Continental Shelf Research 29 (2009) 2020–2036

Contents lists available at ScienceDirect

Continental Shelf Research

journal homepage: www.elsevier.com/locate/csr

Numerical simulation of the circulation within the Perth Submarine Canyon, Western Australia

Susan J. Rennie [a], Charitha B. Pattiaratchi [b,*], Robert D. McCauley [a]

[a] Centre for Marine Science and Technology, Curtin University of Technology, GPO Box U1987, Perth, WA 6845, Australia
[b] School of Environmental Systems Engineering, University of Western Australia, 35 Stirling Highway, Crawley, WA 6009, Australia

ARTICLE INFO

Article history:
Received 15 December 2008
Received in revised form
5 April 2009
Accepted 10 April 2009
Available online 8 May 2009

Keywords:
Submarine canyons
Leeuwin current
Leeuwin undercurrent
Upwelling
Shelf dynamics
Equatorial undercurrents
Eastern boundary currents

ABSTRACT

Surface and sub-surface currents along the ocean boundary of Western Australia were simulated using Regional Ocean Modelling System (ROMS) to examine the circulation within the Perth Canyon. Two major current systems influenced the circulation within the canyon: (1) The Leeuwin current interacted weakly with the canyon as the majority of the canyon was below the depth of the Leeuwin current and (2) Leeuwin undercurrent interacted strongly with the canyon, forming eddies within the canyon at depths of 400–800 m. The results indicated that within the canyon, the current patterns changed continuously although there were some repeated patterns. Recurrent eddies produced regions where upwelling or downwelling dominated during the model runs. Deep upwelling was stronger within the canyon than elsewhere on the shelf, but vertical transport in the upper ocean was strong everywhere when wind forcing was applied. Upwelling alone appeared to be insufficient to transport nutrients to the euphotic zone because the canyon rims were deep. Increased upwelling, combined with entrapment within eddies and strong upwelling-favourable winds, which could assist mixing, may account for the high productivity attributed to the canyon. The Leeuwin current is otherwise a strong barrier to the upwelling of nutrients.

1. Introduction

Many oceanographic studies have researched submarine canyons because of their effect on the local circulation and importance in marine habitats. Canyons have often been associated with marine megafauna, which come to feed in systems where enhanced upwelling boosts productivity. An excellent example is Monterey Canyon, where intense upwelling periods and subsequent *euphausiid* abundance attract many blue whales (Schoenherr, 1991; Croll et al., 2000).

Numerical modelling of submarine canyons was first developed using idealised topography, such as a shelf notch and later used real topography (e.g. Pedlosky, 1974; Klinck, 1988; Hughes et al., 1990; Haidvogel and Beckmann, 1995; Verron et al., 1995; Allen, 1996; Klinck, 1996). Field and laboratory experiments confirmed the results of these numerical studies, which suggested the direction of an alongshore current determined whether the canyon would support upwelling or downwelling conditions. Here, the current's direction determines whether water is transported onshore or offshore, causing upwelling or downwelling. As wind direction can dictate currents, strong winds in favourable conditions can increase cross-shelf exchange (Klinck, 1996; Skliris et al., 2002).

The presence of a canyon changes the cross-shore pressure gradient to enhance the cross-shelf transport and therefore upwelling or downwelling (e.g. Allen, 1996; Klinck, 1996; Granata et al., 1999; Boyer et al., 2000; She and Klinck, 2000; Sobarzo et al., 2001; Skliris et al., 2002; Song and Chao, 2004). When a current meets a curve in the bathymetry, it will first try to follow the curvature. For example, in a submarine canyon, the currents attempt to flow around the canyon head, following the bathymetry and accelerating as the current squeezes between the coast and canyon. The shelf curves too sharply in narrow canyons, however, and the flow crosses isobaths, which can stretch the water column and change the vorticity (Allen, 1996). Sometimes a closed eddy forms within the canyon.

She and Klinck (2000) used Regional Ocean Modelling System (ROMS, Haidvogel et al., 2000) to examine an idealised canyon (resembling Astoria Canyon off the western coast of North America) under constant upwelling- and downwelling-favourable winds. Under upwelling-favourable winds, the alongshore flow showed little effect near the surface, which was beyond the influence of the canyon bathymetry. A cyclonic eddy formed within the canyon rims (near the head and towards the upstream rim) at 150 m depth, with onshore flow farther down the canyon axis. At 300 m depth, the flow followed the isobaths, with strong

* Corresponding author.
E-mail address: chari.pattiaratchi@uwa.edu.au (C.B. Pattiaratchi).

0278-4343/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.csr.2009.04.010

onshore flow on the upstream slope and weaker offshore flow on the downstream slope. Under downwelling winds, the situation was mainly reversed, but the vertical transport was reduced.

Stratification affects the bathymetry's vertical extent of influence. Stronger stratification limits influence, so flow above the canyon may be beyond its influence (Klinck, 1996; She and Klinck, 2000; Skliris et al., 2002). With weak stratification, the bathymetry influences over a greater depth (She and Klinck, 2000; Skliris et al., 2002); thus canyons enhancing cross-shelf exchange is limited in strong stratification cases.

Few studies have included downwelling-favourable systems (Klinck, 1996; Skliris et al., 2002), undercurrent interactions with canyons (Hughes et al., 1990), or canyons with realistic or non-idealised bathymetry (e.g. Ardhuin et al., 1999; Skliris et al., 2002, 2004. This paper presents a case study of the Perth Canyon, which is canyon off the coast of south-western Australia where pygmy blue whales congregate to feed during summer (Branch et al., 2007; Rennie et al., 2009). A strong downwelling-favourable poleward surface current (the Leeuwin current) and a weak undercurrent in the reverse direction (the Leeuwin undercurrent) dominate this region (Pattiaratchi and Woo, 2009). The presence of a downwelling-favourable surface current was expected to counter the upwelling that might otherwise be expected in the canyon. As the only such feature on this part of the Western Australian continental shelf, the canyon is expected to have an impact on the local oceanography, and field observations support this (Rennie et al., 2009), showing enhanced primary production and aggregations of krill.

The main aim of simulating the Perth Canyon circulation was to understand how the surface and sub-surface currents interacted with the canyon, and how the currents respond to typical local wind conditions. Rennie et al. (2007) examined the Leeuwin current and undercurrent over the larger region modelled (Fig. 1a), and included model verification by comparison with field observations and sea surface temperature satellite imagery. Rennie et al. (2009) examined the Perth Canyon by drawing together all available field observations along with the findings of the numerical simulations of the canyon, which are presented in this paper. In particular, eddy formation and the occurrence and location of vertical motion within the canyon are addressed. The analysis included the forcing conditions associated with these fluid movements, such as weather.

The paper is organised as follows: Section 2 describes the model set-up. Section 3 presents the simulated circulation patterns within the canyon, including the occurrence of upwelling and downwelling. Section 4 discusses the implications of the model results for the productivity and aggregation of krill swarms.

1.1. Study area

The Perth Submarine Canyon begins at the 50 m contour, 48 km west of the coast of Western Australia, and is about 100 km long (Fig. 1b). It is about 10 km wide near the canyon head, and reaches depths more than 1000 m. At the shelf slope, the canyon floor is 3 km deep and cuts to 4 km deep into the continental slope. Note that the canyon 'head' refers to the canyon's shoreward section (~10–15 km long), and the 'tip' refers to the head's shoremost point. The canyon bends at 10 and 50 km from the tip and branches south at 40 and 50 km (Fig. 1b). The bend at 50 km is referred to as the 'dogleg' (located in Fig. 1b). The canyon is long, deep, narrow, steep-sided, and intrudes into the continental shelf.

The Leeuwin current at the surface flows southward (poleward) along the shelf break and is up to 300 m deep at 32°S. It reaches speeds over 1 m s^{-1}, with an average speed of 0.4 m s^{-1} (Smith et al., 1991; Feng et al., 2003; Meuleners et al., 2007). The Leeuwin undercurrent flows equatorward along the continental slope with a maximum speed of speeds of 0.1–0.4 m s^{-1} at a depth 450–550 m (Thompson, 1984; Woo and Pattiaratchi, 2008; Rennie et al., 2009). The Capes current was associated with water upwelled from about 100 m and was constrained inside the 50 m isobath (Gersbach et al., 1999); hence it did not pass over the canyon.

The wind regime at 32°S consists of strong southerly winds during summer (October–April), which a sea breeze pattern modulates (Pattiaratchi et al., 1997). In winter, the winds are variable because of the passage of weather systems. Strong winds associated with storm fronts usually occur during winter (April–October). The transition between summer and winter winds usually occurs within a month or two as one pattern begins to interrupt the other. The southerly summer winds oppose the Leeuwin current, causing it to weaken and shallow (Feng et al., 2003; Meuleners et al., 2007). These winds also create the Capes current—a northward-flowing current confined to the shelf and sourced by shallow upwelling (Gersbach et al., 1999; Pearce and Pattiaratchi, 1999).

2. The model set-up: ROMS

The Regional Ocean Modelling System has been developed at Rutgers University and the University of California (Haidvogel et al., 2000). This model was chosen because of its wide spread use in examining the flow characteristics of regions with complex bathymetry using the terrain-following *s*-coordinate system for vertical coordinates (Haidvogel et al., 1991; She and Klinck, 2000), which transforms the *z*-coordinate to layers that conform to the bathymetry. This reduces the bathymetry approximation that occurs with a stepwise vertical grid. The main drawback of a terrain-following coordinate system is the error associated with calculating the horizontal pressure gradient, which needs correcting for the hydrostatic pressure term. This error is mainly due to truncation when subtracting two large, similar-sized values; it also generates spurious currents, which may be problematic, depending on the application. Note that the model outputs horizontal and vertical velocity vectors, not velocities aligned with the *s*-coordinate layers.

Rennie et al. (2007) described the model set-up in detail. ROMS version 1.7 was used, and the model domain ranged from 111 to 116°E and 28 to 36°S (Fig. 1a). The canyon was centrally located near the eastern land boundary (at 32°S and 115°E). The shelf topography was straightened above 30°S and below 34°S to be perpendicular to the north and east boundaries, respectively. The horizontal resolution varied from ~10 km near the north, south, and west boundaries to ~2 km near the canyon. The depth below 1000 m was halved relative to 1000 m, which reduced the steepness and depth without losing the canyon's shape below 1000 m. The topography was then cut below 2100 m and above 30 m (Fig. 1a and c). This was implemented to increase vertical resolution and reduce the error induced by the steepness of the canyon sides below 1000 m. In this study the circulation below 1000 m was not of interest.

All islands were ignored, as they caused instability when wind stress was applied. The topography was smoothed to fit robustness $r<0.2$ (Beckmann and Haidvogel, 1993; Haidvogel et al., 2000) and slope steepness less than 10% (following e.g. She and Klinck, 2000). The original bathymetry's steepness above 1000 m was greater than 20% and below 1000 m was greater than 40% in some areas, for a 0.01° grid. The model used 20 *s*-coordinate layers with $\theta_s = 3$, $\theta_b = 0.1$, and $T_{cline} = 30$ (see Haidvogel et al., 2000; Rennie et al., 2007) so that the vertical resolution was higher near the surface.