Observed bottom boundary layer transport and uplift on the continental shelf adjacent to a western boundary current

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Abstract Western boundary currents strongly influence the dynamics on the adjacent continental shelf and in particular the cross-shelf transport and uplift through the bottom boundary layer. Four years of moored in situ observations on the narrow southeastern Australian shelf (in water depths of between 65 and 140 m) were used to investigate bottom cross-shelf transport, both upstream (30°S) and downstream (34°S) of the separation zone of the East Australian Current (EAC). Bottom transport was estimated and assessed against Ekman theory, showing consistent results for a number of different formulations of the boundary layer thickness. Net bottom cross-shelf transport was onshore at all locations. Ekman theory indicates that up to 64% of the transport variability is driven by the along-shelf bottom stress. Onshore transport in the bottom boundary layer was more intense and frequent upstream than downstream, occurring 64% of the time at 30°S. Wind-driven surface Ekman transport estimates did not balance the bottom cross-shelf flow. At both locations, strong variability was found in bottom water transport at periods of approximately 90–100 days. This corresponds with periodicity in EAC fluctuations and eddy shedding as evidenced from altimeter observations, highlighting the EAC as a driver of variability in the continental shelf waters. Ocean glider and HF radar observations were used to identify the bio-physical response to an EAC encroachment event, resulting in a strong onshore bottom flow, the uplift of cold slope water, and elevated coastal chlorophyll concentrations.

1. Introduction

Coastal upwelling is the major driver of biological productivity in continental shelf regions. Nutrients are supplied from depth to the euphotic zone, allowing photosynthesis and the development of phytoplankton blooms, eventually affecting the whole oceanic food chain. This vertical circulation is a consequence of divergence, in turn associated with cross-shelf transport when adjacent to the coastline.

It is well documented that wind stress and wind stress curl drive upwelling. When an along-shelf wind induces offshore surface transport, it leads to a divergence close to the coast that triggers the upwelling of cold nutrient-rich water originating from greater depths. The theoretical Ekman cross-shelf transport [Ekman, 1905] is now widely used as a proxy for upwelling [Bakun, 1973; Alvarez et al., 2008], while the difference between the theoretical and the observed cross-shelf transport gives some insights into the spatial variability of the upwelling and the coastal divergence of Ekman transport [Kirincich et al., 2005; Dever et al., 2006].

On the continental shelf adjacent to western boundary currents (WBCs), the isotherms are generally uplifted (preconditioned for upwelling) [Gibbs et al., 1998]. In addition, the strong along-shelf bottom stress resulting from the interaction of the WBC with the continental slope strongly influences the bottom boundary layer dynamics. These processes have been shown to occur on the continental shelf adjacent to the East Australian Current (EAC) [Oke and Middleton, 2000; Roughan and Middleton, 2004].

The EAC is the WBC of the South Pacific gyre, which is characterized by intense poleward velocities carrying warm tropical water along the eastern coast of Australia (Figure 1). Typically, a branch of the EAC detaches from the coast heading in an eastward direction between the two instrumented sites at 30°S and 34°S [Godfrey et al., 1980], hereafter, respectively, referred to as upstream and downstream of the EAC separation zone (Figure 1). Downstream, the large-scale dynamics are driven by the mesoscale eddy field shed by the EAC, with a predominance of anticyclonic Warm Core Eddies [Ridgway and Dunn, 2003; Suthers et al., 2011; Everett et al., 2012].
The narrow shelf width allows the EAC to influence shallow depths on the continental shelf and induce cross-shelf flows [Schaeffer et al., 2013]. In contrast to the coastal response to wind-driven upwelling, which often results in a cold surface signature, the tilted isotherms driven by the strong poleward current do not necessarily reach the surface. Thus, Roughan and Middleton [2002] suggested the use of the term “current-driven uplift” rather than “current-driven upwelling.” The consequences of current-driven uplift on the continental shelf of southeastern Australia are significant in terms of nutrient supply and biological productivity [Oke and Middleton, 2001; Roughan and Middleton, 2002; Roughan et al., 2003; Armbrecht et al., 2014]. As this region is generally oligotrophic, it is important to understand and quantify the frequency and magnitude of the sporadic upwelling and uplift events, as well as the mechanisms driving them. Rossi et al. [2014] generated an upwelling climatology along the coast of southeastern Australia using remotely sensed observations of sea surface wind and altimetry. The results showed both seasonal variability and a latitudinal gradient in wind-driven upwelling, with a maximum of 10 upwelling-favorable days per month in the Austral Spring/Summer (September-March). They showed a twofold decrease in the frequency of current-driven uplift between upstream and downstream of the EAC separation zone. However, their results only apply to

Figure 1. (a) SST (3 day composite) and geostrophic currents (reference vector in top left on the figure) on 11 December 2010. The mooring and wind station locations are indicated by black and gray symbols, respectively. The coastline and 20, 100, 200, 500, 1000, and 2000 m isobaths are shown. (b and c) Detailed maps of the mooring locations off Coffs Harbour and Sydney. The 4 year mean velocity vectors of depth average (red) and bottom 15 m average (green) are shown at each mooring location. Mooring names are indicated and the local isobaths are shown in black, as well as the coastline and 200 m isobath (thick lines). Orange squares (blue circles) show the grid points where the altimetry (ASCAT) data are extracted, (used in Figure 10). The blue lines indicate the orientation adopted for the along-shelf direction. The location of HF radar stations (black dots) is indicated in Figure 1b.
large-scale upwelling, as they considered events longer than 2 days on a 0.25° latitudinal grid. Schaeffer et al. [2013] focused on the specific response to individual upwelling-favorable forcings (current or wind or both), by identifying patterns of cross-shelf velocity and temperature gradients from moored observations. They revealed a similar response to current-driven uplift upstream and downstream with predictable mean behavior when EAC encroachment is the major driver and wind stress is weak. Their study used event ensembles to investigate the mean structure under different forcing mechanisms, but did not consider the temporal variability. Here we address the issue of temporal variability; specifically, what is the magnitude, frequency, and temporal evolution of current-driven bottom water uplift? What drives this variability? To what extent does current-driven bottom onshore flow trigger biological productivity?

In the present paper, we focus on cross-shelf transport in the bottom boundary layer (BBL) in an effort to characterize the frequency and variability of current-driven uplift. We use 4 years of moored observations at two different locations from along the coast of southeastern Australia described in section 2. Estimation of the BBL thickness is presented in section 3. In section 4, we compute the actual cross-shelf transport in the BBL from oceanic observations and compare this to theoretical estimates derived from Ekman theory. The relative magnitude and spectral frequency of the cross-shelf transport both upstream and downstream of EAC separation is also examined. We then discuss the influence of both the wind and the EAC as drivers of variability and investigate the relationship with temperature (section 5), focusing on onshore BBL transport. Finally, we use new hydrographic observations from autonomous ocean gliders and surface current velocities derived from HF radar to show an example of current-driven uplift and its biological response upstream of the EAC separation point (section 6).

2. Data Sets

In this study, we use 4 years of in situ observations from two cross-shelf mooring arrays (Figure 1); upstream: off Coffs Harbour (30°S, two moorings: CH070 and CH100) and downstream: off Sydney (34°S, three moorings: ORS065, SYD100, and SYD140). The moorings (at depths between 65 and 140 m) provide measurements of water temperature and current velocities through the water column as part of the Australian ocean observing program IMOS (Integrated Marine Observing System, http://www.imos.org.au/). Thermistors span the water column from 1–2 m above seafloor to 11–24 m below the surface (Figures 2b, 2c, and 3b–3d) at 8 m intervals (4 m at ORS065). Bottom-mounted ADCPs provide quality controlled current velocity measurements 6–9 m above the seabed, upward to 10–23 m from the surface in 4 m bins (8 m at SYD140). While the mooring design accounts for the bottom boundary layer, unfortunately, the surface boundary layer cannot be resolved because the moorings have no surface expression.

Here we focus on the subinertial and subtidal variability, hence the PL-64 low-pass filter (half amplitude 33 h, half power 38 h) [Rosenfeld, 1983] has been applied to hourly averaged time series (as per Schaeffer et al. [2013]). Missing velocity data at the vertical extremities are obtained by extrapolation of the shallowest (deepest) measurement available for the surface (bottom). A total of 4 years of concomitant observations are used, from 1 January 2010 to 31 December 2013. The complete description of the moorings and their temporal coverage are detailed in Roughan et al. [2013] and Schaeffer et al. [2013, 2014] (in particular Table 1). We consider a cross-shelf and along-shelf coordinate system (x,y) based on the local isobath orientation as shown on Figure 1, respectively, 22 and 24° upstream and 20 to 32° downstream, which agrees well with the depth-averaged major axis orientation. Positive values show offshore and northeastward flows, respectively. The benefit of this method is to partially compensate for the topographically induced deviation of the bottom flow at SYD100, as seen in Figure 1 and discussed in Schaeffer et al. [2013].

To complement these in situ observations, wind measurements at proximal land-based stations are obtained from the Bureau of Meteorology [Wood et al., 2012] (location shown in Figure 1) and assessed against daily Advanced Scatterometer (ASCAT) ocean surface winds [Bentamy and Fillon, 2012]. Wind time series were extracted from the ASCAT gridded product (25 km resolution) at the location closest to the shelf break moorings (locations shown in Figure 1). Along-shelf wind stress was derived from the wind speed following the formulation \( \tau_y = \rho_c C_d v_w U_w \), where \((u_w, v_w)\) is the wind velocity, \( \rho_c = 1.3 \text{ kg m}^{-3} \), \( U_w = \sqrt{u_w^2 + v_w^2} \), and the drag coefficient \( C_d \) is characterized by: \( C_d = 1.1 \times 10^{-3} \) for \( U_w < 6 \text{ m s}^{-1} \) and \( 10^{-3} C_d = 0.61 + 0.063 U_w \) for \( U_w > 6 \text{ m s}^{-1} \) [Smith, 1981]. Correlations for along-shelf wind stress between these two wind products are high, >0.75 at both Coffs Harbour and Sydney locations. Compared to the in situ unfiltered daily
averaged measurements, the magnitude of the ASCAT-derived wind stress is much higher than the observed wind stress with regression slopes of 2.3 and 1.6 at the two sites, respectively. Root Mean Square Errors (RMSe) are 0.08 and 0.07 N m$^{-2}$. Interestingly, the Coffs Harbour land-based wind observation site appears to be sheltered in the cross-shelf direction, as the cross-shelf wind stress component is weakly correlated to ASCAT observations (0.35 compared to 0.75 at Sydney).

AVHRR satellite Sea Surface Temperature (SST) maps are also used (daily, resolution of 4 km), as well as sea surface height anomalies and geostrophic velocities derived from altimeter data (gridded at daily and 25 km resolution). The latter product is generated by combining satellite sea surface height weighted from the last 10 days and coastal tide gauge elevations around Australia [Deng et al., 2010].

As of May 2014, 13 cross-shelf glider missions have been undertaken along the continental shelf, inshore of the EAC from approximately 29°5′–32°S, as part of the NSW-IMOS glider program. These observations were...
undertaken with a shallow Slocum ocean glider equipped with a SeaBird CTD, an Oxygen optode and WET Labs ECO-Puck optical sensors measuring fluorescence, colored dissolved organic matter, and backscatter at different wavelengths. We use data from a 21 day deployment in July 2012.

In addition, a snapshot of ocean surface currents measured from two land-based WERA HF radars are presented. The HF Radar systems at the two sites—Red Rock (30°S, Figure 1b) and North Nambucca (30.6°S, Figure 3. (a) Hourly wind stress from Kurnell meteorological station. For clarity, low-pass filtered (over 10 days) along-shelf wind stress is also shown (red thick line). (b–d) Temperature evolution in time and depth from subsurface moorings ORS065, SYD100, and SYD140. Satellite-derived temperature is shown at the surface, hence the gap from 2 to 15 m depth. The BBL from Pollard (PRT, black thick line) and based on a temperature threshold of 0.2 °C (BML02, dotted line) are shown. Boundary layer depths are low-pass filtered for clarity. (e) Time series of depth-averaged along-shelf velocity at ORS065, SYD100, and SYD140. The location of the wind station and moorings are shown in Figure 1.
of freedom and independence time scales are computed following Davis [1976] to account for the temporal coherence in the series.

3. The Boundary Layers

From both a biological and physical perspective, cross-shelf transport is most important in the surface and bottom layers. The surface layer is generally confined to the euphotic zone, providing light for primary production, while bottom slope water is generally nutrient rich. The largest standard deviations of the temperature profiles are confined to the upper and lower water column extremities. It is expected that this high temporal variability in temperature (hours to days) at the top and bottom of the water column will primarily be explained by Ekman dynamics in response to wind or bottom stress. In order to verify this hypothesis and investigate cross-shelf transport, we first need to evaluate the thickness of the boundary layers.

3.1. Estimating BBL Thickness

The data from the mooring arrays are used to describe the near-bottom dynamics, with the lowest temperature and velocity observations 1–2 and 6–9 m above the seabed, respectively. Using these in situ observations, we compare several formulations of the BBL thickness described in the literature.

It is commonplace to estimate the thickness of the boundary layer based on vertical mixing, using the depth where the density or temperature differs from the surface or bottom measurement by a threshold value [e.g., Lentz, 1992; Dever et al., 2006]. While we do not have a bottom time series of salinity, in this region, temperature is a reasonable proxy for density. To illustrate this, we compare actual density versus temperature-derived density, i.e., computed using constant salinity (S = 35.4 based on the average of all available salinity measurements) for a number of different data sets (not shown). Density was calculated from climatological data of temperature and salinity at the mooring locations from the CSIRO Atlas of Regional Seas (CARS) [Ridgway et al., 2002] for the top 100 m of the water column. This was compared to density computed from temperature using constant salinity and showed high correlations (0.99), with linear slope 0.98–0.99, RMSe of 0.07–0.10 kg m\(^{-3}\), with K a proportionality constant [K = 1.7 in Perlin et al. [2007]], \(\bar{u}^*\) the friction velocity estimated by \(\sqrt{\tau_{by}/\rho_0}\), \(\tau_{by}\) is the along-shelf bottom stress, \(\rho_0\) the reference water density, and f the Coriolis parameter. The buoyancy frequency \(N^2 = -\frac{g}{\rho_0} \frac{\partial \rho}{\partial z}\) is computed from two mid-water temperature (T) measurements assuming salinity = 35.4 as discussed above. Based on

| Table 1. The 4 Year Mean (± Standard Deviation) Thickness (m) of the BBL for Each Mooring* |
|-----------------|-------------|-------------|-----------|-----------|
| Mooring         | CH070       | CH100       | ORS065    | SYD100    | SYD140    |
| BML02           | 11 (±6)     | 10 (±6)     | 10 (±6)   | 12 (±6)   | 14 (±10)  |
| BML04           | 12 (±7)     | 12 (±9)     | 13 (±6)   | 18 (±9)   | 18 (±11)  |
| PRT             | 15 (±8)     | 16 (±9)     | 10 (±7)   | 10 (±7)   | 15 (±8)   |
|                 | 18/14/12/17 | 21/15/13/19 | 13/8/7/13 | 14/8/9/12 | 17/13/14/16 |

*Three different estimates are compared: BML02 and BML04 are the bottom mixed layers estimated using a 0.2°C and 0.4°C threshold and PRT is the Pollard et al. [1972] scale depth for the BBL. Shown below are the seasonal (Southern Hemisphere) means specified as Winter(JAS)/Spring(OND)/Summer(JFM)/Autumn(AMJ).
hydrographic observations, the reference density is taken to be $\rho_0 = 1025$ kg m$^{-3}$, $g$ is the gravitational acceleration, and $f = -7.33 \times 10^{-5}$ s$^{-1}$ or $f = -8.13 \times 10^{-5}$ s$^{-1}$ at Coffs Harbour and Sydney latitudes, respectively.

The along-shelf bottom stress $\tau_{by}$ is estimated with the linear drag law as $\tau_{by} = \rho_b v_b$, with $r$ being the resistance coefficient ($r = 5 \times 10^{-6}$ m s$^{-1}$) and $v_b$ the bottom-most along-shelf velocity measurement, located 6–8 m above the seabed. This formulation is widely used in the literature [Lentz, 2001; Oke et al., 2003; and Liu and Weisberg [2005] inter alia] when finely resolved velocity and turbulence profiles [Perlin et al., 2005, 2007] are not available. In order to evaluate the uncertainties derived from the linear law bottom stress formulation, we compare the results to bottom stress estimates based on the drag coefficient ($C_d$):

$$\tau_{by} = \rho_0 C_d v_b \sqrt{u_b^2 + v_b^2},$$

where $(u_b, v_b)$ is the deepest current velocity. We tested $C_d = 1 \times 10^{-3}$, similar to the value Perlin et al. [2005] determined from coincident velocity and turbulence measurements at 20 m height off Oregon.

### 3.2. Overview

The temporal evolution of temperature through the water column is shown for each mooring in Figures 2 and 3. Upstream of the EAC separation zone, temperature ranges from 13 to 27.2°C mid-shelf (CH070) and 11.9 to 27.5°C at the shelf break (CH100). Most of the variability is due to the seasonal cycle, wind forcing and the intermittent intrusions of the EAC bringing warm tropical waters onto the shelf and driving slope water intrusions [Malcolm et al., 2011; Schaeffer et al., 2013]. Episodes of current encroachment appear as intense southward depth-averaged velocities, as shown in Figure 2d. The EAC proper is usually stronger in summer [Ridgway, 1997], but the shelf intrusions appear intermittently all year long with no apparent seasonality. The warmest water at both sites is related to summertime EAC intrusions with southward (poleward) depth-integrated flow reaching 1.1 m s$^{-1}$ near the shelf break (March 2010, February 2011). Daily satellite-derived SST is also shown in Figure 2 and is similar to the uppermost thermistor measurements with correlation coefficients of 0.88 and 0.91 at CH070 and CH100, respectively. Wind forcing is predominantly downwelling-favorable (along-shelf component $>0$ in Figure 2a) in agreement with long-term satellite wind observations [Rossi et al., 2014], but also drives intermittent upwelling events, uplifting cold water (e.g., January 2010, November 2012).

Downstream of the separation zone, surface maxima from the moorings are colder, while bottom minima are similar when compared to similar depths upstream, with temperature ranging 13.3–25.5°C, 11.8–26°C, and 10.7–25.9°C from the inshore mooring to the shelf break, respectively. Off Sydney the agreement between remote-sensed SST and the uppermost thermistor is slightly lower than upstream with correlations ranging 0.78–0.85. The along-shelf depth-averaged current is weaker off Sydney than off Coffs Harbour, with more variability in direction (oscillation of southward and northward flows) in response to the encroachment of warm core and cold core eddies [Schaeffer et al., 2013; Wood et al., 2013]. The wind stress is also predominantly along-shelf, oriented northward (downwelling favorable).

### 3.3. BBL Variability

The time series of the BBL depth based on the 0.2°C threshold (BML02) and the PRT scale are shown in Figures 2 and 3. The upward limit of the BBL is set to half of the mooring depth in order to separate the BBL from the interior flow. Periods when the BBL is thicker, in response to an intense downwelling or mixing event, are disregarded. These periods correspond to a maximum of 12% and 11% of the time at CH070 and ORS065, respectively, when computed with BML04. At the shelf break, the BBL reaches half the water column less than 3% of the time, thus indicating a three-layer structure with an interior flow between the surface and bottom boundary layers. This is consistent with the dominant cross-shelf geostrophic balance evidenced by Schaeffer et al. [2013].

The overall and seasonal means of the BBL depths are detailed in Table 1. Downstream, the thickness of the 4 year BML means and standard deviations increase offshore, with maxima of 14 and 18 m at SYD140 with BML02 and BML04, respectively, compared to 10 and 13 m at ORS065. Conversely upstream, the BML is thinner offshore (10 and 12 m at CH100 with BML02 and BML04) compared to closer to the coast (11 and 14 m at CH070 with BML02 and BML04), while the standard deviations increase offshore. This could be attributed to the larger influence of the warm EAC upstream at CH100, reducing the BML thickness at the shelf break because of the increased stratification [Smith, 1981]. The PRT BBL based on both the bottom stress and the density is thicker upstream (thickness 15–16 m, standard deviation 8–9 m) than downstream.
(thickness 10–15 m, standard deviation 7–8 m). It is largest in winter and autumn due to the weaker stratification. Similar orders of magnitudes were found by Dever [1997] and Perlin et al. [2007] over the northern California and the Oregon shelves, respectively, from mooring observations in water depths of 80–97 m.

4. Cross-Shelf Transport

4.1. Transport Estimates

The observed cross-shelf transport in the BBL, \( U_b \), is computed by integrating the cross-shelf velocities over the BBL thickness, using each method as defined in section 3. As the cross-shelf depth-integrated dynamics are predominantly geostrophic [Schaeffer et al., 2013], the interior cross-shelf flow \( u_i \) is first subtracted following Dever et al. [2006] such that: \( U_b = \int_{-H/2}^{H/2} (u(z) - u_i)dz \), where \( H \) is the water depth, \( \delta \) is the BBL thickness, and \( u_i \) is the vertical average of \( u(z) \) between \( H/2 \) and 20 m, chosen to avoid overlap with the surface and bottom layers, as the maximum BBL extent is set to \( H/2 \) and the surface Ekman layer is assumed to be within the top 20 m. The observed values are then assessed against theory. According to Ekman [1905], the cross-shelf transport in the near-bottom layer (\( U_{bE} \)) is driven by the along-shelf bottom stress \( \tau_{by} \), such that \( U_{bE} = -\tau_{by} / \rho f \).

4.2. Observed Transport and Ekman Theory

We evaluate the observed cross-shelf transport in the BBL (\( U_b \)) against Ekman theory (\( U_{bE} \)) and find the best estimate of the BBL thickness. Figure 4 summarizes the correlation and regression coefficients for observed transports integrated over the different formulations of the BBL presented in section 3: BML02, BML04 and PRT scale. In addition to these three methods, we also assess a constant 15 m layer. The different estimates are referred to as \( U_{bBML02}, U_{BML04}, U_{bPRT}, \) and \( U_{b15m} \).

The effective numbers of degrees of freedom of these time series are less than the total number of data points (35,063 for 4 years of hourly data) as the observations are not independent. Based on the covariance function [Davis, 1976; Emery and Thomson, 2001], the integral time scales of the observational series ranges 39–204 h, being minimum at CH070 and maximum at SYD140. The effective degrees of freedom are between 170 and 533. For \( U_{bE} \), the numbers of degrees of freedom are closer from one site to another.
ranging 247–362. This is important as correlation coefficient greater than 0.18 are significant at the 99% significance level for 200 or more effective degrees of freedom [Emery and Thomson, 2001].

Each of the BBL definitions provide fairly consistent results when compared to Ekman theory in terms of correlation and linear regression coefficients (Figures 4a and 4b, respectively), highlighting the robustness of the cross-shelf transport estimations.

Using the PRT scale, correlation coefficients between $U_{bPRT}$ and $U_{bE}$ are significant and greater than 0.68 at each location. The highest correlations over all formulations are obtained for the inshore moorings, with 0.72–0.76 at CH070 (depending on the BBL formulation) and 0.78–0.84 at ORS065. Even cross-shelf velocities integrated over a constant BBL ($U_{b15m}$) give similar temporal variability when compared to Ekman theory, as shown by the high correlations coefficients between $U_{b15m}$ and $U_{bE}$ (>0.67, except at SYD100). This confirms that the relationship between the observed and theoretical Ekman transport is not a spurious consequence of the BBL definition. The correlation at SYD100 may be lower here compared to the other sites due to the effect of a bathymetric anomaly, as already pointed out in Schaeffer et al. [2013]. The local 100 m isobath shown in Figure 1 highlights an irregularity in the bottom topography, causing the mean bottom flow to deviate slightly.

In terms of magnitude, linear regression slopes for $U_{bPRT}$ compared to $U_{bE}$ are less than 1 at all locations showing an underestimation of the observed transport compared to Ekman theory. The best results are obtained downstream compared to upstream and for $U_{bPRT}$ and $U_{bBML04}$ compared to other formulations. It should be noted that uncertainties in the magnitude of $U_{bE}$ could be derived from the bottom stress estimate and thus affect these values. Overall, PRT provides a reasonable estimate of the height of the bottom mixed layer and gives the best results when comparing the bottom observed transport to Ekman theory.

### 4.3. Mean, Variability, and Frequency

For both the theory ($U_{bE}$) and the observations ($U_{bBML02}$, $U_{bBML04}$, $U_{bPRT}$, and $U_{b15m}$), the mean bottom cross-shelf transport is directed onshore ($<0$) at all sites (Figure 5), as expected for a dominant southward flow. It is greater at the shelf break than at mid-shelf except at SYD100 where it is very weak. The 4 year standard deviations from the observations are in reasonable agreement with the expected values from Ekman theory.

Based on PRT scale, the observed 4 year average transport is $-0.30$ and $-0.37$ m$^2$ s$^{-1}$ upstream (directed onshore), at CH070 and CH100, respectively. However, they are highly variable as the standard deviations are around 3 times the mean value. This is weaker than $U_{bE}$ predicting a mean transport of $-0.58$ (CH070) and $-0.81$ m$^2$ s$^{-1}$ (CH100). Downstream, the observed net transport $U_{bPRT}$ is weaker than upstream with mean values ranging $-0.03$ to $-0.17$ m$^2$ s$^{-1}$ and $U_{bE}$ predicting $-0.10$ to $-0.30$ m$^2$ s$^{-1}$.

Figures 6a and 7a show the temporal variability of the BBL transport $U_{bPRT}$ at each site, as well as from Ekman theory ($U_{bE}$) on the shelf break. The observed transport is correlated between adjacent moorings upstream, with a coefficient of 0.68 with zero lag. Downstream, the correlations are weaker (0.42–0.63), probably due to the more complex topography. In terms of temporal variability, the time series do not show BBL transport to be favored at any particular frequency based on Figures 6a and 7a. Time series of $U_{bE}$ at the shelf break using bottom stress estimates derived from the drag coefficient ($C_d$) as opposed to the linear law formulation, are also shown in Figures 6a and 7a. While the obtained transport extrema are sometimes greater, indicating
uncertainties in the magnitude estimates, both the temporal variability (correlation coefficients of 0.89–0.93) and the sign of the transport do not appear to be affected by the bottom stress definition.

A wavelet analysis [Torrence and Compo, 1998; Liu et al., 2007] of the bottom cross-shelf transport was conducted for each time series to investigate the temporal variability in more detail. The local and global wavelet spectra of $U_{bPRT}$ for CH100 is shown in Figure 8. Significant power is spread across a range of frequencies, from seasonal to the weather band. It should be noted that this analysis has been conducted on the filtered time series, hence removing the suprainertial variability (see section 2). The power is highest in July and October 2012 at a period of around 10 days (Figure 8a). There is a consistent band of energy at a...
period of ∼90 days through the time series, despite the gaps due to missing data. The global wavelet spectrum in Figure 8b represents the 4 year averaged power outside of the cone of influence. The highest energy appears at 9 days, with significant power spread across periods between 1 day and 1 month. The secondary, much sharper peak occurs around 90 days.

Similar bands of energy are evident at the other mooring sites and in each of the various formulations of the BBL transport (Figure 9), with largest peaks consistently at around 9–10 and 90 days. Upstream of the separation point (CH), the sharpest peak corresponds with fluctuations around 90 days at both sites, with higher energy at the shelf break site (CH100) than mid-shelf (CH070). Downstream, periods of ∼100 days are highlighted. At both latitudes, inshore sites show a greater concentration of power in the weather band with primary peaks around a few days. In addition, the annual signal is strongest inshore (significant at ORS065 at the 95% level when using the PRT formulation). At the shelf break, the global spectrum is less definitive and the peak around 90–100 days is relatively more important.

5. Discussion: What Drives the Cross-Shelf BBL Transport?

5.1. Influence of Wind Stress

Previous work has shown that on stratified inner shelves dominated by wind-driven circulation [Lentz, 2001; Kirincich et al., 2005; Fewings et al., 2008], bottom cross-shelf transport is balanced by the surface cross-shelf transport. Unfortunately, the in situ mooring array used here (which lacks surface measurements) prevents us from accurately investigating the surface dynamics. Nevertheless, we can estimate the surface wind-driven Ekman transport, \( u_{se} \), from wind observations. We compare two different wind data sets (described in section 2) in order to minimize the bias inherent to each source. We chose in situ wind measurements from a close-by overland meteorological station operated by the Bureau of Meteorology (BOM) and satellite-derived estimates from ASCAT of over ocean winds at the location closest to the shelf break moorings (locations indicated in Figure 1).

Wind-driven surface Ekman transports computed from both wind products are highly correlated (0.74–0.75) but differ significantly in intensity. Using BOM measurements, the 4 year averaged (standard deviation) surface Ekman transport is \(-0.05 (0.52)\) and \(-0.09 (0.73)\) m² s⁻¹ at Coffs Harbour and Sydney, respectively. Based on ASCAT, the 4 year averaged Ekman transport is \(-0.26 (1.33)\) and \(-0.23 (1.15)\) m² s⁻¹, respectively. While the difference in magnitude is large, both data sets predict a mean negative (i.e., onshore) \( u_{se} \). A mean onshore surface Ekman transport is in agreement with the dominant downwelling-favorable wind direction. In a two-dimensional wind-driven circulation, this would require \( u_b \) to be directed offshore in order to balance the surface transport with opposite volume transports [Fewings et al., 2008]. However, \( u_b \) was found to be predominantly onshore as well (section 4.3). In addition, the surface Ekman transport is weaker in magnitude than the bottom transport (see section 4.3) and is weakly correlated with the bottom cross-shelf transport. Correlation coefficients between \( u_{se} \) (using BOM wind observations) and \( u_{be} \) are weaker than \(-0.30 \) upstream and \(-0.28 \) downstream (weaker than \(-0.29 \) and \(-0.23 \), respectively, using
ASCAT wind observations), in agreement with weak correlations between along-shelf wind and depth-averaged current (<0.32).

The correlations we observed are much lower than those found by Smith [1981] between surface Ekman transport and lower layer transport (0.49–0.64) at different mid-shelf sites off Oregon, Northwest Africa and Peru where the structure of the mean cross-shelf pattern does not include a geostrophic interior flow. These regions are all Eastern Boundary Current regimes characterized by strong upwelling-favorable winds (up to an order of magnitude greater) but with comparable slope topography, stratification and Rossby baroclinic radius of deformation (here the 100 m isobath is 10–22 km offshore, hence a slope $\alpha = 4.5 \times 10^{-3}$, $\Delta \rho \approx 1.1 – 1.8$ kg m$^{-3}$ and $K_0 \approx 12 – 15$ km). Even though the mean cross-shelf structure in these regions suggested a conceptual two layer upwelling model, Smith [1981] showed more complex patterns on event time scales. Here the agreement between bottom and surface variability is even lower, suggesting that the bottom cross-shelf dynamics do not balance the surface wind-driven Ekman transport.

Based on the same data as Smith [1981], Lentz and Chapman [2004] proposed that the two-dimensional cross-shelf structure of the wind-driven return flow depends on the slope Burger number ($Bu$). Here the mean $Bu$, defined as $\alpha N/|f|$, is high, mostly due to the steep slope along the southeastern coast of Australia. Indeed, using a slope of $\alpha = 4.5 \times 10^{-3}$ ($\alpha = 10 \times 10^{-3}$) and a mean buoyancy frequency of $N = 11.8 \times 10^{-3}$ s$^{-1}$ ($N = 11.9 \times 10^{-3}$ s$^{-1}$) upstream (downstream), we get a mean $Bu = 0.7$ upstream and $Bu = 1.4$ downstream. This suggests an interior return flow in response to upwelling-favorable wind stress, with little effect on the bottom dynamics, especially downstream.

### 5.2. Influence of the Western Boundary Current

As wind stress is poorly correlated with the BBL transport variability, we investigate the influence of the highly energetic western boundary current on the BBL transport. Section 4.2 showed that Ekman theory derived from bottom stress could account for a large percentage of the BBL transport. In addition, we know that the along-shelf bottom friction is strongly influenced by the EAC and its eddy field when the jet comes into close proximity of the continental shelf. To investigate the influence of mesoscale circulation on the...
shelf dynamics, we first assume that geostrophic currents from altimeter data (with a resolution of 25 km and daily output) over the continental slope are a reasonable proxy for the adjacent slope circulation. Indeed, Mata et al. [2000] observed the core of the EAC flow within 40 km of the coast at 30°S. The time series of satellite-derived along-shelf velocities was extracted at the grid box closest to the shelf break (see Figure 1, 25 km from the coast). We found correlation coefficients between the satellite-derived along-shelf velocities and $U_{bPRT}$ of 0.30 and 0.46 upstream and downstream, respectively. These correlations are similar and much higher than the correlation between $U_{bPRT}$ and $U_{SE}$ upstream and downstream, respectively, despite the uncertainties arising from the different temporal resolution of the two products.

The wavelet analysis of the bottom cross-shelf transport (section 4.3) showed that there was an energy peak at periods around 90–100 days for all sites both upstream and downstream. This occurs at the same frequency as the fluctuations in the EAC and eddy shedding that has been identified in previous work. Bowen [2005], Mata et al. [2000], and Wilkin and Zhang [2007] identified spectral peaks in the mesoscale energy band at periods between 90 and 180 days, or 90 and 140 days. More specifically, based on 12 years of observations of the surface meridional geostrophic velocity at 30°S from 100 to 4600 m water depth (153.4°E–154.2°E), Mata et al. [2006] found a main peak of 96 days in the variance preserving spectrum. From 15 years of data along a high-density XBT transect between Sydney and Wellington, Ridgway et al. [2008] found a dominant annual component to the transport and an “eddy energy” peak at 100 days.

Using data from 2010 to 2013, we performed the same wavelet analysis as in Figure 9 on both the along-shelf geostrophic velocity and the wind measurements (Figure 10). As the altimeter time series were extracted at the shelf break (location shown on Figure 1), where the EAC (or its warm core eddies) tend to be intense, we do not expect the remote sensed geostrophic velocity estimates to be influenced by coastal wind forcing. A significant energy peak occurs at a period of around 80–90 days (90–110 days) in the geostrophic velocities, in agreement with the literature, upstream (downstream) of the separation zone. In contrast to this, most of the power in the wind stress spectra (from BOM or ASCAT observations with a shift of a few days) is associated with the weather band between 1 and 30 days. The 90–100 day period is a power minima indicating that the periodicity found in the bottom cross-shelf transport is not likely to be driven by the local wind. These results suggest a relationship between the BBL onshore transport on the continental shelf and the boundary current variations: the southward flowing EAC upstream and its Warm Core Eddies downstream.

Comparing the two latitudes, the slight difference in period for the peaks between 90 days upstream and 100 days downstream, identified from the mooring data, is also apparent in the altimetry product. The power concentration around the eddy period on the global spectrum is greater downstream than upstream. Conversely, the annual variability is greater upstream than downstream, with the geostrophic currents showing a primary peak at the annual period. In the wind field, there is also an annual signal, which is stronger upstream than downstream; however, the power is dominated by the weather band signals.
6. Implications for Slope Water Uplift

Assuming two-dimensional dynamics, a mean onshore bottom transport is expected to uplift potentially nutrient-rich deeper water masses originating offshore. Uplift in this region would then occur with a negative (onshore) BBL transport. A two-dimensional relationship however ignores the importance of along-shelf advection and divergence. The importance of nonlinearity was shown by Oke and Middleton [2000] upstream of our region. Along-shelf advective acceleration of the flow was shown to be important due to the varying topography and was linked to the vertical diffusion. Roughan et al. [2003] also describe locations of strong flow convergence and divergence along the coast. Both these results were obtained through idealized modeling studies. In a first attempt to measure these processes, Schaeffer et al. [2013] used 3 years of observations to show a two-dimensional cross-shelf response to strong EAC intrusions using a mean calculated from these specific events. However, these results did not consider the strong temporal variability. In this section, we investigate the relationship between the bottom cross-shelf transport with both temperature variability and biological productivity.

6.1. Temperature Response

Schaeffer et al. [2013] found a linear relationship between the bottom cross-shelf temperature gradient and the along-shelf velocity based on composite values, by considering times when the EAC alone was the main forcing mechanism (i.e., periods of weak wind). Here we look at the complete 4 year time-series of the bottom cross-shelf temperature difference (Figures 6b and 7b). We do not expect perfect agreement between the bottom cross-shelf transport and bottom temperature difference since, in addition to three-dimensional processes discussed above, temperature is also strongly affected by mixing, diffusion and surface heat fluxes. The amplitude of temperature changes (in time or space) is not going to be the same under a stratified versus homogeneous environment. None-the-less, when looking at the strongest temperature difference events (>0 in Figures 6b and 7b, i.e., warmer offshore than inshore at the same depth), they are closely aligned with a local onshore BBL transport extrema (cross-shelf transport <0 in Figures 6a and 7a). For example, the strong negative peaks in March and December 2010 are characterized by a strong cross-shelf temperature difference. The bottom waters (65 m deep) at CH070 are colder by more than 7°C when compared to CH100 (Figure 6b). These events correspond to onshore BBL transport $U_{bPRT}$ at CH100 of 4.5 and 3.6 m² s⁻¹, respectively (3 and 2.1 m² s⁻¹ on Figures 6a and 7a, where the time series are low-passed filtered for clarity).

Figure 11a illustrates the cross-shelf structure of the velocity and temperature during the December 2010 event. Onshore flow in the BBL (around 20 m thick) reaches 0.1 m s⁻¹ and is roughly confined below the 16°C isotherm. The uplifted water is then much colder than the overall 22°C water in the top 50 m. This period was characterized by an EAC encroachment (Figure 1) with southward surface currents of 1.3 m s⁻¹ and an upwelling-favorable wind (Figure 2a). The SST is also consistent with colder water inshore of the EAC (Figure 1) at Coffs Harbour (30°S), suggesting a surface upwelling expression in response to a combination of EAC and wind forcing.
On the 14 July 2012, the wind is not upwelling favorable at Coffs Harbour (Figure 2a). Still, it corresponds to a local maximum in the bottom cross-shelf temperature difference (>4°C in Figure 6b) and a negative bottom cross-shelf transport ($U_{bPRT}$ at CH100 of $-1.5 \text{ m}^2 \text{s}^{-1}$ in Figure 6a). The corresponding cross-shelf velocity section shown in Figure 11b highlights an uplift in temperature, with a return flow in the mid layers, consistent with the conceptual model proposed by Schaeffer et al. [2013] for current-driven uplift during periods of weak wind stress.

Downstream, the temperature differences are globally weaker (Figure 7b). Nevertheless, during intense BBL transport events, we see a similar agreement between negative cross-shelf transport and an increased temperature difference (e.g., January 2011, May 2012, March 2013). The maximum negative correlation between the cross-shelf bottom transport and temperature difference is obtained during Autumn (MAM of the 4 years aggregated, when the water is the most stratified), with coefficients of $-0.41$, $-0.45$, and $-0.50$ at CH100, ORS065, and SYD140, respectively, for lags shorter than 2 days. Correlations between the cross-shelf transport and the rate of change in bottom temperature (difference over 12 h) are only significant at ORS065 and SYD100, but reach 0.35 over the whole years off ORS065. This suggests that the temperature variability is more sensitive to three-dimensional dynamics upstream and offshore. Further
investigation, in particular modeling studies would be necessary to quantify the specific influence and magnitude of these effects.

6.2. Biological Response

In this region, it has been argued that current-driven uplift is a significant driver of productivity in what is generally considered an oligotrophic environment ([Roughan and Middleton, 2002]). In terms of the biological response, chlorophyll-a concentration is a good proxy for understanding the effect on productivity. A Slocum glider was deployed in July 2012, providing measurements of temperature, salinity, density, dissolved oxygen, backscatter, and fluorescence during its frequent shallow dives (to 80 m) across the continental shelf. Figure 12a shows the glider track for 4 days, immediately after the current-driven uplift event associated with a BBL onshore flow that was previously identified (14 July 2012, Figures 6 and 11b). Additional concomitant observations are presented, including the SST and surface currents from HF radar (Figure 12a). All these observations show results consistent with current-driven uplift driving a chlorophyll bloom. During this event, the EAC encroaches upon the continental slope, with surface currents of $1.5 \text{ m s}^{-1}$ and temperatures of $21–22^\circ\text{C}$. The subsurface signature of the EAC is also evident in the offshore segment of the glider measurements (Figure 12b), i.e., temperature of $>20^\circ\text{C}$ and density $<25 \text{ kg m}^{-3}$ in the top 30–40 m. Additionally, backscatter and fluorescence are low, consistent with the oligotrophic waters of the EAC. Closer to the coast, cooler temperatures noted on the SST image ($19^\circ\text{C}$) and in the glider measurements (during times when the glider dive is less than 30 m) are consistent with water uplifted along the slope from underneath the EAC. In these shallow waters (bottom depth $<50 \text{ m}$), the backscatter signal is high close to the bottom, suggesting mixing (also evident in the density field), and potentially higher nutrient concentrations. This is overlain by waters of higher fluorescence concentrations most likely representing phytoplankton production resulting from increased nutrient input. The different water masses are highlighted on a temperature-salinity diagram (Figure 12c). Productive inner shelf waters characterized by high fluorescence have intermediate density compared to the EAC water mass (density $<25$) and the slope water (density $>25.5$).

7. Conclusions

Four years of moored observations along the coast of southeastern Australia are used to study cross-shelf transport in the BBL. The averaged boundary layer thickness computed as the mixed layer depth or using the formula of [Pollard et al., 1972] ranges 10–18 m. The thickness of [Pollard et al., 1972] BBL is larger upstream of the EAC separation point (15–16 m) than downstream (10–15 m) and in winter than in summer, showing the importance of the bottom stress and the stratification, respectively.

Computations of BBL transport from observations appeared to be robust and independent of the BBL formulation, with an onshore net transport at all mooring locations and stronger transport upstream of the separation zone. The time series of cross-shelf transport are correlated between adjacent sites and in good agreement with Ekman theory with 58–71% of the bottom cross-shelf transport variability explained by the along-shelf bottom stress in 70 m water. BBL cross-shelf transport directed onshore occurs 64% of the time upstream and between 50 and 60% of the time downstream. Estimates of surface wind-driven Ekman transport are poorly correlated with the bottom cross-shelf transport.

Wavelet analysis of the BBL transport time series shows significant energy ranging from a few days to annual oscillations, with a distinctive peak at periods around 90–100 days, consistent with previous observations of the EAC fluctuations and eddy shedding. These results suggest that EAC encroachment and eddy shedding has a significant impact on the continental shelf circulation. We suggest that in this region onshore flow in the BBL is driven by variability in the western boundary current as opposed to local wind stress.

We show evidence of strong onshore BBL transport events characterized by positive cross-shelf temperature gradients, associated with the uplift of colder water originating from depth along the continental slope. Complementary observations from HF radar-derived surface velocities, SST and hydrography from an autonomous glider highlight an episode of EAC encroachment driving biological productivity. Differences upstream and downstream of the EAC separation zone appear both in the magnitude and occurrence of the onshore transport. The weaker relationship between bottom temperature and BBL transport upstream suggests a more three-dimensional uplift process compared to downstream. Further
investigation of these along-shelf nonlinearities is needed to fully explain the bottom temperature variability.

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