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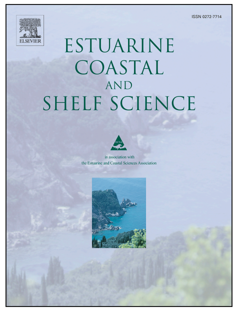

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The Fraser Gyre: A cyclonic eddy off the coast of eastern Australia

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Estuarine, Coastal, and Shelf Science

Abstract

This paper examines the on-shelf circulation of the eastern Australian continental shelf for a region off southeast Queensland. We identify a characteristic seasonally reoccurring wind-driven cyclonic flow. It influences the cross-shelf exchange with the East Australian Current (EAC), which is the western boundary current of the South Pacific Ocean. We refer to this cyclonic circulation as the Fraser Gyre. It is located south of Fraser Island between about 25^{o}S and 27^{o}S. The region is adjacent to the intensification zone of the EAC where the current accelerates and establishes a swift, albeit seasonally variable southward boundary flow. Through the analysis of several data sets including remotely sensed sea surface temperature and sea surface height anomaly, satellite tracked surface drifters, ocean and atmospheric reanalysis data as well as geostrophic currents from altimetry, we find that the on-shelf Fraser Gyre develops during the southern hemisphere autumn and winter months. The gyre is associated with a longshore near-coast northward flow. Maximum northward on-shelf depth averaged velocities are estimated with about 0.15 – 0.26 ms^{-1}. The flow turns eastward just to the south of Fraser Island and joins the persistent southward EAC flow along the shelf break. The annual mean net cross-shelf outward and inward flow associated with the gyre is about -1.17 ± 0.23 Sv in the north and 0.23 ± 0.13 Sv (1 Sv = 10^{6} m^{3}s^{-1}) in the south. Mean seasonal water renewal time scales of the continental shelf are longest during austral winter with an average of about 3.3 days due to the Fraser Gyre retaining water over the shelf, however, monthly estimates range from 2 to 8 days with the longer timescale during the austral autumn and winter. The southerly wind during austral autumn and winter is identified as controlling the on shelf circulation and is the principal driver of the seasonally appearing Fraser Gyre. The conceptual model of the Fraser Gyre is consistent with general

physical principals of the coastal shelf circulation. A southerly wind is associated with surface layer flow toward the coast, a near coast positive SSHa with a current in the direction of the wind, down-welling and export of shelf water. The Fraser Gyre influenced cross-shelf exchanges are possibly facilitating the offshore transport of fish larvae, sediments, nutrients, river discharges, and other properties across the shelf break and into the southward flowing EAC during the austral autumn and winter.

Key words: Fraser Gyre; East Australian Current; residence time scale; geostrophic current; cross-shelf transport

1 Introduction

Western Boundary Currents (WBCs) influence the circulation, renewal and the productivity of coastal shelf waters and often present a barrier that limits the exchange between shelf and ocean water. Cross-shelf exchange processes play an important and prevailing role in coastal shelf ecology, marine species abundance and distribution, shelf water renewal and are the primary conduit for the continental shelf to import and export sediments, nutrients, plankton, fish larvae, and other ocean properties (Brink, 2016). Recent studies of WBC and shelf water interactions through cross-shelf exchanges include those by Matano et al. (2010) for the Brazil Current, Goschen et al (2015) for the Agulhas Current, Zhang and Gawarkiewicz (2015) for the Gulf Stream, and Wang and Oey (2016) for the Kuroshio Current. Schaeffer et al. (2013) and Schiller el al. (2015) provide insight into the current-shelf interactions for the East Australian Current (EAC), the WBC current of the South Pacific Gyre.

The majority of past studies investigating the EAC focused on the south-eastern region of the Australian continental shelf off New South Wales (NSW) and to the south of about 28 ^{o}S (see Suthers et al. 2011 for a review). For example, Huyer et al. (1988) studied cross-shelf transports and exchanges with the EAC finding that the dominant onshore transport occurred concurrently with a persistent inner-shelf northward counter current. This northward flow along the coastal side of the EAC was later documented by Holloway et al. (1992), Cresswell (1994), Gibbs et al. (1997), Gibbs et al. (1998), Gibbs et al. (2000), Roughan and Middleton (2004), Roughan et al. (2011), Schaeffer et al. (2013), Rossi et al. (2014) and Macdonald et al. (2016). For this region, it was found that the prevailing wind direction, the intrusion of the EAC meanders, and the intermittent presence of cyclonic near-coast mesoscale eddies were linked to the northward flow, which, it was argued, all contributed to the formation of the northward on-shelf circulation. This flow impacts on the biological settings of the shelf region. For example, the study of larval fish assemblages by Gray and Miskiewicz (2000) documented the cross-shelf movement of demersal species from the outer shelf toward the coast during the austral autumn and winter. Armbrecht et al. (2014) linked cross-shelf onshore transports to a persistent shift of near coast phytoplankton communities. The lack of similar studies for the EAC intensification zone off southeast Queensland, a region where the eastern Australian continental shelf is at its widest, motivated the investigation that is presented in this paper. We refer to this region as the Southeast Queensland Marine Coastal Zone (SEQMCZ) (Fig. 1).

In this paper, the SEQMCZ is defined as the coastal shelf ocean between 25 ^{o}S to 27^{o}S and it extends eastward to the 150 m isobath. The width of the eastern Australian continental shelf ranges from about 22 km to 43 km in this region, the north to south extent is 220 km, the mean depth is 63 m and the region occupies about 1.2 x$\cdot$10^{10} m^{2} of the continental shelf off southeast Queensland. The climate is subtropical with maximum rainfall during the austral spring and summer (e.g. Ribbe 2014). Hervey Bay is situated in the north (Fig. 1) and Moreton Island to the east of Brisbane near the southern boundary of the region. The location of the eastern boundary coincides with the approximate western climatological mean position of the EAC as derived from the climatological SST (Fig. 1). In this region, the EAC intensifies with the strongest flow occurring during austral spring and summer (Ridgway & Godfrey 1997). The SEQCMZ is adjacent to the EAC intensification zone, which extends from about 24^{o}S to 31^{o}S (Ridgway & Dunn 2003).

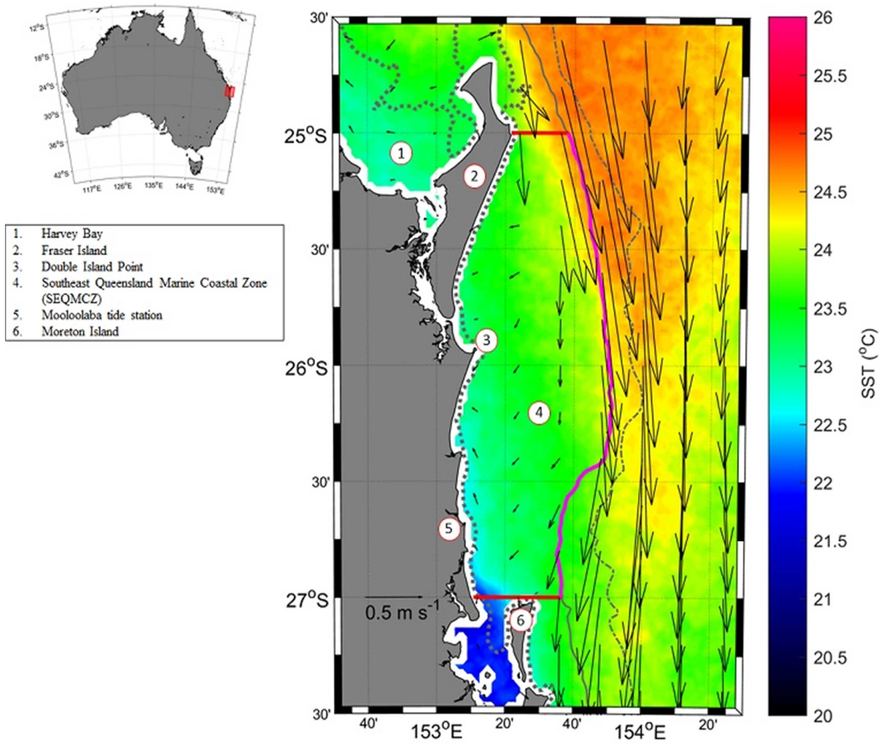


Fig. 1. Representation of the mean SST (°C) and surface geostrophic current vectors in the vicinity of the SEQMCZ waters for the period 1993-2012. The geographic locations as well as the 20 m (dotted), 150 m (solid), and 1000 m (dashed) isobath are shown. The red and magenta lines correspond to the time series of volume transports shown in Fig. 7.

Early insight into the shelf circulation of this region was gained from drifter experiments conducted by (Woodhead 1970). From a September – October 1966 survey, Woodhead (1970) evaluated the trajectory of recovered drifters and found a westward surface circulation with drifters stranded to the south of Fraser Island. The first ever ship ADCP current measurements off Double Island Point (Fig. 1, Middleton et. al. 1994) documented a cyclonic circulation pattern extending across the northern region of the shelf. Furthermore, Middleton et al. (1994) suggested that sporadic upwelling events in the region are generated by the EAC's bottom boundary layer current stress. This is most intense from about September to

March when the EAC is strongest and closely follows the continental slope. This was subsequently demonstrated to be the case by Brieva et al. (2015) who identified the EAC driven Southeast Fraser Island Upwelling System in the northern region of the SEQMCZ from the analysis of remotely sensed sea surface chlorophyll-a concentrations. Brieva et al. (2015) provided insight into the coastal ocean processes that contributed to maintaining an important ecological and marine biodiverse region and identified bottom boundary layer Ekman stress as a primary driver of upwelling. Ward et al. (2003) documented the SEQMCZ as an important spawning region for temperate fish species and postulated that cross-shelf exchanges with the EAC are possibly important for the eastern Australian fisheries species. The cross-shelf exchanges drive larvae away from the SEQMCZ and into the southward flow of the EAC. Thus a better understanding of the physical oceanography of this region would provide valuable information to underpin marine resource management whilst also contributing to an improved understanding of similar shelf processes operating in other WBC regions.

This paper aims to document the existence and mean state of the SEQMCZ shelf circulation. We (1) identify a characteristic seasonally reappearing cyclonic flow pattern referred to as the Fraser Gyre, (2) quantify associated long-shore and cross-shelf volume transports, (3) estimate shelf water renewal time scales and (4) investigate the contribution made by winds in driving the Fraser Gyre. The study focuses on the mean state of the shelf-circulation and expands on the work by Ribbe and Brieva (2016). This focused on the short-term variability of the circulation and found that the region is characterised by the highest number of short-lived (life-time < 28 days) cyclonic eddies observed along the east Australian coast. Data from several independent sources are analysed and include remotely-tracked drifter observations, sea surface height anomalies (SSHa), geostrophic currents and ocean reanalysis model data. Our paper is the first that documents the climatological mean state of a seasonally reoccurring cyclonic coastal circulation for this part of the Australian continental shelf. It is characterised by a near-shore northward longshore flow during austral autumn and winter and southward flow near the shelf break, which establishes a seasonal gyre referred to as the Fraser Gyre. The gyre is wedged between the EAC in the east and the western coastline. A similar on-shelf circulation feature was found to exist off the coast of NSW (e.g Huyer et al. 1988). We identify the seasonally varying southerly winds as the main driver of the gyre.

2 Data and Methodology

2.1 Data

A combination of satellite-tracked surface drifter observations, remotely-sensed estimates of SSHa, surface geostrophic currents, meteorological observations, tide gauge data, and output from ocean reanalysis is used to investigate the circulation of the SEQMCZ. This data is used to quantify the exchange with the open ocean and to determine water renewal time scales. Remotely sensed and ocean reanalysis data with focus on the SEQMCZ was previously described in detail and applied in studies by Brieva et al. (2015) and Ribbe & Brieva (2016). The remotely sensed data and derived properties including surface geostrophic currents are sourced from the Integrated Marine Observing System (IMOS). This is a national collaborative research infrastructure that is supported by the Australian Government (IMOS 2016). IMOS data may be accessed via the Australian Ocean Data Network (AODN, https://portal.aodn.org.au).

2.1.1 Satellite-tracked surface drifters

Early studies that involved satellite-tracked surface drifter deployments in the EAC system date back to the late 1970s. These initial studies aimed to describe the formation and evolution of warm-core eddies (Nilsson & Cresswell 1980). This early research identified instabilities within the EAC and showed the dominance of geostrophic turbulence in the Tasman Sea (Brassington et al. 2011). For the present study, the drifter data were obtained for the period February 1991 to July 2015. These drifter deployments were undertaken as part of the Global Drifter Program (GDP), which is a contribution to the Global Ocean Observing System. The drifter datasets included information on location, period of coverage, tracked distance, and mean velocity and were processed and archived by the Atlantic Oceanographic and Meteorological Laboratory (AOML), Marine Environmental Data Services (MEDS). The data archive was accessed via http://www.aoml.noaa.gov/envids/data_available.php.

A total of 73 satellite-tracked surface drifters were deployed within or drifted into the proximity of the SEQMCZ between 152 ^{o}E - 154.5 ^{o}E and 25 ^{o}S - 27.5 ^{o}S. 14 drifters entered the SEQMCZ. For the purpose of this study, drifters that moved into the SEQMCZ but continued to drift southward are labelled in chronological order with A, B and D, those that stranded in the shallow waters of the SEQMCZ are labelled C, E, F, and G, and those that turned northward following the coastline and recirculate within the SEQMCZ are identified as H, I, J, K, L, M, N. Five of the recirculated drifters also stranded in the zone and only drifters J and L exited in the south. The temporal coverage and ID of the 14 drifters that passed the shelf-break is summarised in Table 1. Drifters only recirculated during the austral autumn and winter, while during spring and summer drifters either continued to be transported by the EAC southward or crossed the shelf in a south-westerly direction, eventually stranding without recirculating. This transport and fate of the drifters is further discussed in Section 3.1.

The procedures used in preparing drifter data, acquisition, and quality-control was outlined by Hansen & Poulain (1996). The expected "slip" exerted by surface winds on the surface float is less than 0.02 ms^{-1} relative to the water for wind velocities up to 20 ms^{-1} (Youngs, et al. 2015). In order to minimize the slip, the surface float design is spherical with low tension between the surface buoy and drogue (Niller, 1987). The individual drifter pathways of all 73 drifters within the vicinity of the SEQMCZ are presented in Figs. 2a and 2b, and those that crossed the shelf break are shown in Figs. 2c and 2d.

Table 1

Mean speed and displacement of drifters within the SEQMCZ.

	Drifter ID*	Label	Period within the SEQMCZ	V (ms^{-1})	**D (m)	Comment
Spring-Summer	7711956	A	20/11 - 22/11/94	1.94	86847.26	Drifting southward
	9730664	B	11/10 -13/10/00	0.88	156579.85	Drifting southward
	30307	C	27/02 - 2/3/03	0.35	64631.23	Stranded
	23149	D	26/10 - 31/10/03	0.59	92460.90	Drifting southward
	60317	E	19/11 to 24/11/06	0.32	117418.19	Stranded
	21618	F	4/10 to 15/10/08	0.27	189833.09	Stranded
	60229	G	6/1 to 9/1/10	0.66	44097.82	Stranded
Autumn-Winter	7711896	H	27/2 to 20/3/91	0.12	205486.25	Recirculate and stranded
	21720	I	9/5 to 20/5/06	0.23	113479.90	Recirculate and stranded
	44318	J	28/7 to 15/8/06	0.34	64112.55	Recirculate
	63144	K	31/5 to 25/6/08	0.17	94094.74	Recirculate and stranded
	62931	L	23/7 to 31/7/08	0.43	27371.89	Recirculate
	62933	M	13/5 to 23/5/09	0.42	116488.43	Recirculate and stranded
	101759	N	12/5 to 15/6/13	0.11	83255.04	Recirculate and stranded

Note: *Drifter ID sourced from ftp://ftp.aoml.noaa.gov/pub/phod/buoydata/; **D is the total distance the drifter was tracked which included time spend outside the SEQMCZ.

2.1.2 Sea Surface Temperature

Daily sea surface temperature (SST) from the Advanced Very High Resolution Radiometer (AVHRR) was provided by IMOS (2016) with spatial resolution of 0.02^{o} for the period 1993 to 2012. The data was previously applied by Brieva et al. (2015) to identify and describe the Southeast Fraser Island Upwelling System.

2.1.3 SSHa, surface geostrophic current, and tide gauge data

Gridded SSHa and surface geostrophic currents, derived from altimeter data, was available with a spatial resolution 0.2^{o} for the period 1993 to 2012; for every second day until December 31, 2010 and daily thereafter (IMOS 2016). All available daily data was used to generate monthly averages which are analysed further in this study. The SSHa were obtained from the ground-tracks of several satellite altimetry missions including Jason-1, Jason-2, Cryosat-2, SARAL, HY2-A, and Envisat and merged with the along-coast interpolated tide-gauge data throughout the Australian region to improve near-coast accuracy of SSHa (Deng et al. 2011).

We utilise the SSHa and investigate the surface circulation variability over the SEQMCZ since SSHa is an indicator of surface layer circulation changes (Cheng et al. 2013). The surface geostrophic currents were calculated from SSHa through the geostrophic equations and using the mean surface velocities obtained from the Ocean Forecasting Australian Model version 3. For a detailed description of this mean and computation of the geostrophic current see IMOS (2016). This geostrophic velocity data was used previously e.g. by Mao & Luick

(2014) to investigate the circulation of the southern Great Barrier Reef in comparison and discussion of local high frequency radar surface current measurements. SSHa anomalies were previously used and applied by Ribbe & Brieva (2016) in an eddy census of the EAC region.

The delayed time mode SSHa products is used in this work as this data has optimal spatial and temporal sampling, and has higher precision than near-real time data (Ruiz Etcheverry et al. 2016). The inclusion of continuous sampling by tide gauges rectified the satellite-based output and improved estimations of geostrophic currents over the shelf (IMOS 2016). In this paper, the tide gauge station located near Mooloolaba at 26.68^{o} S and 153.11^{o} E (see Fig. 1) is also used to both compare with the altimetry SSHa within the larger SEQMCZ and to document near coast changes reflecting the on-shelf circulation patterns. Historical Mooloolaba tide data is sourced from the National Tidal Unit – Bureau of Meteorology of Australia (http://www.bom.gov.au). The tide-gauged derived SSHa was available as monthly-averaged data from 1993 to 2012.

2.1.4 Ocean reanalysis data

Monthly data from Bluelink Reanalysis version 3.5 (BRAN3p5) for the period 1993 to 2012 is used to explore the three-dimensional characteristics and variability of the circulation in the SEQMCZ. The data product resulted from a multi-year integration of the Ocean Forecasting Model version 3 (OFAM3) that assimilated observations including altimetry, SST, Argo temperature and salinity using the Bluelink Ocean Data Assimilation System (BODAS) (see for details Oke et al. 2008; Oke et al. 2013a). OFAM3 is a near-global configuration of the Modular Ocean Model version 4.1 with a horizontal model resolution of about 10 km in the

Australian-Asian region, about 1^o across the Indian and Pacific Ocean and 2^o in the Atlantic Ocean (Griffies et al. 2004). Details of the BRAN3p5 model configuration, data assimilation system, and evaluation were summarised by Oke et al. (2013b).

BRAN3p5 and previous versions were employed for several oceanographic studies in the Australian waters. Schiller et al. (2008) used this data when estimating the volume transports associated with key ocean circulation features of the Asian-Australian region, while Oke & Griffin (2011) studied the formation of a cold-core eddy off NSW. Wang et al. (2013) investigated the seasonal variability of the EAC and Everett et al. (2014) studied EAC induced current-driven upwelling off NSW. He et al. (2015) determined the strength of the South China Sea throughflow. The recent studies by Brieva et al. (2015) and Ribbe & Brieva (2016) employed BRAN3p5 data to investigate ocean circulation characteristics off southeast Queensland, identified current driven upwelling as a driver of an ecological hotspot (Brieva et al. 2015), and quantified short-term variability from an eddy census of the EAC region (Ribbe & Brieva 2016). Overall, these studies found that BRAN3p5 realistically represented the observed time-varying regional coastal ocean circulation.

2.2 Methodologies

In the following sections, we describe the methods used to quantify cross- and long-shelf flows, water renewal time scales, and compute wind stresses.

2.2.1 Cross- and long-shelf transport estimates

Cross- and long-shelf volume transports within the SEQMCZ are estimated by vertically integrating along and cross-shelf BRAN3p5 velocities (see Fig. 1 for domain boundaries) at every grid point from the surface to the bottom using the following equations ((Zhou et al. 2014):

$$U^{inward}(t) = \int_{z1}^{z2}\int_{l1}^{l2}(u * n)\,dz\,dl \text{ when } (u * n) > 0 \quad (1a)$$

$$U^{outward}(t) = \int_{z1}^{z2}\int_{l1}^{l2}(u * n)\,dz\,dl \text{ when } (u * n) < 0 \quad (1b)$$

$$V^{inward}(t) = \int_{z1}^{z2}\int_{l1}^{l2}(v * n)\,dz\,dl \text{ when } (v * n) > 0 \quad (1c)$$

$$V^{outward}(t) = \int_{z1}^{z2}\int_{l1}^{l2}(v * n)\,dz\,dl \text{ when } (v * n) < 0 \quad (1d)$$

$U^{inward/outward}(t)$ and corresponding $V^{inward/outward}(t)$ are volume transports at a particular time t integrated between the depth levels $z1$ and $z2$ across the shelf break and longitudinal lines respectively. u (v) (ms^{-1}) is the zonal (meridional) velocity at each BRAN3p5 grid point, z (m) is water depth; l is the length (m) of the eastern shelf boundary (see Fig. 1), n is the unit vector and refers to the shelf direction. Positive (negative) values indicate on-shelf (off-shelf) flows that are also referred to as inward (outward) volume transports. Seasonal mean values for cross- and long-shelf volume transports as well as annual net-volume transports are summarised in Table 2 and time series of time varying volume transports are shown in Fig. 7.

2.2.2 Residence Time scale

The shelf water residence time definition used by Chen (1996) is adopted to quantify the timescale associated with the water exchange in the SEQMCZ. This characteristic timescale is calculated by dividing the total volume of water residing on the shelf by the inward volume flux for the region estimated using above Equation 1a and 1c. The residence time or flushing time scale is used to characterise the dynamics of shelf waters and is often used for marine resource management purposes. The approximate total water content or volume of the SEQMCZ is estimated with about 7.5×10^{11} m^3 using the bathymetry data from the National Center for Environmental Information, National Oceanic and Atmospheric Administration, U.S. Department of Commerce (Amante & Eakins 2009; https://www.ngdc.noaa.gov/mgg/global/) and the 150 m isobath as the eastern boundary.

2.2.3 Wind Stress

Wind stress has been found to be the main driver of cross-shelf exchanges along the southeast coast off NSW, Australia (e.g. Schaeffer et al. 2014). A similar analysis is provided in this paper with the sea surface wind stress (τ) derived from the following formula (e.g. Trenberth, et al. 1990):

$$\tau_x = \rho_{air} C_d u_w \sqrt{u_w^2 + v_w^2} \quad (2a)$$

$$\tau_y = \rho_{air} C_d v_w \sqrt{u_w^2 + v_w^2} \quad (2b)$$

u_w and v_w are the zonal and meridional wind velocity components, ρ_{air} is the surface air density (assumed to be constant with 1.3 kg m^{-3}) and C_d is the dimensionless wind drag coefficient which depends on the wind speed as defined by Trenberth et al. (1990). The wind data was extracted from the ERA-Interim of the European Centre for Medium-Range Weather Forecast (ECMWF) reanalysis products available at http://apps.ecmwf.int/datasets/. The ERA-Interim wind data has a spatial resolution of 0.75^{o} x 0.75^{o} and was available for the period 1993 to 2012. The details of model and assimilation system used to produce ERA-Interim data can be found in Dee et al. (2011).

3 Results

The mean annual and seasonal circulation patterns of the SEQMCZ are presented in the following sections. These results identify and provide an understanding of the Fraser Gyre and its seasonal variability. Results are derived from several independent data sources including tracked surface drifters (Section 3.1), altimetry derived geostrophic surface currents (Section 3.2) and ocean reanalysis BRAN3p5 data (Section 3.3). Along-shelf and cross-shelf volume transports and associated water renewal times scales are quantified and summarised in Section 3.4 and Section 3.5 respectively. Results presented in Section 3.6 relate to the principal forcing process of the Fraser Gyre.

3.1 Evidence of the Fraser Gyre from surface drifters

Surface drifter pathways and velocities are analysed to identify the existence of the Fraser Gyre (Fig. 2). For all 73 drifters located within the vicinity of SEQMCZ, individual tracks for austral spring to summer (September-February) and austral autumn to winter (March-July) are shown in Fig. 2a and 2b. The trajectories are color-coded to denote each drifter track for spring (pink), summer (red), autumn (orange), and winter (blue). The trajectories provide a Lagrangian view of both cyclonic circulation pattern in the SEQMCZ and the southward flow of the EAC. Trajectories indicative of circulation features such as mesoscale eddies and current meanders are evident in the tracks found over the shelf and in the vicinity of the shelf-break. The trajectories reveal a dominant cyclonic semi-circular flow, inducing inward (coastward) cross-shelf transport that appears to primarily occur during the austral autumn to winter. The inward drifters follow a northerly pathway indicative of a northward alongshore current. This cyclonic movement of the drifters is similar to that observed by Woodhead (1970). Furthermore, the trajectories elucidate clearly the seasonal variability of the circulation within the SEQMCZ with no recirculating drifter found during austral spring and summer.

It is evident (Fig. 2a and 2b) that the majority of the 73 tracked drifters moved in a southward to south-westward direction and toward the shelf break, but did not enter the SEQMCZ and were restrained within the EAC jet. The drifters instead followed a southern pathway alongside the shelf-break to the south of 27^{o} S (Fig. 2a and 2b). The presence of a strong southward EAC flow appears to act like a partial barrier, which prevented the cross-shelf movement of most drifters. Such barrier flow characteristic is consistent with previous studies conducted in waters of south-eastern Australia (e.g. Condie et al. 2011; Roughan et al. 2011; Suthers et al. 2011). A total of 14 drifters entered and crossed the shelf, seven drifters during austral spring to summer (A, B, C, D, E, F, G shown in Fig. 2c) and seven during austral autumn to winter (H, I, J, K, L, M, N shown in Fig. 2d). Some of these drifters recirculated and eventually stranded further north. These pathways are indicative of an inward cross-shelf and long-shore transport pattern.

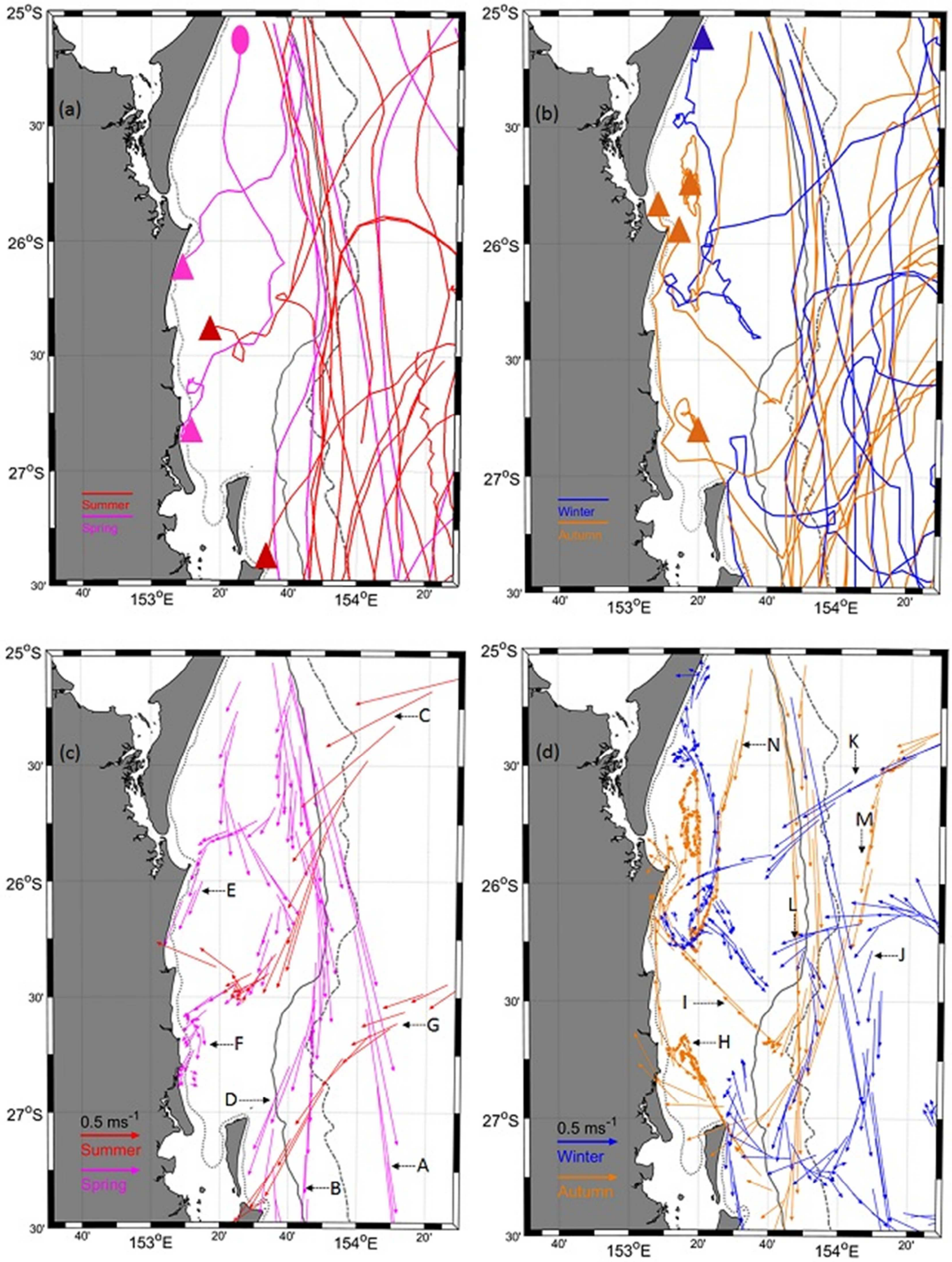


Fig. 2. Seasonal composite of all seventy-three drifter trajectories in the vicinity of the SEQMCZ during the austral (a) spring to summer and (b) autumn to winter, and velocities of the 14 drifters that entered the SEQMCZ in (c) spring-summer and (d) autumn-winter.

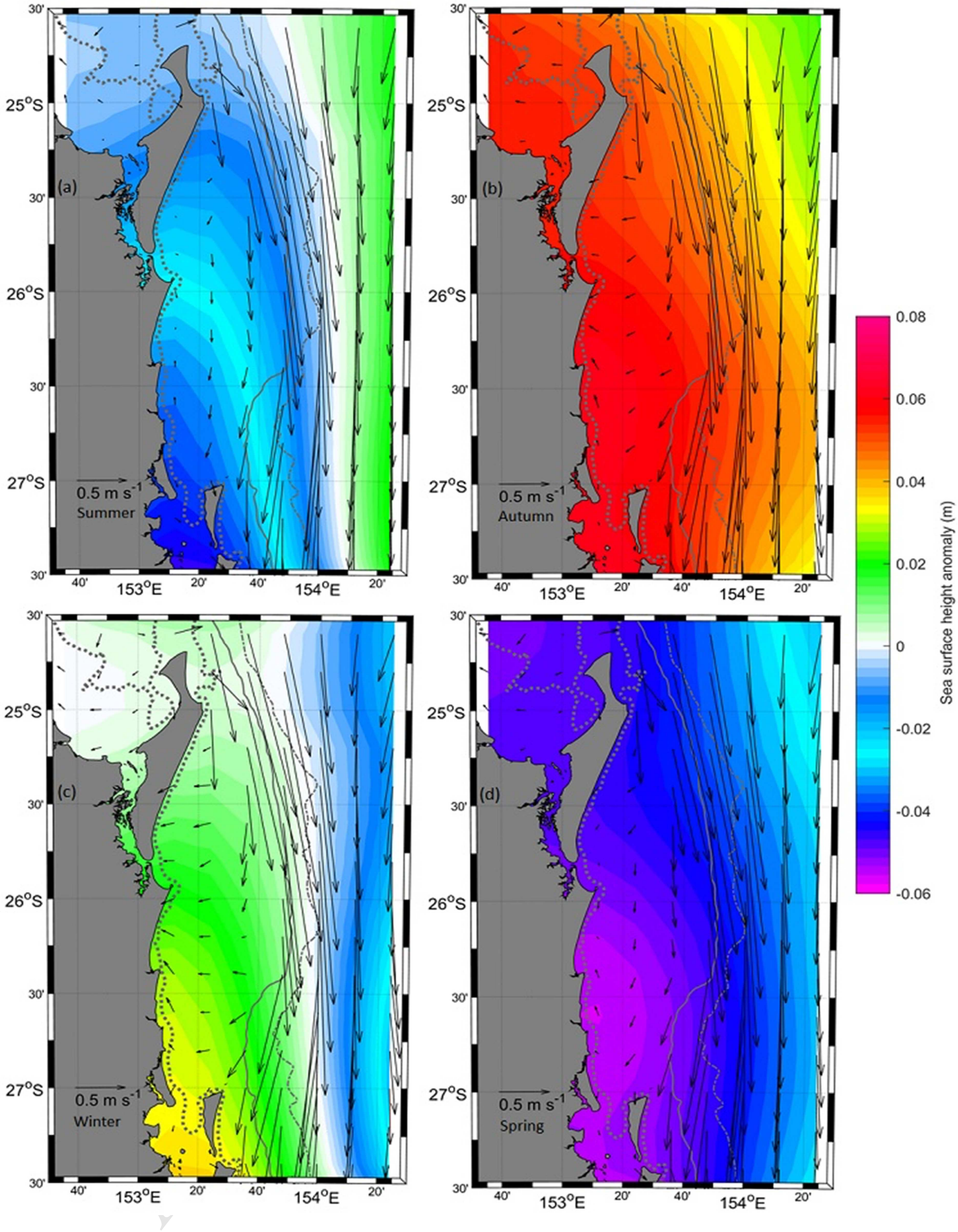
Trajectories are colour coded: spring (magenta), summer (red), autumn (orange) and winter (blue). The 20m (dotted line), 150m (solid line) and 1000m (dash/dot line) isobaths are shown in grey. Letters in the lower panels represent the individual drifters reported in Table 1. Triangle indicates the end-position for stranded drifters. Only one drifter (F) is released in the domain. Note that drifter J leaves the domain in the southeast, enters the domain again further in the north at about 26.5^{o}E and then follows a cyclonic pathway within the SECQMZ. Drifter L enters the region from the east, and its pathway partially overlap with that of drifter J (see Fig. 5).

The seasonal composites of near-surface velocity and flow direction for drifters that entered the SEQMCZ are shown in Fig. 2c and 2d (see also Table 1). The velocity field pattern for the austral spring to summer and autumn to winter differs significantly. During the austral spring to summer, all drifters followed a south to southwest pathway and either travelled with the main flow of the EAC (drifters A, B) exiting the region of interest or crossed the shelf break, entering the SEQMCZ, crossing the 20 m isobath and continued on a southern pathway before stranding (drifters C, D, E, F, G). This pattern of trajectories contrasts with that observed during the austral autumn to winter when drifters within the SEQMCZ followed mostly cyclonic pathways with near-coast and northward tracks (Fig. 2d). Velocities for the on-shelf recirculating drifters (see Table 1) ranged from 0.11 – 0.43 ms^{-1} during the autumn to winter period. The highest velocity of any of the drifters is found to be about 1.94 ms^{-1} during November 1994 (see Table 1, drifter A). This drifter appears to be well embedded within the southward flow of the EAC and during a period, when the EAC is known to be most intense. The drifter's velocity is within the range of Suthers et al. (2011), who reported EAC flows of up to 2 ms^{-1}. All southward moving drifters reflect the higher velocities associated with the EAC.

From an analysis of the trajectories of recirculating drifters, it appears that these drifters primarily entered the SEQMCZ between about 26.5°S and 27.5°S (Figs. 2d; H, I, J, L, M). Thus, in the austral autumn and winter, the cross-shelf exchange is predominantly inward in the southern portion of the SEQMCZ. The distribution of the trajectories provides a proxy for understanding the most likely mean water renewal pathway of the SEQMCZ. The preferential region for the cross-shelf exchange implies that the physical processes for the cross-shelf variability and entrainment act along this part of the shelf-break. During August 2006 and July 2008, an anticyclonic eddy-like circulation is shown offshore of Moreton Island (Fig. 2d, drifter J and L). Drifter J travelled southward and turn eastward at about 27.5°S in an anticyclonic rotation and exiting the region of interest. It re-joined the EAC flow further north at about 26.5 °S before being finally carried away along a cyclonic trajectory into the SEQMCZ near about 27.25 °S. The offshore anticyclonic flow appears to be associated with the separation point of the EAC as previously demonstrated (e.g. Ridgway & Dunn 2003; Cetina-Heredia et al. 2014; Macdonald et al. 2016). The cyclonic trajectory of drifter K is characterised by the most northern displacement within the SEQMCZ and it stranded at the northern end of Fraser Island. It was also one of two drifters (K, N) that were entrained in the northern region of the SEQMCZ. The trajectories of both drifters indicate the presence of on-shelf eddies, initially trapping both drifters, before progressing further in a cyclonic pattern toward the north and stranding.

3.2 Evidence of the Fraser Gyre from surface geostrophic currents

The seasonally averaged surface geostrophic currents derived from SSHa for the period 1993-2012 (Fig. 3) reveal an intense and persistent southward flow of the EAC along the shelf break. The apparent and direct influence of the EAC on the circulation of SEQMCZ is evident with the flow along the shelf break mostly directed southward east of about 153.33 ^{o}E during the austral spring and summer (Fig. 3a and 3d). This near-shelf break southward flow weakens and is replaced by west to north westward flow during austral autumn and winter, particularly south of 26 ^{o}S (Fig. 3b and 3c). The overall flow pattern portrays the seasonal characteristics of a seasonal cyclonic circulation encompassing the SEQMCZ during the austral autumn and winter (Fig. 3b and 3c) with positive SSHa near the coast. Furthermore, the flow pattern suggests the presence of cross-shelf flow toward the coast near the shelf-edge just to the north of Moreton Island (~27 ^{o}S). The cross-shelf inshore flow, more evident in austral autumn and winter, feeds into a northward longshore current, which follows the coastline. Seasonally averaged maximum velocities of up to 0.26 ms^{-1} are obtained for the northward current at 26.4 ^{o}S 153.2 ^{o}E during winter. Southward flows during austral spring-summer at this location are much smaller with about 0.12 ms^{-1}.



1

2 **Fig. 3.** A presentation of the seasonal mean geostrophic surface currents (ms^{-1}) and SSHa (m)
3 for the period 1993 – 2012. Arrows indicate current magnitude and directions. SSHa is
4 shaded in intervals of 0.02 m, with positive values in the green to red range.

3.3 Evidence of the Fraser Gyre from BRAN3p5 model

BRAN3p5 model data was found previously to be consistent with observations (e.g. Schiller et al. 2008). Thus in the following, our analysis is focused on the seasonally varying flow pattern within the SEQMCZ (Section 3.3.1). This is followed by a comparison between BRAN3p5 model and drifter data (Section 3.3.2).

3.3.1 Mean seasonal circulation from BRAN3p5

The mean seasonal climatology of depth-averaged circulation for the SEQMCZ taken from twenty years of BRAN3p5 reanalysis data is shown in Fig. 4. The strong southward flow of the EAC is captured in BRAN3p5 data during all seasons. The general pattern of the surface circulation agrees with that found for the SSHa derived surface geostrophic circulation (Fig. 3). During austral spring and summer, the depth-averaged mean flow is primarily southward across the whole region, including the shelf. However, during the austral autumn and winter, the circulation rotates clockwise, broadly following the bathymetry, and displays clear evidence of an on-shelf cyclonic gyre west of the 150 m isobath. The EAC flows continuous to be evident to the east of the shelf. The non-depth-averaged circulation (not-shown) indicates that the cyclonic flow during austral autumn and winter is more pronounced in the sub-surface layer.

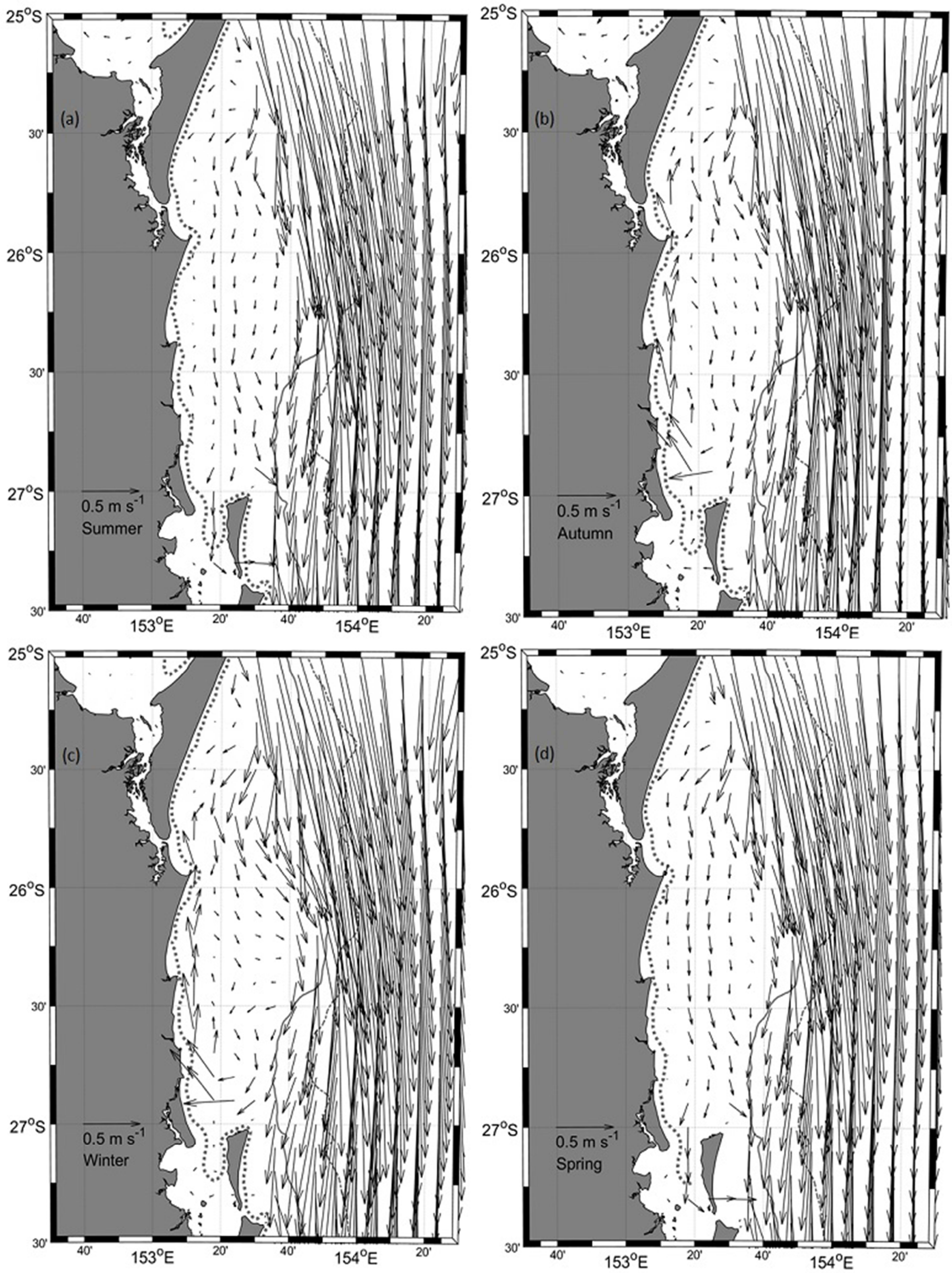


Fig. 4. Seasonal climatology of the depth-averaged mean circulation (ms^{-1}) of the SEQMCZ. The locations of the 20 m (dotted), 150 m (solid), and 1000 m (dashed) isobaths are shown.

A distinct feature of the inner-shelf circulation is the presence of a northward longshore current and a cross-shelf flow, toward the east in the north and toward the west in the south. The mean maximum depth-averaged northward long-shore current is about 0.15 ms^{-1}. During the austral autumn and winter, the cross-shelf flow appears as an extension of the westward veering EAC following the shelf-break curvature at about 153.7^{o}E, 26.5^{o}S. The main flow of the EAC continues its southward flow beyond 26.5 ^{o}S, however, a westward branch establishes the southern edge of a shelf-encompassing cyclonic circulation associated here with the Fraser Gyre. The circulation shifts from southward to northward flow just to the north of Moreton Island. The inward directed cross-shelf flow is found in all model layers and more distinctly found in the sub-surface layer at 20 m depth (not shown). The U-shape flow shown in BRAN3p5 data is consistent with drifter trajectories and geostrophic current as derived from satellite altimetry and discussed in the previous sections.

3.3.2 Comparison between BRAN3p5 and drifters data

In the following section, we compare BRAN3p5 model data with drifter trajectories for the SEQMCZ. Five drifters (I, J, K, L, M) entered the region during the period BRAN3p5 data are available for. In addition, the drifter data were not assimilated into BRAN3p5 (unlike altimetry data for instance), therefore also act as set of independent in-situ measurements to evaluate the model performance.

Mean daily surface currents are compared with trajectories from all five drifters (Fig. 5). The daily mean surface current is computed for the period a drifter resided within the SEQMCZ.

For example, drifter K spent a total of 25 days in the domain; therefore the daily mean is obtained as an average over that period. The BRAN3p5 near-surface circulation pattern is found to be in good agreement with the trajectories obtained from the drifters. Mean daily surface currents from BRAN3p5 consistently show the inward meanders that emanate from the southward flow of the EAC along the shelf break. This flow forms a cyclonic surface circulation that branches away from the EAC south of about 26°S (Figs. 5a – 5d), and feeds the previously identified northward coastal longshore current. This current forms the western branch of the Fraser Gyre.

Statistical analysis using the complex cross-correlation of daily velocity method (Kundu 1976) confirms the good agreement between model flow fields and observed drifter trajectories. This method measures the angle between two vectors, here the directions between the drifters and the BRAN3p5 flows. The mean complex correlation coefficients between BRAN3p5 and corresponding drifter velocities at a given location and period is about 0.85. The mean difference between the flow direction of the BRAN3p5 current and the direction of the drifters is about 12.33°. The positive value of the directional error indicates that the BRAN3p5 velocity field is on average directed counter-clockwise away from the direction of the drifters. From this BRAN3p5 versus drifter comparison it is concluded that the model represents the key features of the SEQMCZ’s surface circulation. The good agreement is of interest to all other studies of shelf circulation and cross-shelf exchanges that utilise BRAN3p5 data (Schiller et al. 2015). For this paper, it provides further support in identifying the Fraser Gyre and utilising BRAN3p5 to quantify associated transports and residence time scales (see following sections).

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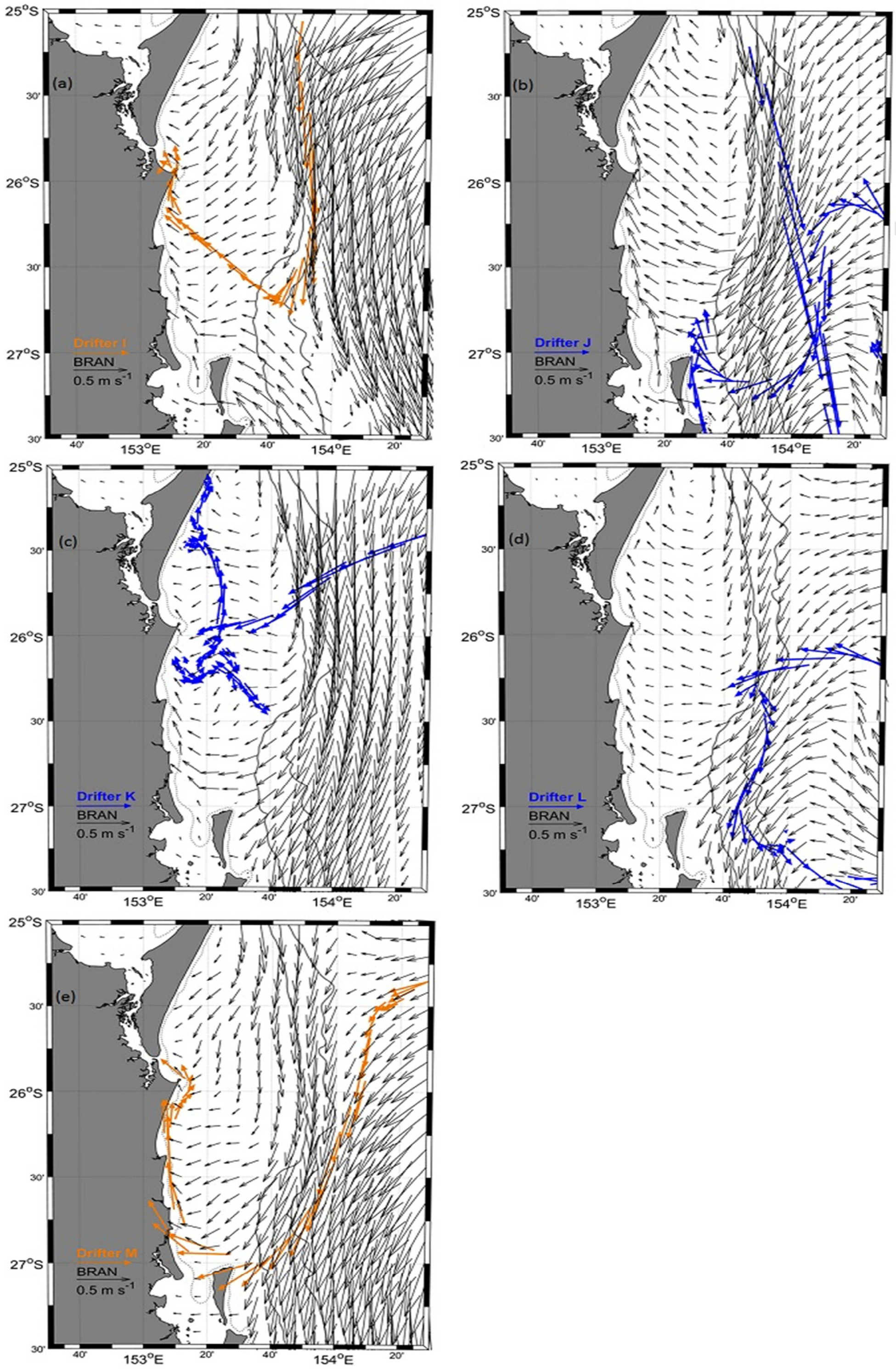

2

3 **Fig. 5.** Comparison between daily mean BRAN3p5 surface currents (ms^{-1}) and trajectories of

4 selected drifters within the SEQMCZ. The daily mean current is obtained over the period the

5 drifter is located within the region.

3.4 Fraser Gyre volume transports

Depth-integrated long- and cross-shelf volume transports associated with the Fraser Gyre using BRAN3p5 data for the period 1993 to 2012 are shown in Fig. 6 for the cross-sections at 25^{o}S and 27^{o}S and the along shelf-break section following the 150 m depth contour (see Fig. 1), respectively. The latter is shown for the total cross-shelf transport between 25-27 ^{o}S and for the northern (25-26 ^{o}S) and southern region (26-27 ^{o}S) with cross-shelf outward flow characterising the northern section. The annual mean transport at 25^{o}S (Fig. 6a) is dominated by southward transport onto SEQMCZ. The southward transport is reminiscent of the long-shelf southward EAC that dominates the circulation to the east near Fraser Island. Further analysis of the seasonal climatology of the net long-shelf transport reveals a clear seasonal feature at 25^{o}S. The intensification period of the southward transport at 25^{o}S commences in about spring with the mean of about 2.24 ± 0.05 Sv (Table 2). It is at a maximum during summer with a mean of about 2.36 ±0.28 Sv, weakens during autumn with a mean of about 1.71±0.08 Sv and reaches a minimum transport with mean of about 1.60 ±0.19 Sv during winter.

Table 2

Seasonal volume transports (1 Sv = 10^6 m^3s^{-1}) for the SEQMCZ using Equation 1. Positive (negative) values indicate inward (outward) transport to (from) the SEQMCZ. Transport across shelf break is shown for the total (25-27 ^{o}S) and for the 25^o-26^o S (northern section) and 26^o – 27^o S (southern section).

	Volume Transport (1 Sv = $1 \cdot 10^{6}$ m^3s^{-1})				
Location	**Summer**	**Autumn**	**Winter**	**Spring**	**Annual**
25 ^{o}S	2.36 ± 0.28	1.71 ± 0.08	1.60 ± 0.19	2.24 ± 0.05	1.97 ± 0.77
27^{o}S	-1.27 ± 0.13	-1.05 ± 0.27	-0.83 ± 0.12	-1.16 ± 0.17	-1.07 ± 0.61
Shelf break 25-26 ^{o}S	-1.35 ± 0.24	-0.96 ± 0.07	-1.04 ± 0.14	-1.34 ± 0.18	-1.17 ± 0.23
Shelf break 26-27 ^{o}S	0.21 ± 0.08	0.28 ± 0.18	0.22 ± 0.08	0.20 ± 0.16	0.23 ± 0.13
Shelf break 25-27 ^{o}S	-1.09 ± 0.39	-0.60 ± 0.27	-0.87 ± 0.29	-1.08 ± 0.50	-0.90 ± 1.15

The mean transport at 27^{o}S is southward and away from SEQMCZ and seasonal variability is consistent with that at 25^{o}S. During austral spring, the along-shelf mean net transport reaches a mean of about -1.16±0.17 Sv at 27^{o}S, increases to -1.27±0.13 Sv during summer before it decreases to a mean of about -1.05±0.27 Sv and -0.83±0.12 Sv during autumn and winter, respectively. The annual net volume transport for the SEQMCZ at the shelf break toward the east of -0.90 ± 1.15 Sv is the balance between transports at 25 ^{o}S of 1.97±0.77 and 27 ^{o}S of -1.07±0.61. Thus, the SEQCMZ exports water eastward across the shelf throughout the year.

Eastward net-transport away or export from the SEQMCZ characterises the cross-shelf flow along the shelf break (Fig. 6c). Inward cross-shelf transport is also evident particularly during the late summer (February), autumn and winter. Similar to seasonal along-shelf transport pattern, the cross-shelf transports in the SEQMCZ reveals seasonal characteristics and the highest (lowest) mean net-transport occurred during austral summer (winter) (Table 2). The total annual along-shelf and cross-shelf transport is balanced and approximately zero integrated across the enclosed boundary of the SEQMCZ (Fig. 1), i.e. there is no net-gain or loss of water within the SEQMCZ.

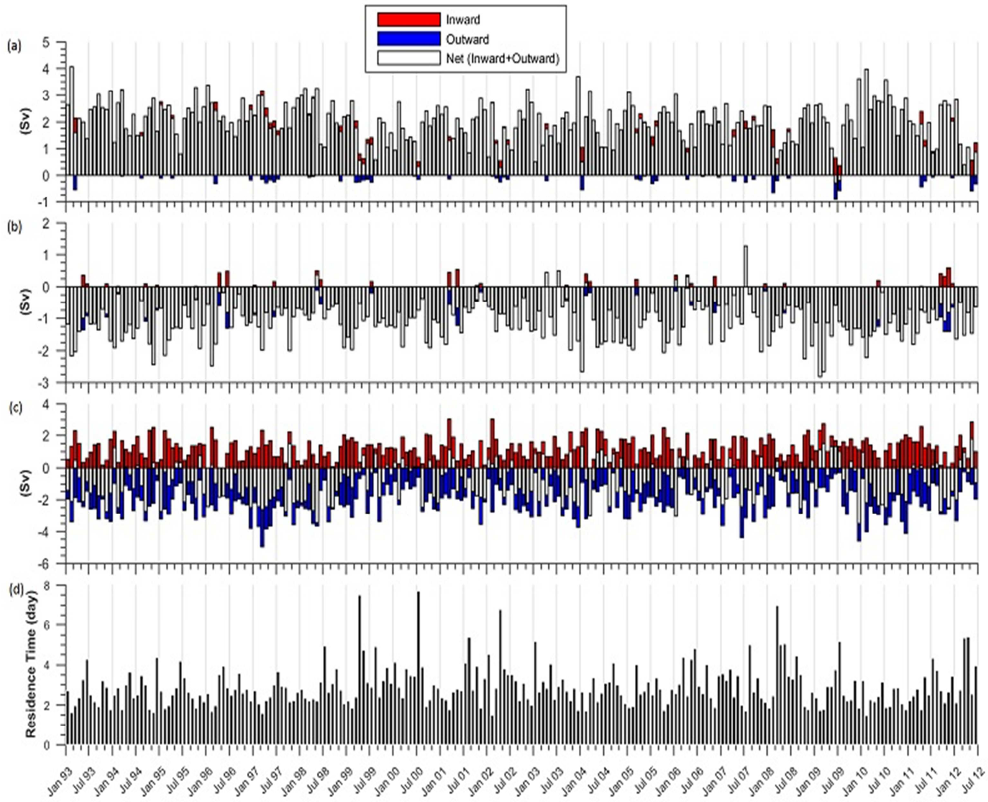

Fig. 6. Monthly volume transports (1 Sv = 10^6 m^3s^{-1}) at latitudes (a) 25°S, (b) 27°S, and (c) the shelf break across the 150 m isobath. Positive (negative) values indicate inward (outward) transport to (from) the SEQMCZ. (d) Residence time scale (days) for SEQMCZ water.

3.5 Residence time scale

A time series of the residence time scale for the entire SEQMCZ is calculated using the approach by Chen (1996). Values range from a minimum of about 2.7 days to more than 5 days and a maximum of about 8 days (Fig. 6d). The residence time appears to be shorter during austral spring to summer than during autumn to winter. Mean time scales for the period 1993-2012 are about 2.53 days, 3.19 days, 3.33 days and 2.63 days for summer, autumn, winter and spring respectively. The longer time scales during autumn-winter are most likely a result of the on-shelf water recirculation due to the Fraser Gyre. The overall mean residence time scale average is about 2.9 ± 1.02 day. This finding is consistent with the short residence times in the order of several days computed by Schiller et al. (2015) using volume transports from a high-resolution model of the Great Barrier Reef. Schiller et al. (2015) found that short residence time scales of a few days characterise most of the northern Australian continental shelf. In shelf regions that are more confined, such as Hervey Bay (Ribbe 2014), residence times are much longer and in the order of several tens of days.

3.6 Results from wind stress and SSHa analysis

Results of the previous section identify the presence of an episodic seasonally reoccurring cyclonic circulation within the SEQMCZ, which is referred to as the Fraser Gyre. In this section, we explore the link between local wind forcing and changes in the coastal circulation. Remotely sensed SSHa serves as a surrogate that captures the time-varying changes in the circulation (see Fig. 7).

The cross-shelf and long-shelf wind stress components (τ_x , τ_y) over the SEQMCZ for the period 1993 – 2012 display a distinct seasonal cycle (Fig. 7a). A positive long-shelf wind stress ($\tau_y > 0$) component indicates southerly wind (i.e. directed to the north) while a negative value ($\tau_y < 0$) represents a northerly wind (i.e. directed to the south). Positive ($\tau_x > 0$) and negative ($\tau_x < 0$) cross-shelf components of the wind stress τ_x denote westerly (i.e. directed to the east) and easterly (i.e. directed to the west) wind respectively. The wind stress data indicate that the southerly ($\tau_y > 0$) and easterly wind ($\tau_x < 0$) is present 77% and 89% of the time. In contrast, northerly ($\tau_y < 0$) and westerly ($\tau_x > 0$) wind occurs only 23% and 11% of the time respectively (Fig. 7a). Southerly wind (which is down-welling favourable) prevails for most of the year and a relatively weak northerly wind (which is up-welling favourable) occurs only in spring to early summer.

The wind stress over the SEQMCZ is characterised by distinct seasonal variability (Fig 7a). Strong and persistent southerly wind stress occurs frequently during early autumn to winter (March to August) with an average value for τ_y of about 0.014 N/m^2. The wind changes direction to relatively weak northerly wind stress with an average value for τ_y of about -0.004 N/m^2 during spring to early summer (September to January). The conceptual framework of the coastal circulation and Ekman dynamics (e.g. Talley et al. 2011) leads to the conclusion that the intensification of the southerly wind generates downwelling favourable conditions, while the sporadic and weaker northerly wind is possibly associated with upwelling.

We also examine the link between the long-shelf wind stress (i.e. parallel to the coast) and SSHa variability in the SEQMCZ. Remotely sensed SSHa averaged over the SEQCMZ is shown in comparison with SSHa data from coastal tide gauge measurements for the period of 1993 to 2012 in Fig. 7b. The linear correlation between the data is about 0.74 (95% confidence level). SSHa is characterised primarily by negative anomalies during austral spring and summer and positive SSHa during autumn and winter.

The relationship between long-shelf wind stress and SSHa reveals a positive (negative) SSHa when the wind stress is southerly (northerly) in the SEQMCZ region. The southerly wind stress and positive SSHa correspond to a strengthening of the recirculation in autumn and winter (Fig. 4), and the establishment of a near-coast geostrophic northerly flow in the direction of the wind (Fig. 3). We identify a strong positive relationship between long-shelf wind stress and SSHa with a correlation coefficient of about 0.53. In contrast, the cross-shelf wind and SSHa correlation is weak with about -0.1; both correlations with a confidence level at 95%. A positive relationship in the long-shelf wind stress suggests that the southerly wind stress ($\tau_y > 0$) induces an onshore flow within the surface Ekman layer. This surface layer wind-driven transport increases the on-shelf positive SSHa during austral autumn and winter and is likely to induce downwelling consistent with general theory (Talley et al. 2011). In contrast, the northerly wind results in a decrease of SSHa, which in turn is likely to be associated with upwelling during spring and summer; although Brieva et al. (2015) demonstrated that spring and summer upwelling is predominately due to current driven upwelling, since northerly wind is weak and too sporadic in this region.

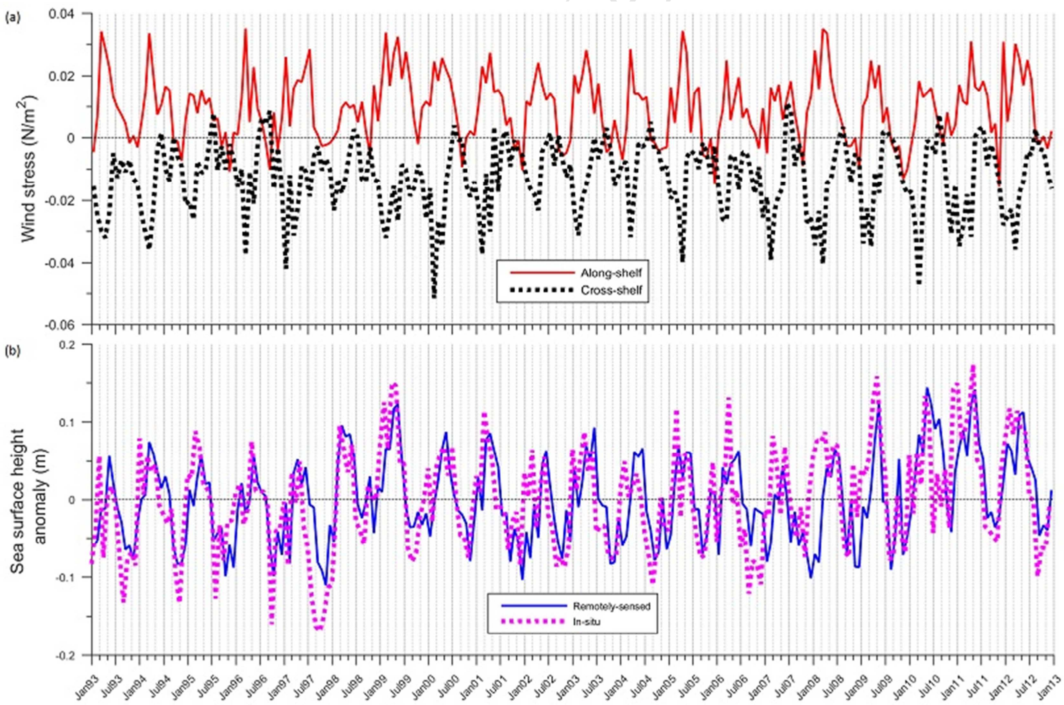

Fig. 7. (a) Monthly long-shelf (solid line) and cross-shelf (dotted line) wind stress (N/m^2) over the SEQMCZ, (b) SSHa (m) remotely sensed averaged over the SEQCMCZ (solid line) and from the Mooloolaba tide station (dotted line). Please see Section 2.1 for data sources.

4 Discussion and Conclusion

In this study, we document the climatological mean state of the circulation of the SEQMCZ off central eastern Australia. A most characteristic feature is the existence of a seasonally reoccurring cyclonic circulation. This is referred to as the Fraser Gyre. It is wedged between the coast and the southward flowing EAC and occupies the shelf from north of Moreton Island at about 27^o to the south of Fraser Island at about 25 ^{o}S. The gyre forms during the austral autumn to winter and the southerly wind is identified as its main driver. The gyre is characterised by a westward extending southern branch that emanates from the EAC at about 27 ^{o}S. After crossing the shelf, the flow turns northward forming a northward long-shore current of about 0.15 ms^{-1} that follows the shelf for about 200 km northward before it turns eastward just to the south of Fraser Island. This eastward branch of the gyre joins the southward flow of the EAC near the shelf break. We find evidence of the gyre from several independent data sources including trajectories of surface drifters, remotely sensed SSHa, geostrophic surface velocities from satellite altimetry and ocean assimilation model data. Our findings confirm much earlier postulations of a possible cyclonic gyre. These were based on the analysis of non-satellite tracked traditional sea surface drifter observations (Woodhead 1970) and current meter measurements (Middleton et al. 1994), but these studies did not present clear evidence for the temporal and spatial extent of the gyre, the associated volume transports, longshore current velocities and on-shelf water residence time scale. The existence of similar shelf constraint cyclonic gyres was shown for the southern region of the EAC by e.g. (Huyer et al. 1988) and other WBC regions including the Charleston Gyre (Govoni et al. 2010) wedged between the Gulf Stream and North American continental shelf and the Tortuga gyre (Fratantoni et al. 1998). The average residence time for the SEQMCZ based on an analysis of volume transports is about 2.9 ± 1.02 day, which is short but characteristic for the near-shore regions of the northern Australian continental shelf (e.g. Schiller et al. 2015).

The seasonally reoccurring flow of the Fraser Gyre identified in this study and the associated volume transport, current velocities and water residence time scales are likely to have biological implications. Ward et al. (2003) referred to the migration pattern of several temperate fish species that are known to spawn in subtropical waters of the SEQMCZ. The Fraser Gyre represents a mechanism that would assist the cross-shelf export of larvae and their entrainment and southward advection with the EAC as well as assisting the northward migration of adult species along the shelf during the austral autumn and winter months. Similarly, Gray & Miskiewicz (2000) and Armbrecht et al. (2014) identified the existence of these on-shelf quasi-stationary cyclonic gyres as important cross-shelf transport mechanism for larval fish, phytoplankton and other oceanic properties.

We identify two opportunities for future work that also represent limitations to our study. Firstly, the analysis presented here focuses largely on the long-term seasonal change and mean state of the coastal ocean off southeast Queensland. However, it is known that short-term variability in the form of mesoscale eddies is a characteristic feature for this region (see Ribbe and Brieva 2016). This can also lead to cross-shelf transports induced by associated single current filaments (Shapiro et al. 2010). Secondly, our study relies on remotely sensed and reanalysis data and lacks in direct field observations. Thus, future work is to focus on investigating the contributions made by mesoscale eddies to cross-shelf exchanges and the variability of the Fraser Gyre from higher resolution modelling and in-situ observations.

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