Cross-Shelf Dynamics in a Western Boundary Current Regime: Implications for Upwelling

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ABSTRACT

The cross-shelf dynamics up- and downstream of the separation of the South Pacific Ocean’s Western Boundary Current (WBC) are studied using two years of high-resolution velocity and temperature measurements from mooring arrays. The shelf circulation is dominated by the East Australian Current (EAC) and its eddy field, with mean poleward depth-integrated magnitudes on the shelf break of 0.35 and 0.15 m s⁻¹ up- and downstream of the separation point, respectively. The high cross-shelf variability is analyzed through a momentum budget, showing a dominant geostrophic balance at both locations. Among the secondary midshelf terms, the bottom stress influence is higher upstream of the separation point while the wind stress is dominant downstream. This study investigates the response of the velocity and temperature cross-shelf structure to both wind and EAC intrusions. Despite the deep water (up to 140 m), the response to a dominant along-shelf wind stress forcing is a classic two-layer Ekman structure. During weak winds, the shelf encroachment of the southward current drives an onshore Ekman flow in the bottom boundary layer. Both the bottom velocity and the resultant bottom cross-shelf temperature gradient are proportional to the magnitude of the encroaching current, with similar linear regressions up- and downstream of the WBC separation. The upwelled water is then subducted below the EAC upstream of the separation point. Such current-driven upwelling is shown to be the dominant driver of cold water uplift in the EAC-dominated region, with significant impacts expected on nutrient enrichment and thus on biological productivity.

1. Introduction

Cross-shelf circulation is a key component of the dynamics on continental shelves. It influences water stratification, cross-shelf exchange, and mixing or entrainment of water masses. The dynamics across the shelf control primary productivity as vertical uplift supplies nutrients into the euphotic zone. Furthermore, variability in cross-shelf structure has been shown to aid in either cross-shelf transport or inshore retention especially during upwelling (Roughan et al. 2006). Many physical processes interact to control the complex dynamics in continental shelf regions. To aid our understanding of these complex interactions, typically, the continental shelf is divided into different zones: surfzone, inner, mid-, and outer shelf (or shelf break). Many studies have focused on the inner shelf, where the dynamics tend to be primarily wind driven, but also influenced by stratification and river discharge (Lentz 2001; Fewings et al. 2008; Dzvonkowski et al. 2011a,b). At the mid- and outer shelf, cross-shelf structure can be more complicated than 2D wind-driven flow, as the surface and bottom boundary layers are separated by an interior flow (Dever 1997; Liu and Weisberg 2005). The large-scale circulation can then significantly interact with the coastal dynamics, even driving upwelling through bottom stress (Oke and Middleton 2000; Roughan and Middleton 2004; Hyun and He 2010; Castelao 2011).

The focus of this study is to examine the mechanisms that drive the cross-shelf dynamics along the continental shelf of eastern Australia. In this region the large-scale circulation is dominated by the East Australian Current (EAC), which forms the western boundary of the South Pacific Ocean’s subtropical gyre. It flows poleward along the coast of eastern Australia transporting heat and biota, as shown in the typical summer condition of sea surface temperature (SST) and geostrophic dynamics (Fig. 1a). It thus has impacts on coastal weather systems, climate, and the transport and distribution of species. Less known, however, is the subsurface impact of the current on
continental shelf waters. The EAC has been known to influence cross-shelf processes in a number of ways including driving the upwelling of cold nutrient-rich waters at the shelf break through bottom friction effects (Oke and Middleton 2000; Roughan and Middleton 2002, 2004). Encroachment of the jet (at times $>2 \text{ m s}^{-1}$) onto the continental shelf displaces shelf waters with warmer oligotrophic water, potentially advecting productivity southward.

Downstream of the separation point of the EAC, mesoscale eddies are shed from the current. Large warm core (anticyclonic) and smaller cold core (cyclonic) eddies form regularly at the separation point (Gibbs et al. 2000; Mata et al. 2006; Wilkin and Zhang 2007; Oke and Griffin 2011). As the EAC separates from the coast it has been seen to entrain coastal waters with higher nutrient concentrations and advect these waters offshore into the eddy field or along the separating front (Roughan et al. 2011). The EAC usually separates from the coast around $31^\circ$–$32^\circ$S, as evident in Fig. 1a. From the monthly satellite observations of SST and geostrophic velocities in 2010/11, the EAC appears to extend as far as Sydney (34°S) for just 2 months out of the 2-yr study period (not shown). Thus, Sydney is considered to be downstream of the EAC separation point with eddy-dominated dynamics.

Until recently this dynamic Western Boundary Current (WBC) system and its impacts on the continental shelf have been observed through intermittent process studies involving a combination of short mooring deployments and hydrographic surveys, upstream (Oke et al. 2003), downstream (Cresswell 1994; Gibbs et al. 1998), and straddling the EAC separation point (Roughan and Middleton 2002, 2004). In addition, remote sensing has played an important role in elucidating the nature of the dynamic eddy field (Wilkin and Zhang 2007; Everett et al. 2012) and, more recently, the associated chlorophyll response to upwelling via data from Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and Moderate Resolution Imaging Spectroradiometer (MODIS) satellites (Oke and Griffin 2011).

In recent years the Australian Integrated Marine Observing System (IMOS) has been developed to provide...
sustainable observations of Australian coastal waters. In particular, arrays of moorings were installed up- and downstream of the EAC separation point along the coast of eastern Australia (Roughan et al. 2010). This unprecedented long-term dataset of water temperature and velocity is used here to provide a comprehensive investigation into the cross-shelf dynamics in this WBC regime.

The paper is organized as follows. The next section describes the observations and processing used. A brief description of the dynamics in the region is provided in section 3. The dominant mechanisms driving the cross-shelf flow are then highlighted through a momentum balance analysis (section 4) and uncertainties and limitations are addressed (section 6). In section 5, the influence of the main forcing mechanisms is investigated, looking independently at the cross-shelf structure of the flow when the wind stress or the large-scale circulation is dominating. Particular attention is given to the resultant cold water intrusions, with a discussion on the extent of both the physical and biological response up- and downstream of the WBC separation.

2. Observations and data processing

The New South Wales (NWS) node of the IMOS was designed to examine the physical and ecological interactions of the East Australian Current and its eddy field with coastal waters. To achieve this, seven moorings have been deployed along the coast in three across-shelf transects (Fig. 1) off Coffs Harbour, Sydney, and Narooma (at 30°, 34°, and 36°S, respectively; Roughan et al. 2010; Roughan and Morris 2011). The first of these moorings was deployed in mid-2008. In addition, the Ocean Reference Station off Sydney (ORS065) has been deployed since 1990 (Wood et al. 2012). In this study, two years of observations are analyzed using the Coffs Harbour and Sydney arrays (latitudes listed in Table 1) from January 2010 to December 2011. The Coffs Harbour array consists of 2 sites over the mid- (70-m isobath) and outer shelf (100-m isobath), while off Sydney (450 km to the south) three sites are instrumented on the 65-, 100-, and 140-m isobaths. The distance from the coast ranges from 2 to 25 km (Fig. 1 and Table 1).

At each mooring, a bottom-mounted ADCP measures the current velocity in 4-m bins (8 m at SYD140). The water temperature is also measured through the water column with thermistors at 8-m intervals (4 m at ORS065), up to 11–24 m below the surface (Table 1) to avoid damage from boat traffic. These temperature data are complemented by pressure sensors at strategic depths in the water column. All data are recorded every 5 min and quality controlled through the IMOS toolbox (http://code.google.com/p/imos-toolbox/).

The temporal coverage of the measurements (Table 1) highlights gaps in the time series because of instrument failures or other data losses. Gaps shorter than 24 h were filled using linear interpolations, while longer gaps were not considered for the analysis performed. Monthly hydrographic data were also collected off Port Hacking (20 km south of Sydney sites) and Coffs Harbour (since September 2011) providing salinity measurements along cross-shelf conductivity–temperature–depth (CTD) transects. Hourly wind observations were obtained from the Bureau of Meteorology at the closest and most significant sites, Coffs Harbour and Kurnell (Wood et al. 2012), wind stress is computed after Gill (1982) and Wood et al. (2012), then low-pass filtered in the same way as the ocean variables.

The 5-min current and temperature time series are averaged to hourly intervals and are 38-h low-pass filtered to focus on the subtidal variability using the PL64 filter (Rosenfeld 1983). Current measurements are not possible in the surface and bottom boundary layers because of limitations in the moored ADCP configuration (Table 1). Hence, the observations are extrapolated to the bottom and surface assuming a constant velocity following Shearman and Lentz (2003), to compute the cross-shelf full depth transports. The analyses were also performed using a linear extrapolation to the surface and bottom but showed little differences. An across- and along-shelf coordinate system was determined using the orientation of the principal axis of the depth-averaged current (Table 1).
current, summarized in Table 1, with the $x$ and $y$ axes chosen to be positive for offshore and northeastward flows, respectively. The choice of this rotation angle is discussed in section 6.

3. Context

a. Mean flow

The mean depth-averaged current vector and variance ellipse at each site (computed from the two years of measurements) shows that the circulation is predominantly southward along the shelf with higher magnitudes at Coffs Harbour (0.35 m s$^{-1}$ at CH100) relative to Sydney (0.15 m s$^{-1}$ at SYD140) (Fig. 1). This is consistent with the prevailing synoptic circulation, with the intense EAC flowing poleward along the coast until around 31°S where it partly bifurcates eastward, as shown on the typical SST and geostrophic velocity map of the 7 January 2010 (Fig. 1a). The shelf at 34°S (Sydney) is then dominated by a resulting weaker EAC flow or the western branch of large warm core eddies (Godfrey et al. 1980; Ridgway and Dunn 2003). The mean circulation is also more intense over the shelf break (CH100 and SYD140), with the mean southward velocity at the midshelf site being only 0.21 and 0.08 m s$^{-1}$ (CH070 and ORS065, respectively). Though the along-shelf current variability shown with the ellipses is high at all locations it is, relatively, higher off Sydney than off Coffs Harbour when compared with the average velocity vectors. This is again a consequence of the large-scale circulation-inducing intermittent current reversals; for instance, when cold core eddies encroach (Oke and Griffin 2011) off Sydney while upstream (Coffs Harbour), the southward currents are observed more than 80% of the time. Even with the dominant along-shelf circulation, the variance ellipses still show across-shelf variability, which is of significance to the work presented here.

The mooring arrays up- and downstream of the EAC separation were used to generate cross-isobath sections of velocities and temperature (Fig. 2). The temporal averages over the whole 2-yr period show the vertical structure of the dynamics. The mean along-shelf velocity is highest in the surface layer both up- and downstream, with maxima of 0.5 and 0.2 m s$^{-1}$ respectively, decreasing with depth. The water is overall warmer (17.8°–23°C) and more stratified up- than downstream (14.8°–19.9°C) by 2°–3°C. At Coffs Harbour, the influence of the intruding EAC is also evident in the isotherm tilting, with the 22°C contour roughly coinciding with the maximum along-shelf current.

The mean across-shelf circulation is onshore at both Sydney and Coffs Harbour, but weak (less than 0.04 m s$^{-1}$). The only exception is a slightly offshore current in the bottom boundary layer at SYD100, which can be attributed to local topographic effects (see the isobath contours in Fig. 1).
More quantitatively, the cross-shelf heat transport can be computed for each mooring as \( r_0 C_p \int_0^H uT \, dz \). Here, \( u \) is the cross-shelf velocity, \( T \) is the temperature, \( C_p = 3989 \text{ J kg}^{-1} \text{ C}^{-1} \) is the heat capacity, \( r_0 \) is the reference density of the water, and \( H \) is the water depth. The EAC intrusions at CH100 lead to a mean onshore heat transport more than twice as high as the one measured on the same isobath downstream (Table 2). Conversely the midshelf site CH070 is characterized by low heat transport relative to ORS065, but very high variability with the standard deviation being 18 times the mean value.

The correlations between velocity components across the shelf as a function of nominal depth give insight into the intratransect dynamics (Fig. 3). The adjacent mooring pairs are highly correlated (>0.7) for all depths when considering the along-shelf component of velocity, while Sydney’s furthest sites (ORS065–SYD140) show lower correlation coefficients (0.5) because of their spatial separation (Table 1). The corresponding lags are short at the surface, where the flow is maximum (Fig. 2), increasing with depth to a maximum of 7 h between SYD100 and SYD140. The correlation coefficients for across-shelf velocities (Fig. 3b) are lower and more variable, with maximum lags of 10 h. Here, the Coffs Harbour sites are still related but the correlation between the Sydney midshelf mooring ORS065 and the outer sites is reduced. This suggests distinct across-shelf dynamics on the Sydney shelf within a few kilometers of the coast. In contrast to the along-shelf component, the depth profiles of the correlations for cross-shelf velocities tend to show a local maximum close to the bottom, indicating consistent cross-shelf dynamics in the bottom boundary layer for adjacent moorings.

As the local dynamics are dominated by the EAC or eddy encroachments on the shelf, the intrusions are quantified at each mooring site over the 2-yr period (Fig. 4a). As evidenced in Fig. 1, the along-shelf current intrusions are more frequent and of higher magnitude upstream of the separation point. Upstream, the most intense EAC encroachment at the shelf break is characterized by a depth-averaged along-shelf current of \(-1.3 \text{ m s}^{-1}\), while the 25% percentile is \(-0.57 \text{ m s}^{-1}\), relative to \(-1.1 \text{ m s}^{-1}\) and \(-0.28 \text{ m s}^{-1}\) downstream, respectively. Considering the intrusion frequency, southward depth-averaged currents with intensities higher than 0.3 m s\(^{-1}\) are observed 34% and 55% of the time at Coffs Harbour (CH070 and CH100, respectively), while only 9%, 20%, and 22% of the 2-yr period off Sydney (ORS065, SYD100, and SYD140, respectively). For section 5, we define current intrusion into the shelf as \( \bar{v} < -0.3 \text{ m s}^{-1}\), with \( \bar{v} \) being the depth-averaged along-shelf current at the midshelf locations (CH070 and SYD100).

### Wind forcing

The eastern coast of Australia is not characterized by strong persistent winds. From a 5-yr study of observed land and overocean wind data from Sydney, Wood et al. (2012) evidenced three main directions: northward

![Fig. 3. Max correlations and associated time lags between the (a) along- and (b) across-shelf velocity component from intratransect moorings. Velocity profiles are normalized by the mooring depth in a sigma coordinate system (1 is top, 0 is bottom). All correlation coefficients are significant at the 95% confidence level.](image-url)
(downwelling favorable) characterized by the highest intensities, southwestward (upwelling favorable), and eastward winds. They also identified the Kurnell land station as the most relevant site close to Sydney relative to offshore buoy measurements. Wind observations for the two years of interest in this paper confirm these results. The mean measured wind stress is downwelling favorable, with magnitudes of 0.003 N m$^{-2}$ at Coffs Harbour and double that off Sydney (Figs. 1b,c). Defining a weak wind from the low-pass-filtered time series as $|\tau_x| < 0.03$ N m$^{-2}$, the wind is weak 67% and 40% of the time at Coffs Harbour and Sydney, respectively. Significant downwelling conditions ($\tau_w > 0.04$ N m$^{-2}$) happen 11% and 19% of the time at Coffs Harbour and Sydney, respectively (Fig. 4b). Upwelling-favorable winds occur at both sites (negative along-shelf component in Fig. 4b), with higher intensity and occurrence downstream of the separation point. Using a threshold of $|\tau_{bx}| > 0.04$ N m$^{-2}$, upwelling-favorable winds occur 9% and 13% of the time off Coffs Harbour and Sydney, respectively. Their influence on the cross-shelf dynamics relative to other forcing mechanisms is investigated in the following sections.

4. Cross-shelf depth-integrated momentum balance

a. Estimation of terms from observations

The momentum balance is used to estimate the relative importance of the different forcing mechanisms driving the cross-shelf dynamics (Lentz et al. 1999). This analysis also provides insights into the differences between the dynamics up- (Coffs Harbour, 30°S) and downstream of the EAC separation point (Sydney, 34°S).

The depth-averaged cross-shelf momentum equation can be written after Oke et al. (2003):

$$\frac{\partial \overline{\Pi}}{\partial t} - f\overline{u} + \overline{u} \frac{\partial \overline{\Pi}}{\partial x} + \overline{v} \frac{\partial \overline{\Pi}}{\partial y} = -\frac{1}{\rho_0} \frac{\partial \overline{P}}{\partial x} + \tau_{sx} \overline{u} + \tau_{bx} \overline{v},$$

(1)

where $\overline{\Pi}$, $\overline{u}$, and $\overline{v}$ are the depth-averaged velocities, $f$ is the Coriolis parameter; $\tau_{sx}$ and $\tau_{bx}$ are the surface and bottom across-shelf stress, respectively; and $\overline{\partial P/\partial x}$ is the depth-averaged pressure gradient. Because of limitations in the mooring array, the nonlinear advection term is limited to $\overline{u} \overline{\partial u/\partial x}$, since the along-shelf gradient $\overline{\partial u/\partial y}$ could not be estimated. This hypothesis is justified by considering the local dynamics, which do not vary significantly in the along-shelf direction in regions where the topographic variations are limited [see Fig. 1a, Oke and Middleton (2000), and Oke et al. (2003)]. The bottom stress is computed using the linear drag law $\tau_{bx} = \rho_0 \nu_b$, with the resistance coefficient $r = 5 \times 10^{-4}$ m s$^{-1}$ (Lentz 2001) and $v_b$ the measured bottom along-shelf velocity.

Making the hydrostatic assumption, the pressure gradient term can be computed from the surface or bottom pressure measurements (Brown et al. 1985). While the latter is often used when available (Liu and Weisberg 2005; Shearman and Lentz 2003) here the drifts in the observations of bottom pressure and the bias resulting from the frequent mooring redeployments (servicing every 6 weeks on average) led to very noisy values. Thus, the pressure gradient is computed as

$$\overline{\partial P/\partial x} = \frac{1}{H} \int_{-H}^{0} \overline{\partial P/\partial x} dz = \rho_0 g \frac{\partial \overline{\eta}}{\partial x} + g \int_{-H}^{0} \int_{z}^{0} \overline{\partial \rho'/\partial x} dz' dz,$$

(2)
where \( g = 9.81 \text{ m s}^{-2} \) is the gravitational acceleration and \( \rho' \) is the density anomaly. The sea level gradient \( \frac{\partial \eta}{\partial x} \) is computed from daily satellite altimetry observations (see section 6 for discussion), and is referred to as the barotropic pressure gradient, in contrast to the baroclinic term based on the density gradients.

All of the terms in the momentum balance, except for the barotropic pressure gradient, are estimated between adjacent moorings following the method described in Liu and Weisberg (2005). New depth-averaged velocity time series are generated using a weighted sum of both mooring measurements:

\[
(\mathbf{u}, \mathbf{v}) = \left( \frac{\mathbf{u}_1 h_1 + \mathbf{u}_2 h_2}{h_1 + h_2}, \frac{\mathbf{v}_1 h_1 + \mathbf{v}_2 h_2}{h_1 + h_2} \right),
\]

where the subscript numbers correspond to the moorings and \( h \) is the local water depth.

The density time series are computed from the temperature observations assuming a constant salinity of 35, however, a number of quasi-monthly CTD profiles were also used to justify this assumption.

### b. Temporal analysis and standard deviations

The varying importance of the terms in the depth-averaged momentum balance is examined over the two years of the study period. Upstream of the separation point (Coffs Harbour), periods of strong negative Coriolis forcing correspond to the intrusion of the EAC onto the shelf \((f < 0 \text{ in the Southern Hemisphere})\) (Figs. 5a,b). These occur all year round without any clear seasonal signal \([\text{as also observed by Malcolm et al. (2011)}]\). However, during summer, they are associated with high negative baroclinic pressure gradients as the EAC is much warmer than the shelf waters \((\text{March 2010 and January–February 2011 in Fig. 5a})\) (Oke et al. 2003). This contrasts with spring or wintertime \((\text{e.g., June, September, and October 2010, and October and November 2011})\) when the baroclinic pressure gradient is weak. The latter time series computed from the mooring temperature assuming constant salinity is in good agreement with the terms computed from monthly CTD density profiles off Coffs Harbour at the end of 2011 (black versus gray dots, respectively; Fig. 5a).

The dominant Coriolis term seems to be balanced by the sum of both components of the pressure gradient \((\text{Fig. 5b})\) in geostrophic equilibrium, as suggested by Oke et al. (2003), although they did not calculate the pressure term. The secondary terms are shown in Fig. 5c. Both the wind stress and acceleration terms show high temporal variability, while the advection and bottom stress extrema are in phase with the Coriolis term. In other words,
the EAC intrusions are characterized by relatively important cross-shelf advection and bottom stress.

The momentum balance downstream of the separation point shows smaller extrema, both between inner-(Fig. 6) and outer-shelf mooring pairs (Fig. 7). Note that the barotropic terms are similar for both because of the coarse horizontal resolution of the altimetry product used to compute these pressure gradients (see discussion section 6). The baroclinic term computed from constant or vertically resolved salinity are in good agreement (Fig. 6a) despite the different measurement locations, the monthly CTD profiles are sampled at Port Hacking, 20 km south of the Sydney moorings (Roughan and Morris 2011). Here, the negative Coriolis peaks are shorter than upstream of the separation point and correspond to the western branch of warm core eddies encroaching into the shelf (e.g., in January 2010 and 2011, and in May, July, and November 2011 in Figs. 6a and 7a) as confirmed by SST figures (for instance Fig. 1a). The advection terms are still correlated to the Coriolis forcing, but the amplitude of the bottom stress is smaller than upstream, while the wind forcing appears to be one of the main secondary terms (Figs. 6c and 7c).

This is confirmed by the standard deviations of the individual momentum terms listed for each mooring pair (Table 3). Of the stress terms, the bottom stress is more important upstream of the separation point (CH) while the standard deviation of the wind stress term is higher downstream (SYD), especially for the inner-shelf pair where it is the dominant secondary term as the water is shallow. This is expected to have major impact on vertical movements (see section 5). For all locations, the strongest terms are Coriolis and the barotropic pressure gradient, while the standard deviations of the baroclinic terms are lower. The standard deviations of each of the terms except wind stress are the largest at Coffs Harbour, again highlighting the influence of the EAC on the cross-shelf dynamics upstream of the separation point.

Downstream, the main difference between the inner-and outer-shelf pairs is the magnitude of the baroclinic pressure gradient, which is the largest on the shelf break relative to the barotropic term. The large standard deviation of the residual is attributed to missing data and uncertainties in some calculations, especially the barotropic pressure gradient term computed from satellite observations (see section 6). Nevertheless, it is not expected to have a significant impact on the results of this study (see section 4c).

c. Correlation and regression analysis

The dominant geostrophic equilibrium at all locations is evident when comparing the temporal variability and the magnitude of different terms of the momentum balance (Table 4). Indeed, both the highest correlation and regression coefficients are obtained between the Coriolis and the total pressure gradient term. Including all the secondary terms does not improve the budget closure as their magnitude is significantly lower.
When separating the baroclinic from the barotropic components of the pressure gradients, the results differ. As is evident for the data in Table 3, the magnitude of the baroclinic pressure gradient is low relative to the Coriolis term, leading to low regression coefficients for all mooring pairs (0.21–0.33). Nevertheless, these terms are highly correlated (0.63–0.70) indicating that the main buoyancy forcing mechanisms are associated with the synoptic circulation: the EAC upstream and its eddy field downstream. The geostrophic balance is then mostly barotropic, with regression slopes closer to 1, while the weak correlation between the Coriolis terms and the barotropic pressure gradients can be partly attributed to the difference in the observation time step (hourly versus daily because of the lack of observations).

Comparing the different sites, the momentum budget would appear to be approaching closure, more so at the Sydney site than the Coffs Harbour site (correlations of 0.72–0.73 and regressions of 0.96–0.99). The weaker statistics at Coffs Harbour may be because of missing terms or computational uncertainties (see section 6). Between the Sydney inner- and outer-shelf locations, the dynamics

![Fig. 7. As in Fig. 5, but for the Sydney outer-shelf mooring pair (SYD100-SYD140).](image)

<table>
<thead>
<tr>
<th>Term</th>
<th>CH midshelf pair std dev</th>
<th>SYD inner-shelf pair std dev</th>
<th>SYD outer-shelf pair std dev</th>
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<tr>
<td>Coriolis</td>
<td>−f(\bar{v})</td>
<td>16.00</td>
<td>11.12</td>
</tr>
<tr>
<td>Barotropic pressure gradient</td>
<td>(\frac{\partial \bar{\eta}}{\partial x})</td>
<td>13.57</td>
<td>13.13</td>
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<tr>
<td>Baroclinic pressure gradient</td>
<td>(\frac{g}{\rho_0 H} \int_{-h}^{0} \int_{\bar{z}}^{0} \frac{\partial \bar{\rho}}{\partial \bar{x}} dz' dz)</td>
<td>6.07</td>
<td>3.57</td>
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<tr>
<td>Acceleration</td>
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<td>0.08</td>
</tr>
<tr>
<td>Advection</td>
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<td>0.14</td>
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<tr>
<td>Wind stress</td>
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<tr>
<td>Bottom stress</td>
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<td>Residual</td>
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</table>
appear to be more affected by the buoyancy gradients on the shelf break.

5. Investigation of forcing mechanisms

Through the depth-integrated cross-shelf momentum balance, the importance of bottom and surface stress appeared to vary significantly up- and downstream of the EAC separation point. This section investigates the respective influence of these forcing mechanisms on the cross-shelf dynamics with a particular focus on the resulting upwelling processes. We separate them by looking at the circulation when only one of the forcing mechanisms is strong, either the along-shelf wind stress, or the bottom stress resulting from the along-shelf current. Mean cross sections are generated by averaging the circulation during specific wind or along-shelf current conditions. The interaction of both stresses is also considered and the frequency of these features over the two years is discussed.

a. Influence of wind forcing

In the Sydney region, Middleton et al. (1996), Roughan and Middleton (2002), and Wood et al. (2012) identified a significant ocean response for oversea wind stress of around 0.1 N m$^{-2}$, corresponding to 0.04 N m$^{-2}$ locally over land [Kurnell site; Wood et al. (2012)]. The latter threshold is used here for along-shelf wind and is referred to in the following as strong up- or downwelling-favorable wind when the along-shelf component is dominant ($|\tau_{sx}| > |\tau_{sw}|$). To focus on the response of the ocean to wind forcing only, we also consider weak current conditions as periods when the midshelf depth-averaged along-shelf current is greater than $-0.2$ m s$^{-1}$. This threshold is chosen to eliminate large-scale southward current intrusions (EAC or its eddies), while allowing the wind-driven circulation.

These down- and upwelling proxies are significant, corresponding to 13% and 10% of the dataset downstream and 8% and 2% upstream, respectively (Fig. 8). At both sites, the cross-shelf dynamics follow Ekman theory (Ekman 1905) when the along-shelf wind stress is the dominant forcing. In response to a downwelling-favorable wind, the surface layer is pushed onshore and subducted at the coast in a deeper offshore flow (Fig. 8, top panels). At Coffs Harbour, the surface layer is around 30–40 m deep with onshore velocities up to 0.04 m s$^{-1}$ while the rest of the water column is characterized by flow in the opposite direction with maximum velocity close to the bottom up to 0.06 m s$^{-1}$. Off Sydney, the surface onshore flow is similar in depth but faster (up to 0.06 m s$^{-1}$) while the offshore flow is limited to the bottom layer.

The response to a strong upwelling-favorable wind is shown in Fig. 8 (second row). At both sites, the surface flow is thinner than for the downwelling response, characterized by an offshore flow of 0.01–0.02 m s$^{-1}$. The water column below 20-m depth moves onshore to compensate the depression at the coast with velocities up to 0.03 m s$^{-1}$ and the isotherms are uplifted relative to the downwelling scenario.

As expected, the upwelling process is intensified when the wind stress duration is longer. Off Sydney, the cross-shelf response to a minimum of 48-h upwelling-favorable wind stress is shown in Fig. 8 (bottom row, panels on rhs). Relative to the instantaneous ocean response with the same wind intensity (see above), the two-layer circulation is intensified. The near-surface offshore currents are more intense (up to 0.05 m s$^{-1}$) and extend offshore to the SYD140 mooring, 20 km away from the coastline. The water gets colder close to the coast, with an important isotherm uplift between the two midshelf sites (up to 15 m for the 16°C isotherm). Unfortunately, over the two years of observations only three events satisfied the criteria during summertime (one should remember the limiting weak current criteria as well).

To provide quantification, the cross-shelf response to wind stress forcing is investigated for different wind intensities. Here, the same proxy $\theta > -0.2$ m s$^{-1}$ and $|\tau_{sx}| > |\tau_{sw}|$ is considered, but the along-shelf wind stress intensity has been binned into 0.02 N m$^{-2}$ intervals, including both up- ($<0$) and downwelling-favorable ($>0$) wind stress. Different parameters describing the response of the ocean to the forcing are investigated, that is, the cross-shelf velocity and temperature gradient at two

### Table 4. Correlation coefficient $C$ and linear regression slope $R$ in the across-shelf momentum balance for the CH midshelf (CH070–CH100), SYD inner-shelf (ORS065–SYD100), and SYD outer-shelf (SYD100–SYD140) pair against the Coriolis term with zero lag, for times when all terms are available.

<table>
<thead>
<tr>
<th></th>
<th>CH midshelf pair</th>
<th>SYD inner-shelf pair</th>
<th>SYD midshelf pair</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$C$</td>
<td>$R$</td>
<td>$C$</td>
</tr>
<tr>
<td>Barotropic pressure gradient</td>
<td>0.64</td>
<td>0.21</td>
<td>0.70</td>
</tr>
<tr>
<td>Baroclinic pressure gradient</td>
<td>0.52</td>
<td>0.44</td>
<td>0.64</td>
</tr>
<tr>
<td>Baroclinic + barotropic pressure gradient</td>
<td>0.65</td>
<td>0.68</td>
<td>0.72</td>
</tr>
<tr>
<td>Sum of all terms</td>
<td>0.64</td>
<td>0.68</td>
<td>0.72</td>
</tr>
</tbody>
</table>
FIG. 8. Cross-isobath section of along-shelf velocity $v$ (first column on lhs) along the Coffs Harbour CH line and (second column on rhs) Sydney SYD line, cross-shelf velocity $u$ with temperature contours [along the (second column on lhs) Coffs Harbour line and (first column on rhs) Sydney line], temporally averaged for different forcing conditions. Conditions are: (top row) downwelling-favorable wind forcing ($>0.04 \text{ N m}^{-2}$) during weak southward circulation; (second row) upwelling-favorable wind forcing ($>0.04 \text{ N m}^{-2}$) during weak southward circulation; (third row) southward current intrusion ($>0.3 \text{ m s}^{-1}$) during weak wind; (fourth row) simultaneous upwelling-favorable wind forcing and southward current intrusion; and (bottom row, panels on lhs) strong southward current intrusion ($>0.6 \text{ m s}^{-1}$) during weak wind; (bottom row, panels on rhs) 48-h upwelling-favorable wind forcing ($>0.04 \text{ N m}^{-2}$) during weak southward circulation. The number of days for each condition and the corresponding percentage of the complete dataset coverage are also specified.
fixed depths, one close to the surface and one in the bottom layers (Fig. 9a).

Over the two years of measurements, the number of days when this proxy is satisfied is overall lower upstream of the separation point (Coffs Harbour) because first the wind is weaker (Fig. 4b) and second the EAC intrusions tend to dominate the circulation off Coffs Harbour (Fig. 4a). Nonetheless, the major oceanic patterns are similar at both latitudes. The near-surface cross-shelf velocities show linear trends, with offshore currents \((u > 0)\) for upwelling-favorable winds and onshore currents \((u < 0)\) during downwelling-favorable winds. For the shelf break mooring at Sydney (SYD140), a similar slope is obtained, but the values are mostly negative, indicating the offshore extent of the wind-driven circulation. The circulation near the bottom is opposed to the surface circulation in agreement with a classic two-layer dynamic, but with weaker current magnitudes. At the ORS065 mooring (located 2 km away from the coast), the regression line is the closest to the origin for both surface and bottom cross-shelf velocities, showing an almost symmetric response to down-/upwelling processes.

The temperature gradients are predominantly positive, showing a colder water mass close to the coast. The only exception is between the Sydney moorings at the 100- and 140-m isobaths with slightly warmer water at 25-m depth. While an increase in wind stress does not influence the bottom isotherms (no significant trend), upwelling-favorable winds induce a larger near-surface temperature difference especially between the inshore mooring pair (SYD100 – ORS065). The upwelling response although weak (a gradient of 0.1°C km\(^{-1}\) corresponds to a 0.8°C temperature difference between ORS065 and SYD100), is similar to the findings of McClean-Padman and Padman.

**Fig. 9.** (a) Influence of along-shelf wind stress intensity (x axis, discretized in 0.02 N m\(^{-2}\) intervals) with a weak southward current \((\tau > -0.2 \text{ m s}^{-1})\) and (b) influence of along-shelf depth-averaged current intensity (x axis, discretized on 0.1 m s\(^{-1}\) intervals), while weak wind stress \((|\tau| < 0.03 \text{ N m}^{-2})\) for (first two columns on lhs) near-surface and bottom cross-shelf velocity for each mooring, (third and fourth columns from lhs) near-surface and bottom temperature gradient for each mooring pair. (fifth column from lhs) The number of days used to compute each composite value for Coffs Harbour and Sydney moorings are shown, with a lower threshold of 5 days. Each dot is statistically independent. Because of the lack of boundary layer measurements, the near-surface and bottom are defined as 15- and 25-m depth for current and temperature respectively, and 5 m above bottom (from the shallower site when a gradient is considered).
(1991) who identified three major wind-driven upwelling events off Sydney over a 6-yr analysis.

b. Influence of along-shelf current

Typically in this strong WBC regime, the along-shelf current dominates the cross-shelf dynamics through the encroachment of the EAC or the western arm of both cyclonic and anticyclonic eddies. As evidenced in section 4, this large-scale circulation impacts the dynamics of the shelf through Coriolis acceleration, advection, bottom stress, and buoyancy gradients.

A number of previous studies highlighted the EAC as a major driver of current-driven upwelling along the coast, based on sporadic observations (Cresswell 1994; Gibbs et al. 1998; Roughan and Middleton 2002, 2004) or modeling (Oke and Middleton 2001; Roughan et al. 2003). Here we investigate the response of the ocean to the intrusion of a strong southward current ($\bar{v} < -0.3 \text{ m s}^{-1}$ midshelf) using two years of high-resolution observations up- and downstream of the EAC separation point. We also consider weak wind conditions $|\tau_{y}| < 0.03 \text{ N m}^{-2}$, to focus solely on the influence of the large-scale dynamics. These conditions were satisfied 124 and 32 days, representing 21% and 6% of the complete dataset, up- and downstream, respectively, over which time the current and temperature measurements were averaged (Fig. 8, third row).

The cross-shelf response is more complex than a typical two-layer wind-driven system. Off Coffs Harbour, the encroaching EAC is warm (average $T$ of 22–24°C) and has an onshore component on the shelf break (0.04 m s$^{-1}$). In agreement with Ekman theory, the bottom stress drives an onshore current in the bottom boundary layer (BBL) (~10–20-m height above bed) reaching 0.05 m s$^{-1}$ and associated with colder water ($T < 20^\circ$C). This upwelled water seems then to be advected offshore at the surface, inducing a surface frontal convergence zone with the tropical EAC waters. The offshore extension, variability and vertical movements induced by this front could not be investigated with only two moorings, but the impact of a more intense EAC ($\bar{v} < -0.6 \text{ m s}^{-1}$) is considered in Fig. 8 (bottom row). The onshore Ekman current in the BBL is intensified, up to 0.06 m s$^{-1}$, in agreement with the results of the modeling study by Oke and Middleton (2000). At the surface, the frontal zone is more pronounced, and the offshore flow observed midshelf appears to be subducted under the intruding EAC on the shelf break.

Downstream, the Ekman geostrophic response to an intruding southward current ($\bar{v} < -0.3 \text{ m s}^{-1}$) is also apparent in the bottom layer on both the shelf break (SYD140) and the inner site (ORS065). Interestingly, there is no evidence of such an onshore flow at the midshelf mooring SYD100. This is likely explained by the local topography (Fig. 1), as the 100-m isobath shows some irregularities relative to the other isobaths. Nevertheless, the isotherms are strongly uplifted, both in response to the warmer water characterizing the synoptic circulation and to the bottom onshore flow associated with colder slope water.

In a similar way to the wind stress, the influence of the along-shelf current magnitude on the cross-shelf velocity and temperature gradient close to the surface and in the bottom layers is investigated (Fig. 9b). The near-surface cross-shelf velocities are mostly negative and do not show a linear relationship with the along-shelf current intensity, except at the inshore moorings (ORS065 and CH070), where a strong southward current induces offshore (positive) flow close to the coast. This is consistent with an upwelling feature driven by the bottom stress, uplifting water along the coast, which is then driven offshore at the surface by continuity. Indeed, the bottom velocities are strongly related to the along-shelf current intensity: northward currents (>0) induce positive cross-shelf bottom velocities, while the stronger the EAC or its warm core eddies (WCE) are (southward currents, <0), the more intense the onshore bottom Ekman flow is. This feature is observed for all moorings except SYD100 where the local topography is believed to cause the flow to deviate (see discussion above). The near-bottom temperature gradient at a fixed depth in response to the along-shelf circulation is surprisingly coherent for all moorings, up- and downstream of the separation point. The regression slope shows coefficients between 0.27 and 0.33 and zero intercepts ranging from −0.03 to −0.08. This implies that for an along-shelf southward current of 1 m s$^{-1}$ at midshelf, the bottom water on the shelf gets colder by 3°–3.5°C relative to the same depth 10 km farther offshore.

Close to the surface, a northward flow off Sydney induces a negative temperature gradient at the shelf break. This corresponds to the encroachment of cold core eddies leading to warmer water on the shelf (Oke and Griffin 2011). Otherwise, the linear regression with negative slopes at all sites is related to the intrusion of the warm EAC waters inducing a strong thermal gradient across the front (Oke et al. 2003). Nevertheless, the slope is less steep than close to the bottom, indicating a different process occurring in the BBL.

The relationship between the bottom onshore flow and the temperature gradient is emphasized in Fig. 10. Including all the average values obtained for different along-shelf current intensities (indicated by the grayscale) for all the moorings (Fig. 10a), the $R^2$ value indicates that 62% of the near-bottom composite temperature gradient is explained by the BBL Ekman flow in
response to bottom stress. The intrusion of the cold slope water onto the shelf is also evidenced when comparing the bottom temperature for two adjacent moorings (Fig. 10b). The bottom temperature at the midshelf site (CH070) becomes consistent with the temperature at 100 m on the shelf break (CH100) when the onshore Ekman flow reaches 0.06 m s\(^{-1}\). Downstream, the same feature is evident between the ORS065 and SYD100 moorings; however, the intensity of the bottom flow needs to be higher to completely uplift the cold water as the depth difference is more important. In contrast, the \(R^2\) value is higher, suggesting a more two-dimensional process, with a weaker influence of horizontal along-shelf advection through the EAC. Such slope water intrusions have significant biological implications as they are expected to carry nutrient-rich water onto the shelf, enabling primary production.

c. Mixed scenario: Upwelling-favorable wind and current

A number of studies have highlighted the cumulative effect of the simultaneous occurrence of bottom and wind stress as a more efficient mechanism for upwelling (Tranter et al. 1986; Roughan and Middleton 2002, 2004). Gibbs and Middleton (1997) suggested that the current-driven uplift may be a preconditioning for a stronger wind-driven upwelling. To test this theory, we looked at the cross-shelf response to a period with concurrent southward current and upwelling-favorable wind stress (Fig. 8, fourth row). The forcing magnitudes considered are the same as used previously: \(t_{w} < -0.04\) N m\(^{-2}\) and \(v < -0.3\) m s\(^{-1}\) (see above). Relative to an isolated wind forcing alone (Fig. 8, second row), the bottom Ekman flow is more apparent and the isotherms are more uplifted both up- and downstream of the separation point. Relative to a simple along-shelf current forcing (Fig. 8, third row), the surface offshore flow at the coast is intensified, especially at Coffs Harbour where the EAC seems to be pushed offshore by the wind-driven Ekman transport. At the same time, the bottom onshore current is more intense, with up to 0.10 and 0.05 m s\(^{-1}\) at the Coffs Harbour and Sydney shelf breaks, respectively, thus twice as high as for the simple current forcing scenario and even more intense than for a stronger current without wind stress (see above).

6. Uncertainties and limitations

All circulation patterns presented in this study were defined following an along- and cross-shore coordinate system based on the principal axis of the depth-averaged velocity (see section 2). While this is a common practice, it is still necessary to evaluate to what extent the results are dependent on this choice. Figure 10a includes results obtained when the coordinate system is rotated by an additional 2\(^\circ\), either clockwise or counterclockwise.
figure was chosen because it includes all mooring data and is assumed to be the most sensitive to the coordinate system as it presents the regression between the bottom temperature gradient and the cross-shelf velocity, for different along-shelf current intensities. The results appear to be robust, with significant regressions for all coordinate systems and fluctuations of \( R^2 \) values less than 6%.

Errors in the momentum balance can arise through various limitations or uncertainties. One of the primary issues arises from data gaps near the surface. This is a result of instrument limitations (e.g., ADCP) and the physical challenges when deploying shelf moorings in an intense WBC. Furthermore, because of a high volume of vessel traffic along the coast of eastern Australia, for security reasons the moorings do not reach the surface (Table 1). The buoyancy gradient terms presented in this study were thus computed using only the available temperature measurements, leading to a probable underestimation of the pressure gradient term. The use of satellite SST time series for the surface extrapolation of the mooring observations was also tested to compute the baroclinic term. The standard deviation of the cross-shore gradients did not change significantly, but the correlations with other terms happened to be reduced by the use of the daily and cloudy SST dataset. The accuracy of the barotropic term is a major issue, considering that it was estimated using altimetry observations, with a low spatial (0.25°) and temporal resolution. The daily sea surface height (SSH) products were provided by IMOS (Oke and Sakov 2012), constructed from both coastal tide gauge observations and altimetry. As the tracks are repeated only every 10 days, short time-scale dynamics are not expected to be resolved. An estimation of the characteristic time scales can be obtained by determining the maximum lag for which the autocorrelation of the time series is higher than a threshold (for instance 0.7, corresponding to 50% of the explained variability). At the mooring locations, the characteristic time scale for the satellite SSH is more than twice as high as that obtained from in situ depth-averaged velocities (5 days compared to 1–2 days, respectively). Other uncertainties could derive from the parameterization of bottom stress as shown in Lentz (2008). The consequence of the missing nonlinear terms in the balance is uncertain (Lentz and Chapman 2004), but in a short-term study the cross-shelf advective term appeared to be low (Oke and Middleton 2000) and both wave and tidal forcing is expected to be negligible in the region. All of these limitations lead to large residuals (Table 3); however, their magnitude remains smaller than other terms and the correlation/regression analysis (Table 4) led to high coefficients such that we have confidence in the main conclusions.

The wind stress is underestimated using inland relative to offshore measurements and might be sheltered by the local orography. The difference in magnitude for the Sydney station has been taken into account following Wood et al. (2012), but no information is available for Coffs Harbour station. However, Roughan and Middleton (2002) and Gibbs et al. (1998) suggest that the wind stress intensity required for upwelling generation may be lower than the theoretical value when the water is already preconditioned by the current, which appears to be a common feature upstream (see discussion).

7. Discussion and conclusions

The eastern Australian continental shelf circulation is dominated by along-shelf currents from the WBC (EAC) flowing poleward and the western arm of warm or cold core eddies. Nevertheless, the variability of the cross-shelf circulation is shown to be important on small length scales (less than 25 km from the coast). This study presents the first long-term observational analysis of the cross-shelf dynamics along the east coast of Australia, both up- and downstream of the EAC separation point.

The mean cross-shelf circulation is weakly onshore at both sites, with warmer water close to the shelf break, consistent with the encroachment of the warm EAC or a WCE.

The forcing mechanisms for a cross-shelf exchange were identified through an investigation of the momentum balance. The main dynamical balance is geostrophic both up- (Coffs Harbour, 30°S) and downstream (Sydney, 34°S) of the EAC separation, with a dominant barotropic pressure gradient relative to the baroclinic one, especially at the most inshore moorings. The influence of the EAC encroachment off Coffs Harbour is also apparent in the secondary terms, through advection, local acceleration, and bottom stress as modeled by Roughan et al. (2003). Off Sydney the main secondary driver appears to be the wind stress.

The major implication of cross-shelf flows is the uplift of cold and generally nutrient-rich water, which can be wind- or current-driven (through bottom friction). The separate response of the cross-shelf velocity and temperature structure to these forcing mechanisms is shown to be similar up- and downstream of the EAC separation. During weak large-scale circulation, along-shelf wind stress drives a classic two-layer circulation, with the cross-shelf current intensity being linearly dependent on the wind stress magnitude. As expected, the temperature structure depends on both the intensity and the duration of the wind stress.

The encroachment of a southward current onto the shelf substantially influences the cross-shelf circulation.
The cross-sectional structure shows an onshore bottom flow in agreement with Ekman theory that uplifts cold water along the slope. The surface onshore intrusion of the EAC appears to be limited by the offshore flow of upwelled waters before the latter is subducted under the EAC as shown on the schematic in Fig. 11a, adapted from Roughan and Middleton (2004).

Through a modeling study, Oke and Middleton (2000) showed that the magnitude of the southward transport of the EAC influenced the amount of cold water upwelled to the surface. Here, we show from observations that the intensity of the onshore bottom flow is actually proportional to the southward current’s magnitude and similar up- and downstream of the separation point. The only mooring where this relationship is not evident is SYD100, which appears to be influenced by the complex local topography. The southward current’s intensity also acts on the bottom cross-shelf temperature gradient. The relationship is linear with a very similar slope for all locations. It is shown that this bottom temperature gradient is driven by the onshore bottom flow bringing cold slope water into the shelf. This average relationship has been quantified from the 2-yr observations. On the eastern coast of Australia, this implies that around Smoky Cape (31°S), where the shelf is the narrowest (16 km) and the EAC reaches speeds of 2 m s⁻¹ (Roughan and Middleton 2002), the midshelf bottom temperature would be 5.5°–7°C colder than 10 km offshore at the same depth.

The occurrence frequency of these bottom slope water intrusions can also be estimated. Considering an observed depth-averaged current of 0.3 m s⁻¹ at midshelf inducing a strong enough bottom stress (Fig. 9), the process would occur roughly 34% and 20% of the time (Fig. 4a), based on the two years of observations up- and downstream of the EAC separation point, respectively. The resulting onshore BBL flow brings slope water, colder by at least 1°–1.5°C onto the midshelf as compared to the same depth 10 km offshore. This result is comparable to the Gulf Stream region where Castelao (2011) estimated the occurrence of bottom intrusions at midshelf up to 35% of the time in summer. The outcropping of these water masses was then shown to be much reduced and related to upwelling-favorable winds. In this study, we also evidenced a significant intensification of the bottom cross-shelf velocity and the isotherm uplift when an upwelling-favorable wind blows simultaneously. In this case, the upwelled water is transported offshore in a wind-driven Ekman surface flow as shown on the schematic in Fig. 11b.

Un fortunately, the limited temperature observations at the surface and on the inner shelf did not allow us to quantify the occurrence of this outcropping process. Furthermore, while the dynamics of current-driven upwelling in the BBL are shown to be very similar up- and downstream of the separation point, the upwelled cold water can be more or less advected along the coast when uplifted, depending on the shelf width and current strength (Oke and Middleton 2001).

Quantifying the occurrence of current- versus wind-driven upwelling is problematic, as the two processes can interact and have different impacts on the water column. Nevertheless, the dominant process upstream of the EAC separation point appears to be current related while downstream both processes are expected to be important, in agreement with the results of McClean-Padman and Padman (1991) and Roughan and Middleton (2002).
To evaluate the impact of these processes, the most relevant proxy would be related to the resultant biological productivity. The strong uplifts are expected to have significant impacts on the biology as these water masses are very rich in nutrients. Roughan and Middleton (2002) suggested a higher nutrient response for current encroachment than wind-driven upwelling from two short-term hydrographic surveys. This result may vary depending on the location and the time frame considered. Nevertheless, the importance of current-driven upwelling along the eastern coast of Australia for the supply of nutrients to the euphotic zone, and hence for primary production, is undeniable.

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