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Research papers

Observations of the shelf circulation dynamics along Ningaloo Reef, Western Australia during the austral spring and summer

Jiangtao Xu [a,b,*], Ryan J. Lowe [b,c,d], Gregory N. Ivey [a,b], Nicole L. Jones [a,b], Richard Brinkman [e]

[a] School of Civil, Environmental and Mining Engineering, University of Western Australia, Crawley, Australia
[b] The UWA Oceans Institute, University of Western Australia, Crawley, Australia
[c] School of Earth and Environment, University of Western Australia, Crawley, Australia
[d] ARC Centre of Excellence for Coral Reef Studies, University of Western Australia, Crawley, Australia
[e] Australian Institute of Marine Science, Townsville, Queensland, Australia

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A B S T R A C T

The dynamics of the three-dimensional circulation on the shelf off Ningaloo Reef in Western Australia were investigated using observations from two field experiments (Nov 2009–Jan 2010 and Sep 2010–Nov 2010). The observations revealed an onshore geostrophic flow of $\sim$0.015 m s^{-1} along the relatively straight Ningaloo Peninsula, coinciding with a substantial poleward increase of the along-shelf flow along this short (~60 km) section of coast. The cross-shelf transport analysis distinguished between two cross-shelf advection scenarios prevalent along this coast: 1) a transient coastal upwelling scenario when the offshore surface Ekman transport was replenished by an onshore transport, supplied mainly from the interior of the water column due to the combined effects of the mild stratification and steep continental slope; and 2) a downwelling scenario when offshore bottom boundary layer Ekman transport occurred, associated with a deeper pressure-gradient driven flow. A detailed along-shelf momentum balance indicated that there was a southward increase in the along-shelf pressure gradient from the northern limit of the Ningaloo Peninsula (the North West Cape), which explains the increase in the along-shelf flow down the coast. The results indicate that the Ningaloo shelf can be considered as one of the important formation regions of the poleward Leeuwin Current which, while very weak on Australia North West Shelf, is the dominant current feature south of Ningaloo and along the remaining southwestern Australia coast.

1. Introduction

The physical oceanography of the shelf waters offshore Ningaloo Reef (hereinafter referred to as the 'Ningaloo shelf'), located near the North West Cape of Western Australia (Fig. 1), is characterized by sporadic coastal upwelling events (Lowe et al., 2012; Rossi et al., 2013b; Xu et al., 2013) that are thought to contribute to this region's higher rates of pelagic production compared with most other Western Australian coastal regions to the south (Furnas, 2007; Hanson et al., 2005). These episodic upwelling events are now known to provide an important source of both dissolved and particulate nutrients for the United Nation's World Heritage listed Ningaloo Reef, an $\sim$300 km long fringing coral reef system that stretches along this coast (Wyatt et al., 2010).

The Western Australian coastline is unlike other eastern ocean margins globally, such as the coastlines of Northern California, Northern Africa and Peru, where the dominant wind-driven equatorward boundary currents promote strong and persistent coastal upwelling (Capet et al., 2008). In contrast, the Western Australian eastern boundary current system (i.e. the Leeuwin Current, LC) flows poleward against the dominant equatorward wind stresses, and is instead driven by a year-round strong poleward-directed geopotential gradient (Ridgway and Condie, 2004). As a result, the Western Australian coastline has been historically classified as a downwelling-dominated coast (Godfrey and Ridgway, 1985; Smith et al., 1991). The LC meanders along the Western Australian shelf-break as it moves southward, due to the influence of spatially variable coastal wind fields, along-shelf bathymetry variations and instabilities of the current itself (Meuleners et al., 2008; Weller et al., 2011). As the LC meanders down the coast, its interactions with the opposing wind leads to a generally unsteady flow environment on the shelf and causes this region to have some of the highest eddy kinetic energy of any shelf region worldwide (Feng et al., 2005).

* Corresponding author at: University of Western Australia, The UWA Oceans Institute, 35 Stirling HWY, Crawley, Western Australia 6009, Australia.
E-mail address: jiangtao.xu@uwa.edu.au (J. Xu).

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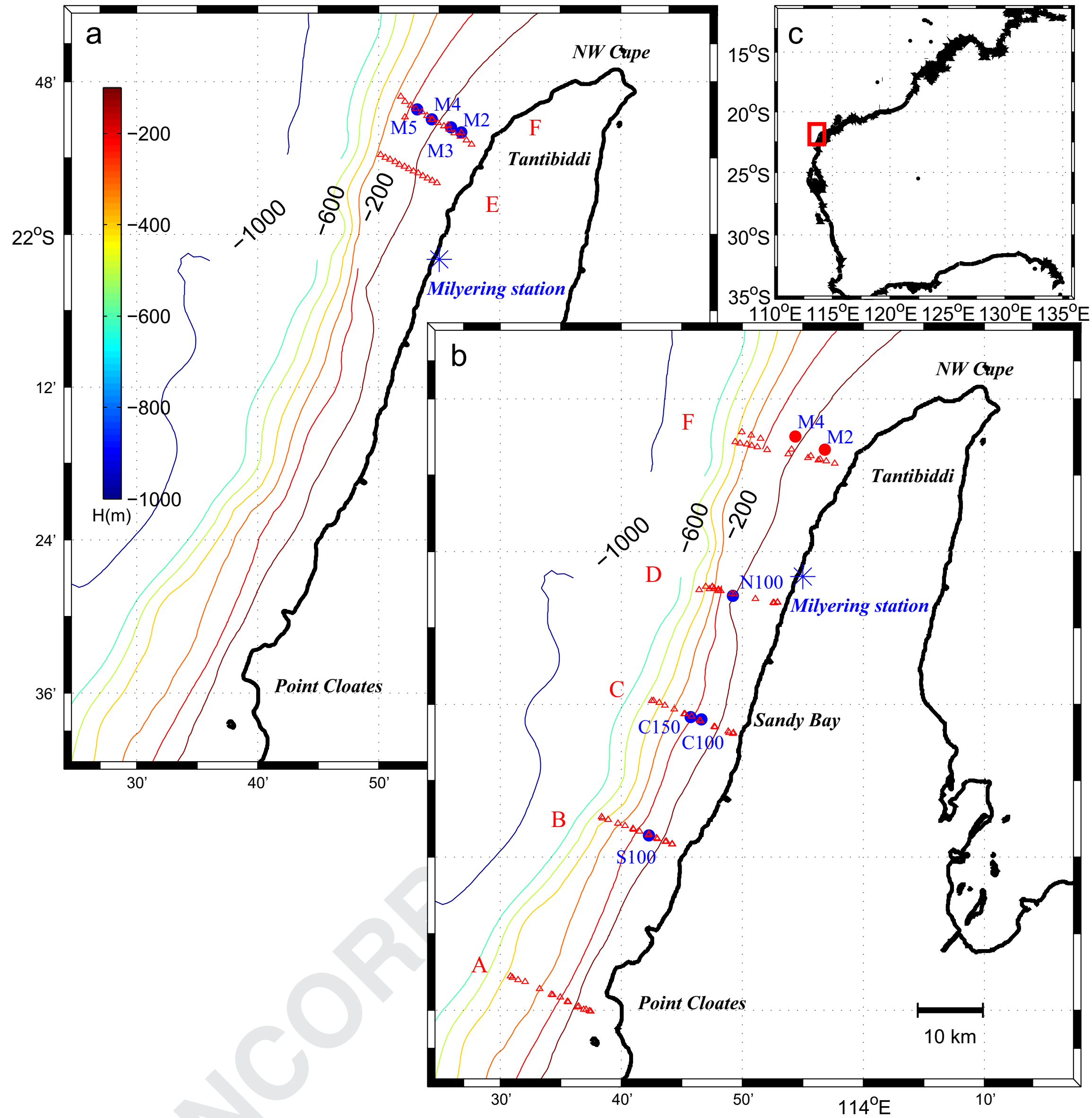

Fig. 1. Ningaloo bathymetry and field experiment configuration. Instrument mooring and CTD sampling locations (a) during EXP1 (Nov 2009–Jan 2010), and (b) during EXP2 (Sep 2010–Nov 2010). (c) Map of Western Australia showing the location of the Ningaloo shelf. The blue dots denote mooring locations. The red triangles denote the CTD cast locations, with each letter (A, B, C, D, E) referencing an individual CTD transect. The blue asterisk denotes the location of wind measurements at the coastal Milyering weather station. Some key bathymetry contours in meters are included (refer to the colorbar in (a) for the values). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Although the dynamics of the shelf circulation and the LC in the southwestern region of Australia (i.e., at ~30–34°S) have been relatively well-described, the dynamics of the LC further north have remained poorly studied. Smith et al. (1991) found a relatively persistent poleward flow that was in phase with the LC far south of the North West Cape near Point Cloates (Fig. 1), but they had no direct observations along the Ningaloo Peninsula to the north. Much further north on the Australian North West Shelf, Holloway (1995) observed periods of persistent poleward flow during some parts of the year, with this poleward flow sometimes referred to as the Holloway Current (Dadamo et al., 2009) to distinguish it from the persistent LC that occurs south of the North West Cape. However, a large scale water mass analysis by Domingues et al. (2007) suggested that the coastal waters of the Ningaloo shelf and the LC to the south may be largely sourced from the west from the Eastern Gyral Current. Weller et al. (2011) reported, using ship-based velocity measurements along the entire west Australia coast, that the large contribution of inflow to the LC during autumn-winter is on the same order of magnitude as the contribution from the North West Shelf during that ~2 week study. Recent measurements reported by Lowe et al. (2012), from two long-term shelf moorings near the North West Cape, found that any persistent poleward flows associated with the LC were extremely weak (<0.1 m s^{-1}) year round over the 6 year study period. However, the shelf circulation was observed to be driven strongly by large (>0.5 m s^{-1}) transient flow reversals with a ~1–2 week periodicity that coincided with the time-scale of synoptic wind forcing in the region.

The occurrence of coastal upwelling on the Ningaloo shelf was first identified by Taylor and Pearce (1999) in satellite images, and then confirmed in opportunistic ship-based transects in the region (Hanson et al., 2005; Woo et al., 2006). Due to the presence of stronger equatorward winds during the austral summer, upwelling had initially been thought to be primarily confined to summer

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