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A continental shelf scale examination of the Leeuwin Current off Western Australia during the austral autumn–winter

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A B S T R A C T

A continental shelf scale survey from 22°S to 34°S along the Western Australia coast provides the first detailed synoptic examination of the structure, circulation and modification of the southward flowing Leeuwin Current (LC) during the late austral autumn–early winter (May–June 2007). At lower latitudes (22°S–25°S), the LC was masked within a broad expanse of warm ambient surface water, which extended across the shelf and offshore before becoming constrained at the shelf break and attaining its maximum velocity of ~1.0 m s^{-1} at 28°S. The temperature and salinity signature of the LC experienced substantial modification as it flowed poleward; surface temperature of the LC decreased by ~5.25 °C while surface salinity increased by ~0.72, consistent with climatology estimates and smaller (larger) for temperature (salinity) than those found during summer. Subsequently, LC water was denser by ~2σ_T in the south compared to the north, and the surface mixed layer of the LC revealed only a small deepening trend along its poleward trajectory. Modification of the LC resulted from a combination of mixing due to geostrophic inflow and entrainment of cooler, more saline surrounding subtropical waters, and convective mixing driven by large heat loss to the atmosphere. Air–sea heat fluxes accounted for 50% of the heat lost from the LC in the south, whilst only accounting for 25% in the north, where large geostrophic inflow occurred and the LC displayed its maximum flow. The onshore transport was characterised by distinct jet-like structures, enhanced in the upper 200 m of the water column, and the presence of eddies in the vicinity of the shelf break generated offshore transport.

1. Introduction

Upper-ocean circulation in the southeastern Indian Ocean off Western Australia (WA) is driven by the Leeuwin Current (LC) system that consists of the near surface flow of the LC, the deeper flow of the Leeuwin Undercurrent and variable coastal (Capes and Ningaloo) currents (Cresswell and Golding, 1980; Thompson, 1984; Cresswell, 1991; Woo et al., 2006; Batteen et al., 2007; Rennie et al., 2007). The LC is an atypical eastern boundary current and transports warmer, lower-salinity tropical waters poleward (Pearce, 1991; Feng et al., 2003; Ridgway and Condie, 2004). Maximum poleward flow by the LC is reached during the austral autumn–winter (May–July) and there is distinct interannual variability associated with El Niño Southern Oscillation (ENSO) events; the volume transport of the LC is greater during La Niña years than during El Niño years (Feng et al., 2003). Corresponding with its peak transport in autumn–winter, the LC is highly energetic and characterised by numerous mesoscale features such as meanders, filaments and eddies. The LC is reported to have the highest eddy kinetic energy amongst all the midlatitude eastern boundary currents (Feng et al., 2005).

The seasonal properties and distribution of water masses and circulation in the LC off the coastline of WA were examined in the Leeuwin Current Interdisciplinary Experiment (LUCIE) during 1986–1987 (Church et al., 1989; Smith et al., 1991). Later, from shipboard observations during the austral spring and summer, Fieux et al. (2005), Woo et al. (2006) and Woo and Pattiaratchi (2008) detailed the different water masses and current systems over the shelf and offshore, including the tropical LC. Generally, the signature of the LC waters is gradually modified, becoming cooler and more saline along its southward trajectory as a result of geostrophic inflow of offshore waters and air–sea heat and freshwater fluxes. These studies also described the dynamical signature of the LC in terms of its depth and width, as well as experiencing periodic acceleration and deceleration, and directional changes in response to alongshore wind stress and variable shelf and bottom topography. In the austral summer, water

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masses are strongly influenced by localised upwelling and downwelling events mainly due to fluctuations in northward wind stress and interaction between the LC and regional wind-driven shelf currents, such as the Capes and Ningaloo Currents (Woo et al., 2006). However, during the autumn–winter, the LC is the dominant current of the system, often flooding the shelf where these seasonal shelf currents are generally found.

The strength of the LC and its eddies are intimately linked to evaporative heat loss, upper ocean mixing and nutrient fluxes, but the mechanisms which contribute to variability of biological production off WA are yet to be determined (Feng et al., 2007, 2009; Paterson et al., 2008). Thompson et al. (2011) have shown that seasonally enhanced primary production off WA during autumn–winter is driven largely by circulation of the LC. Specifically, by vertical mixing, which is facilitated by an increase in the density of the LC due to entrainment and cooling along its trajectory. Such mixing was shown to be an important mechanism for delivering nutrients, derived from a narrow high nitrate layer located below the LC, to the surface mixed layer (Thompson et al., 2011). They found this layer to range in depth from ~85 m in the north (22°S–25°S) to 100–150 m further south (29°S–30°S). This supports Hanson et al. (2005) who stated that the shelf break is an area of enhanced mixing and/or current shear which can facilitate nutrient fluxes into the euphotic zone from deeper (70–150 m depth) high nitrate layers to the base of the mixed layer.

This study presents a detailed synoptic, continental shelf scale survey of the LC between 22°S–34°S during the late autumn-early winter (May–June) in 2007 to describe the modification of its physical and chemical characteristics and compare with similar observations during the austral spring-summer period. Except for some earlier measurements during LUCIE, there is currently no comparative examination of the LC at this latitudinal scale or level of detail in the austral autumn–winter, a period when the LC is most energetic and dominates the oceanography off most of the WA coast. Shelf currents and the northward Leeuwin Undercurrent are not analysed in this study due to the general absence of shelf currents during this time of year, and underway velocity data only extending to ~300 m. An eddy-resolving, hydrodynamic model is also examined over the same period to facilitate in smoothing and/or completing gaps in the instantaneous survey data.

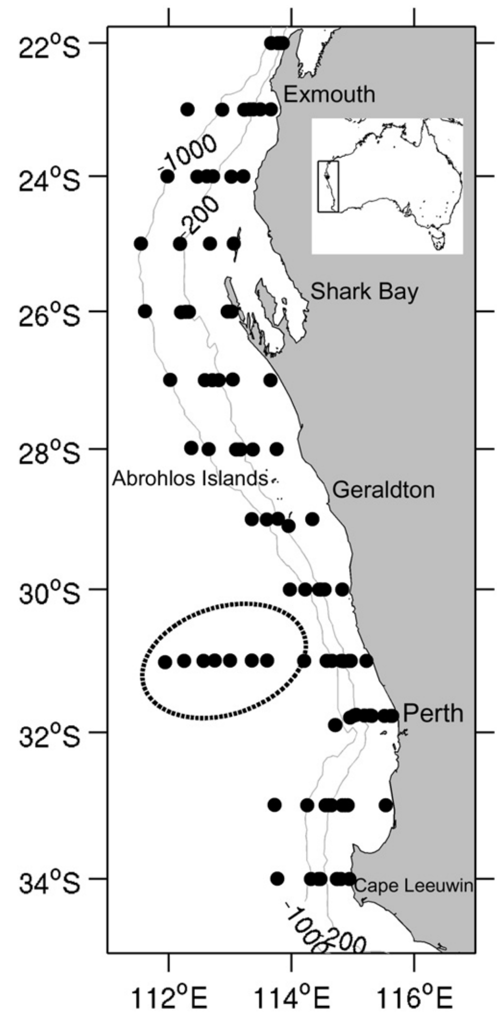

Fig. 1. Continental shelf region of Western Australia, showing the location of sampling stations (black circles) surveyed in May–June 2007. The ellipse represents the approximate position of an anticyclonic eddy, which was surveyed as part of the study. Also shown are the 200 m and 1000 m bathymetric contours.

2. Methods

2.1. Study area and sampling design

A multidisciplinary research voyage aboard the R.V. *Southern Surveyor* (SS04/2007) surveyed 13 cross-shelf transects, working from south to north at every degree of latitude between 34°S and 22°S off the WA coast, from 16 May to 5 June 2007 (Fig. 1). Each transect was surveyed from the 50 m to 2000 m isobaths. Major sampling stations were set at specific depth contours (50, 100, 300, 500, 1000 and 2000 m isobaths) and a suite of oceanographic and biological measurements were carried out. Opportunistic sampling of a developing anticyclonic eddy, located approximately 200 km offshore between 30°S–32°S was performed along a seaward extension of the 31°S transect beyond the 2000 m contour from 21–23 May (Fig. 1).

2.2. Remote sensing

Synoptic patterns of the surface oceanography, development of an anticyclonic eddy and chlorophyll *a* distributions off WA corresponding with the period of field investigation were evaluated using remote sensing products. Single day, snapshot sea surface temperature (SST) images (Group for High-Resolution SST, GHRSST) were supplied by the Australian Bureau of Meteorology facility (http://aodaac2-cbr.act.csiro.au:8080/opendap/imos/) with a resolution of 1 km. Surface chlorophyll *a* images (Moderate Resolution Imaging Spectroradiometer, MODIS, on EOS Aqua) of 4 km resolution were acquired from the NASA Ocean Colour website (http://oceancolor.gsfc.nasa.gov/). Sea surface height anomalies based on the combined TOPEX Poseidon (Jason-1) and ERS-1/ERS-2 (Envisat) satellite missions, obtained from CLS Space Oceanography Division (Le Traon et al., 1998; Ducet et al., 2000), were also used to monitor the LC and its variability associated with its mesoscale structures.

2.3. Underway measurements

Continuous underway measurement of the horizontal velocity along the ship's track was obtained using a vessel-mounted RDI 150 kHz Broadband Acoustic Doppler Current Profiler (ADCP). The instrument was set to record from just below the surface to a maximum water column depth of 300 m and data were averaged in 8 m depth bins. Meteorological conditions (e.g. wind speed and direction, atmospheric pressure) were also measured by shipboard instrumentation during the voyage. The mean daily air–sea