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On the magnitude of upwelling fluxes in shelf-break canyons

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Abstract

A hydrodynamic model is employed to derive the magnitude of on-shelf fluxes through a shelf-break canyon for a wide range of canyon sizes and ambient oceanic conditions. Predicted canyon-upwelling fluxes are of the order of 0.05–0.1 Sv (1 Sv = 1 million m^3/s), being several orders of magnitude greater than upslope fluxes in the bottom Ekman layer on the ambient continental slope. On the basis of ~150 simulations conducted, a bulk formula of upwelling flux in a submarine canyon is derived. For typical conditions, the upwelling flux varies quadratically with forcing strength (speed of incident flow), linearly with canyon depth, and is inversely proportional to the buoyancy frequency of the density stratification inside the canyon. Other parameters such as density stratification above shelf-break depth and bottom friction are found to have minor influences on the resultant canyon-upwelling flux.

Keywords: Upwelling; Physical oceanography; Submarine canyons; Numerical models

1. Introduction

Shelf-break canyons are submarine canyons cutting across the shelf break. They are bathymetric features found along many continental margins. Their typical width is 10–50 km, depth variations across canyons are 100–500 m, and cross-canyon topographic slopes can be as steep as 45°. In the presence of upwelling favourable coastal winds, observational evidence from various regions around the world suggests that submarine canyons locally enhance the upwelling of sub-surface water onto the continental shelf. During a stronger upwelling event, lasting ~5 days, the mass flux across the shelf break through a canyon is one order of magnitude larger than upwelling fluxes in the bottom Ekman layer on the adjacent continental slope (Kinsella et al., 1987; Hickey, 1997; Signorini et al., 1997). During stronger upwelling events, upwelling prevails throughout the canyon, while a cyclone is found within the canyon (Hickey, 1997). Numerical models of various kinds have been employed to explore the general nature of canyon flow (e.g. Klinck, 1996; Ardhuin et al., 1999; She and Klinck, 2000; Allen et al., 2003; Haidvogel, 2003; Boyer et al., 2004; Kämpf, 2006).

In a series of laboratory and numerical experiments Boyer et al. (2004) studied canyon–flow interaction by oscillatory currents in a stratified fluid. Oscillatory forcing resulted in a residual up-canyon flow in upper parts of the canyon. The magnitude of this time-mean up-canyon flow increased quadratically with forcing strength

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(amplitude of along-shore flow variations), linearly with forcing period and was inversely proportional to the buoyancy frequency. Net volume transports associated with these flows, however, remained unclear.

Haidvogel (2003) employed the spectral element ocean model (SEOM) and studied canyon–flow interaction under oscillatory forcing with a configuration very similar to that of Boyer et al. (2004). This author derived the net on-shelf mass flux of dense water from several bulk measures such as the shelf area occupied by the residual pool of dense water formed on the shelf, the volume of this dense pool, and maximum and average density anomalies within this dense pool. In agreement with Boyer et al. (2004), Haidvogel (2003) found that the net mass flux of dense water (derived from volume times average density of the dense pool) increases quadratically with forcing strength. Interestingly, the volume of the dense pool decreased markedly for an increase in buoyancy frequency of the ambient density stratification. On the other hand, relatively denser water was found in this pool, so that density stratification had only little impact on the net on-shelf mass flux, as defined by this author, of dense water. Nevertheless, the bulk measures used by Haidvogel (2003) cannot distinguish between shallow and deep upwelling, which is an obvious shortcoming.

Mirshak and Allen (2005) studied the on-shelf mass flux induced by upwelling through a shelf-break canyon in a series of spin-up laboratory experiments. Trials were performed across a range of values for shelf-break velocity, Coriolis frequency, and buoyancy frequency. Variations of canyon bathymetry were not considered. Under the assumption that the drag force within the canyon be balanced locally by rotation Mirshak and Allen (2005) proposed a parameterization of this mass flux. Application of this parameterization to the Astoria Canyon gave maximum upwelling fluxes of $\sim 6\times10^{-3}$ Sv (1 Sverdrup $= 10^6\,\mathrm{m^3/s}$). The author deems this value too small, given that for the cross-sectional area of the Astoria Canyon of approximately 8 km × 250 m, this flux would correspond to a transverse flow of a speed of only 3 mm/s, which is far less than observed up-canyon flow speeds of >10 cm/s (Hickey, 1997).

Systematic studies on the combined effects of varied canyon bathymetry (width and depth), ambient conditions (speed of incident along-slope flow, density stratification and bottom drag), and geographical location on on-shelf fluxes through a submarine canyon are incomplete.

This paper employs a three-dimensional hydrodynamic model to quantify the magnitude of upwelling fluxes for a wide range of conditions. As will be shown with the results, on-shelf fluxes through a shelf-break canyon are of the order of 0.05–0.1 Sv, which is one order of magnitude larger than suggested by Mirshak and Allen (2005). This paper is organized as follows. Chapter 2 describes the numerical model used and gives details of the experimental design of the case studies conducted. Chapter 3 presents and discusses results. Chapter 4 summarizes the key findings of this study and makes suggestions for future research.

2. Methods

2.1. Model description

This study employs the hydrodynamic module of the model COHERENS (Coupled Hydrodynamical-Ecological Model for Regional Shelf Seas) (Luyten et al., 1999). The governing equations are the finite-difference forms of conservation equations for momentum, heat, volume and scalars (salinity) for an incompressible fluid on the f plane cast in terrain-following sigma coordinates. For more details, see Luyten et al. (1999). The southern hemisphere situation is considered throughout this study. Results can be readily adopted for the northern hemisphere. In this process-oriented application, evolution of seawater density is directly predicted from an advection–diffusion equation; that is, a density conservation equation (see Cushman-Roisin, 1994).

Vertical diffusion of momentum and density is parameterized by means of the classical turbulence closure scheme proposed by Pacanowski and Philander (1981). A uniform background vertical viscosity/diffusivity of $10^{-4}\,\mathrm{m^2/s}$ is used. A linear bottom-friction parameterization is employed in which the bed shear stress is given by

$$\vec{\tau}_b = \rho_o A_z \frac{\partial(u,v)}{\partial z} = \rho_o r(u,v), \tag{1}$$

where A_z is the vertical eddy viscosity, ρ_o is mean density, and r is a linear bottom-friction parameter. Typical values of r in oceanic applications are $1\text{–}5\times10^{-4}$ m/s, which, for a bottom current of 10 cm/s, corresponds to bed shear stresses of 0.01–0.05 Pa. In a quadratic bottom-drag law, this