Annual cycling in wind, temperature and along shore currents on the Sydney shelf

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Abstract
The seasonality of coastal wind, temperature and along shore currents on the continental shelf adjacent to Sydney is investigated using more than three years of data. These data were obtained from two moorings (maintained as part of the NSW Integrated Marine Observing System) and a third, in-shore mooring (maintained under contract by Sydney Water). We detected an asymmetrical warming and cooling pattern in the annual cycle of the temperature with gradual heating in summer and rapid cooling. There is a marked difference in the temperature cycle between the interior and at depth. The annual cycle in the along shelf currents and wind explained less than 5 % of the variability. We discuss the merit of two different regression models used in the analysis and their ability to fit the annual cycle in the data. Off the coast of Sydney, the impact of warm core and cold core eddies on the shelf reduces the variability that is explained by the annual cycle in the observed signal. Furthermore, we have identified a non-stationary process with a period of peak energy between 90 and 120 days in the along shelf currents. This corresponds to the period that eddies are shed from the East Australian Current indicating a link between eddy formation and interaction with the continental shelf in the Sydney region.

Keywords: East Australian Current, western boundary current, shelf processes, Integrated Marine Observing System.

1. Introduction

Seasonality affects the dynamics on the continental shelf due to changes in heating and cooling and wind regimes. The purpose of this study is to describe the structure and timing of the annual cycles in coastal wind, temperature and along shore currents on the continental shelf adjacent to Sydney, Australia.

The dynamics on the continental shelf adjacent to Sydney are strongly influenced by the East Australian Current (EAC), a strong western boundary current. The EAC has been shown to exhibit seasonality, being faster and lying closer to the shelf in summer compared with winter [9]. It separates from the shelf upstream of Sydney in a zone between 30˚S to 34˚S [5]. Downstream of its separation zone, large eddies are formed which may encroach on the shelf affecting temperature and currents [11].

Investigations on this shelf to date have largely been short-term process studies. The introduction of a mooring array across the shelf by the NSW Integrated Marine Observing System (NSW-IMOS) since June 2008 has now allowed investigations into low-frequency time scales possible. In this study we focus on the variability explained by annual harmonics vertically and across the shelf downstream of the EAC separation zone.

2. Methods

2.1 Study site and in-situ observations

Three moorings are located off the coast of Sydney (34˚S) (Figure 1). The mooring closest to shore, ORS065 is maintained by Sydney Water Corporation and is located in nominally 65 m of water. It was first deployed in November 1990, however in May 2006, it was re-configured to include an upward facing acoustic Doppler current profiler (ADCP).

The additional moorings, SYD100 and SYD140, were deployed in June 2008 by NSW-IMOS.

At each site, an upward facing ADCP and thermistor string collects current and temperature data respectively every 5 minutes at least 8 m through the water column. All data was quality controlled using the IMOS ToolBox version 2.1 (http://code.google.com/p/imos-toolbox/) as is available through the IMOS portal (imos.aodn.org.au/imos).

We used hourly wind observations from Kurnell (located 15.3 km from the mooring array) provided by the Australian Bureau of Meteorology. Observations from this location are similar to those observed directly over the coastal ocean in this location [13]. Wind stresses were calculated using the method provided by Gill [4] as per Wood *et al.* [13].

The 5 minute temperature and current observations were box-averaged to hourly. Wind, temperature and current data were low-passed filtered [1] to obtain a 6 hourly average. Wind and current data were rotated along their calculated principle axis to give along shore and across shore components. These were well aligned with the topography at each site.

2.2 Fitting of harmonic regression models

Two harmonic regression models were used. The first, designated HR-S87 [10] includes both an annual and semi-annual cos curve

$$A(t)=A_0+A_1 \cos(\omega t-\theta_1)+A_2 \cos(2\omega t-\theta_2) \quad (1)$$

where A(t) is the variable at time t, A_0 is the annual mean value, A_1 and A_2 are the amplitudes of the annual and semi-annual harmonics, ω is the annual frequency ($2\pi/365.25$) and θ_1 and θ_2 are the phases corresponding to the maxima in the cycles. This harmonic was used to fit the temperature observations.

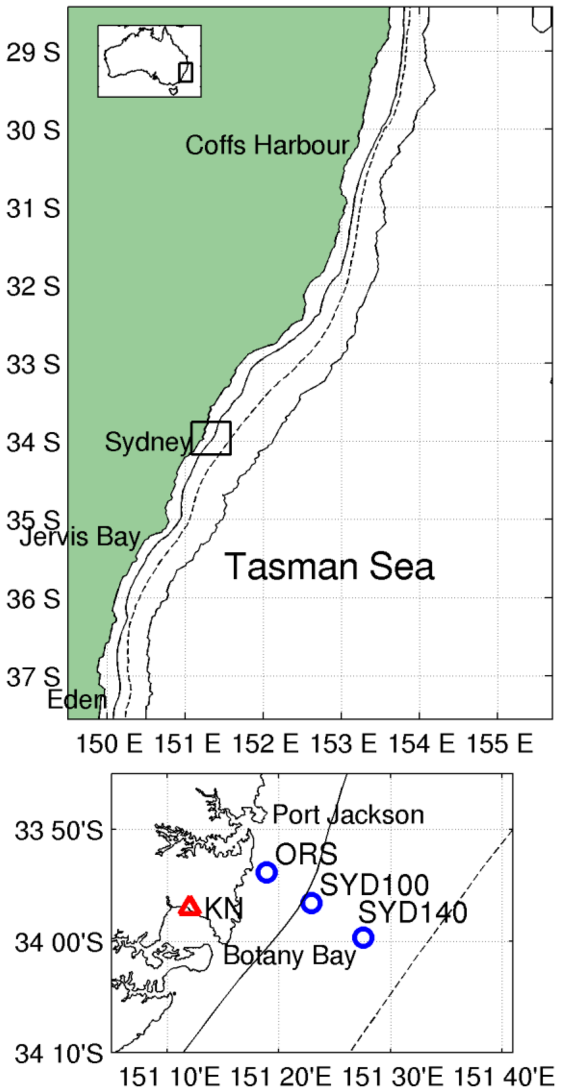

Figure 1 Map of the study site. The location providing wind is indicated by a red triangle and the locations collecting current and temperature are indicated by the blue circles. The solid line on the zoomed in map shows the 100 m isobath and the dashed line is the 200 m isobath.

The second harmonic model, HR-L08 [6], only includes the annual harmonic

$$A(t)=A_0+a \sin(\omega t)+b \cos(\omega t) \quad (2)$$

with calculation of the associated amplitude and phase of the annual cycle. We calculated the variance explained by each model and the significance of the fit using the method provided by Strub *et al.* [10]. This harmonic was used to fit the along shore wind and current observations.

2.3 Wavelet analysis

Hourly filtered data were used to calculate the wavelet analysis using a Morlet wave using the MATLAB program provided by Torrence and Compo [12].

3. Results

3.1 Annual variability

3.1.1 Temperature

The water column temperature shows a strong annual cycle (Figure 2). At the surface the water is warmer in-shore compared with the shelf break, while at depth the opposite is true. A strong asymmetry is apparent in the water temperature closer to the surface with a gradual warming through the austral summer followed by a rapid cooling. At the sea floor, the annual cycle tends to be more symmetrical, particularly at the shelf break (SYD140). The temperature observations near the sea floor for the ORS065 and SYD100 tend to have a short peak in winter and a long flat trough during summer. We attribute this to steady cold water intrusions which occur more frequently in the summer [7].

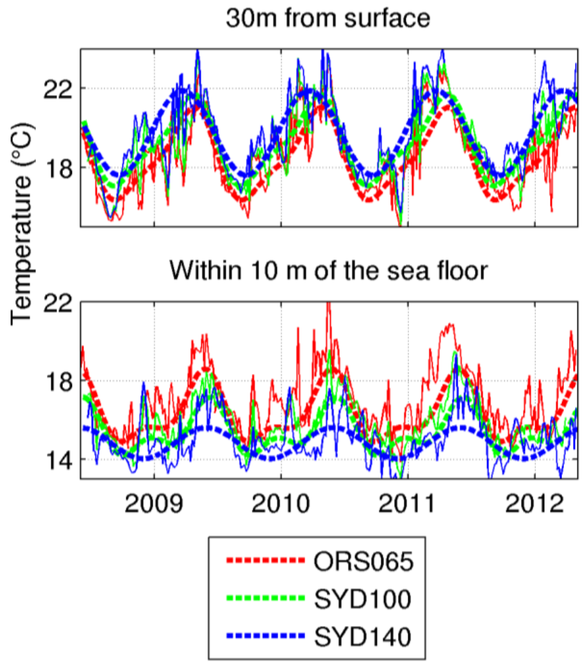

Figure 2 Time series of temperature at each mooring across the shelf with the dashed line indicating the fit using HR-S87 and the solid line being a 5 day average of the data. There is an obvious asymmetry in the temperature cycle at 30 m from the surface, while the temperature cycle within 10 m of the sea floor is more symmetrical. At depth the cooler temperatures occur during the summer which is a consequence of cold water intrusions.

The amplitude of the seasonal variability is smaller at the shelf break (SYD140) compared with the moorings closer to shore (SYD100 and ORS065) at depths below 40 m (Figure 3 Top). The phase

changes with depth with the maximum occurring in mid March at SYD140 near the surface.
The maximum temperature near the sea floor lags the interior temperature by three months for SYD140. Inshore the maximum temperature occurs later in the year at SYD100 and ORS065 (April) (Figure 3 Middle).
One particular feature is the rapid phase shift from the surface to 60 m (for every 8 m change in depth the phase change more than 7 days at SYD140). At depths greater than 60 m the lag is reduced to between 0 to 4 days at SYD140. This pattern is also replicated at the moorings closer to the coast (SYD100 and the ORS065) (Figure 3 Middle).
Near the surface to depths of around 60 m, external heating (solar) during summer, here and further north, gradually stratifies the water column. This causes the observed lag in the timing of the maximum temperature.

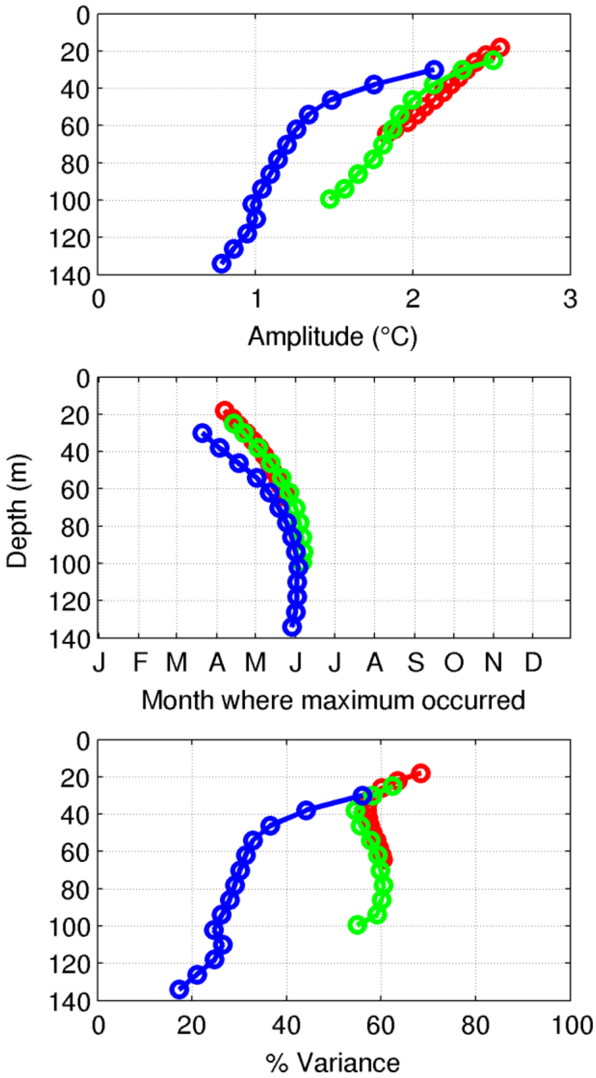

Figure 3 The statistics of fit for the amplitude (top), phase/month where the maximum occurred (middle) and the percentage of variability explained by the harmonic (HR-S87) (bottom) with the same colour scheme as for Figure 2. Note the rapid phase shift in the time of year where the maximum temperature occurred with depth less than 60 m compared to depth greater than 60 m.

This indicates a two layer system with different mechanisms driving these seasonal cycles.

At depths below 60 m, we suggest that solar heating is not a dominate mechanism for heat transfer. Rather that these waters are affected by advection of water either along or across the shelf (through upwelling or downwelling) and cycle together indicating the seasonality of the bottom boundary layer.
In the surface waters the variability explained by the harmonic is highest explaining about 60 % of the variability at 30 m depth. This is consistent across the shelf. At the shelf break (SYD140), the variability explained by the harmonic reduces considerably with depth. At the ORS065 and SYD100, the variability explained by the annual harmonic initially reduces with depth but then increases close to the sea floor. This is a result of the regularity of the cold water intrusions at the bottom and the heating at the surface. The middle depths may at times be affected by both the heating from the surface and the cold water intrusions (depending on their strength), and thus the annual cycle is weaker due to the different timing of the maxima for temperature for these two processes.

3.1.2 Along shore wind and current

Compared with the temperature, there is much greater variability in both the along shore wind and current observations (Figure 4). The annual cycle in the along shore winds is equatorward in winter (downwelling favourable) and poleward (upwelling favourable) in summer. During summer, north easterly (poleward) wind events are often observed, while the flow tends to be westerly (towards the east) in winter. Southerly (equatorward) wind events also occur in winter causing the observed pattern of the winds oscillating between poleward and equatorward.
The harmonic fit for the along shore currents indicates them to be always poleward flowing at all depths and across the shelf. There are times of current reversals allowing equatorward currents [8], however these are usually short term events. Thus the annual harmonic consists of weakening and strengthening poleward flowing currents. The currents near the surface are stronger at sites closer to the shelf break (SYD140) and weaker closer to the coast. At depth, the currents tend to be around the same magnitude across the shelf.
The mean flow near the surface at SYD140 is greater than 0.2 m s^{-1} poleward. The amplitude of the annual cycle is approximately a quarter of the mean flow near the surface and decreases with depth at SYD140.
Closer to the coast, both SYD100 and the ORS065 have a maximum amplitude at approximately the middle of the water column. The variability explained by the harmonic is also greatest at this depth. This could be because, at shallower depths, other processes such as surface waves and wind

driven effects are increasing the variability in the along shore currents.

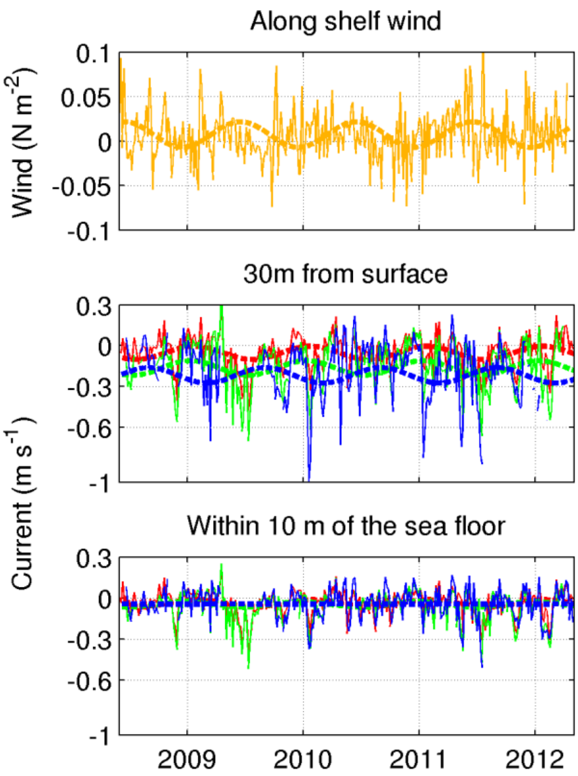

Figure 4 Time series of along shore wind and along shore current at each mooring across the shelf with the dashed line indicating the fit using HR-L08 and the solid line being a 5 day average of the data using the same colour scheme as in Figure 2. The annual cycle in the wind oscillates between poleward and equatorward, while the annual cycle in the current consists of a strengthening and weakening poleward current. Equatorward currents occur, but tend to be observed for only short periods hence poleward currents dominate the flow.

There is a phase shift between the month of the maximum poleward currents between the shelf break mooring (SYD140) and the mid shelf mooring (SYD100 and the ORS065). At the shelf break (SYD140), the poleward maximum in the along shore currents occurs during the austral summer. This coincides with the reported seasonality of the EAC being faster in summer [9]. The maximum poleward flow in the wind also occurs in the austral summer leading the poleward flow in the shelf break (SYD140) currents by two months. This could also be contributing to the annual cycle at SYD140.

Closer to shore, the annual cycles in the along shore currents at SYD100 and the ORS065 show a strengthening poleward flow in the austral winter.

Finally it is important to note that the variability explained by the annual cycle is very low (less than 5 % for the along shore winds and currents). Therefore the annual time scale is not a dominant period of variability for the wind and currents on the continental shelf adjacent to Sydney.

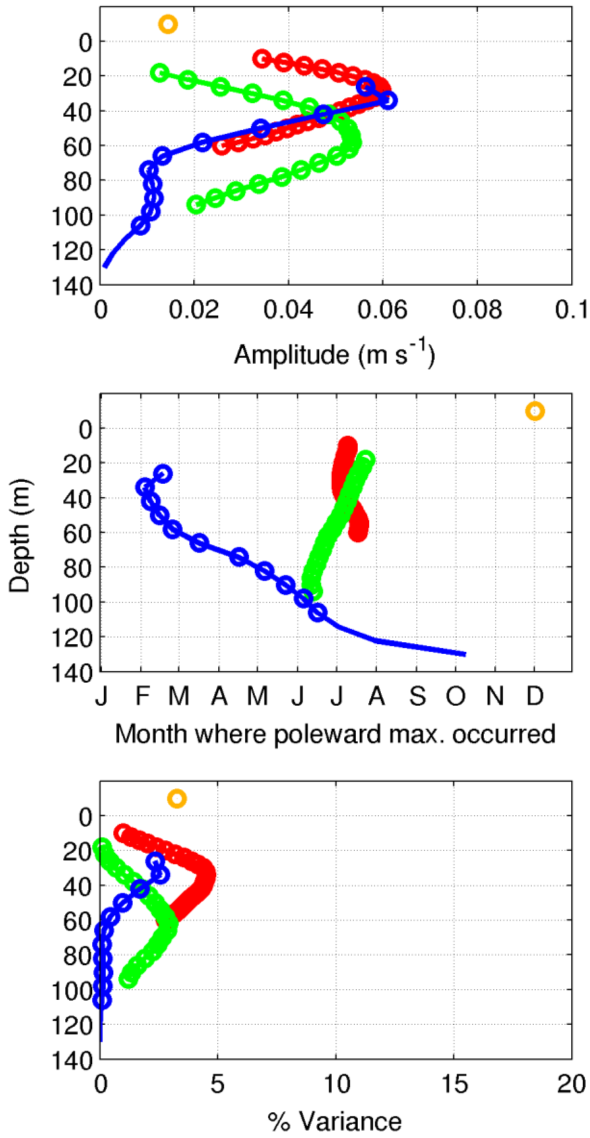

Figure 5 The statistics of fit for the amplitude (top), phase/month where the maximum poleward flow occurred (middle) and the percentage of variability explained by the harmonic (HR-L08) (bottom) with the same colour scheme as for Figure 2 and with the along shore wind indicated by the orange circles at the top of each plot (for amplitude the unit of the wind is N m^{-2}). The annual harmonic explains only a small amount of the variability in both the along shore wind and current observations across the shelf. This is due to the influence of eddies which encroach on the continental shelf downstream of the EAC separation zone affecting the circulation.

3.2 Identification of a non-stationary process

Since the annual cycle only explained a small amount of the variability on the shelf, we investigated other periods of variability using wavelet analysis. The advantage of wavelet analysis is that it can uncover non-stationary (*ie.* processes that may act on varying time scales) patterns.

Energy appears at all periods between 30 to 365 days in the along shore currents at each location across the shelf (Figure 6).

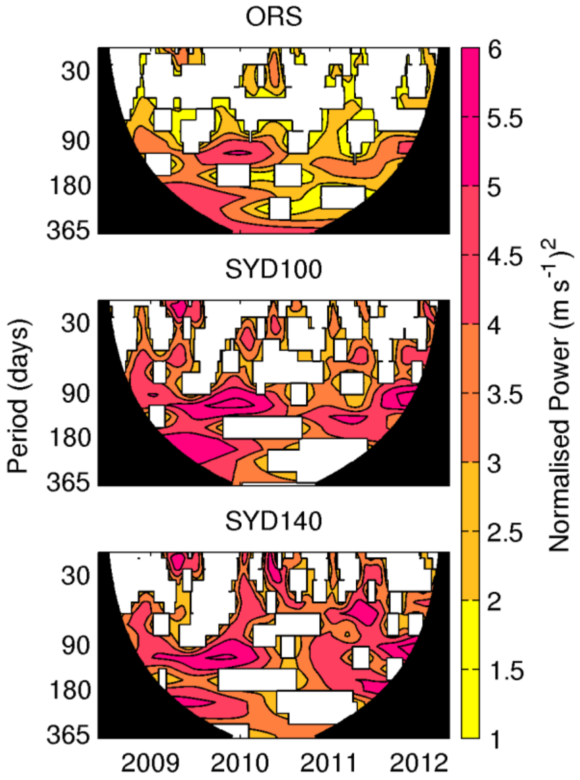

Figure 6 Wavelet spectra for the along shore currents. Energy appears at many different periods, however there always energy within the 90 to 180 day period. This range is further narrowed down in Figure 7.

The energy is stronger at the shelf break (SYD140) compared to the moorings closer to the coast (SYD100 and the ORS065). Taking SYD140 as an example of how to interpret the wavelet output in Figure 6, we see that there is a band of high spectral energy between the periods of 90 to 180 during 2009 and into 2010. This means that a signal is observed in the along shore currents with a period that varies between 90 and 180 days The energy becomes less during the end of 2010, but is then stronger in 2011 and the beginning of 2012. There is a band of energy for each mooring between 90 to 180 days indicating that there may be an irregular process occurring at this period. The global wavelet spectrum highlights the important periodicities and allows us to focus on the spectral band(s) at which energy is present across the whole time period (Figure 7).
Here a strong peak is observed at SYD100 and SYD140 with a period of 93 to 122 days. An additional peak is also apparent at 187 days for SYD100 and SYD140. We suggest that these energy peaks are related to the occurrence of EAC eddies encroaching on the shelf and their inshore research.

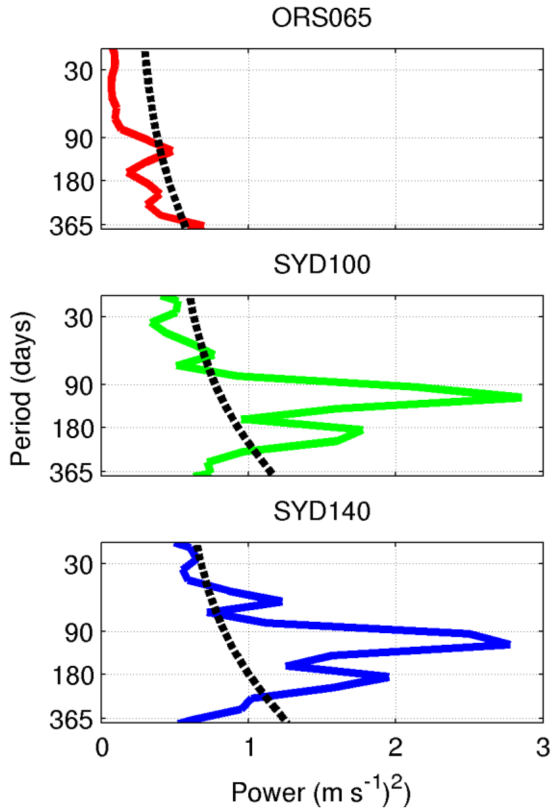

Figure 7 Global wavelet spectrum where the solid line indicates the spectral energy and the dashed line indicates the significance at the 98 % confidence level. There is strong energy at the period of 93 to 122 days at SYD100 and SYD140. This indicates a non-stationary process to be occurring at this period.

4. Discussion

4.1 Seasonality on the shelf

The seasonality in the temperature was much higher than the along shore currents and winds. We found that the seasonality of the surface temperature differed from the seasonality of the temperatures near the bottom of the water column. We suggest that heating in the surface waters (and gradual stratification of the water column) drives the seasonality in temperature in the interior to upper part of the water column. In the bottom temperatures, advection through upwelling controls the seasonal cycle. This theory fits with the observed seasonality at depth. During summer, there are cooler waters at the bottom caused by cold water intrusions on the shelf which tend to occur more often in summer on the Sydney shelf [7]. During winter this upwelling is reduced and hence the bottom temperatures increase.
Sydney is downstream of the EAC separation zone within a region where eddies are the dominant feature that influence circulation on the shelf [3]. Studies conducted in the separation zone of the EAC have identified eddy shedding to occur at periods of 90 to 180 days [2]. This coincides with the periodicity that we found in the along shore currents. This is the first time the influences of

eddies on the shelf has been linked directly to the shedding of eddies from the EAC.

4.2 Selection of an appropriate harmonic regression model

Two harmonic regressions models were used in this study; HR-S87 was constructed with an annual and semi-annual harmonic while HR-L08 used only an annual harmonic. In this region, HR-S87 was much better at describing the seasonal cycle in temperature. This is because the addition of the semi-annual harmonic allowed for a fit to the asymmetrical warming and cooling that was observed on the shelf. HR-L08 is unable to isolate this pattern due to the mathematical symmetry of the model. In the temperature observations, the amplitude of the semi-annual harmonic was always less than the amplitude of the annual harmonic (data not shown) and hence the annual process is still discernible from the fit.

We found that when using HR-S87, if the amplitude of the semi-annual model is the same or higher than the annual amplitude, then the interpretation of the annual cycle becomes unclear. This happened when we applied this regression model to the along shore currents causing multiple peaks and troughs within one year which were difficult to relate to a physical process (data not shown). Using HR-L08 (with only the annual harmonic) the, albeit weak, seasonal pattern is more easily detected.

5. Conclusions

The following conclusions are drawn from this study:

- We propose differing mechanisms to account for the differences in the seasonal cycles in the temperature between the interior and at depth;
- We identified a non-stationary processes with a period of 93 to 122 days which influences the along shore currents on this shelf. This period is consistent with the period that eddies are shed from the EAC indicate a link between eddy shedding and encroachment on the continental shelf downstream of the separation zone; and
- Using an annual harmonic only is useful in identifying a weak annual signal. The addition of a semi-annual harmonic highlights asymmetry in a time series with a strong annual cycle.

6. Acknowledgements

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