Summer circulation dynamics within the Perth coastal waters of southwestern Australia

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\textbf{A B S T R A C T}

The dynamics of the summer circulation in the coastal waters off Perth in Western Australia were investigated during a two-month field experiment. The study included the deployment of an array of moorings spanning the outer shelf, the inner shelf, within the inshore Perth coastal lagoon, and in the large coastal embayment of Cockburn Sound. The results revealed highly transient coastal circulation patterns that responded to variability in both the locally- and remotely-generated forcing. Local wind forcing played a primary role in driving much of the alongshore current variability at the shallower (<20 m depth) inshore sites, with a well-defined peak wind forcing time scale of \textasciitilde 1 week that fell within the synoptic weather band in the region. Due to the mean northward wind stress that persisted during this summer period, a mean northward current of 0.05–0.1 m s\textsuperscript{-1} was observed at these inshore sites. Large-scale variations in alongshore water level (pressure) gradients also episodically generated strong along- and cross-shore current oscillations throughout the region. Major events were associated with the propagation of coastally-trapped waves generated by a tropical low pressure system far (\textasciitilde 1000 km) to the north of Perth, which propagated down the Western Australia coast. On the outer shelf, local wind forcing played a minor (but still not a negligible) role in driving alongshore current variability, with this momentum balance instead dominated by the alongshore pressure gradient variability. Due to the unusually large alongshore pressure gradient that persists year round along the Western Australia coast, currents on the shelf were on average southward. However, large-scale northward reversals of the shelf flow were also observed when northward wind stresses were sufficiently large and/or the local alongshore pressure gradient became episodically weak.

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1. Introduction

The southwest coastal region of Western Australia (32° S) is characterized by its unique ocean conditions, its complex coastal topography, and as a marine biodiversity hotspot (Phillips, 2001). It is also adjacent to the population center for the western half of Australia’s population (Perth), which extends along the coast surrounding the Swan River. The bathymetry of the region is shaped by an extensive network of submerged offshore and fringing rocky reefs formed by Pleistocene coral reefs (Kendrick et al., 1991). The coastal region is also enclosed by three islands (Rottnest, Garden and Carnac), which form the relatively shallow (<20 m depth) coastal lagoon off Perth, including the large coastal embayment of Cockburn Sound (Fig. 1). The ecology of Perth’s coastal lagoon is dominated by extensive seagrass meadows, kelp, and a diversity of other temperate reef communities (e.g. Carruthers et al., 2007; Kerswell, 2006; Wernberg et al., 2003). The ocean dynamics of the shelf region of Western Australia are strongly influenced by the year-round southward (poleward) flowing Leeuwin Current, which is driven by an unusually large steric height pressure gradient that is on-average roughly an order of magnitude larger than along other eastern ocean margins (Smith et al., 1991). The strength of the Leeuwin Current seasonally varies, reaching a maximum during the austral autumn to winter period (April–July), and strengthens as it flows southward down the coast from the North West Cape (22° S). Off Perth at 32° S, the core of the Leeuwin Current is typically located near the 200 m isobath, with current speeds seasonally exceeding 0.5 m s\textsuperscript{-1} (Feng et al., 2003). This region is also characterized by the presence of large meandering shelf eddies which influence the coastal
dynamics and can locally promote upwelling in their core (Feng et al., 2005).

The coastal region of southwestern Australia is also strongly influenced by strong northward winds, which are greatest during the austral summer when wind speeds average more than 5 m s$^{-1}$ and frequently exceed 15 m s$^{-1}$. Other processes such as tidal forcing tend to be very weak in Perth's coastal waters, given its microtidal regime (maximum tidal range of only $\sim 0.6$ m) (Lemm et al., 1999). Buoyancy forcing is also usually weak, due to the limited freshwater discharge into this region. The strong local wind stresses, which oppose the poleward pressure gradient along this coast, thus play a role in regulating the strength of the Leeuwin Current on the outer shelf. However, on the shallower inner shelf and in nearshore areas, this local wind forcing is also known to drive seasonally strong northward currents inshore of the Leeuwin Current (e.g., Gersbach et al., 1999; Lowe et al., 2012) as well as adjacent to Perth's beaches (e.g., Pattiaratchi et al., 1997). Several studies have shown how these winds drive current variability along the broader Western Australia coastline over a number of time scales, including studies focusing on the response to the strong diurnal sea breeze cycle in the region (e.g., Pattiaratchi et al., 1997; Gallop et al., 2012) and lower frequency variability associated with propagating synoptic weather systems (e.g., Cresswell et al., 1989; Lowe et al., 2012).

The detailed dynamics of Perth's inshore coastal circulation have remained surprisingly understudied, despite the great ecological, economic and social significance of this coastal region. While a number of historical studies exist, they have tended to focus on the circulation of local geographic regions as well as the circulation response to specific forcing mechanisms. Early studies of the local circulation within the Cockburn Sound embayment focused on the response of the depth-averaged currents to wind forcing (Steedman and Craig, 1983), with subsequent studies providing additional insight on the vertical structure of the transport processes and their response to both wind forcing and episodic freshwater discharge during winter storms (D’Adamo, 2002). More recent studies of Cockburn Sound have been motivated by large-scale industry projects on its coast; for example, to understand the role of hydrodynamics on the dynamics of effluent plumes from a major desalination plant (Marti et al., 2011).

Other studies have focused on the sources of current variability in the Perth coastal lagoon region to the north of Cockburn Sound.

![Fig. 1](image_url) (a) Bathymetry contours of the study area with the instrument locations superimposed. (b) Geographical location of the study area and location of the deep shelf mooring at P6.

<table>
<thead>
<tr>
<th>Site</th>
<th>Easting (m)</th>
<th>Northing (m)</th>
<th>Depth (m)</th>
<th>Sampling Period</th>
<th>Instrument</th>
<th>Bin size (m)</th>
<th>Sampling frequency (Hz)</th>
<th>Averaging interval (s)</th>
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<td>370,044</td>
<td>6,435,516</td>
<td>18</td>
<td>12/11/10–04/01/11</td>
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<td>0.5</td>
<td>1</td>
<td>600</td>
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<tr>
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<td>6,438,124</td>
<td>20</td>
<td>12/11/10–01/01/11</td>
<td>ADCP (600 KHz)</td>
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<td>0.33</td>
<td>600</td>
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<td>6,443,674</td>
<td>4</td>
<td>12/11/10–19/12/10</td>
<td>ADV</td>
<td>–</td>
<td>2</td>
<td>–</td>
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<tr>
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<td>6,449,803</td>
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<td>12/11/10–04/01/11</td>
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<td>6,458,035</td>
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<td>20/11/10–04/01/11</td>
<td>ADV (2 MHz)</td>
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<td>6,461,582</td>
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<td>5</td>
<td>1200</td>
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<td>6,466,986</td>
<td>20</td>
<td>20/11/10–03/01/11</td>
<td>Thermistor chain</td>
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<td>ADP (190 KHz)</td>
<td>8</td>
<td>1</td>
<td>600</td>
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The most substantial of these studies was conducted by Zaker et al. (2002, 2007), which investigated current variability in the reef-protected Whittfords lagoon (~30 km north of Perth). That study was based on data obtained from the Perth Coastal Waters study in 1993, motivated by the need to understand specific water quality issues in this lagoon. Collectively these studies revealed the dominant role that local wind forcing played in driving current variability at this site. More recently, Symonds et al. (2011) investigated the circulation within the reef-protected Marmion Lagoon (~20 km north of Perth) and also showed that local wind forcing played a dominant role in driving alongshore current variability under most conditions (especially in summer); however, currents driven by wave breaking were also found to be important in the vicinity of reefs when offshore wave heights exceeded 1.5 m, particularly during winter months.

In this paper, we describe results from a comprehensive broad-scale (synoptic) field study of the dynamics of the summer circulation of Perth’s coastal and shelf waters. The observational array extends 50 km surrounding Perth, and for the first time provides simultaneous observations throughout the region, including at sites on the outer shelf, the inner shelf, the Perth coastal lagoon and within Cockburn Sound. The results thus provide the first opportunity to investigate how the circulation and momentum dynamics vary across the study area, including the different (and often opposing) role played by both local and remotely-generated forcing mechanisms. The paper is organized as follows. In Section 2 we describe the study area, the field experiment and the methods used in the data analysis. Results from the field study are described in Section 3, which include a detailed examination of the role that different forcing mechanisms play in driving current variability and circulation patterns throughout the study area. In Section 4 we discuss the dominant momentum balances that occurred within three distinct geographic zones during this summer period. Finally, in Section 5 we summarize the major conclusions of the study.

2. Methods

2.1. Field sites and instrumentation

Current velocities were recorded from 12 November 2010 to 4 January 2011 at eight sites within a 50 km section of coast surrounding Perth, Western Australia. Three Nortek Vector Acoustic Doppler Velocimeters (ADV) measured velocities roughly 1.5 m above the seafloor at the shallow (<10 m) nearshore sites (V1–V3 in Fig. 1). Five current profilers, including three RD Instruments Acoustic Doppler Current Profilers (ADCPs), a Nortek AWAC profiler and a Nortek AquaDopp profiler (ADP), each recorded current velocities through the water column in deeper (>10 m) areas (P1–P5 in Fig. 1). On the outer shelf (P6) near the 200 m isobath, current profile data was also obtained from a Nortek ADP profiler as part of the Integrated Marine Oceanographic System (IMOS) (www.imos.org.au). The vertical temperature stratification at a site (20 m deep) within the Perth coastal lagoon was continuously recorded using a thermistor chain array, using 6 Sea-bird Electronics SBE 39 thermistors distributed uniformly over the 20 m water column. A summary of the instrument locations and their configurations is provided in Table 1.

Hourly-averaged wind data were obtained from a Bureau of Meteorology weather station on Rottnest Island, near the center of the study area (Fig. 1). The corresponding wind stress vectors were computed using a quadratic friction law based on the measured wind speed and empirical drag coefficients derived from Large and Pond (1981). Water level time series $\eta$ were recorded by coastal tide gauges at four locations along the coast (Geraldton, Jurien Bay, Hillarys and Bunbury), maintained by the Western Australia Department of Transport (Fig. 1b). Some snapshots of the regional-scale shelf surface currents in the study area were also obtained from a High Frequency (HF) radar system (WERA, ASL Environmental Services) operating at 8.5 MHz, which provided estimates of the surface current vectors at 250 m resolution.

2.2. Data analysis

The measured current data were pre-processed to filter out bad data points and then hourly-averaged to a common time base. For the current profiler data, bad data near the surface due to side lobe interference (~10–20% of the total water depth) were removed. The data were then used to compute time series of depth-averaged current vectors as well as surface current vectors, the latter defined as the average velocity within the top 2 m of good data near the surface. The point-based ADV data were also used to estimate depth-averaged velocities assuming a 1/6 power velocity profile distribution (e.g., Taebi et al., 2011). Assuming this profile shape resulted in only a small correction to point velocity measurement (<10%), yet was still included to provide the most robust estimate of the true depth-integrated transport.

The velocity and water level time series were low-pass filtered using a PL64 filter (half-power period 38 h) to remove tidal and inertial fluctuations (Beardsley et al., 1985). A principal component analysis (Emery and Thomson, 2001) was conducted between the eastward and northward depth-averaged current components, to rotate the data into the major (alongshore, $V$) and minor (cross-shore, $U$) axes of the flow variability, with the directions expressed in degrees clockwise from true north.

Alongshore water level gradients $\partial \eta / \partial y$ time series were estimated from the low-pass filtered tide gauge data between Geraldton (north of Perth) and Hillarys (330 km apart), which were corrected to “adjusted sea level” using locally recorded atmospheric pressure at each site (Hickey et al., 2003). A time-lagged correlation analysis between the currents along the major flow axis ($V$) and the various forcing mechanisms were also quantified at each site, with significance levels computed from the effective degrees of freedom of the low-pass filtered time-series (Emery and Thomson, 2001).

3. Results

3.1. Study conditions

Throughout the two-month study period, the winds were consistently from the south (mean direction towards 351°) (Fig. 2a), but their magnitude varied both diurnally due to the sea breeze cycle as well as on longer time-scales, coinciding with the dominant time-scale of weather pattern variability in the Western Australia region (Gentilli, 1972) (Fig. 2b). The well-defined spectral peak in the alongshore wind speed variability at ~7 days highlights the strong wind forcing in this synoptic “wind band” (Fig. 3a). During the study, wind speeds averaged 8.5 m s$^{-1}$, ranging from 10 to 15 m s$^{-1}$ during strong events, but also ceased for several days (Fig. 2b). Water level variability was influenced by the relatively small diurnal tides off south-western Australia (with a maximum range of up to 0.7 m during the study; Fig. 2c), but was also influenced by subtidal water level fluctuations with a range of 0.3 m (Fig. 2d).

Water temperature in the Perth lagoon was relatively constant (~21 °C) during most of the study, but increased from 21 °C to 23 °C during the final two weeks (i.e., after 22 December). No salinity measurements were available on the thermistor chain mooring, but the water column was generally thermally well-mixed with an average
temperature difference over the study period of only \( \sim 0.05 \) °C from surface to bottom (Fig. 2e). This surface to bottom temperature difference corresponds to a density difference of just \( \sigma_T \sim 0.02 \) kg m\(^{-3}\) (at constant salinity). Based on this density difference, the estimated gradient Richardson number was \( \text{Ri} = \left(-\frac{g}{ho_0} \frac{\partial \rho}{\partial z}\right) / \left(\frac{\partial u}{\partial z}\right)^2 < 0.02 \), where \( g \) is the gravitational acceleration, \( \frac{\partial \rho}{\partial z} \) is the estimated

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**Fig. 2.** Time series of (a) wind velocity vectors; (b) low-pass filtered wind velocity vectors; (c) water level variability at a shoreward (V2) and a seaward (P3) site in the coastal lagoon; (d) the corresponding low-pass filtered (subtidal) water level variability and (e) subtidal temperatures from the near-surface and near-bottom thermistors at T1.

**Fig. 3.** Spectra of the alongshore components of the low-pass filtered (a) wind velocity (b) offshore currents (P6), and (c) inshore currents at P3 and V2. The 95% confidence intervals in the computed spectra are shown.
vertical density gradient and $\frac{\partial u}{\partial z}$ is the vertical velocity shear, which indicates that the water column was well-mixed throughout the entire month of December so the conditions during this brief period were unusual.

3.2. Current observations

The depth-averaged mean (experiment-averaged) current vectors at all inshore coastal sites were northward with speeds ranging between 0.02 and 0.07 m s$^{-1}$, except in the deep central basin of Cockburn Sound (P2) where the mean depth-averaged flow was negligible (Fig. 4a, Table 2). The mean surface current vectors matched the depth-averaged current vector patterns, except in Cockburn Sound (P2) where a weak mean northward surface current (0.02 m s$^{-1}$) occurred (Fig. 4a). At this site, the discrepancy between the depth-averaged flow and the surface flow is explained by a net southward inflow in the bottom waters into Cockburn Sound (see below). The mean surface current vectors at the relatively deep P3 and P4 sites were oriented slightly counter-clockwise from the depth-averaged vectors by $\sim 10^\circ$ (Fig. 4a). At the deep offshore shelf site (P6), the mean depth-averaged flow during the experiment was southward ($\sim 0.05$ m s$^{-1}$), due to the influence of the along-shelf pressure gradient that drives the Leeuwin Current year round (Fig. 4a). The mean surface flow at P6 was rotated onshore (counter-clockwise) by $40^\circ$ relative to the depth-averaged flow direction.

The major axes of the depth-averaged and surface current variance ellipses (Fig. 4b) were, for the most part, oriented similarly to the mean current vectors and were steered parallel to the local isobaths. The exceptions are the three sites in the shoreward lee of Rottnest Island (P3, P4, P5), where the flow passes over a shallower shoal. The magnitude of the depth-averaged alongshore current variability tended to increase offshore (Fig. 5c). For example, the subtidal alongshore current velocities often reached speeds of $0.3$ m s$^{-1}$ at the offshore site (P6), but rarely reached $>0.15$ m s$^{-1}$ inshore at P3 and V2. Interestingly, the magnitude of the cross-shore (east–west) subtidal current fluctuations were comparable (up to $0.1$ m s$^{-1}$) across these same three sites (Fig. 5b, Table 2). Vertically through the water column, there was consistency in both the alongshore surface and bottom currents across all sites, except within the deep enclosed basin of Cockburn Sound (P2) and on the outer shelf (P6). At P2, the moderate-to-strong northward winds that persisted during the middle of the study (roughly during the first three-weeks of December) drove a northward flow that was strongest within the top $5$ m of the water column. This flow was often, but not always, compensated by a weak southward inflow at depth (Fig. 6c), consistent with a two-layer flow structure. The time-averaged current profile during the study also displayed a similar two-layer flow pattern (Fig. 6d). During the study there were three periods of sustained wind relaxation (20 November, 29 November and 21 December), with two of these (20 November and 21 December) leading to strong reversals of the flow profile, i.e. with a southward inflow at the surface and a compensating northward outflow at the bottom (Fig. 6c). However, during the 29 November relaxation period, a moderately strong surface outflow still persisted; likely due to the strong northward-directed alongshore pressure gradient and the corresponding falling coastal water levels that preceded this period (Fig. 6b, 2d). Strong fluctuations in the alongshore pressure gradient, particularly during the period 12–23 December, also led to the repeated reversal of these exchange flows within this narrow time frame (Fig. 6c).

Although the alongshore flow on the outer shelf (P6) was on average weakly southward, there were also strong current fluctuations that led to large northward flow events (up to $0.5$ m s$^{-1}$ at
Table 2

Depth-averaged current statistics for all sites. Directions are positive clockwise from true north. Correlations between the alongshore currents and both the alongshore components of the wind (\(R_{\text{wind}}\)) and water level gradient \(\partial \eta / \partial y\) (\(R_{\text{wlt}}\)) are based on the current variability along the major axis at bold 99% and italicized 95% confidence levels. Note that a positive lag time indicates the current lagged the wind or water level gradient response.

<table>
<thead>
<tr>
<th>Site</th>
<th>Mean current</th>
<th>Principal component axes</th>
<th>Wind correlation</th>
<th>Water level gradient correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Magnitude (m s(^{-1}))</td>
<td>Direction (deg)</td>
<td>Major (m s(^{-1}))</td>
<td>Minor (m s(^{-1}))</td>
</tr>
<tr>
<td>P1</td>
<td>0.041</td>
<td>355</td>
<td>0.041</td>
<td>0.005</td>
</tr>
<tr>
<td>P2</td>
<td>–0.004</td>
<td>17</td>
<td>0.000</td>
<td>0.004</td>
</tr>
<tr>
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<td>341</td>
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</tr>
<tr>
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<tr>
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<td>9</td>
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</tr>
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<td>–0.052</td>
<td>328</td>
<td>–0.043</td>
<td>–0.030</td>
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</table>

Fig. 5. (a) Low-pass filtered wind velocity vectors, (b) depth-averaged subtidal cross-shore currents at three sites, and (c) the corresponding depth-averaged subtidal alongshore flows. Note that the shaded area highlights the period of a coastally-trapped wave train event.

3.3 Influence of local (wind) versus remote (alongshore pressure gradient) forcing on current and water level variability

The alongshore subtidal current variations at the inshore shallow coastal sites (<20 m depth) were strongly correlated with the alongshore wind stress variations (Table 2), with \(R_{\text{wind}}\) ranging from 0.6 to 0.9 based on the depth-averaged currents and slightly higher 0.7–0.9 based on the surface currents (not shown), except within Cockburn Sound (P2). At these sites, the depth-averaged currents responded rapidly to the local wind forcing (lag times <10 h) at all sites. At P2, \(R_{\text{wind}}\) between the wind and depth-averaged currents was only ~0.1; however, the surface currents were much better correlated with the wind (\(R_{\text{wind}}~0.4\)) (Table 3). Offshore at P6, the depth-averaged current variability was only weakly correlated with the wind and with an opposite (negative) sign to what would be expected (\(R_{\text{wind}}~0.2\)); however, a weak positive \(R_{\text{wind}}~0.2\) occurred with the surface currents at zero lag (Table 3). The cross-shore component of the surface currents at P6 were somewhat better correlated with the alongshore component of the wind (\(R_{\text{wind}}=0.32\), not shown), suggesting that some offshore-directed surface Ekman transport occurred in response to variations in the strength of the predominantly northward wind stress.

The strong dependency of the alongshore current variability on the local wind forcing at the inshore coastal sites is visible in the current time series (Fig. 5). However, the offshore (shelf) flow at P6 visually appears largely decoupled from the local wind. The energy associated with the alongshore current variability on the outer shelf (P6) was also decoupled from the peak wind forcing period of ~7 days (Fig. 3a), with the spectral peak in the alongshore current variance shifted to ~2 weeks (Fig. 3b). At the inshore sites (P3 and V2) the peak in alongshore current variability occurred...
at the dominant wind forcing period of 7 days (Fig. 3c), consistent with the strong and immediate response of the currents to the direct wind forcing at these sites (Table 2). At the seaward P3 site there was also a second peak (~2–3 weeks) in the alongshore current variance, comparable to what was observed offshore, suggesting some encroachment of these offshore dynamics onto the inner shelf region of the study area.

There were significant (albeit weaker) correlations $R_{WL}$ between the alongshore currents and the estimated alongshore water level (pressure) gradient $\partial \eta / \partial y$; however, these responses differed among groups of sites (Table 2). $R_{WL}$ tended to be negative (values $-0.3$ to $-0.4$) at deeper or exposed sites (P3, P4, V2, P5, P6), which is the expected response to a positive value of $\partial \eta / \partial y$ where elevated water levels to the north lead to a southward alongshore flow. At these sites the currents responded rapidly (within ~1 day) to the subtidal pressure gradient fluctuations. The remaining sites (P1, P2, V1 and V3) unexpectedly showed a positive correlation with $\partial \eta / \partial y$; however, all of these show a much different temporal response with the currents leading the pressure gradient response by ~3 days. A closer inspection indicates that the currents at these sites tend to be those most strongly correlated with the local wind forcing ($R_{wind} > 0.8$), with the exception of P2. It appears that these positive correlations are partially a reflection of the alongshore pressure gradient itself responding to the regional wind forcing. In other words, sustained periods of northward wind stresses elevate the water levels regionally to the north after a period of several days. As a result, there is not a simple direct response of the alongshore currents to the pressure gradient variability at these sites, given that the local wind forcing tended to dominate the dynamics.

Subtidal variability in the local water levels (irrespective of the gradient) were also moderately correlated with local alongshore wind fluctuations (i.e., $R = -0.43$ at P4), indicating that periods of strong northward winds coincided with a slight reduction in the coastal water levels (Fig. 9a). However, there was a stronger relationship ($R = -0.73$) between the observed subtidal coastal water level fluctuations and the strength of the depth-averaged alongshore current recorded on the outer shelf at P6 (Fig. 9b), consistent with a dominant cross-shore geostrophic momentum balance associated with the Leeuwin Current that has been observed on this section of shelf by e.g. Feng et al. (2003).

3.4. Alongshore momentum balances

The depth-averaged alongshore momentum balances were investigated at both an inshore (P4) and offshore (P6) site, to quantify the role of the various momentum terms on the observed alongshore current variability. The simplified depth-averaged alongshore momentum equation is (e.g. Allen and Smith, 1981; Lentz and Winant, 1986)

$$\frac{\partial V}{\partial t} = -g \frac{\partial \eta}{\partial y} + \frac{\tau_{xy}}{\rho_o h} - \frac{\eta \tau_{by}}{\rho_o h}$$

where $\eta$ is the adjusted sea level, $\rho_o$ is the mean seawater density, $\tau_{xy}$ is the alongshore wind stress, $\tau_{by}$ is the alongshore bottom stress and $h$ is the local water depth. The four terms in Eq. (1)
represent (from left to right): (1) the local flow acceleration, (2) the alongshore pressure gradient, (3) the alongshore wind stress and (4) the bottom stress. Eq. (1) neglects an advective acceleration term, due to the difficulty in accurately quantifying the alongshore velocity gradients with local point measurements, as well the local Coriolis forcing and horizontal momentum diffusion terms.

Time series of each of the terms in Eq. (1) were computed from the raw data sources. The local acceleration \( \partial V / \partial t \) was calculated using central differencing of the subtidal alongshore current time series. The subtidal alongshore water level gradients \( \partial \eta / \partial y \) were estimated from the adjusted sea level data recorded by the tide gauges at Geraldton and Hillarys. This approach only provides water level gradient anomalies between the tide stations relative to the long-term mean dynamic topography of the sea surface and hence would not capture the background mean alongshore pressure gradient that operates along this coast. Rather than neglect this mean forcing contribution entirely, in the analysis we also included a mean value of this alongshore pressure gradient term based on historical observations along this coast during the summer season (taken as \( 1.3 \times 10^{-6} \) m s\(^{-2} \)) following Godfrey and Ridgway (1985) and Smith et al. (1991). Surface wind stresses were inferred from the local wind measurements (see Section 2.1). Bottom stresses \( \tau_{b,y} \) were estimated assuming a quadratic drag formulation, i.e. \( \tau_{b,y} = \rho C_{Db} V_b |V_b| \), where \( C_{Db} \) is a bottom drag coefficient (assumed to be \( 3 \times 10^{-3} \)) as a function of the near-bottom alongshore velocity \( V_b \).

Time series of the decomposed momentum terms at sites P4 and P6 are shown in Fig. 10 and Fig. 11, respectively. Table 4 also summarizes the estimated mean magnitude and standard deviation of each momentum term. At the shallower inshore site (P4) located inside the Perth coastal lagoon, the primary forcing was provided by the local wind stresses (Table 4). On average, the wind stress term was counteracted almost equally by both the bottom stress and alongshore pressure gradient terms (Table 4). However, inspection of the time series of the individual momentum terms (Fig. 10) shows a very transient system where the flow accelerated both northward during periods of strong wind stresses, or southward when either the winds relax and/or the pressure gradient term became comparatively strong (for example, around both 17 December and 20 December). Fig. 10 shows a comparison of the simple depth-averaged alongshore momentum balance given by Eq. (1) with the alongshore current variability that was observed. We do note that during some times (especially between 17 and 20 December) there is a visible phase difference between the observations and predictions, with the observed current accelerations leading the predictions by \( \sim 1 \) day. This response, attributed to forcing by the dominant pressure gradient term at the time, is a consequence of the time scale required for water level anomalies to propagate over the distance between the two sites where the pressure gradient term was estimated (between Geraldton and Hillarys). This propagation is not captured in a simple local momentum balance given in Eq. (1), where the responses are assumed to be instantaneous.

At the offshore shelf site (P6) the pressure gradient term was the dominant forcing term in the momentum balance as a result of the bottom stress and wind stress terms generally playing only a small role in the much deeper water column (Fig. 11). When considering the time-averaged momentum balance over the study, the wind stress term was more comparable (but still lower by a
factor of 5) than the poleward pressure gradient term (Table 4). However, there were much larger fluctuations in the pressure gradient term (by roughly an order of magnitude) than in the local wind stress term (Table 4).

3.5. Transient events: the role of coastally trapped waves

While variability in the local wind forcing drove most of the subtidal current variability within the Perth coastal lagoon, as well as a limited amount of variability on the shelf (Table 2), large subtidal current fluctuations in the study area were associated with abrupt subtidal fluctuations in the regional-scale alongshore pressure gradient. Particularly strong events occurred within a period from 12 to 23 December, when there was a sequence of three alongshore pressure gradient reversals, each with a cycle spanning ~3 days, which are discussed in more detail here. These events drove alongshore depth-averaged current fluctuations at all sites in the study area. The cross-shore velocities during this period were also much more spatially-complex, i.e. during this period these velocities were much less consistent among the sites

Table 3
Surface and bottom current statistics for sites P2 and P6. Directions are positive clockwise from true north. Correlations between the alongshore currents and both the alongshore components of the wind ($R_{\text{wind}}$) and water level gradient ($\partial \eta / \partial y$) are based on the current variability along the major axis at bold 99% and italicized 95% confidence levels. Note that a positive lag time indicates the current lagged the wind or water level gradient response.

<table>
<thead>
<tr>
<th>Site</th>
<th>Mean current</th>
<th>Principal component axes</th>
<th>Wind correlation</th>
<th>Water level gradient correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Magnitude (m s$^{-1}$)</td>
<td>Direction (deg)</td>
<td>Major (m s$^{-1}$)</td>
<td>Minor (m s$^{-1}$)</td>
</tr>
<tr>
<td>P2 surface</td>
<td>0.018</td>
<td>346</td>
<td>0.004</td>
<td>0.018</td>
</tr>
<tr>
<td>P2 bottom</td>
<td>-0.013</td>
<td>17</td>
<td>-0.006</td>
<td>-0.010</td>
</tr>
<tr>
<td>P6 surface</td>
<td>-0.032</td>
<td>284</td>
<td>-0.006</td>
<td>-0.032</td>
</tr>
<tr>
<td>P6 bottom</td>
<td>-0.085</td>
<td>349</td>
<td>-0.002</td>
<td>-0.020</td>
</tr>
</tbody>
</table>

Fig. 8. HF radar surface current vector data showing (a) a southward shelf flow event on 21 November followed by (b) a northward shelf flow event on 8 December. (c) and (d) show the transient draining and flooding of the Perth coastal region on 19 December and 21 December, respectively, associated with a southward propagating coastally-trapped wave train through the region.
(from shelf to inshore) (Fig. 5b). At P2 in Cockburn Sound, these alongshore pressure gradient fluctuations also drove large cyclical (~3 day) reversals of the two-layer exchange flow profile in and out of Cockburn Sound (Fig. 6c).

Fig. 12 shows observations of regional adjusted sea level observations at four sites along the Western Australia coast. Over this 10 day period, three large (~0.3 m range) subtidal water level signals propagated southward from Geraldton to Bunbury past Perth, at a speed of roughly 4 m s\(^{-1}\). These signals were the result of remotely-generated coastally-trapped waves propagating down this coast, which have a speed comparable to the theoretical mode 1 barotropic shelf wave speed (~5 m s\(^{-1}\)) computed along this coast by Eliot and Pattiaratchi (2010). The specific events described here were generated by the propagation of a tropical low system near the northwest coast of Australia during this period (Fig. 12a), which moved on and then off the coast around 18 December (this event is also discussed further below).

4. Discussion

This study has provided the first synoptic observations of the dynamics of the subtidal circulation throughout the Perth coastal waters of Western Australia, which included observations within the shallow Perth coastal lagoon, within Cockburn Sound, as well as on both the inner and outer shelf. This extensive instrument array has provided an opportunity to investigate how the complex circulation patterns throughout the study area during the summer season respond to the unique forcing conditions present along the Western Australian coast, due to its anomalously large and transient poleward pressure gradient countered by strong equatorward wind stresses. The results revealed that the circulation and associated momentum dynamics can be geographically separated into three distinct zones, which are discussed in detail below: (1) a 'Perth coastal lagoon region' including the inner shelf (comprising sites P1, V1, P3, P4, V2, P5 and V3); (2) the outer shelf region (comprising site P6); and the Cockburn Sound semi-enclosed embayment (comprising site P2).

4.1. Perth coastal lagoon

The subtidal circulation patterns in this shallow coastal region, where depths are mostly <15 m, were strongly locally forced by the predominant northward winds during this summer study period, resulting in a consistent northflow of order 0.05 m s\(^{-1}\) throughout this zone (Fig. 4a). Subtidal fluctuations in both the surface and depth-averaged alongshore currents were thus strongly correlated with variability in the alongshore wind stress (\(R_{\text{wind}}\) typically > 0.8 with a ~1/2 day lag) (Table 2). The local wind forcing recorded during the study showed a well-defined spectral peak at ~1 week (Fig. 3a), coinciding with the dominant time-scale of the wind forcing associated with the synoptic band of propagating weather patterns (~1–2 weeks) in the Western Australia region (Gentilli, 1972). The strong coupling of the local winds and currents in the Perth coastal lagoon region led to a similar peak (~1 week) in the alongshore current spectra (Fig. 3c), which was most pronounced at shoreward sites (e.g., at site V2); however, a secondary spectral peak at ~2 weeks was observed at sites near the seaward edge of the region (site P3), which coincides roughly with the dominant spectral peak of the currents observed on the outer shelf (see Section 4.3).

Historically, the importance of local wind forcing to current variability in Perth's coastal waters has been recognized. While not the focus of the present study, higher frequency wind variability due to the strong diurnal sea breeze cycle present during summer along the southwest coast of Western Australia can drive higher frequency (diurnal) current variability, particularly in the shallow nearshore zone adjacent to beaches, which can also be influenced by wave-driven alongshore currents driven by local wind waves (Gallop et al., 2012; Pattiaratchi et al., 1997). The most similar observations to the present study are those from Zaker et al. (2007), who investigated the circulation and heat budget within a localized study area sheltered by offshore reefs in Whitfords Lagoon, which is located ~10 km north of the most northern site (V3) in the present study. That study found that the forcing in the local alongshore current momentum balance was almost entirely driven by local wind stresses. Other studies have also revealed that some fine-scale circulation patterns can be influenced locally by wave breaking, leading to radiation stress gradients on offshore reefs (Symonds et al., 2011). However, over the broad Perth coastal lagoon region, direct wind forcing was clearly the dominant forcing mechanism during this summer study period. Although detailed measurements of horizontal stratification were not made during the study period, historical hydrographic observations reported by Zaker et al. (2007) showed that horizontal temperature and salinity gradients were minimal during the summer.

**Fig. 9.** (a) Relationship between the low-pass filtered alongshore wind velocity and the low-pass filtered (subtidal) water level measured at P4. (b) Relationship between the low-pass filtered alongshore current measured offshore at P6 and the low-pass filtered (subtidal) water level measured at P4. Note that daily-averaged values of each parameter are plotted.
period (November–January) and thus buoyancy effects on Perth’s coastal circulation are expected to have been negligible during the study period.

Despite the importance of local wind forcing to Perth’s coastal lagoon region, variations in the strength of the regional-scale alongshore pressure gradient also episodically played an important role.

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**Fig. 10.** Time series of the depth-averaged alongshore momentum terms estimated from Eq. (1) for site P4 (Perth coastal lagoon). (a) Local acceleration term, (b) pressure gradient term, (c) wind stress term, (d) bottom stress term and (e) the local acceleration term (the left side of Eq. (1)) compared against the sum of the terms in (a)–(e) (the right side of Eq. (1)). $R$ denotes the correlation coefficient of the local acceleration and local forcing terms (significant to the 99% confidence level).

**Fig. 11.** Time series of the depth-averaged alongshore momentum terms estimated from Eq. (1) for P6 (outer shelf). (a) Local acceleration term, (b) pressure gradient term, (c) wind stress term, (d) bottom stress term and (e) the local acceleration term (the left side of Eq. (1)) compared against the sum of the terms in (a)–(e) (the right side of Eq. (1)). $R$ denotes the correlation coefficient of the local acceleration and local forcing terms (significant to the 99% confidence level).
Table 4
Mean and standard deviation of the estimated depth-averaged alongshore momentum terms (expressed in $10^{-7}$ m s$^{-2}$) for sites P4 (Perth coastal lagoon) and P6 (outer shelf).

<table>
<thead>
<tr>
<th>Site</th>
<th>$\partial V / \partial t$</th>
<th>$-\frac{g \delta h}{\rho g}$</th>
<th>$\tau_o / \rho g$</th>
<th>$-\frac{\delta \tau_o}{\partial t}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>P4</td>
<td>Mean</td>
<td>1.22</td>
<td>12.27</td>
<td>38.60</td>
</tr>
<tr>
<td></td>
<td>Stdev</td>
<td>18.77</td>
<td>21.41</td>
<td>36.11</td>
</tr>
<tr>
<td>P6</td>
<td>Mean</td>
<td>-0.96</td>
<td>12.45</td>
<td>3.54</td>
</tr>
<tr>
<td></td>
<td>Stdev</td>
<td>15.20</td>
<td>20.82</td>
<td>3.34</td>
</tr>
</tbody>
</table>

role in driving current variability within these inshore waters. In terms of the average momentum balance during the study, the southward-directed pressure gradient was estimated to be roughly as important as the bottom stress term in countering the northward flow. As a consequence, the mean northward flow would be 0.01 m s$^{-1}$ relative to the depth-averaged flow. There are a number of mechanisms that may contribute to the cross-shore current profile including wind-driven Ekman transport, the influence of surface wave-induced mass fluxes, and local interactions with bottom topography. The theoretical (deep water) offshore-directed Ekman transport velocity $U_E$ integrated within an Ekman layer of thickness $\delta_E$ is $U_E = \tau_o / (\rho g \delta_E)$, where $\tau_o$ is the northward wind stress and $f = 0.77 \times 10^{-4}$ s$^{-1}$ is the Coriolis frequency at 32$^\circ$ S. In water depths $h$ of order $\delta_E$ or less, the cross-shore Ekman transport in response to an alongshore wind stress is known to decrease until the flow becomes entirely downwind when $h \approx \delta_E$ (Lentz, 2001). A rough estimate of the local unstratified Ekman layer thickness is $\delta_E \approx 0.4 u_w / f = 30$ m (Cushman-Roisin, 1994), where $u_w = \sqrt{\tau_o / \rho g}$ is the wind surface friction velocity, implying that for Perth's coastal waters where typically $h \approx 10-20$ m, Ekman transport should be substantially reduced from its theoretical limits. But if we still conservatively assume that offshore Ekman transport occurs over the full water column ($\delta_E = h$) then from Table 4 we obtain a theoretical maximum value $U_E \approx 0.05$ m s$^{-1}$ that is much greater than the $\approx 0.01$ m s$^{-1}$ discrepancy that was observed. In reality, any Ekman transport should be substantially reduced from this theoretical maximum value; however, this does suggest that the relatively weak offshore surface transport observed at P3 and P4 could be due to some weakened Ekman transport within the Perth coastal lagoon. Surface root-mean-squared wave heights ranged between only 0.6–1.3 m (averaging 0.9 m) during the summer study period (not shown), which for the average peak wave period of 9 s, predicts that shoreward depth-averaged Stokes drift velocity $U_k$ would be $0.01–0.02$ m s$^{-1}$, which is weak but not negligible. However, the Eulerian flow measured by the ADCPs that is required to compensate this shoreward wave-induced mass transport, should be directed offshore in the bottom of the water column (Lentz et al., 2008), which is in fact opposite to what is observed in Fig. 4a. Finally, the interaction with the alongshore coastally-trapped waves through the study area, which were generated by the migration of a low pressure system on and then off the northwest coast of Western Australia (Fig. 12). These transient events had a major influence on the circulation over a broad coastal region, as revealed within the HF radar data (Fig. 8). For example, within this period there was a broad draining of the Perth coastal lagoon on 19 December (Fig. 8c), whereas only two days later (21 December) the cross-shore flow reversed to flood the coastal lagoon (Fig. 8d). Eliot and Pattiaratchi (2010) examined the role of tropical cyclones on the generation and propagation of coastally trapped waves along the entire ~5000 km Western Australia coast between 1988 and 1998 and on-average identified that 4 strong events occurred each year during the austral summer period (November–January), with heights averaging 0.3 m once they reach Perth (thus comparable to the magnitude of the observations in Fig. 12); however, in some cases these fluctuations historically exceeded 0.6 m. These large coastally trapped waves are typically generated $> 1000$ km north of Perth on Australia’s North West Shelf in one of the most active tropical cyclone regions globally (Nicholls et al., 1998), and thus clearly play an important role in modulating the summer circulation of Perth’s coastal waters. Finally, additional sources of strong subtidal water level and current variability are also likely important, in particular the encroachment of shelf eddies into the coastal zone, which have not been considered here.

We finally note that while the focus of this study has been on the processes that drive the dominant alongshore current variability across the study area, some discussion of the dynamics that may more subtly influence the observed cross-shelf flow structure is provided here. In particular, the current profiles for sites located on the seaward margin of the Perth coastal lagoon (i.e. sites P3 and P4) revealed that the surface current vectors were on average oriented slightly offshore by $\approx 10^\circ$ relative to the depth-averaged flow. There are a number of mechanisms that may contribute to the cross-shore current profile including wind-driven Ekman transport, the influence of surface wave-induced mass fluxes, and local interactions with bottom topography. The theoretical (deep water) offshore-directed Ekman transport velocity $U_E$ integrated within an Ekman layer of thickness $\delta_E$ is $U_E = \tau_o / (\rho g \delta_E)$ where $\tau_o$ is the northward wind stress and $f = 0.77 \times 10^{-4}$ s$^{-1}$ is the Coriolis frequency at 32$^\circ$ S. In water depths $h$ of order $\delta_E$ or less, the cross-shore Ekman transport in response to an alongshore wind stress is known to decrease until the flow becomes entirely downwind when $h \approx \delta_E$ (Lentz, 2001). A rough estimate of the local unstratified Ekman layer thickness is $\delta_E \approx 0.4 u_w / f = 30$ m (Cushman-Roisin, 1994), where $u_w = \sqrt{\tau_o / \rho g}$ is the wind surface friction velocity, implying that for Perth’s coastal waters where typically $h \approx 10-20$ m, Ekman transport should be substantially reduced from its theoretical limits. But if we still conservatively assume that offshore Ekman transport occurs over the full water column ($\delta_E = h$) then from Table 4 we obtain a theoretical maximum value $U_E \approx 0.05$ m s$^{-1}$ that is much greater than the $\approx 0.01$ m s$^{-1}$ discrepancy that was observed. In reality, any Ekman transport should be substantially reduced from this theoretical maximum value; however, this does suggest that the relatively weak offshore surface transport observed at P3 and P4 could be due to some weakened Ekman transport within the Perth coastal lagoon. Surface root-mean-squared wave heights ranged between only 0.6–1.3 m (averaging 0.9 m) during the summer study period (not shown), which for the average peak wave period of 9 s, predicts that shoreward depth-averaged Stokes drift velocity $U_k$ would be $0.01–0.02$ m s$^{-1}$, which is weak but not negligible. However, the Eulerian flow measured by the ADCPs that is required to compensate this shoreward wave-induced mass transport, should be directed offshore in the bottom of the water column (Lentz et al., 2008), which is in fact opposite to what is observed in Fig. 4a. Finally, the interaction with the alongshore

Fig. 12. (a) Position of the center of a low atmospheric pressure system from the 14th to the 20th of December 2010. (b) Subtidal water level time-series recorded at the four coastal stations (see Fig. 1b), showing a propagating coastally trapped wave traveling south (note that an offset of 0.2 m has been added between stations).
flow and topographic variability in the lee of Rottnest Island may also contribute to the generation of secondary flows that may influence the cross-shore flow structure. In general, the processes that control the vertical structure of the cross-shore circulation of inner shelf regions are known to be complicated even along the simplest coastlines (Lentz and Fewings, 2012). The dynamics of the cross-shore circulation on the Perth shelf are likely extremely complex, as they are the product of the transport and mixing processes associated with the strong local wind stresses, the opposing along-shelf pressure gradient, surface wave forcing, and relatively complex topography. To fully elucidate these dynamics will require further study.

4.2. Cockburn sound

The circulation within the relatively deep (~20 m) and partially-enclosed embayment of Cockburn Sound operated distinctly from the other regions of Perth’s coastal waters. Variability in the depth-averaged transport were very poorly correlated (\( R_{\text{wind}} \approx 0.1 \)) with the local wind stresses (Table 2). Instead, periods of relatively strong (~0.1 m s \(^{-1} \)) two-layer exchange flows were regularly observed (Fig. 6c). As a result, the surface and bottom currents were separately much better correlated with the wind (\( R_{\text{wind}} \approx 0.4-0.6 \), Table 3). Interestingly, the role of regional-scale fluctuations of the alongshore pressure gradient also had a substantial influence on these exchange flows (\( R_{\text{vt}} \approx 0.4 \)). The strongest of these were associated to the propagation of a sequence of coastally-trapped waves down the coast (Fig. 6), highlighting the importance of these much larger-scale and remotely-generated shelf processes on the local exchange and flushing of Cockburn Sound.

Historically, some observations of the circulation within Cockburn Sound have been described, based primarily on studies to support industry developments along its eastern shore and broader investigations into its water quality. Steedman and Craig (1983) first described currents in a different season (austral autumn and winter; March-July) at two sites on Cockburn Sound’s southern and eastern shoals (depths < 10 m), as well as measurements from a site in its central basin (located 4 km north of the present site P2). The focus of that study was on the depth-averaged transport. As a result, they described weak currents within the deep central basin of Cockburn Sound (similar to the present study despite the different season), but with much stronger flows within its shallow shoals (typically ~0.1 m s \(^{-1} \)). Since then, a more comprehensive study of the oceanography of Cockburn Sound, including its hydrography, has been described by D’Adamo (2002). That study provided some current observations (two point measurements near the surface and near the bottom) within the central basin of Cockburn Sound, as well seasonal descriptions of its salinity and temperature distributions. During winter months, freshwater discharge from the Swan River ~10 km to the north of Cockburn Sound was found to generate weak buoyancy-driven exchange flows. Although we did not record stratification within Cockburn Sound in this present study, D’Adamo (2002) found that stratification played a negligible role on the summer dynamics (i.e., from November to March) when negligible rainfall historically occurs, and instead suggested wind-driven currents are dominant. Due to the historical lack of detailed current profile observations in Cockburn, the role of depth-dependant flows (including those driven by wind) had not previously been well-documented. Results from the present study reveal that much of the exchange of water between Cockburn Sound and the coastal waters to the north are driven by transient two-layer exchange flows that are forced primarily by local wind stresses, similar to the two-layer exchange flow profiles that are generated by steady wind forcing within narrow, unstratified semi-enclosed or closed water bodies such as in lakes (Hutter et al., 2011). The results also reveal that offshore dynamics that generate large, local alongshore pressure gradient fluctuations can episodically play an important role and reverse the exchange flow within Cockburn Sound.

4.3. Mid and outer shelf

The circulation of the shelf region off Perth (and Western Australia more broadly) has been the most well-studied, due to interest in understanding the dynamics of the Leeuwin Current, a unique poleward flowing eastern boundary current that plays an important role in regulating the climate of Western Australia. While some of the basic features of the Leeuwin Current have been observed for some years (Cresswell, 1980; Gentilli, 1972), the general momentum dynamics were first examined in detail by Thompson (1984), who presented a simple analytical model to describe the seasonal mean (steady-state) momentum balance that included the influence of the alongshelf pressure gradient and wind stresses on the Leeuwin Current’s depth-integrated transport (thus similar to the approach used here). Subsequently, the most detailed observational study of the shelf circulation along the entire west coast of Australia was conducted as part of the Leeuwin Current Interdisciplinary Experiment that is described in Smith et al. (1991). This and subsequent work (e.g., Feng et al., 2003) provided insight into the seasonal cycle of the shelf circulation off Perth and how it is modulated by variability in local wind stresses and the alongshore pressure gradient over seasonal time scales. But the dynamics influenced by higher frequency transient forcing events, and how these influence the circulation of Perth’s shallow coastal waters, have historically received limited attention.

Results from the present study conducted during the summer revealed a relatively weak time-averaged southward (poleward) flow of ~0.1 m s \(^{-1} \) on the outer shelf at site P6 (Fig. 4a; Table 2). These observations are consistent with the Leeuwin Current being weakest during the early-summer (November–January), with surface currents historically reaching much higher values > 0.5 m s \(^{-1} \) during late-summer (April–May). During this summer period, we observed strong alongshore current fluctuations on the shelf, oscillating from 0.3 m s \(^{-1} \) southward to 0.3 m s \(^{-1} \) northward over weekly time scales (Fig. 5c, Fig. 7c). We found that almost none of this variability could be explained by direct local wind forcing (\( R_{\text{wind}} \approx 0.2 \)), with more explained by the large-scale fluctuations in the alongshore pressure gradient (\( R_{\text{vt}} \approx 0.4 \)) (Table 2, Table 3). In addition, while the peak in the alongshore current spectrum on the shelf at P6 had a period of 2 weeks (Fig. 3b), these dynamics have no relationship to the spring–neap cycle of the tide. There was no correlation (\( R < 0.1 \), not shown) between the low-pass filtered alongshore currents and the envelope of the local tidal level record representing the amplitude of the spring–neap cycle, as obtained by applying a Hilbert transform to the data (Emery and Thompson, 2001). This decoupling between the local wind forcing and the alongshore current variability, is consistent with recent observations on the northern Western Australian shelf at 21°S, which showed a similar frequency separation that likely resulted from larger regional-scale interactions of synoptic weather patterns within the deeper ocean (see Lowe et al., 2012). This shift in shelf current energy toward much lower frequencies than the local wind band is also similar to what has been observed on, for example, the Northern California shelf by Largier et al. (1993).

The detailed inspection of the momentum budget on the shelf indicated that the pressure gradient term was up to an order of magnitude larger than the wind stress term, in terms of its influence on the alongshore current variability (Table 4). In other
words, the long wind stress forcing was important to countering the alongshore pressure gradient, but its direct role on current variability on the mid- and outer-shelf was minimal compared to what occurred within the inner shelf and nearshore regions. Finally, much of the remaining, unaccounted for variability in the alongshore currents could be due to presence of offshore mesoscale and sub-mesoscale eddies that are known to be a prominent feature of the Leeuwin Current system. While the processes that drive these complex offshore dynamics and how they encroach onto the shelf will require further study, previous work has shown that the Leeuwin Current has the highest eddy kinetic energy of any eastern boundary current system in the world due to the unusually strong poleward pressure gradient in the region (Feng et al., 2005).

5. Conclusions

These field observations of the summer circulation in the coastal waters off Perth in southwestern Australia have revealed an extremely transient system driven by the opposing unsteady forcing provided by the local alongshore wind stresses and regional-scale alongshore pressure gradients. The response to this forcing varied among different zones across the study region. On the outer shelf, the remote poleward pressure gradient drove a relatively weak southward current, consistent with the presence of a seasonally weak Leeuwin Current during this time of year; however, remotely-generated water level gradients that propagated through the region (e.g., due to the propagation of coastal-trapped waves and perhaps other mesoscale features such as eddies) contributed to the substantial alongshore current variability that was observed on the outer shelf. Within the shallower (<20 m) inshore coastal lagoon region surrounding Perth, local wind stresses instead dominated the alongshore momentum balance, resulting in the alongshore flows responding directly to the ~1 week wind forcing variability associated with synoptic weather systems passing through the region. The persistent opposing alongshore pressure gradient was also identified as playing an important role in reducing the mean northward transport in this coastal region (on average by a factor of 2).

At times, large episodic fluctuations in the alongshore pressure gradient also led to large reversals in both the along- and cross-shore flows within the shallow Perth coastal lagoon region. The depth-averaged flows within the semi-enclosed embayment of Cockburn Sound showed little response to local wind forcing; however, exchange was dominated by a two-layer flow structure that responded strongly to the wind, and on occasion, remotely generated water level fluctuations. Overall, the summer dynamics that were the focus of this study may differ significantly during other seasons, when the northward wind stresses are on average weaker, large storms are frequent, and the Leeuwin Current is much stronger. Further work is required to elucidate the seasonal (and especially the winter) dynamics of Perth’s broader coastal waters.

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