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Scattering of low-mode internal tides at different shaped continental shelves

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ABSTRACT

A series of numerical simulations have been performed to investigate the scattering of low-mode internal tides on different shaped continental shelves, and topographies with a linear slope, Gaussian slope and sinusoidal slope for a wide range of slope steepness are used in the model. The results indicate that 3 beams radiate from the abrupt shelf break, and 2 beams radiate from the gentle shelf beak during the scattering process. The greatest amount of energy can be reflected by the linear slope, whereas the least energy can be transmitted onto the shelf, and the results are contrary to those for the Gaussian slope. Modal decomposition are applied and the results indicate that the transmitted wave is dominated by mode 1, whereas the energy fluxes of higher modes increase with critical parameters and then decrease. For the reflected waves, the energy flux of the higher mode is obviously influenced by the topography. More energy in high modes can be reflected off-shore by topography with an abrupt junction point, and thus, the magnitude of vertical shear is enhanced in front of the slope. In addition, the region where the shear is influenced by the reflection process is within a wavelength of the incident wave.

1. Introduction

Internal tides are internal waves with tidal frequency and play key roles in a number of processes in the ocean, especially in ocean mixing (Munk and Wunsch, 1998; Rudnick et al., 2003), and they are also the energy resources for thermohaline circulation (Garrett, 2003). In the ocean, high-mode internal tides dissipate near the generation sites due to their low phase speeds and strong shears (Pickering and Alford, 2012), whereas low-mode internal tides can propagate thousands of kilometers away and impact the redistribution of energy in the global ocean (Alford, 2003; Zhao et al., 2010, 2016; Zhao, 2017). According to Kelly et al. (2013), semidiurnal internal tides can lose 60% of their energy on continental margins, indicating the importance of the interactions between low-mode internal tides and continental shelves in the process of energy dissipation. Thus, this topic is a focus of ongoing efforts by oceanographers.

Theoretical work, in-situ observations and laboratory experiments (e.g., Muller and Liu, 2000; Ivey et al., 2000; Dauxois et al., 2004; Nash et al., 2004; Klymak et al., 2011; Rodenborn et al., 2011) have been carried out to investigate the interactions between internal tides and continental shelves. Numerical simulations are also an effective approach to explore the factors that influence the scattering of low-mode internal tides at continental shelves, as those factors, including topography and stratification, can be adjusted easily in numerical models. Legg and Adcroft (2003) performed a series of numerical simulations with a non-hydrostatic numerical model to investigate the breaking of internal tides on different continental margins, and for this non-linear circumstance, the results are similar, and internal bores can be observed to propagate upon the continental slope. A similar model has also been used by Hall et al. (2013), who intended to explore the reflection and transmission of linear internal tides on a continental shelf with different stratifications, and their results indicate that a fraction of the energy is reflected off-shore and is dependent only on slope criticality and independent of the depth of the pycnocline, whereas the transmission is dependent on the depth-structure of the stratification. Legg (2014) explored the breaking of low-mode internal tides on subcritical and critical slopes of different shapes with a non-hydrostatic model, and the dissipation and reflection of internal tides are calculated. Klymak et al. (2016) set up a hydrostatic model to investigate the reflection of low-mode M2 internal tides at the Tasman continental slope and noted that 76% of incident internal tides can be reflected by the supercritical slope.

On the other hand, the generation of internal tides at continental shelf has been explored in previous studies (e.g., Baines, 1982; Griffiths

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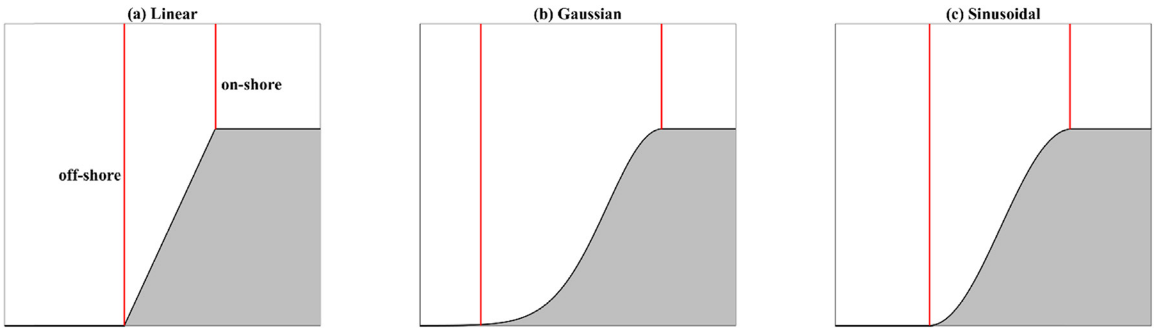

Fig. 1. Schematics of continental slopes used in the simulation. (a) a linear slope; (b) a Gaussian slope; (c) a sinusoidal slope. The off-shore profile and on-shore profile are shown by red lines.

and Grimshaw, 2007). But recently, the results of Wang et al. (2012) and Chen et al. (2017) demonstrated that internal tide generation can be influenced by the shape of the continental shelf, and they emphasized that the appearance of the third beam is determined by the presence of an abrupt junction point at the shelf break, prompting us to consider how the shape of a continental shelf influences the scattering of low-mode internal tides. Furthermore, the theoretical work conducted by Maas (2011) also indicates that there exist a large class of topographies which actually lacking scattering of incident internal waves. Therefore, a question is raised: when low-mode internal tides scattering on continental shelves with different shapes, is the reflectivity or transmittivity of energy the same if the slope and height of these topographies are equal? Previous studies have focused on several influencing factors (e.g., slope criticality, stratification and strength of incident wave) on internal tide-topography interactions, but only one kind of topography is used, such as Gaussian slope (Peacock et al., 2009) and sinusoidal slope (Hall et al., 2013; Legg, 2014). Therefore, the influence of topography shape on the scattering of low-mode internal tide has not been adequately explained, which provided the motivation for the present work.

In this work, numerical simulations of low-mode internal tide scattering at continental shelves are conducted to investigate how the shape of topography influences the reflection and transmission of internal tides. The article is organized as follows. The setup of numerical model and the method used for data analysis are presented in Section 2. The results of the numerical simulations are displayed in Section 3. Finally, the conclusions are drawn in Section 4.

2. Model setup and data analysis

2.1. Model setup

A series of simulations are performed using the Massachusetts Institute of Technology General Circulation Model (MITgcm, Marshall et al., 1997) following the work of Legg and Adcroft (2003) and Hall et al. (2013). The model is configured in a two-dimensional (x, z) plane without rotation (the Coriolis frequency is zero). The depth of the domain is set to 200 m, and a 67 m deep continental shelf is set on the right-hand side. The resolution is non-uniform along the x direction, with most grids concentrated over the continental slope, where the minimum resolution Δx is 6 m, whereas the resolution is uniform along the z direction over 80 grids ($\Delta z = 2.5$ m). The model is run in non-hydrostatic mode, and the time step Δt is set to 3 s to satisfy the Courant-Friedrichs-Lewy (CFL) criterion. Uniform stratification ($N = 1.1 \times 10^{-3}$ rad/s) is set in the model, which is dominated by temperature, and a linear equation of state is applied. Viscosity is uniform ($\nu_h = 10^{-2}$ m^2 s^{-1} and $\nu_z = 10^{-3}$ m^2 s^{-1}), and diffusivity is set to zero as suggested by Legg and Adcroft (2003), so that the stratification can not be eroded in the absence of wave motion.

A free-slip boundary condition is applied at the bottom boundary since the process in the bottom boundary layer is not taken into consideration, whereas a linear free surface condition is applied at the top surface. The model is forced by oscillation velocity and temperature consistent with mode-1, M2 internal tides at the left-hand side boundary:

$$u(0, z, t) = U_0 \cos(\frac{\pi z}{H})\sin(\omega t), \tag{1}$$

$$w(0, z, t) = -U_0(\frac{\omega^2}{N^2 - \omega^2})^{1/2} \sin(\frac{\pi z}{H})\cos(\omega t), \tag{2}$$

$$\theta(0, z, t) = \theta_0(z) + U_0\frac{N}{gt_\alpha} \sin(\frac{\pi z}{H})\sin(\omega t), \tag{3}$$

where $U_0 = 0.4$ cm/s is the forcing amplitude, $\omega = 1.41\times10^{-4}$ rad/s is the tidal frequency, θ_0 is the initial potential temperature, t_α is the thermal expansion coefficient, and H is the depth of the domain, which has been used by Legg and Adcroft (2003) and Hall et al. (2013), and the wavelength of the incident mode-1 internal tides is 3.09 km, which is calculated by the given ω, N and H according to dispersion relation of the mode-1 internal tide. The model is run for 10 tidal periods. The Orlanski radiation boundary condition is applied to the right-hand side of the domain to allow the internal tides to propagate out of the domain.

In order to investigate the scattering of internal tides at different continental shelves, three kinds of topography are set in the model: a linear slope, Gaussian slope and sinusoidal slope (Fig. 1). For the topography with a linear slope, two abrupt junction points occur at the shelf break and at the bottom of the slope. The Gaussian slope and sinusoidal slope are smooth at both the shelf break and the bottom of the slope. In addition, it should be note that the curvatures are not equal at the two regions previously mentioned for the Gaussian slope, whereas the curvature is equal for the sinusoidal slope. The distances between the off-shore profile and the left open boundary vary between runs and are set to 2.5 wavelengths, 3.5 wavelengths and 4 wavelengths for the subcritical, critical and supercritical runs, respectively (the reader can refer to Section 2.2 for the description of "subcritical", "critical" and "supercritical"). For the critical and supercritical runs, the distance should be longer, as otherwise, the waves that are re-reflected by the left boundary can reach the topography after several periods. Runs without topographies are performed, and the results demonstrated that the dissipation is small (1% per wavelength) when mode-1 internal tides propagate on the flat bottom, and we therefore posit that the variation in the distances between the topography and the left boundary do not affect the accuracy of the data analysis.

2.2. Non-dimensional parameters and data analysis

Several non-dimensional parameters that characterize the behaviors of internal tide-topography interactions should be taken into consideration in this study (Table 1) as suggested by Legg and Adcroft