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Internal wave scattering in continental slope canyons, Part 2: A comparison of ray tracing and numerical simulations

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ABSTRACT

When internal waves interact with topography, such as continental slopes, they can transfer wave energy to local dissipation and diapycnal mixing. Submarine canyons comprise approximately ten percent of global continental slopes, and can enhance the local dissipation of internal wave energy, yet parameterizations of canyon mixing processes are currently missing from large-scale ocean models. As a first step in the development of such parameterizations, we conduct a parameter space study of M2 tidal-frequency, low-mode internal waves interacting with idealized V-shaped canyon topographies. Specifically, we examine the effect of varying the canyon mouth width, shape and slope of the thalweg (line of lowest elevation) (i.e. flat bottom or near-critical slope). In Part 1 of this study (Nazarian and Legg, 2017a), we developed a ray tracing algorithm and used it to estimate how canyons can increase the wave Froude number, by increasing energy density and increasing vertical wavenumber. Here in Part 2 we examine the internal wave scattering in continental slope canyons using numerical simulations, and compare the results with the linear ray tracing predictions. We find that at intermediate canyon widths, a large fraction of incoming wave energy can be dissipated, which can be explained as a consequence of the increase in ray density and, for near-critical slope canyons, increase in vertical wave number, which leads to lower Richardson number followed by instability. Relative to a steep continental slope without a canyon, we find that V-shaped flat bottom canyons always dissipate more energy and are an effective geometry for wave trapping and subsequent energy loss. When both flat bottom canyons and near-critical slope canyons are made narrower, less wave energy enters the canyon, but a larger fraction of that energy is lost to dissipation due to subsequent reflections and wave trapping. There is agreement between the diagnostics calculated from the numerical model and the linear ray tracing, lending support for the use of linear theory to understand the fundamental dynamics of internal wave scattering in canyons.

1. Introduction

Internal waves are efficient transmitters of energy across ocean basins. As internal waves propagate away from their generation site, they may encounter the continental slope, where they can break and lead to diapycnal mixing. One of the continental slope features that can induce wave breaking are continental slope canyons. Despite observations highlighting their potential to be a sink of internal tidal energy, continental slope canyons have been largely overlooked by the modeling community (Bosley et al., 2004; Bruno et al., 2006; Codiga et al., 1999; Gardner, 1989; Gordon and Marshall, 1976; Gregg et al., 2011; Hall and Carter, 2011; Hotchkiss and Wunsch, 1982; Lee et al., 2009a; 2009b; Petruncio et al., 1998; Vlasenko et al., 2016; Waterhouse et al., 2013; Xu and Noble, 2009). Here, we put forth a parameter space sweep to better understand the processes involved in internal wave scattering and mixing in continental slope canyons.

In conducting this parameter space study of internal wave scattering in continental slope canyons, our overarching goal is to contribute to the development of parameterizations of mixing by internal wave breaking. Such parameterizations, regardless of the topography for which they are applied, are increasingly formulated in terms of the global energy budget for internal waves. Parameterizations have been developed from the entire lifecycle of internal waves; from their generation at regions of rough topography (Buijsman et al., 2012) to their propagation over ocean basins and interaction with other waves and eddies (MacKinnon et al., 2013; Polzin, 2008), as well as their eventual breaking at topographic

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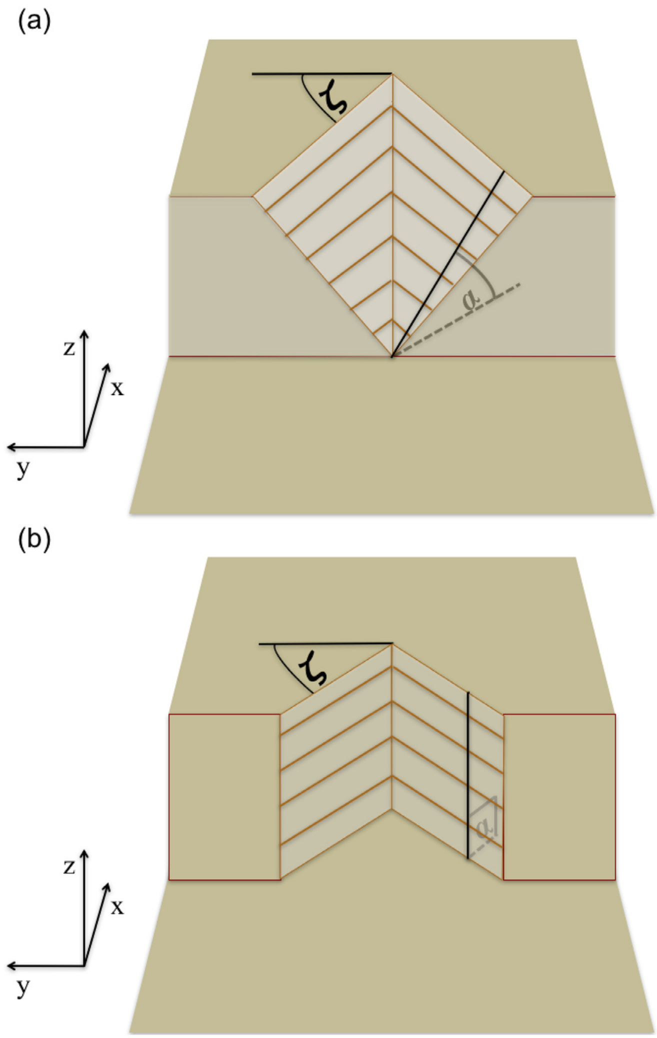

Fig. 1. Two classes of V-shaped canyons analyzed in this study. (a): near-critical slope canyon, (b): flat bottom canyon. Note that throughout our suite of experiments, angle ζ is varied identically for both class of canyons. Thus, the two different classes of V-shaped canyons are different in angle α only. The sidewalls of each canyon have isobaths, or lines of constant depth, drawn for clarity. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

features in the ocean interior or continental slope (Klymak et al., 2013; Legg, 2014). These studies have used a full internal wave energy budget to study the scattering effects of various, isolated, topographies (Klymak et al., 2013; Legg, 2014). By accounting for all terms in the energy budget, such studies have provided useful scalings for instability and turbulent dissipation based on properties of the topography; namely, the ratio of topographic height to the domain depth, the topographic width, and the relative topographic steepness. Given that mixing in the ocean is strongest around regions of varying topography (Polzin et al., 1997), and the location and magnitude of such mixing has ramifications for the large-scale ocean circulation (Melet et al., 2016), it is important for the formulation of ocean model mixing parameterizations to understand which and how topographic parameters modulate mixing. It is thus crucial to understand how much of the internal wave energy that encounters the continental slope topography is lost to mixing and dissipation. Our study analyzing the topographic dependence of internal wave dissipation is one component of this overall understanding.

Table 1
Summary of parameters of interest for all simulations.

α	ζ (°)	H (m)	L (m)	ω^2 (10^{-8} s^{-2})	N^2 (10^{-6} s^{-2})
$\alpha_{\text{near-critical}}$	19.9	100	744	1.99	1.00
	26.1	100	744	1.99	1.00
	30.8	100	744	1.99	1.00
	35.9	100	744	1.99	1.00
	46.2	100	744	1.99	1.00
	52.3	100	744	1.99	1.00
	64.4	100	744	1.99	1.00
	73.5	100	744	1.99	1.00
	76.5	100	744	1.99	1.00
	80.0	100	744	1.99	1.00
	83.2	100	744	1.99	1.00
	88.3	100	744	1.99	1.00
90°	19.9	100	744	1.99	1.00
	26.1	100	744	1.99	1.00
	30.8	100	744	1.99	1.00
	35.9	100	744	1.99	1.00
	46.2	100	744	1.99	1.00
	52.3	100	744	1.99	1.00
	64.4	100	744	1.99	1.00
	73.5	100	744	1.99	1.00
	76.5	100	744	1.99	1.00
	80.0	100	744	1.99	1.00
	83.2	100	744	1.99	1.00
	88.3	100	744	1.99	1.00

While our study is motivated by observations of mixing in actual continental slope canyons, we begin by focusing on idealized V-shaped canyons in order to tease out the fundamental dynamics. In Part 1 of this study, we developed a ray-tracing algorithm which we used to explore the impact of canyon geometry on ray focusing and wave number in a linear context (Nazarian and Legg, 2017a). We used the ray tracing algorithm to gain a first-order understanding of the physical processes than can lead to instability in canyons as well as understand the regime where waves become nonlinear. Here in Part 2 we will compare the predictions of this linear ray tracing algorithm with fully nonlinear numerical simulations of internal waves scattering in identical canyon geometries using the Massachusetts Institute of Technology global circulation model (henceforth MITgcm). The idealized canyons we have chosen to analyze are oversimplifications of real canyon bathymetry; however our focus here is not to capture every detail of particular wave-topography interaction, but to explore the parameter space. In this part of our study, we explicitly diagnose the fraction of the incoming energy lost in the canyon, which is a quantity needed for parameterization development. The rationale for the V-shaped, idealized canyons that we have developed is described in Part 1.

The goal of this study is to understand the parameter dependence of internal wave energy dissipation and develop a physical framework to extend this theory to more realistic canyon topographies. We are particularly interested in the topographic parameters of canyon sidewall steepness (α) and canyon aspect ratio (ζ). In the process we seek to understand and predict the spatial structure of dissipation and determine the scenarios in which enhanced mixing is most likely. In this second part, we undertake a numerical parameter space study of idealized continental slope canyons and compare with theoretical predictions. We begin with a brief summary of the parameters of interest (covered in more detail in Nazarian and Legg, 2017a) in Section 2. In Section 3, we describe the MITgcm setup and how the model compares with the ray tracing algorithm developed in Part 1. We also provide a full summary of the calculations used to diagnose energy loss in the model. In Section 4, we take a holistic view of the parameter space, and use a combination of both the ray tracing and numerical simulations to construct an argument for the parameter dependence of internal wave breaking and dissipation in this idealized topography. We find that canyons are indeed efficient dissipators of incoming