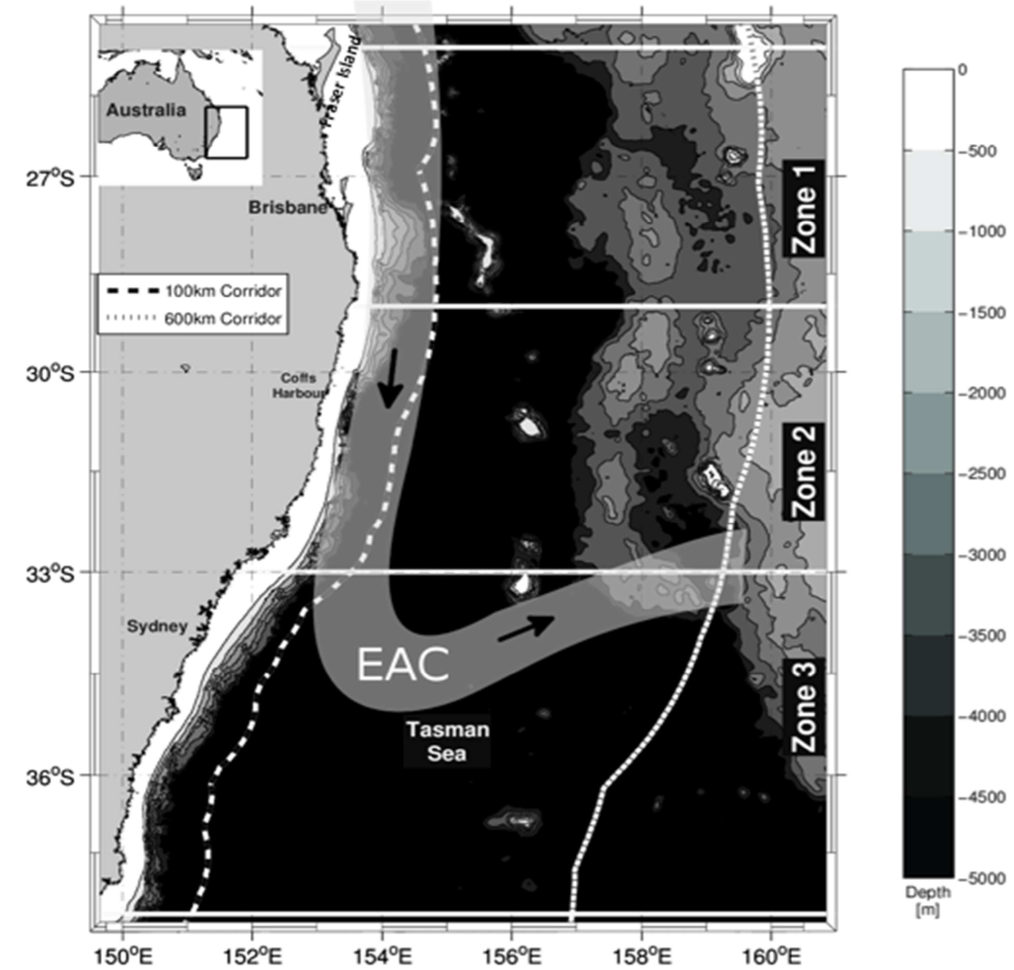

Figure 1: Location of the study site along the east coast of Australia. The boundaries (white lines) between Zone 1 (Z1) and Zone 2 (Z2) at about 29° S and Z2 and Zone 3 (Z3) at about 33° S were identified in this study from minima in eddy activity. Approximate mean path of the East Australian Current (EAC) is shown in light grey. Eddies were tracked over the whole region. An eddy census was conducted and the analysis limited to two coastal corridors of 100 km and 600 km width each (dash lines).

Ward et al. (2003) and Mullaney et al. (2014) speculated that the northern sub-tropical shelf waters (~25-27 °S) of the EAC intensification zone supply larvae of temperate fish species that are transported southward with the EAC. These return at a later stage in their lifecycle to spawn again during early winter. Gruber et al. (2011) find that eddy induced transports appeared to be close to a maximum within a near-shore 100 km wide zone. Mullaney and Suthers (2013) argued for the importance of these near-coast short-lived eddies for fisheries. The eddies were also found to be associated with the northward countercurrent and entrainment of coastal waters (Huyer et al. 1988, Mullaney and Suthers 2013). Thus, the analysis presented in this study was focused on eddies and their characteristics identified for a narrow 100 km wide coastal corridor (Figure 1). The characteristics were obtained from a new eddy census for the southwestern Pacific Ocean using the Halo et al. (2014) eddy detection method. It led to the identification of three zones (Zone 1 or Z1, Zone 2 or Z2 and Zone 3 or Z3) distinguished from minima in eddy activity (Figure 1). Z1 was identified as the region with the highest number of short-lived cyclonic eddies along the east coast of Australia.

2. Data and Methodology

2.1 Data

Daily estimates of Chl-a ($mg \cdot m^{-3}$) and SST (^{o}C) were disseminated via the data portal of Australian Integrated Marine Observing System (IMOS 2015a) and were used in this study for the period 09/08/2002 to 31/10/2015. The data was gridded with a spatial resolution of 0.01^{o} (IMOS 2015a). The data was derived from MODerate resolution Imaging Spectroradiometer (MODIS) measurements with methodological details provided by O’Reilly et al. (2000) and Claustre and Maritorena (2003).

Gridded sea surface height anomaly (SSHa) was available for the period 01/01/1993 – 31/10/2015 and for every second day until 31/12/2010 and daily thereafter (IMOS 2015b). The eddy detection tool provided by Halo et al. (2014) was applied to SSHa data for this period (Section 2.2 Methodology). The spatial resolution of SSHa data used in this study was $1/5^{o}$. This compared to the $1/4^{o}$ resolution in Chelton et al. (2011), which was evaluated by Everett et al. (2012) and Pilo et al. (2015) resolving eddies with a minimum radii of >40 km and lifetime larger than 28 days. Halo et al. (2014) used SSH gridded data with 0.25^{o} resolution and tracked eddies with lifetime larger than 30 days. Census data from the application of the Halo et al. (2014) method in this study and for lifetimes of at least 7 days were presented in Table 1.

The mean eddy core characteristics such as Chl-a, SST and SSHa were determined for all detected eddies (Table 2). The core size was defined in this study to have a radius of 20 km. Chl-a and SST anomalies were also computed as the difference in mean value for the core and the value computed for a larger area with radius of 40 km, but excluding any values within the core. The number of observations to determine Chl-a and SST anomalies was much reduced compared to SSHa data due to frequent and extensive cloud coverage (see also discussion in Brieva et al. 2015).

2.2 Methodology

Methods to track eddies in remotely sensed observation of SSHa and ocean model data were described by e.g. Chelton et al. (2007), Henson and Thomas (2007), Chelton et al. (2011), Morrow and Le Traon (2012), Mason et al. (2014), Halo et al. (2014), Karstensen et al. (2015), and Pegliasco et al. (2015). The eddy-tracking algorithm utilised in this study was initially proposed by Penven et al. (2005) to assess eddy characteristics of the Peru Current System. Halo et al. (2014) used the method for an eddy census of the Mozambique Channel and provided the method as a Matlab toolbox, which was implemented for this study.

Halo et al. (2014) combined a geometry approach with a dynamic criterion. The former method detected closed SSHa loops (Chelton et al. 2011), whereas the latter involved computing the Okubo-Weiss parameter. The Okubo-Weiss parameter was applied as a criteria or filter to identify regions of vorticity. Negative values beyond a defined negative threshold value were being indicative of a vorticity dominated flow field (Chelton et al. 2007, 2011). Thus, regions within a closed loop of SSHa and characterised by negative vorticity were then typical for the presence of an eddy. The threshold value for the Okubo-Weiss parameter W used by Halo et al. (2014) was $W < 0\ s^{-2}$. Chelton et al. (2007) applied a value of $W < -2x10^{-12}\ s^{-2}$.

The parameters values adopted in this study were the following: a maximum radius R_o of 200 km to exclude larger eddies and ocean gyres, a contour interval of 0.002 m to identify closed loops of SSHa, an Okubo-Weiss parameter $W < -2x10^{-12}\ s^{-2}$ as per Chelton et al. (2007) to identify regions of vorticity characterising the flow field, and a Hanning filter that was applied twice to reduce grid scale noise in the computed Okubo-Weiss parameter. The tracking code was limited to identify eddies with radii larger than 22.5 km and a minimum amplitude of 0.02 m. Following an eddy census of the entire domain (Figure 1), eddy statistics were provided for two coastal corridors. These extended eastward from the location of the 100 m depth contour by 100 km and 600 km. The western boundary of the each corridor was the coastline, meaning both corridors varied by the width of the continental shelf west of the 100 m depth contours. The shelf is widest just to the south of Fraser Island (Figure 1). The 100 km corridor limited the census to eddies that were closest to the coast. These most likely led to the entrainment of near-shore water and subsequent across-shelf transport and observed evidence of entrainment was presented below (section 3.1). The wider corridor of 600 km was used to allow for some limited comparison with Everett et al. (2012) and Pilo et al. (2015).

The Halo et al. (2014) eddy detection and tracking tool was applied: firstly, to detect eddies, which provided information on mean radius and SSHa; secondly, to track their movements, which provided information about lifetime; and thirdly, to determine their location within the 100 km corridor and a 600 km coastal corridor for comparison with previous studies. A tracked eddy may have enterd or left one of the corridors. The number of detected eddies was much larger than the number of tracked individual eddies. A tracked eddy was referred to as an eddy event. It was found that this study utilising the Halo et al. (2014) algorithm identified several important climatological features of the EAC as highlighted by Ridgway and Dunn (2003) and many of the mean eddy characteristics identified in the previous censuses.

3. Results

The application of the Halo et al. (2014) resulted in an archive of detected eddies and the location of eddy cores at a particular date. Once detected, we then inspected the database of daily Chl-a and SST images for evidence of these eddies in ocean colour. Several examples of identified eddies were presented in Section 3.1 showing the detected eddy core location and remotely sensed Chl-a for the shelf region of southeast Queensland. In Section 3.2, a tracked eddy was presented as an example for all those tracked in the census. The census was described further in Section 3.3 with results being summarised in Table 1 and 2.

3.1 Detected individual cyclonic eddies

The eddy detection tool identified CEs on July 31, 2003 with an eddy core located at 154.2087 ^{o}E and 26.4739 ^{o}S; on August 14, 2004 with an eddy core located at 154.2286 ^{o}E and 28.1857 ^{o}S; on October 8, 2007 with an eddy core located at 154.181 ^{o}E and 27.0143 ^{o}S; and on June 25, 2013 with an eddy core located at 154.2303 ^{o}E and 26.8758 ^{o}S. CEs and corresponding Chl-a concentrations were shown in Figure 2.

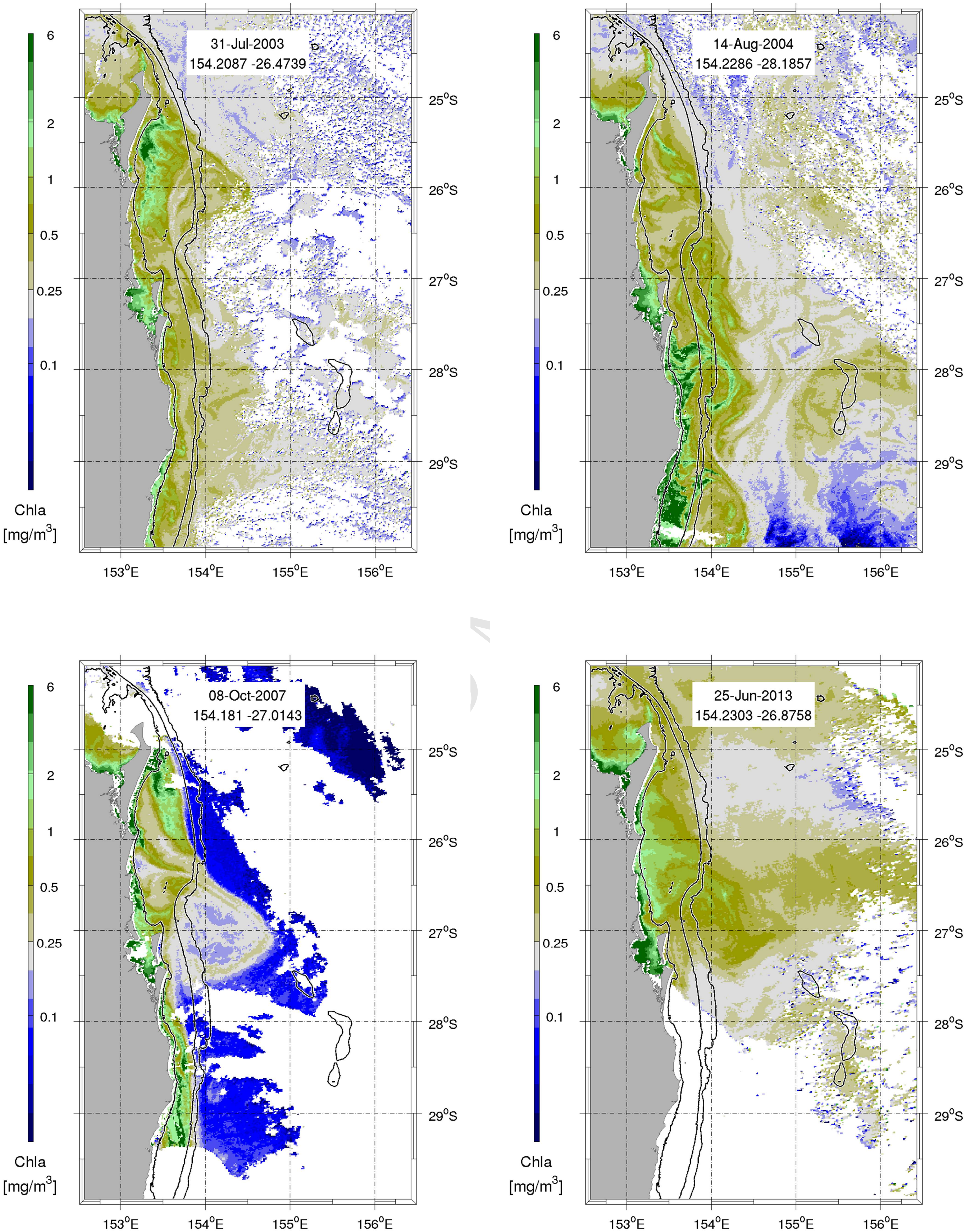
31-Jul-2003
154.2087 -26.4739
14-Aug-2004
154.2286 -28.1857
08-Oct-2007
154.181 -27.0143
25-Jun-2013
154.2303 -26.8758
6
2
1
0.5
0.25
0.1
Chla
[mg/m^3]
25^{o}S
26^{o}S
27^{o}S
28^{o}S
29^{o}S
153^{o}E
154^{o}E
155^{o}E
156^{o}E

Figure 2: Series of detected CE with coordinates of detected eddy cores on July 31, 2003; August 14, 2004; October 8, 2007 and June 25 2013 indicated and corresponding images of the Chl-a concentration (mg/m^3) on those dates. Indicated are the 40 m, 200 m, and 1000 m depth contours.

The Chl-a images (Figure 2) were selected following the identification of an eddy core on a particular day. In all cases, the region of the eddy's location was characterised by higher Chl-a concentrations. Elevated Chl-a filaments (e.g. with values of about 6 mg/m^3 on August 14, 2004) extended away from near coastal waters in a cyclonic fashion across the 40-80 km wide shelf off southeast Queensland. This was indicative of the eddy's interaction with the shallow shelf waters and the entrainment of near coastal high nutrient primary productivity stimulating waters.

3.2 Tracking a cyclonic eddy

Chl-a and SST filaments observed for a detected and tracked eddy, indicated that this particular CE interacted with the shallow (<40 m) near-coast shelf (Figure 3). It exported water off-shore in a cyclonic fashion as evident from entrained water characterised by elevated Chl-a and cooler coastal water.

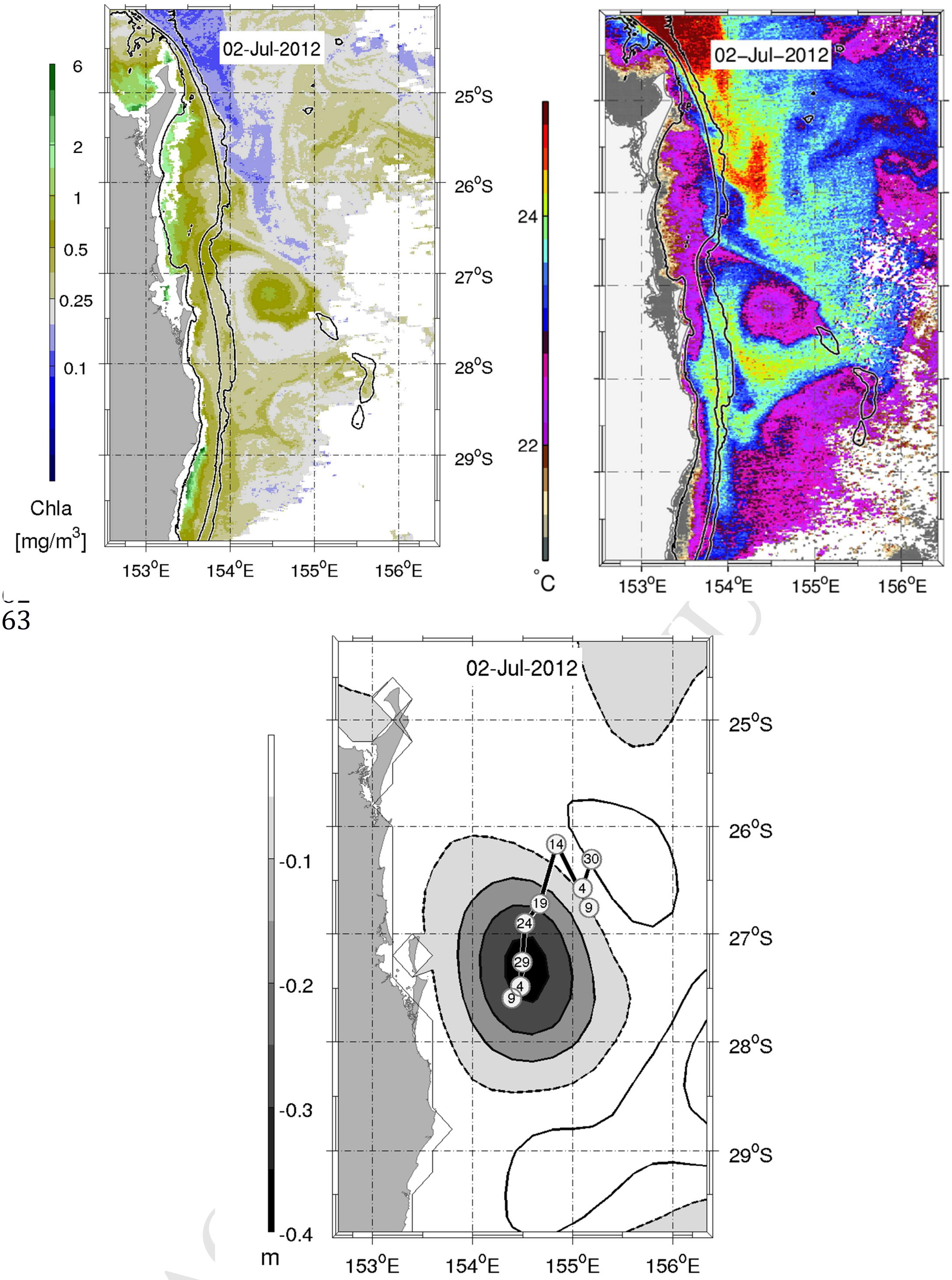

Figure 3: Evidence of a CE detected on July 2, 2012 from remotely sensed (top left panel) Chl-a (mg/m^3), (top right panel) SST (^{o}C), and (lower panel) SSHa (m) with negative SSHa anomalies contoured in intervals of 0.05 m. The location of the core of the eddy was traced from its initial detection on May 28 to its dissipation on July 12.

Circles in (c) indicate location and date of core with core locations shown for May 30, June 4-29 and finally for July 9, 2012.

The CE appeared to be wedged between the shelf break and the EAC. The core of the CE was situated at about 154.5 ^{o}E. The EAC was evident from the higher SST (>25 ^{o}C) emerging in the north and extending southward along the shelf break and was associated with lower Chl-a concentrations (Figure 3). The CE appeared to deflect the EAC flow eastward.

First identified on May 28th, 2012, the eddy was initially located at about 155.2 ^{o}E and 26.3 ^{o}S or about 150 km to the northeast of its location on July 2, 2012. Its radius was about 46 km, covering a surface area of 6642 km^{2} and extended westward close to the coast with SSHa at about -0.05 m. The eddy was tracked over a period of about six weeks (Figure 3 with core locations indicated). After a maximum in SSHa of about -0.2 m on July 2, 2012 at location 154.5 ^{o}E and 27.25 ^{o}S, the CE started to rapidly decay. It had dissipated by about July 11, 2012 with SSHa of less than 0.05 m and reached a most southern location of 154.4^{o}E and 27.5 ^{o}S. Its mean latitudinal displacement speed in a south-westerly direction from about 26.3 ^{o}S to about 27.3 ^{o}S (~110 km) over the six week period was estimated with about ~3 km per day. This displacement speed was similar to the mean speed of 3.2 km per day identified by Pilo et al. (2015) for CEs from the Chelton et al (2011) eddy census. It was representative for the mean displacement speeds (~4 km per day) found for all CE detected in this study. On July 2, 2012, the SST anomaly was about -0.9 ^{o}C and the Chl-a eddy core concentration was about 1 mg/m^{3} and above a typical background level of about 0.2 mg/m^{3}. The maximum SSHa was about -0.2 m (Figure 2c).

3.3 The East Australian Current Eddy Census

The number of all tracked eddy events across the region (see Figure 1) with lifetime of at least 1-2 weeks was 804 (Figure 4). This included 395 CEs (49%) and 409 ACEs (51%). There were on average about 37 eddy events per year. Short-lived eddies (lifetime 7-28 days) contributed about 64% of all tracked eddies. Eddies lasting more than 10 weeks made up 16% of the total and potentially exited from the area considered in this study.

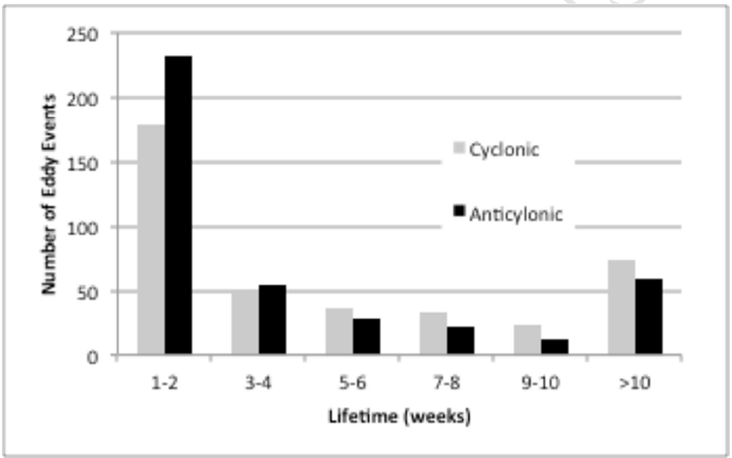

Figure 4: Lifetime (weeks) of CE and ACE during the period 1993 to 2015.

The total number of detected eddies per degree latitude was shown for both the 100 km and 600 km wide coastal corridors and for detected eddies with lifetime >7 days and >28 days (Figure 5). The distribution of detected CEs and ACEs per degree latitudes was represented in Figure 6.

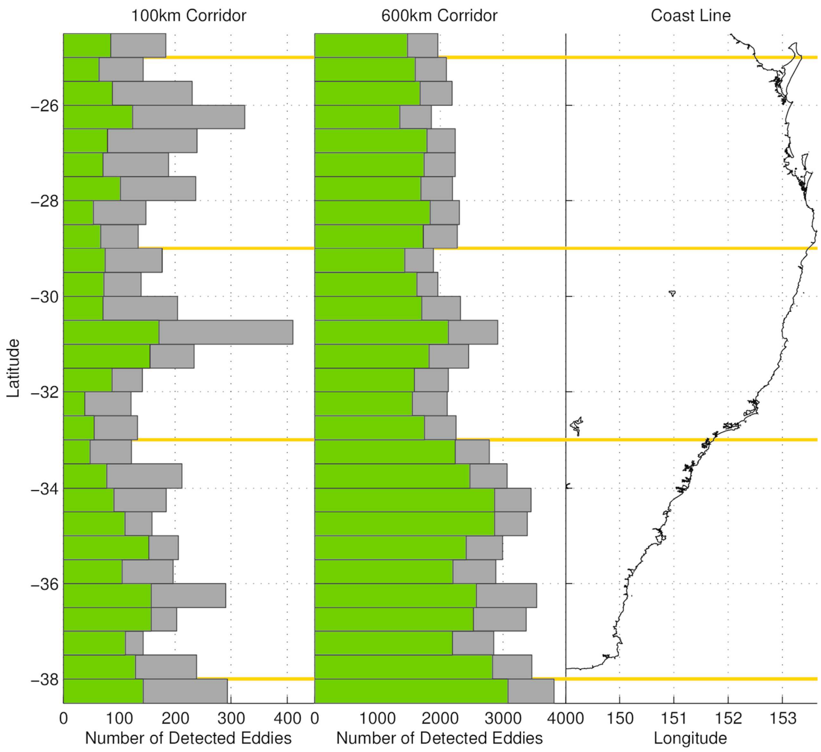

Figure 5: Eddy census for the period 1993-2015 and coastal corridors of 100 km (left panel) and 600 km (right panel) width. Shown is the total number of detected eddies per degree latitude for eddies with lifetime > 7 days (light grey) and >28 days (green). The right hand panel shows the coast and horizontal lines were shown to coincide with minima in eddy activity, which result in distinguishing between the three zones.

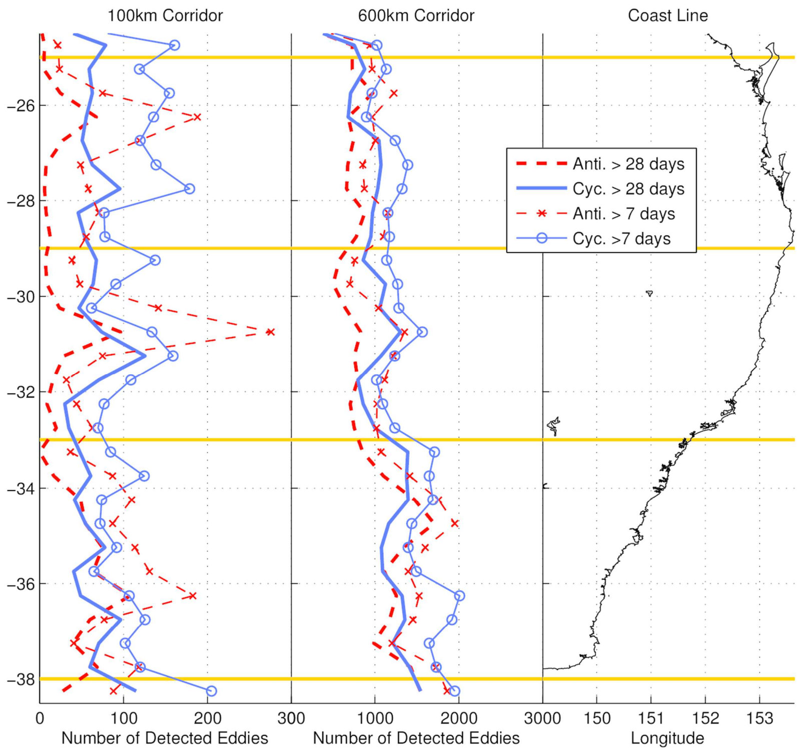

Figure 6: Total number of detected ACE (dashed lines) and CE (solid lines) shown for both 7 days and 28 days lifetime.

The number of detected short-lived (7-28 days) eddies and tracked eddy events (Table 1) followed from the difference between eddies lasting at least 7 days and those lasting more than 28 days. For example, in the case of the 600 km wide corridor, the number of total detected CEs and ACEs was at a maximum within Z3 (Table 1). About 67273 detected eddies (Σ1 with 35805 plus Σ2 with 31468) were identified that lasted at least 7 days and of those, 52300 (Σ1 with 28211 plus Σ2 with 24089) lasted 28 days and longer. Therefore, about 14973 detected eddies were short-lived (7-28 days) within the 600 km corridor of Z3.

Short-lived detected ACEs (7-28 days) dominated the 100 km coastal corridor and contributed about 64% of all detected ACEs along the EAC. In contrast, only about 23% of all detected ACEs were short-lived within the 600 km wide coastal corridor. This followed from an evaluation of the data presented in Table 1. The total number of detected ACEs with lifetime of more than 7 days was 2554 (Σ2, 100 km) and 31468 (Σ2, 600 km). Of those, 1645 detected eddies or 64% in the 100 km corridor and 7379 detected eddies or about 23 % in the 600 km corridor were short-lived.

Short-lived (7-28 days) detected eddies (CEs and ACEs) dominated the northern zone (Z1) of the 100 km corridor. The total number of all detected short-lived eddies was 994 in Z1 (Table 1: 515 CEs and 479 ACEs) from a total of all detected eddies (>7 days) of 1643 (Table 1: 1003 CEs and 640 ACEs). This corresponded to a total of 202 short-lived eddy events or 41% in Z1 (Table 1: 94 CEs plus 108 ACEs), 154 short-lived eddy events or 31% in Z2 (Table 1: 57 CEs plus 97 ACEs), and 141 short-lived eddy events or 28% in Z3 (Table 1: 70 CEs plus 71 ACEs). In other words, of the total number of 497 short-lived eddy events tracked within the 100 km corridor (Σ1 = 221 CE events plus Σ2 =276 ACE events), Z1, Z2 and Z3 each contributed 41%, 31%, and 28 % of short-lived eddy events respectively.

Table 1
Number of detected eddies and tracked eddies for both EAC corridors

100 km corridor	C□□□□□□□				□□□□□□□□□□□□□			
	Z1	Z2	Z3	Σ□	Z1	Z2	Z3	Σ□
Life-time > 7 days								
Detected eddies	1003	840	1264	3107	640	719	1195	2554
Eddy events	153	121	151	425	138	127	150	415
Life-time > 28 days								
Detected eddies	488	515	602	1605	161	211	537	909
Eddy events	59	64	81	204	30	30	79	139
Life-time 7-28 days								
Detected eddies	515	325	662	1502	479	508	658	1645
Eddy events	94	57	70	221	108	97	71	276
600 km corridor								
Life-time > 7 days								
Detected eddies	9277	9840	16688	35805	8148	8218	15102	31468
Eddy events	585	590	1011	2186	616	628	762	2006
Life-time > 28 days								
Detected eddies	7340	8077	12794	28211	6110	5551	12428	24089
Eddy events	266	309	438	1013	268	245	393	906
Life-time 7-28 days								
Detected eddies	1937	1763	3894	7594	2038	2667	2674	7379
Eddy events	319	281	573	1173	348	383	369	1100

The Halo et al. (2014) detection and tracking tool appeared to have also captured the approximate location of the centre of two quasi-permanent anticyclonic EAC recirculation cells that were identified previously by Ridgeway and Dunn (2003, their Figure 7). This was evident from two maxima in detected ACEs at about 26°S and 31°S (Figure 6). The latter maximum was also evident in the total of all detected eddies (Figure 5) and found to be close to the approximate location of the EAC separation point. It further vindicated the use of Halo et al. (2014) as an appropriate tool to detect and track eddies.

The northern zone Z1 off the coast of southeast Queensland was characterised by the largest number of tracked short-lived CE events (94 or 43% of the total of 221 tracked eddy events) within the 100 km wide coastal corridor (Table 1). Z1 was part of the previously identified EAC intensification zone (Ridgeway and Dunn 2003).

The total number of detected ACEs in the 100 km wide corridor and with lifetime > 7 days was found to be about 2554 (Table 1). The number of detected ACEs per zone increased north to south from 25% (640 detected eddies in Z1) and 28% (719 detected eddies in Z2) to a maximum of 47% (1195 detected eddies in Z3) (in Table 1) south of about 33^{o}S (Z3) and within the EAC separation zone where the EAC's eastward flow eastward is often associated with the spawning long-lasting anticyclonic eddies (e.g. Nielson and Cresswell 1981).

The identified minima in the latitudinal distribution of detected eddies located at about 29^{o} S and 33^{o} S (see Figure 5 and Figure 6) divided the east Australian coast into three discernible zones. These zones were previously distinguished based on the mean EAC characteristics by Ridgway and Dunn (2003) and referred to as the intensification (Z1, north of about 29 ^{o}S) and separation zone (combined Z2 and Z3, south of about 29 ^{o}S), which includes the location of the EAC separation point and where the EAC turns toward the east. In the northern region Z1 and within the 100 km wide coastal corridor, the total number of short-lived (7-28 days) tracked CEs and ACEs was found to be highest. The southern boundary of Z1 was evident from a minimum in eddy activity located at 29 ^{o}S coinciding with the approximate southern boundary of the EAC intensification zone (Ridgway and Dunn 2003).

The combined two southern zones Z2 and Z3 comprised the EAC separation zone (Ridgway and Dunn 2003). The southern boundary between both zones was found to coincide with the approximate location of the EAC separation point (30 ^{o}S or 31 ^{o}S to 34 ^{o}S, e.g. Godfrey et al. 1980; Ridgeway and Dunn 2003) and where EAC turns toward the east between about 33-35 ^{o}S (Ridgway and Dunn 2003) and into the Tasman Sea. The number of eddies detected in both the 100 km and particular the 600 km wide corridors increased south of about 33 ^{o}S and the boundary between zones Z2 and Z3, which is within the region where the EAC separates from the coast. This finding was consistent with previous findings (Everett et al. 2012).

The number of detected and tracked eddies lasting at least four weeks was compared with the Everett et al. (2012) and Pilo et al. (2015), noting that Everett et al. (2012) only reported detected eddies and individual eddies were not tracked.

Everett et al. (2012) reported 50.2% CEs and 49.8% ACEs from a total of 2613 detected eddies for "Eddy Avenue". In this study, Z2 and Z3 combined (100 km corridor) were broadly part of the "Eddy Avenue", which found 59.89% CEs and 40.10% ACEs from a total of 1865 detected eddies (i.e. 515+602+211+537; Table 1, >28 days). The total number of detected eddies was about 1/3 less than that reported by Everett et al. (2012), who reported 1314 CEs (this study 1117 CEs) and 1299 ACEs (this study 748 ACEs). Everett et al. (2012) and this study found agreement in the tendencies for the total number of detected eddies to increase significantly for the larger Tasman Sea area. Everett et al. (2012) reported a total of 14094 CEs and 14892 ACEs, this study found a total of 28211 CEs and 24089 ACEs (Table 1, >28 days, 600 km corridor).

Pilo et al. (2015) identified a total of 1050 individually tracked eddies (51% CEs, 49% ACEs, lifetime >28 days) or 50 on average per year. This study found to a total of 1919 individually tracked eddies (Σ1 1013 plus Σ 2 906, see Table 1, >28 days, 600 km corridor) or about 87 on average per year (53 % CEs, 47 % ACEs, see Table 1, >28 days, 600 km corridor). In both studies more CEs than ACEs were tracked.

Mean characteristics quantified for detected eddies within the 100 km wide coastal corridor appeared to be consistent with the conventional eddy model (e.g. Bakun 2006; Everett et al. 2012; Weeks et al. 2010) with mean Chl-a high for CEs than ACEs. The model postulates that CEs are to be associated with higher Chl-a due to upwelling that supplies primary productivity enhancing nutrient rich water to the surface, while ACE characterised by lower Chl-a. Yet, inspection of satellite imagery (Figure 2 and 3) indicated that SST and Chl-a core characteristics identified in this study were likely to be a significantly controlled by the entrainment of coastal waters and potential entrainment from other depths. Everett et al. (2012) also found and discussed a significant departure of mean SST and Chl-a characteristics from the conventional eddy model. In this study, mean SSHa was negative for detected CEs and positive for ACEs (Table 2). Detected CEs had lower mean SST and higher mean Chl-a compared to detected ACEs (22.5 ^{o}C vs 22.7 ^{o}C and 0.27 mg/m^3 vs 0.17 mg/m^3, see Table 2), which appeared to be consistent with the standard model, but was potentially contributed to by significant entrainment (Figure 2).

There appeared to be no discernable difference in mean eddy radii between CEs and ACEs found for all zones (Table 2). Mean radii determined in this study were smaller than those reported by Everett et al. (2012) and Pilo et al. (2015) who reported 92 km and 83.4 km radii for CEs and 95 km and 82.5 km for ACEs 95 km respectively. These previous studies were based on eddies with lifetime >28 days and mean radii larger than 40 km (Chelton et al 2011). This study's minimum detected eddy radius was 22.5 km. Rotational speeds (~0.4 m/s to 0.5 m/s) and mean displacement speeds (about 0.05 m/s or about 4 km/day) were similar to values reported by Everett et al. (2012) and Pilo et al. (2015). Considering an estimated mean displacement speed of the 4 km/day and a lifetime of 7-28 days, a short-lived eddy potentially travelled a distance of about 115 km. This mean value based on the tracking tool was found to be similar to the value estimated from tracking the individual eddy shown in Figure 3. Mean core characteristics SST and Chl-a displayed no discernable difference between CEs and ACEs (Table 2) Anomalies for both where found to be very small (not shown). This was likely due to the entrainment process of coastal water, which was likely associated with high Chl-a and low SST filaments near the edge of the eddy, which appeared to emanate from the near shore shelf waters as apparent from inspection of Figure 3 and Figure 4.

Table 2
Mean cyclonic and anticyclonic eddy characteristics for the 100 km wide coastal corridor, individual zones Z1 to Z2 and the average of all zones.

Eddy Characteristics		Cyclonic Eddies			Anticyclonic Eddies	
Life-time > 7 days	Z1	Z2	Z3	Z1	Z2	Z3
Radius (10^3 m)	60±14	57±14	52±12	55±12	53±13	53±14
SSHa (10^{-2} m)	-12±9	-17±11	-12±8	10±6	17±10	19±13
Rotational Speed (10^{-2} m/s)	44±22	53±23	47±23	29±12	35±16	50±25
Chl-a (mg/m^3)	0.18±0.13	0.22±0.12	0.43±0.36	0.11±0.08	0.14±0.09	0.26±0.78
SST (^{o}C)	24.08±1.98	23.13±2.17	20.24±2.38	24.63±1.77	23.03±1.93	20.45±2.12
Radius (10^3 m)	66±13	62±13	55±11	61±14	56±13	60±13
SSHa (10^{-2} m)	-16±10	-19±11	-14±8	12±6	17±10	24±13
Rotational Speed (10^{-2} m/s)	52±24	60±23	52±23	35±13	37±16	63±25
Chl-a (mg/m^3)	0.22±0.15	0.23±0.12	0.44±0.42	0.11±0.1	0.1±0.08	0.2±0.12
SST (^{o}C)	24.14±2.3	23±2.2	20.36±2.4	24.15±1.6	23.91±2.1	20.34±1.9

4. Discussion and Conclusion

The latitudinal location with maxima in detected ACEs at about 26°S and 31°S was found to be consistent with the climatological location of two centres of previously identified EAC anticyclonic recirculation cells (Ridgway and Dunn 2003). The location of the EAC separation point at about 31.5 °S was evident from the maximum of detected eddies between 30 °S and 31 °S (Figure 5 and Figure 6). Here, the separation of the EAC from the coast alleviates the restriction for ACEs formation and the number of detected ACEs increased again southward of 33 °S (Figure 6). This was found to be consistent with other studies (Everett et al. 2012, Piolo et al. 2015). The increase was more apparent for the 600 km corridor where the most southern zone Z3 was characterised by the highest number of detected eddies (Figure 5).

In the northern zone Z1 off the coast of southeast Queensland, both short-lived (7-28 days) CE and ACE events were found to be dominant within the 100 km wide corridor (Table 1). Mean eddy characteristics such as radii, SSHa, SST, Chl-a and total number of detected eddies confirmed with the conventional eddy model and were found to be broadly consistent with those derived from the Chelton et al. (2011) data base (Everett et al. 2012, Pilo et al.2015). Dissimilarities were expected due to different detection and tracking tools, SSHa temporal resolution, the actual regions analysed, different minimum radii applied and minimum lifetime of eddies considered (i.e. 7-28 days versus >28 days in previous studies). The eddy census based on the Halo et al. (2014) method was broadly in good agreement with that from Chelton et al. (2011) for the same coastal domain between total number of detected eddies, but some differences in their distribution. The comparison also identified the two maxima in detected eddies at 27°S and 31°S in the Chelton et al. (2011) database.

The continental shelf off southeast Queensland and to the south of Fraser Island was found to be home to about 43% of all short-lived detected CEs within a 100 km coastal corridor along the east Australian coast. This corresponded to a total of 94 individual CE events tracked during the period 1993-2015 or about 4-5 CEs on average per year. These CEs were likely to encroach onto the shelf leading to the entrainment of near shore water and across-shelf transport as discussed for several individual events (Figure 2 and Figure 3). The frequent occurrence of these CEs could likely contribute to establishing a quasi-permanent alongshore near coast northward flow as it was observed for the separation zone of the EAC (Huyer et al. 1988, Roughen et al. 2011). This potentially established a quasi-permanent cyclonic on-shelf EAC recirculation cell south of Fraser Island referred to as the Fraser Island Gyre. The cyclonic on shelf circulation is similar to that of other continental shelf regions characterised by transient CE genesis such as the Charleston Gyre (Govoni et al. 2009). The continuous, but transient throughout the year, entrainment characteristic of the short-lived CEs generated in this region was likely to be part of the enhancement of primary productivity in this region, which was in part also driven by the Southeast Fraser Island Upwelling System (Brieva et al. 2015). The transient eddies were likely to transport in a cyclonic fashion fish larvae across the shelf that were subsequently transported to the southern temperate waters of the Tasman Sea by the EAC. This mechanism was postulated by Ward et al. (2003) and this study identified the possible role of CEs and the existence of a quasi-permanent gyre in contributing to the cross-shelf exchange process.

Previous studies of EAC eddy generation and their role in ecosystem dynamics focused on the coastal ocean of New South Wales and the separation zone of the EAC (e.g. Suthers et al. 2011). Results presented here were from an eddy characterisation study with some focus on the coast off southeast Queensland finding that CEs appeared to be a distinct and most prominent feature for this region of the eastern Australian coast. It is noted that this eddy study may have underestimated the presence of CEs for this (and other) region since it is difficult to capture smaller-scale CEs in satellite derived SSHa with a spatial resolution of 22.5 km (see e.g. Macdonald et al. 2016). In the future, it would be prudent to investigate the on-shelf flow pattern and the role of the EAC in this region from in-situ observations augmented with detailed higher resolution modelling studies to confirm the apparent dominant role played by CEs gleaned here from remote sensing data.

In the case of the EAC, we found that it is the northern EAC intensification zone that was dominated by short-lived CEs (7-28 days). These provided a possible key cyclonic and cross shelf transport mechanism for fish larvae, which is a poorly understood physical process of biological significance (Ward et al. 2003, Mullaney et al. 2013, Mullaney et al. 2014). Frequent CEs of the EAC intensification zone were likely to lead to an alongshore-northerly flow as also documented for the southern EAC separation zone (e.g. Roughen et al. 2011). Combined with a southward flowing EAC along the shelf-break, this would establish an on-shelf characteristic mean oceanographic circulation feature referred to as the Fraser Island Gyre.

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Figure 1: Location of the study site along the east coast of Australia. The boundaries between Zone 1 (Z1) and Zone 2 (Z2) at about 29^{o} S and Z2 and Zone 3 (Z3) at about 33^{o} S were identified in this study from minima in eddy activity. Approximate mean path of the East Australian Current (EAC) is shown in light grey. Eddies were tracked over the whole region. An eddy census was conducted and the analysis limited to two coastal corridors of 100 km and 600 km width each (dash lines).

Figure 2: Series of detected CE with coordinates of detected eddy cores on July 31, 2003; August 14, 2004; October 8, 2007 and June 25 2013 indicated and corresponding images of the Chl-a concentration (mg/m^3) on those dates. Indicated are the 40 m, 200 m, and 1000 m depth contours.

Figure 3: Evidence of a CE detected on July 2, 2012 from remotely sensed (a) Chl-a (mg/m^3), (b) SST (^{o}C), and (c) SSHa (m) with negative SSHa anomalies contoured in intervals of 0.05 m. The location of the core of the eddy was traced from its initial detection May 28 to its dissipation on July 12. Circles in (c) indicate location and date of core with core locations shown for May 30, June 4-29 and finally for July 9, 2012.

Figure 4: Characteristic lifetimes of CE and ACE (in weeks) detected during the period 1993 to 2015.

Figure 5: Eddy census for the period 1993-2015 and coastal corridors of 100 km (left panel) and 600 km (right panel) width. Shown is the total number of detected eddies per degree latitude for eddies lasting at least 7 days (light grey) and 28 days (green). The right hand panel shows the coast and horizontal lines were shown to coincide with minima in eddy activity, which result in distinguishing between the three zones.

736 Figure 6: Total number of detected ACE (dashed lines) and CE (solid lines) per
737 degree latitude and shown for both 7 days and 28 days lifetime

- 497 short-lived eddies detected in a coastal corridor off eastern Australia.
- About 23 individual short-lived eddies traced per year.
- 43% of cyclonic eddies (4-5 per year) found off southeast Queensland.
- Cyclonic eddies displaced shelf water by about 110-120 km.
- Cyclonic eddies postulated to establish quasi-permanent northward flow.