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Diagnoses of vertical transport in a three-dimensional finite element model of the tidal circulation around an island

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Abstract

A three-dimensional finite element model is used to investigate the formation of shallow-water eddies in the wake of Rattray Island (Great Barrier Reef, Australia). Field measurements and visual observations show that stable eddies develop in the lee of the island at rising and falling tides. The water turbidity downstream of the island suggests the existence of strong upwelling that would be responsible for carrying bed sediments up to the sea surface. We first propose to look at the upwelling velocity and then use the theory of the age to diagnose vertical transport. The water age is defined as the time elapsed since particles of water left the sea bottom, where the age is prescribed to be zero. Two versions of this diagnosis are considered. Although the model predicts upwelling within the eddies, it is not sufficiently intense to account for vertical transport throughout the water column during the life span of the eddies. As mesh resolution increases, this upwelling does not intensify. However, strong upwelling is then resolved off the island's tips, which is confirmed by the results obtained with the age. This study also shows that the finite element method, together with unstructured meshes, performs well for representing three-dimensional flow past an island.

Keywords: age; upwelling; unstructured mesh; finite element method; island wake; Rattray Island

1. Introduction

In shallow coastal regions, flow disturbances caused by topographical features, such as islands, headlands, reefs and narrow passages, can have strong effects on marine ecosystems. Topographically generated circulation affects the distribution of sediments and can significantly influence the local dispersal of pelagic organisms (Hamner and Hauri, 1981; Wolanski and Hamner, 1988; Wolanski et al., 1988; Wolanski, 1994; Coutis and Middleton, 1999, 2002). As pointed out by Wolanski et al. (1984), this has important implications in the location of fisheries and waste outfalls. Due to the presence of islands and reefs, oncoming currents separate and, as water is stripped away at the surface, it is replaced by upwelled water (Hamner and Hauri, 1981). Upwelled water is generally enriched with nutrients, which may locally alter the biotic diversity (Wolanski et al., 1988). Depending on flow characteristics and island geometry, stable or unstable eddies may develop in the island wake (Wolanski et al., 1984; Pattiaratchi et al., 1986; Ingram and Chu, 1987; Wolanski et al., 1996). These eddies may have a local impact on the ecosystem because of secondary circulation, enhanced turbulence and upwelling (Hamner and Hauri, 1981; Wolanski and Hamner, 1988; Wolanski et al., 1988).

Of particular concern are the shallow-water eddies generated in the wakes of islands by oscillating tidal flows. By shallow water, it is meant here that the ratio of the water depth to the island width (facing the current) is much less than one. Shallow-water flows are characterized by dominant bottom friction, which has important consequences onto their

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dynamics (Ingram and Chu, 1987; Tomczak, 1988). Unsteadiness of tidal flows was shown to play a crucial role in the formation of eddies (Black and Gay, 1987). To take into account bottom friction in the description of the island wake dynamics, Wolanski et al. (1984) suggested to use the "island wake parameter" P rather than the usual Reynolds number prevailing in the description of two-dimensional wake flows. Pattiaratchi et al. (1986) confirmed this concept with laboratory and field experiments. The island wake parameter P is defined as the ratio of nonlinear acceleration to bottom friction. For $P < 1$, no wake is present. For $P \simeq 1$, two stable eddies form in the lee of the island and remain attached while for increasing values of P, instabilities occur in the wake, following by eddy shedding. In this paper, we will focus on the case $P \simeq 1$ for which eddies essentially result from a balance between radial pressure gradient and centrifugal effect due to flow curvature. Near the bottom, the azimuthal velocity decreases because of bottom friction. However, a constant pressure gradient is maintained throughout the water column. Therefore, the balance breaks down near the seabed, leading to flow convergence towards the center of the eddy and upwelling within the water column.

Among shallow-water islands for which stable tidal eddies are observed, Rattray Island (Great Barrier Reef, Northeast Australia) has been the focus of many studies in the past two decades (Wolanski et al., 1984; Falconer et al., 1986; Black and Gay, 1987; Wolanski and Hamner, 1988; Deleersnijder et al., 1992; Wolanski et al., 1996, 2003). Rattray Island is 1.5 km long and lies in well-mixed water approximately 25 m deep. The currents are dominated by the tides, whose ellipses are strongly polarized and essentially oriented from northwest to southeast. The island was subject to an extensive field survey in 1982 (Wolanski et al., 1984). Twenty-six current meters were deployed in four transects in the wake of the island during flood tide and made clear the existence of a clockwise-rotating eddy extending across the wake. No measurements were made at falling tide but aerial photographs suggested the presence of two counter-rotating eddies. Aerial photographs also showed turbid water in the wake both at rising and falling tides, suggesting upwelling capable of carrying bed sediments upwards. While two-dimensional numerical models are able to faithfully represent depth-averaged features (e.g., Falconer et al., 1986; Black and Gay, 1987), only three-dimensional models can account for vertical motion. There have been only a few attempts in the past at analyzing vertical motion in shallow-water island wakes. Deleersnijder et al. (1992) utilized a 200-m horizontal resolution finite-difference model to compute the three-dimensional velocity field in the vicinity of Rattray Island. Although upwelling was predicted within the bulk of the eddies, its intensity was too low to account for vertical transport across the entire water column during the lifetime of the eddies. It was put forward that the model used a resolution that was too low to accurately represent velocity gradients (and hence divergence). Wolanski et al. (1996) used the same model as that by Deleersnijder et al. (1992) with an additional parameterization to account for the impact of the free shear layer extending downstream from the tips of the island. Later on, Alaee et al. (2004) also used a three-dimensional finite-difference model but they focused on upwelling at the tips of an idealized elliptic island. The main difference between the work by Alaee et al. (2004) and the previous one is that Alaee et al. (2004) worked with flow regimes for which no eddies were generated.

In this paper, we wish to continue along the path set out by Deleersnijder et al. (1992) with two crucial improvements. The first one is concerned with the numerical method, as we use a three-dimensional finite element model. The finite element method (FEM) allows for conveniently using unstructured meshes, whose resolution may vary and increase within regions of interest to attain higher accuracy. In addition, the ability of unstructured meshes to conform to complex coastlines is attractive. The FEM has been successfully utilized in the past for the modeling of coastal flows and oceanic processes (e.g., Walters, 1992; Lynch et al., 1996; Le Roux et al., 2000; Hanert et al., 2005b; Pietrzak et al., 2005; White et al., 2006) and its popularity within the ocean modeling community is likely to grow in the future. With the FEM, we will be able to increase the mesh resolution around the island and in the wake, and analyze the sensitivity of upwelling intensity on resolution. The second improvement is achieved by using a more sophisticated diagnosis of vertical transport. By looking at the upwelling velocity, Deleersnijder et al. (1992) considered vertical transport due to advection only. However, because vertical transport is a combination of advective and diffusive effects, we need a diagnosis that is able to account for both. The concept of the age may be used for that purpose. It is presented in detail by Delhez et al. (1999), Deleersnijder et al. (2001) and Delhez and Deleersnijder (2002). It is a component of CART (Constituent-oriented Age and Residence time Theory, http://www.climate.be/CART). The age of a particle of seawater is defined as the time elapsed since the particle under consideration left the region in which the age is prescribed to be zero. In the theory of the age, all classical advection–diffusion operators are accounted for. By prescribing the age of all particles lying on the seabed to be zero, we may track the time needed for those particles to reach the sea surface. The main goal of this paper is to determine whether the eddies are partly or fully responsible for the vertical transport of bed sediments. Thus, we would like to answer the following question: How much time is required for particles of a non-buoyant, passive tracer to travel from the seabed to the sea surface?

This paper is organized as follows. Section 2 describes the three-dimensional hydrodynamic model together with its implementation with the FEM. In Section 3, two different diagnoses of vertical transport using the age are laid out. Results are presented in Section 4 and we conclude with Section 5.

2. Model description

In this section, the underlying physical assumptions are outlined. The equations, the domain of interest and the boundary conditions are presented. The finite element method is briefly explained. Because of the limited extent of the region of