Continental Shelf Research 42 (2012) 78–88

Contents lists available at SciVerse ScienceDirect

Continental Shelf Research

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

Research papers

# Lee effects of localized upwelling in a shelf-break canyon

Jochen Kämpf*

*School of the Environment, Flinders University, PO Box 2100, Adelaide, SA 5001, Australia*

ARTICLE INFO

*Article history:*
Received 14 December 2011
Received in revised form
2 May 2012
Accepted 4 May 2012
Available online 14 May 2012

*Keywords:*
Upwelling
Submarine canyons
Hydrodynamic modeling
Cross-shelf exchange

ABSTRACT

Using a process-oriented modeling approach, this work explores the interaction between flow disturbances created by an isolated shelf-break canyon with coastal flows modulated by an irregular coastline such as a headland. Findings show that, on their own, both the canyon and the headland produce individual stationary barotropic topographic Rossby waves extending considerable distances $>100$ km) along the continental shelf. The canyon-induced wave is instrumental in the formation of stationary alternating zones of upwelling and downwelling along the shelf break. Waves created by a headland located downstream of the canyon tend to dramatically enhance the cross-shelf flow in favor of the formation of stationary coastal upwelling centers. In this case, process-individual zones of "squeezing vorticity" (negative ratio of relative vorticity to planetary vorticity) combine such as to trap previously upwelled water on the continental shelf. In contrast, headland-induced flow disturbances created upstream of the shelf-break canyon have only little impact on the cross-shelf flow. Moreover, sensitivity studies indicate that the efficiency of cross-shelf exchange critically depends on topographic parameters (in particular onshore variations of bottom slope) of the continental shelf.



## 1. Introduction

For many decades, scientists have been studying topographic influences on geophysical flows. The pioneering work of Charney and Eliassen (1949) demonstrated the orographic forcing of large-scale stationary Rossby-wave disturbances in the midlatitude westerlies. From the late 1960s onwards, oceanographers undertook similar studies on flow disturbances near seamounts (e.g. Huppert and Bryan, 1976) and submarine ridges (e.g. McIntyre, 1968, Clark and Fofonoff, 1969; Ikeda, 1979). Dickinson (1978) presents a comprehensive review of early research on Rossby waves in the oceans and the atmosphere. Previous research has shown that topographic obstacles such as islands (Rhines, 2007) or headlands (Freeland, 1990) can trigger stationary topographic Rossby waves on the continental shelf.

Apart from topographic Rossby waves, continental margins support a variety of so-called Coastally Trapped Waves (CTWs) first observed by Hamon (1962, 1963, 1966) and Robinson (1964). CTWs are a subclass of waves that are characterized by an exponential decrease of the amplitude of dynamical pressure anomalies with increasing distance from the coast. The most basic form of a CTW is the barotropic coastal Kelvin wave in an ocean of uniform depth. Dependent on the situation, CTWs can attain different forms resembling continental shelf waves, internal coastal Kelvin waves or bottom edge waves (see Baines et al., 2005).

Martell and Allen (1979) studied barotropic shelf waves in a channel of weak cross-channel slope and small-amplitude longshore variations in bathymetry. Their findings suggest that wind fluctuations can resonantly trigger stationary topographic Rossby lee waves. Haidvogel and Brink (1986) adopted this theory to demonstrate in a numerical model that the excitation of lee waves can contribute to the creation of mean flow. It should be pointed out that Martell and Allen (1979) assumed vanishing anomalies of dynamic pressure along both walls of the channel. This treatment explicitly eliminates CTW-type waves as solutions. Martell and Allen (1979) demonstrated the direction-dependency of interactions between coastal flows with longshore bathymetric variations such as a shelf-break canyon.

Submarine canyons cutting through the shelf break are ubiquitous features that frequently indent the continental shelf as much as 60 km (Hickey, 1995). Typical canyons are of the order of 50–500 m deep and 5–30 km wide. Shelf-break canyons are often regions of enhanced localized upwelling (e.g. Freeland and Denman, 1982; Hickey, 1997), and they are important for cross-shelf-break exchange including nutrient flux onto the continental shelf (Hickey and Banas, 2008; Kämpf, 2010). They are often biologically active areas with dense krill (euphausiid) and fish aggregations (e.g. Allen et al., 2001) during upwelling favorable conditions. The dynamics of upwelling in shelf-break canyons have been examined using observations (e.g. Hickey, 1997; Allen et al., 2001), laboratory models (e.g. Codiga et al., 1999; Pérenne

* Corresponding author. Tel.: +61 8 8201 2214.
*E-mail address:* jochen.kaempf@flinders.edu.au

0278-4343/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.csr.2012.05.005

et al., 2001; Boyer et al., 2004), analytical models including scaling considerations (Mirshak and Allen, 2005; Allen and Hickey, 2010), and hydrodynamic models (e.g. Klinck, 1996; Kämpf, 2006, 2007, 2009). All of these studies agree in that localized canyon upwelling which follows from ambient flow running opposite to the propagation direction of free CTWs. These are flows being right (left) bounded by both shallower water and the coast in the southern (northern) hemisphere.

Despite the richness of scientific understanding derived from these canyon-upwelling studies, lee effects of localized canyon upwelling on the ambient shelf circulation remain understudied. The main reason for this knowledge gap is a focus on regional canyon scales while ignoring that canyon upwelling may give rise to and form part of a stationary topographic Rossby wave—as earlier suggested by Martell and Allen (1979). Motivated by the latter, this paper investigates the possibility that shelf-break canyons create stationary topographic Rossby waves that, in interaction with other Rossby-type shelf waves, trigger substantially enhanced cross-shelf flows—possibly at considerable distances away from a shelf-break canyon. The work has been motivated by observational evidence from the eastern Great Australian Bight where water properties of a coastal upwelling center could be traced back to deep localized upwelling in shelf-break canyons of the Murray Canyon Group that are located at a considerable distance ( $>100$ km) from this center (Kämpf, 2010).

This paper is organized as follows. Section 2 describes the hydrodynamic model used in this work and the configuration of experiments. Section 3 presents and discusses the findings. Section 4 closes with a summary and conclusions.

## 2. Methodology

### 2.1. Model description and configuration of control experiments

This work employs the three-dimensional sigma-coordinate COHERENS model (Luyten et al., 1999). The model domain (Fig. 1) is 240 km in length and 120 km wide. The horizontal grid spacing is 1 km, and 20 vertical sigma levels are used. The idealized continental shelf has a width of $B=60$ km, a shelf-break depth of 200 m, and is gently tilted towards the coast at an angle of $0.08^\circ$ (inclination is 1.4 m/km) (Fig. 2a). Water depth at the coastline is set to 100 m. The model's shelf width corresponds to the average width of real continental shelves. The continental slope has a topographic slope of $1.8^\circ$ (inclination is 31.4 m/km), which is within a realistic range (typical slopes are $1^\circ$–$10^\circ$). The total water depth is limited to 1000 m to maximize model efficiency.

Control experiments of this study comprise three different cases; namely, a canyon-only, a headland-only, and a combined case (Table 1). The model's canyon is created via application of the diffusion equation to a coarse block-type canyon prototype. The shelf-break canyon of the control experiment has a width of $\sim$25 km and a maximum depth relative to the ambient seafloor of $\sim$400 m (Fig. 2b). Canyon walls have a maximum topographic slope of $2.4^\circ$ (inclination is 42 m/km). Note that this canyon resembles milder shelf-break canyons (such as those found on the continental margin of southern Australia) rather than steeper-sided canyons, such as the Astoria Canyon, of wall slopes of up to $45^\circ$ (see Hickey, 1997). Note that vertical grid spacing increases to 50 m in the deepest portions of the model domain. At shelf-break depth, vertical grid spacing decreases to 30 m inside and 10 m outside the canyon. The model's canyon vanishes on the continental shelf within an assumed "indentation distance" of $B_c=30$ km from the shelf break. Both canyon depth and width are assumed to decrease linearly to zero over this distance. An idealized headland is included at a distance of $L=70$ km downstream of the canyon. The shape of this headland is computed from

$$y^* = B_h \cos\left[\frac{\pi}{L_h}(x-x_o)\right] \text{ with} |x-x_o| \le 0.5L_h, \tag{1}$$

where $y^*$ is the distance of the headland's coastline from the reference coast, $B_h=30$ km, $L_h=50$ km, and $(x-x_o)$ is longshore distance measured from the center of the headland. Other shapes are not considered in this work. Flows along the coastline are made subject to no-slip boundary conditions.

Seawater density is assumed to initially increase linearly with depth at a stability frequency of $N=3.25\times10^{-3}\,s^{-1}$, corresponding to a maximum internal wave period of 32 min. This simplified density configuration eliminates the creation of baroclinically controlled coastal upwelling fronts. The study of the additional level of complexity associated with these fronts and their instabilities remains for the future. The Coriolis parameter is set to $f=-1\times10^{-4}\,s^{-1}$ (southern hemisphere). Upwelling dynamics on the smooth continental shelf void of submarine canyons can be characterized by a topographic Burger number defined by $B_u=s\,N/|f|$, where $s$ is topographic slope (Jacox and Edwards, 2011). This model's configuration corresponds to $B_u\approx0.055$ for the continental shelf and $B_u\approx1.02$ for the continental slope. Both values are within a realistic range (see Jacox and Edwards (2011)). The Pacanowski–Philander turbulence scheme (Pacanowski and Philander, 1981) is adopted to calculate sub-grid scale vertical turbulent viscosity and diffusivity. This scheme is Richardson-number dependant. Bottom friction is calculated from a quadratic

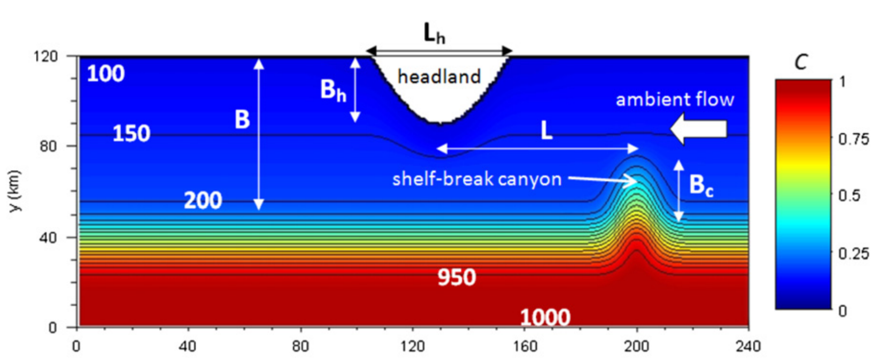


**Fig. 1.** Bathymetry of control experiments of this study. Lines are bathymetric contours shown at an interval of 50 m. The distance between centers of the headland and the canyon is $L=70$ km. Colors refer to near-bottom values (in decimal fraction) of the Eulerian concentration field. Initial values are equivalent to total water depth in km. (For interpretation of the reference to color in this figure legend the reader is referred to the web version of this article.)