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Internal tides near the Celtic Sea shelf break: A new look at a well known problem

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ABSTRACT

Internal waves generated by tides in the Celtic Sea were investigated on the basis of in situ data collected at the continental slope in July 2012, and theoretically using a weakly nonlinear theory and the Massachusetts Institute of Technology general circulation model. It was found that internal solitary waves generated over the shelf break and propagated seaward did not survive in the course of their evolution. Due to the large bottom steepness they disintegrated locally over the continental slope radiating several wave systems seaward and transforming their energy to higher baroclinic modes. In the open part of the sea, i.e. 120 km away from the shelf break, internal waves were generated by a baroclinic tidal beam which was radiated from the shelf break downward to the abyss. After reflection from the bottom it returned back to the surface where it hit the seasonal pycnocline and generated packets of high-mode internal solitary waves. Another effect that had strong implications for the wave dynamics was internal wave reflection from sharp changes of vertical fluid stratification in the main pycnocline. A large proportion of the tidal beam energy that propagated downward did not reach the bottom but reflected upward from the layered pycnocline and returned back to the surface seasonal pycnocline where it generated some extra higher mode internal wave systems, including internal wave breathers.

1. Introduction and motivation

The Celtic Sea (CS) shelf break is one of the "hot spots" of the global ocean where barotropic tidal energy is converted into a baroclinic component (Baines, 1982) making a great contribution to the sustainability of the meridional overturning circulation. This is the reason why much attention is focussed on this site with the aim of quantifying baroclinic processes that develop there. The earliest works by Pingree and Mardell (1981, 1985) followed by more recent studies (Pingree and New, 1995; Holt and Thorpe, 1997; Huthnance et al., 2001; Hopkins et al., 2012) reported the characteristics of internal waves generated by tides over the Celtic Sea shelf break.

The most recent observations were conducted on the 376-th cruise of the RRS "Discovery" (hereafter D376) in June 2012 in the slope-shelf area. The task of the cruise was to quantify the cross shelf transport on the NE Atlantic Ocean margin. In doing so, several long-term moorings with thermistor chains and ADCPs were deployed in the area (some of them are shown in Fig. 1), accompanied by CTD surveys and glider missions.

The data collected in situ revealed evidence of a strong semi-diurnal baroclinic tidal signal that was accompanied by packets of short-period internal solitary waves with amplitudes up to 100 m. A detailed analysis of the characteristics of these waves, their spatial structure and dynamics was reported by Vlasenko et al. (2014) who replicated the generated wave fields numerically using the Massachusetts Institute of Technology general circulation model (MITgcm, Marshall et al., 1997). The model results were validated against the observational data collected during the D376 cruise.

Two classes of tidally generated internal waves were identified in the area with highly corrugated topography shown in Fig. 1. Spiral-type internal waves similar to those typical for isolated underwater banks were generated over the headland. The other type was a system of quasi-planar internal wave packets that were generated in the area of several canyons. The spatial structure of these two wave systems is shown in Fig. 1a (see Vlasenko et al., 2014 for more details). Note that the water stratification during the experiment was characterised by a relatively sharp interface at the depth of 50 m and less pronounced main pycnocline located between 500 and 1200 m (Fig. 2a).

Vlasenko et al. (2014) concluded that the strongest internal wave system is a superposition of a 20 m amplitude semi-diurnal baroclinic tidal wave and a series of internal solitary waves (ISW). These waves were generated over the top of the headland (just in the place of the mooring ST2 deployed at isobath 185 m, see Fig. 1a) and radiated to the shelf and to the deep water towards mooring ST1. The isotherm time series, Fig. 3a, shows the vertical structure of the

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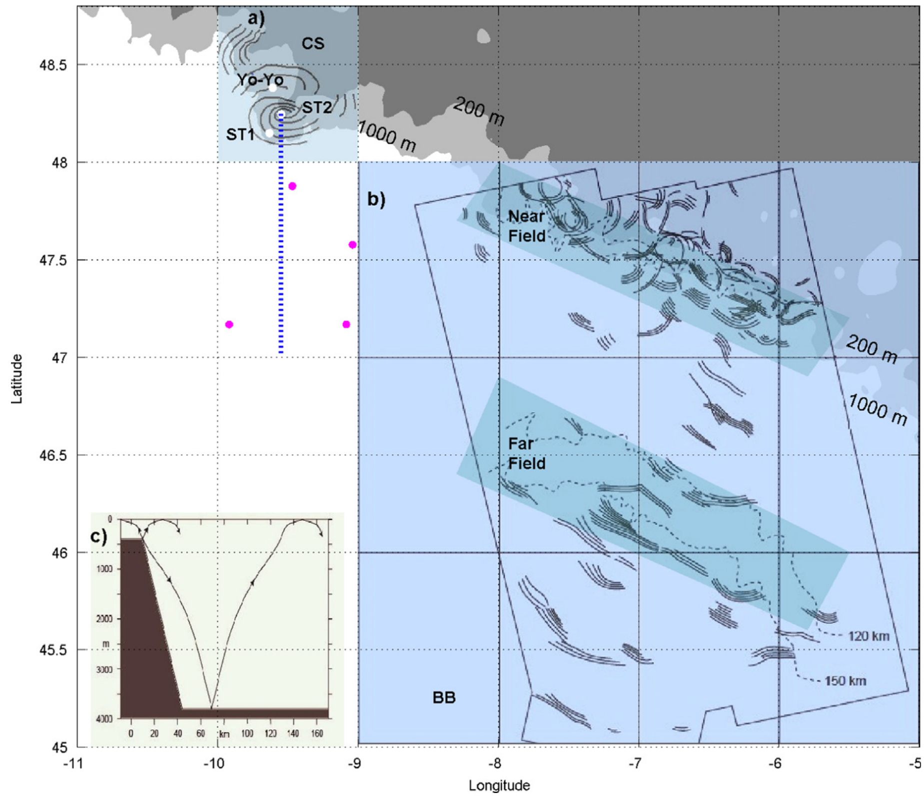

Fig. 1. Shelf break of the Celtic Sea presented by the 200 m izobath. Positions of three moorings, Yo-Yo, ST1, and ST2 deployed during cruise D376 are depicted by white dots. Vertical dotted line shows the cross-section used in numerical modelling. (a) Plan view of tidally generated internal wave systems predicted by the MITgcm (Vlasenko et al., 2014). Time interval between two wave fronts equals 2 h. (b) Composite image of all ISW packets observed in July 1994 and July–September 1999 in the Bay of Biscay and reported by New and Da Silva (2002). The observational area ranges from 5 to 9°W which is adjacent to the domain considered here. (c) The tidal beam that is mentioned in the aforementioned paper as a reason for a local generation of internal waves in the far field.

internal waves recorded at mooring ST1, and Fig. 3b represents a 5-h fragment with the strongest leading ISW of 105 m amplitude.

The normalized vertical profile of the largest ISW recorded at mooring ST1 is shown in Fig. 3c. It was built by calculation of the displacement of the chosen isotherm from its equilibrium depth before the ISW arrival and normalized by the wave amplitude. Fig. 3c shows that the wave profile reveals the properties of the second baroclinic mode that produces counter-phase displacements of isotherms in the surface and bottom layers. To get a more statistically justified result on the possible appearance of second-mode ISWs at mooring ST1, another 45 of the largest ISWs, with amplitudes larger than 30 m, were analysed in a similar way. Considering the whole cluster of the dots together it was expected to find a general tendency of their distribution that is noise free and statistically significant. It is clear from Fig. 3d that all ISWs are waves of depression in the surface 120 m layer. Below this depth the dots are randomly distributed across the whole range between -1 and 1, so that both the waves of depression and elevation were equally observed.

To make the point clearer, the eigenfunctions of the boundary value problem (BVP)

$$\frac{d^2\Phi}{dz^2}+\frac{N^2(z)}{c_i^2}\Phi=0, \quad \Phi(0)=\Phi(-H)=0. \tag{1}$$

were calculated. Here $\Phi(z)$ is the vertical modal structure function, c_i is the phase speed of the i-th mode, $N(z)$ is the buoyancy frequency shown in Fig. 1d, H is the water depth.

Two first eigenfunctions of the BVP (1) are presented in Fig. 3d. It is clear that the vertical structure of the ISWs recorded at ST1 does not fit either the first or the second baroclinic mode. However, initially at the place of their generation (in the area of the mooring ST2, see Fig. 1), the internal waves had the structure of the first baroclinic mode (for the details see Vlasenko et al., 2014). Thus, it is unclear what happened to these waves on their way from shallow mooring ST2 to the deeper ST1 , i.e. in the course of their seaward propagation (hereafter, "antishoaling"). What is the ultimate fate of the waves generated on the CS slope: Do they dissipate locally or radiate far away from the place of generation? These fundamental questions on the mechanisms of the tidal energy conversion and its dissipation were a strong motivation for the present study.

The paper is organized as follows. Section 2 describes the antishoaling process of ISWs in terms of a weakly nonlinear theory and using fine-resolution modelling based on a 2D version of the MITgcm. Section 3 summarises the finding from the antishoaling study and formulates some further questions to be answered. Section 4 reports results of a high-resolution modelling of baroclinic tides in the area. Section 5 outlines the main findings.

2. Does the antishoaling kills all ISWs?

2.1. Weakly nonlinear analysis

Evolution of seaward propagating first mode ISW can be investigated in terms of the Gardner equation:

$$\frac{\partial\eta}{\partial t}+(\alpha\eta+\alpha_1\eta^2)\frac{\partial\eta}{\partial x}+\beta\frac{\partial^3\eta}{\partial x^3}=0. \tag{2}$$

Here η is the displacement of the isopycnals; x is the spatial variable in the direction of wave propagation, and t is the time; α and α_1 are the coefficients of quadratic and cubic non-linearities, respectively; β is the coefficient of dispersion. Note that α, α_1, and β