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Seasonal variability in the continental shelf waters off southeastern Australia: Fact or fiction?

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ABSTRACT

Seasonality is an important timescale driving variability in the waters of many continental shelf regions globally. Along the east coast of Australia, it has been recognised that the East Australian Current (EAC), the Western boundary current (WBC) of the South Pacific gyre, warms and strengthens in the Austral summer. Thus it has been hypothesised that shelf currents also warm and strengthen (poleward) annually. However, the EACs highly dynamic nature results in large variations in the latitude of separation from the coast and eddy shedding. Until recently the lack of long term in-situ observations on the shelf has precluded a study into low frequency (seasonal) variability in shelf circulation. Using at least 3 years of moored *in situ* temperature and velocity observations we investigate low frequency variability in shelf waters at 2 cross-shelf locations (i) upstream and (ii) downstream of the typical EAC separation latitude. The local winds vary bi-modally upstream and tri-modally downstream varying with the passage of fronts, thus do not drive a seasonal response in the circulation. Harmonic analysis of the velocity and temperature fields shows that upstream of the separation zone, only 6% of the velocity variability occurs on the seasonal timescale, compared to 49% of the temperature variability. Cross shelf temperature gradients and vertical velocity shear increase in summer with an increase in poleward heat advection in the EAC. Downstream of the separation point the influence of episodic eddy encroachments precludes seasonality in the vertical structure of the flow despite an annual cycle in the stratification. The seasonal cycle in temperature moves out of phase with increasing depths, with maxima (minima) in March (September) at 30 m compared to maxima (minima) in May (November) at the bottom. This is expected to have a large influence on the timing of nutrient injection onto the shelf, and thus phytoplankton species composition and abundance.

1. Introduction

Seasonal changes have been shown to have large influences on the waters of continental shelf regions. Processes such as annual heating and cooling, freshwater input through seasonal changes in rainfall and seasonal wind regimes have been shown to cause changes in the circulation and hydrography on the shelf in coastal regions (Amorim et al., 2012; Davis et al., 2013; Rennie et al., 1999).

The continental shelf of southeastern Australia is generally narrow, dropping to a depth of 4000 m often within 25–100 km of the coast (See Fig. 1). It is flanked by the EAC (the WBC of the South Pacific sub-tropical gyre), which flows along the eastern coast of Australia. The EAC tends to hug the continental slope north of 30° S periodically encroaching on the shelf (Roughan and Middleton, 2004; Schaeffer et al., 2013, 2014a) and separating from the coast around 31–32°S (Cetina-Heredia et al., 2014). Downstream of the separation zone, both warm and cold core eddies are formed (Everett et al., 2012; Mata et al., 2006). These eddies dominate regional circulation patterns and encroach on the shelf, driving cross-shelf water mass exchanges on the continental shelf (Cresswell, 1994; McClean-Padman and Padman, 1991; Schaeffer et al., 2013, 2014a).

Studies have shown that the EAC has a seasonal cycle; being stronger in summer compared to winter (Godfrey et al., 1980; Hamon et al., 1975; Ridgway and Godfrey (1997). Whether or not this leads to seasonality in the shelf circulation adjacent to the EAC has not previously been examined. Ridgway and Godfrey (1997) found a seasonal pattern in the transport of the EAC between 25

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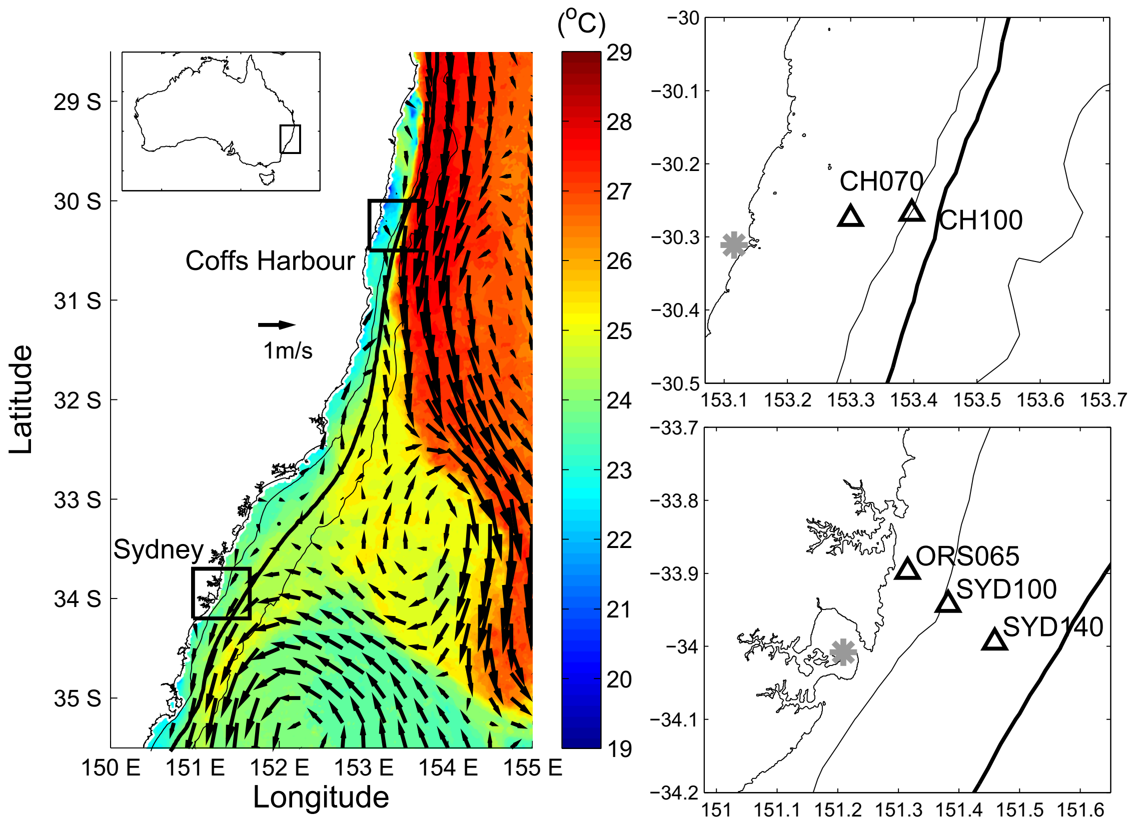

Fig. 1. Map of the study site. The black triangles indicate the location of the moorings measuring temperature and velocity. The grey stars show the location of the two wind stations. Super imposed on left panel is AVHRR L3S satellite sea surface temperature (colour) and velocity (arrows) from the 19th February 2010 (14 day composite) which shows the fast flowing warm EAC waters adjacent to Coffs Harbour and a large warm core eddy just south of Sydney. The coastline, 100 m, 200 m (bold) and 2000 m isobaths are also indicated.

to 45°S by investigating offshore steric heights derived from expendable bathythermograph data and historical hydrography. They used vertical profile observations of temperature and salinity to show that the EAC has a stronger poleward flow in the austral summer. They also showed that the EAC is broader in winter and then narrows in summer lying closer to the continental shelf with a strong return flow offshore (Ridgway and Godfrey, 1997).

Previous studies in this narrow (approximately 30 km wide) shelf region have shown faster poleward along-shelf currents on the continental shelf in summer compared with winter based on ship drift observations (inferring current velocities) between 25 and 38°S from 1854 to 1938 (data in the atlas Sea Areas Around Australia by the Nederlands Meteorologisch Instituut (1949) shown in Godfrey et al. (1980)). This was also confirmed by ship board currents taken upstream of the separation zone (27 to 32°S) at a mean distance offshore of 19 km over 18 months from in 1971 to 1973 (Hamon et al., 1975). However, recent work by Schaeffer et al. (2014b) used a 4 year time-series of moored observations at 5 min intervals in 65–140 m of water to show that EAC-driven bottom cross-shelf transport shows a quasi-periodical signal at a frequency of 90 (110) days upstream (downstream) respectively.

In terms of hydrography, seasonal variation on the continental shelf has previously been investigated by Malcolm et al. (2011) (upstream) and Hahn et al. (1977) (downstream) who both found a strong seasonal cycle in *in situ* temperatures. Downstream of the EAC separation zone, a suite of hydrographic parameters have been collected from two long term hydrographic stations located south of Sydney (Port Hacking) with seasonal and decadal processes identified in the temperature and biogeochemical fields (Hahn et al., 1977; Thompson et al., 2009).

Apart from the above mentioned studies, the waters of the continental shelf of southeastern Australia have been the subject of several short term (approximately one year or less) observational process studies (e.g., Church et al. (1986); Huyer et al. (1988); Griffin and Middleton (1991); Gibbs et al. (1998); Roughan and Middleton (2002, 2004)) or longer term studies using spatially limited hydrographic data (e.g., Newell (1966); McClean-Padman and Padman (1991); Thompson et al. (2009); Malcolm et al. (2011)). Many of the short term process studies were conducted during the austral spring and summer since it was expected that shelf currents are stronger in summer (Tranter et al., 1986). One example of the longest observational study, prior to 2008, was the Australian Coastal Experiment (Freeland et al., 1986). This 7 month experiment was designed to capture observations of coastal trapped waves with three mooring arrays collecting velocity data deployed at varying latitudes between September 1983 and March 1984 (Freeland et al., 1986). However a monthly breakdown of the data to determine seasonality was not undertaken. Furthermore, the point current meter moorings were deployed at the shelf-break (~140 m) and shelf slope (200 to 2000 m) rather than focusing on the continental shelf as is done here.

In 2008, the New South Wales node of the Australian Integrated Marine Observing System (IMOS) deployed two mooring arrays on the continental shelf of southeastern Australia upstream and downstream of the EAC separation zone. These mooring arrays provide an unprecedented dataset in temperature and current velocity, both upstream and downstream of the EAC separation zone. This dataset has brought new insight into the cross-shelf transport dynamics and the influence of the EAC in driving cold dense water uplift (Schaeffer et al., 2013, 2014a; Schaeffer et al.,