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Resolving high-frequency internal waves generated at an isolated coral atoll using an unstructured grid ocean model

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ABSTRACT

We apply the unstructured grid hydrodynamic model SUNTANS to investigate the internal wave dynamics around Scott Reef, Western Australia, an isolated coral reef atoll located on the edge of the continental shelf in water depths of 500,m and more. The atoll is subject to strong semi-diurnal tidal forcing and consists of two relatively shallow lagoons separated by a 500 m deep, 2 km wide and 15 km long channel. We focus on the dynamics in this channel as the internal tide-driven flow and resulting mixing is thought to be a key mechanism controlling heat and nutrient fluxes into the reef lagoons. We use an unstructured grid to discretise the domain and capture both the complex topography and the range of internal wave length scales in the channel flow. The model internal wave field shows super-tidal frequency lee waves generated by the combination of the steep channel topography and strong tidal flow. We evaluate the model performance using observations of velocity and temperature from two through water-column moorings in the channel separating the two reefs. Three different global ocean state estimate datasets (global HYCOM, CSIRO Bluelink, CSIRO climatology atlas) were used to provide the model initial and boundary conditions, and the model outputs from each were evaluated against the field observations. The scenario incorporating the CSIRO Bluelink data performed best in terms of through-water column Murphy skill scores of water temperature and eastward velocity variability in the channel. The model captures the observed vertical structure of the tidal (M_2) and super-tidal (M_4) frequency temperature and velocity oscillations. The model also predicts the direction and magnitude of the M_2 internal tide energy flux. An energy analysis reveals a net convergence of the M_2 energy flux and a divergence of the M_4 energy flux in the channel, indicating the channel is a region of either energy transfer to higher frequencies or energy loss to dissipation. This conclusion is supported by the mooring observations that reveal high frequency lee waves breaking on the turning phase of the tide.

1. Introduction

Topographic internal wave generation occurs at length-scales ranging from $\sim O(0.1–100)$ km. Important parameters that influence the type of internal wave response include the tidal excursion ratio, the ratio of the internal wave characteristic slope to topographic slope, and the topographic Froude number Legg and Klymak (see e.g., 2008); Winters and Armi (see e.g., 2013). In regions where these parameters are all of order one, nonlinear effects due to advection influence the generation process. Lee waves, characterized by higher frequency harmonics, form when internal wave generation is affected by barotropic advection (Bell, 1975). These transient lee waves formed by oscillatory flow are referred to as tidal lee waves in the literature (Nakamura and Awaji, 2001). Other phenomena, including transient hydraulic jumps and internal wave breaking, have been observed in locations such as the Hawaiian Ridge (Alford et al., 2014), the Luzon Strait (Buijsman et al., 2012) and the Mendocino Escarpment (Musgrave et al., 2016). Coral atolls and island chains along continental slopes fall within this regime of the flow parameter space, a regime where vertical mixing is likely to be enhanced and, in turn, can have a strong influence on the local ecology (e.g., Gove et al., 2016).

Three-dimensional Reynolds-averaged Navier–Stokes (RANS) ocean models in island regions must therefore resolve the wide range of topographic length scales to adequately capture the internal wave generation process. The models also need to capture the larger scale background forcing processes, such as the shelf-scale barotropic and baroclinic (internal) tides plus the regional mesoscale circulation. RANS models that employ an unstructured grid discretization are particularly suitable for this task. Furthermore, island atolls are often steep-sided with topographic gradients as large as 50%, meaning that models using

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sigma-coordinate vertical discretization have strict horizontal resolution requirements due to pressure gradient calculation issues (see e.g., Shchepetkin and McWilliams, 2003).

Modeling the time-varying flow of the tidally-driven, stratified flow around and through the channel at the steep-sided Scott Reef atoll system is the focus of this paper. The key differences between Scott Reef and other channel sites, such as at the mouth of an estuary or an ocean strait, are that the reef is located in the open ocean, the water column is continuously stratified and, as opposed to forcing from a horizontal density gradient, a large-amplitude barotropic tide drives an unsteady flow through this channel. At Scott Reef the tidal excursion distance is comparable to the length scale of the channel. To model these processes, one must capture the shelf-scale circulation, the tidal forcing, and the internal tides, while also resolving all the topographic length scales of interest.

The long-term motivation here is to understand the internal wave-driven vertical mixing near coral reef systems that are particularly sensitive to ocean warming caused by climate change (Hughes et al., 2017). Identifying topographically-induced mixing processes will help identify regions within a reef that are less susceptible to surface warming because cooler water can be lifted from depth to mix with warm surface waters. A first step is to model the transfer of the internal tide energy into higher frequencies and wavenumbers that are more conducive to dissipation and small-scale mixing. The next step, and beyond the scope here, is to quantify the mixing rates associated with the breaking of the internal waves (e.g., Sarkar and Scotti, 2017).

In Section 2 of this paper, we give an overview of the study region and present the numerical model setup procedure. In Section 3, we present a quantitative comparison between the numerical model and the through water-column mooring observations collected during a field experiment in April 2015. A description of the internal tide dynamics in the channel is then presented in Section 4, along with model estimates of the internal wave energy generated by the island topography. We conclude with a brief discussion of the dynamics and overview of the model performance.

2. Methods

2.1. Study site

Scott Reef is an island atoll reef system lying on the edge of the continental shelf in water depths of 500 m (see Fig. 1). It is one of several offshore reef systems along the shelf edge of the Australian North West Shelf - Timor Sea region. The reefs have continued to grow despite being situated on a subsiding shelf (Collins and Testa, 2010). The topography of Scott Reef consists of two near-circular reefs, North and South Scott Reef, with dimensions 38 km from north to south, and 28 km from east to west. South Scott Reef, the larger of the two reefs, has a deep lagoon with an average depth of 40 m, which is open along its northern side. The two reefs are separated by a 500 m deep channel approximately 15 km in length from east to west and 2 km wide at its narrowest point. Corals in the lagoons were affected during both the 1998 and 2016 global bleaching events (Gilmour et al., 2013; Hughes et al., 2017, respectively).

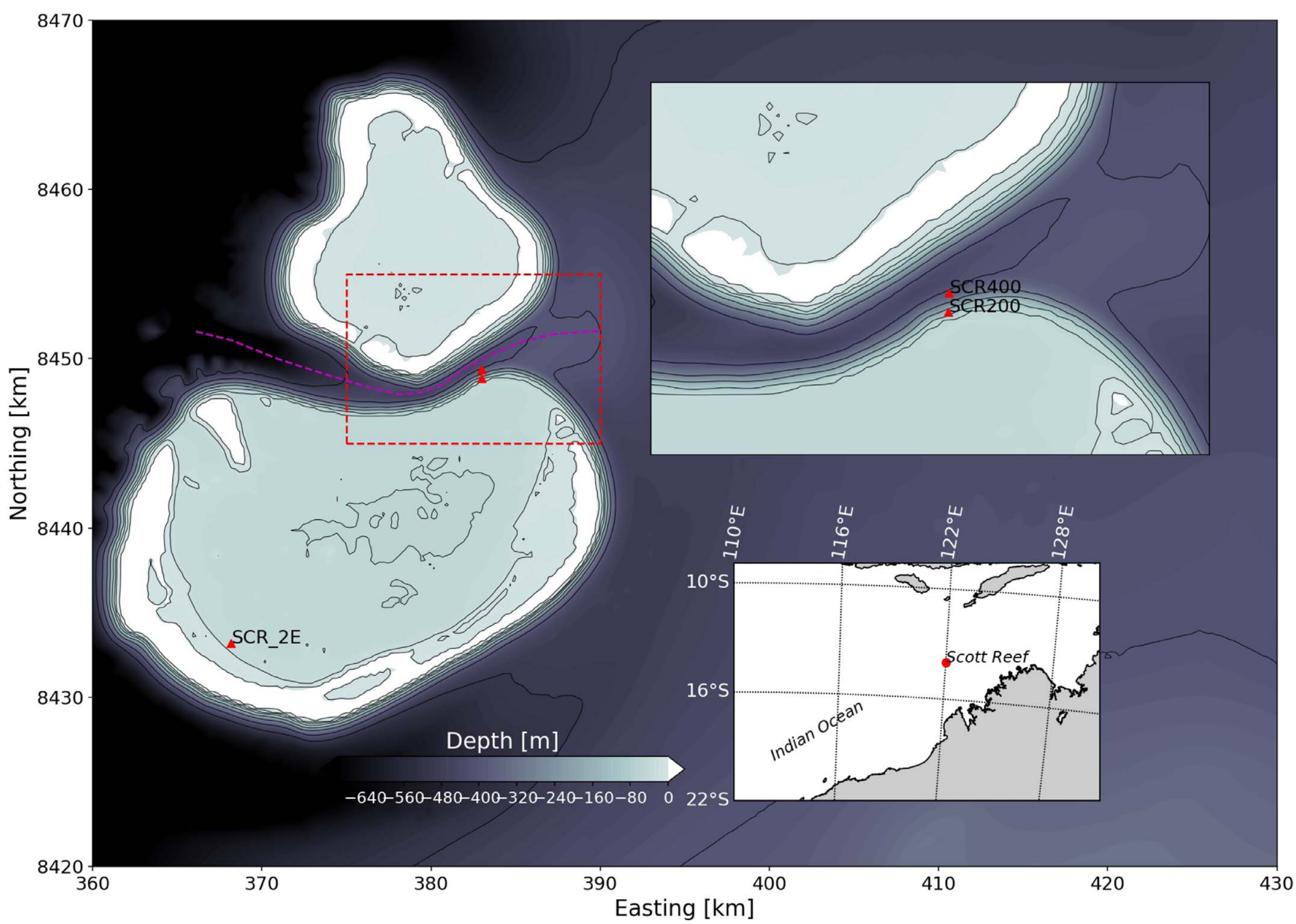

Fig. 1. Bathymetric contour map of Scott Reef with mooring locations indicated by red triangles. The red dashed box indicates the region in the top-right inset panel. The purple dashed line indicates the channel *thalweg*.