Internal gravity waves and topography: emission, propagation and reflection.

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Abstract :

We study the interplay between internal gravity waves and topography. When internal waves are impinging onto a sloping bed, striking phenomena are expected to occur close to the slope due to the unusual reflection properties. We have designed several internal wave generators to study experimentally this reflection. We have also designed a simple laboratory experiment to study the internal tide generation. We consider a steep continental shelf in an oscillating flow, for which an internal tide is shown to be emitted from the critical point. We discuss the dependence of the width of the emitted beam on the local curvature of topography and on the viscosity, by drawing an analogy with an oscillating cylinder in a static fluid.

Résumé :

Nous étudions l'interaction entre les ondes internes de gravité et la topographie. Lorsque des ondes internes viennent se réfléchir sur un fond incliné, des phénomènes étonnants sont prédits étant donné les caractéristiques inhabituelles de la réflexion de ces ondes. Nous avons proposé plusieurs générateurs d'ondes internes pour étudier cette réflexion de manière expérimentale. Nous avons également conçu une expérience simple pour étudier la génération de la marée interne. Dans le cas d'une pente continentale abrupte, nous montrons que la marée interne est émise à partir de ce point critique. Nous discutons la dépendance de la largeur du faisceau émis sur la courbure locale de la topographie et de la viscosité, en faisant l'analogie avec le cas d'un cylindre oscillant dans un fluide statique.

Key-words :

Internal waves; Internal tides; Stratified Fluids

1 Introduction

Internal gravity waves in the atmosphere and in the ocean are often due to the topography: the interaction of the wind with the orography in the atmosphere creates mountain waves while the passage of the barotropic tide over bathymetry in the ocean generates internal waves, commonly referred to as the internal tide. We briefly review in this paper recent experimental studies we have performed to study on the one hand internal wave reflection on topography, and generation of internal tides from topography on the other hand.

2 Reflection of internal waves

We devised a novel generator (Gostiaux *et al*. (2007)) which consists of sheets free to slip one over the other. Two identical camshafts impose the relative position of the plates. At rest, the plates are sinusoidally shifted, due to the helicoidal repartition of the cams (see left panel in Fig. 1). The rotation of the latter applies a periodic motion to the plates which propagates upward (resp. downward) for a clockwise (resp. anti-clockwise) rotation. The eccentricity of the camshafts defines the amplitude of oscillation of the plates (see Gostiaux *et al.* (2007) for experimental details).

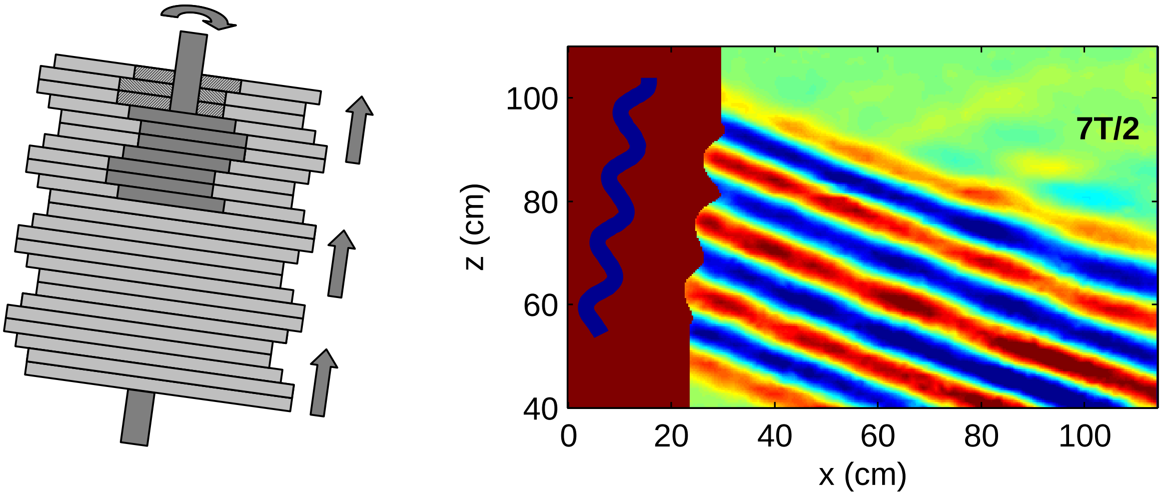

Figure 1: Left panel: side-view of the new internal wave generator. One can distinguish the different plates which are oscillating one over the other with a phase difference. Right panel: horizontal velocity field emitted from the internal wave generator after 7 half-periods. The location of the internal wave generator is indicated by the thick blue curve. The maximum velocity amplitude in this case is of 3 mm/s

The design of this internal wave generator imposes a rigid boundary condition compatible with the equations governing the propagation of plane internal waves. Right panel of Fig. 1 presents the experimental horizontal velocity field that we measured using the PIV technique. It is clear that we obtain a large beam with very good spatial and temporal monochromaticities (see Gostiaux *et al.* (2007) for the careful study).

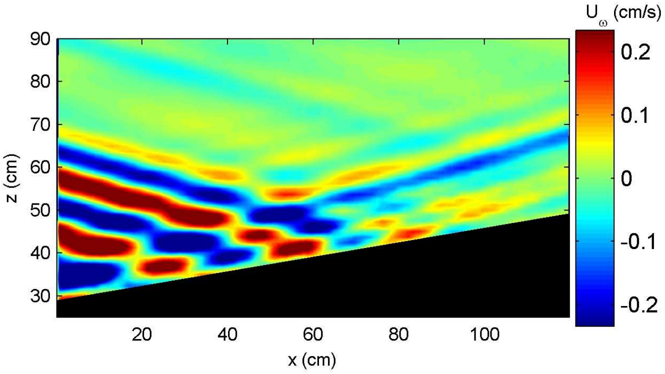

Figure 2: Horizontal velocity field in a super-critical case ($\theta = 17°$ and $\alpha = 9.5°$) filtered at the excitation frequency. A large beam emitted from the internal wave generator on the left of the picture hits the slope represented by the black triangle.

This large beam of internal waves is ideal to study carefully the peculiar reflection properties of those waves impinging onto a slope. Indeed, theoretical predictions have been recently derived by Dauxois & Young (1999) for a plane wave. Unfortunately, all previous experimental results were either of poor quality, or were considering very thin wave beams, with comparable wavelength and width. Figure 2 is a typical result for a supercritical case. The first quantitative laboratory observations of internal wave reflection on ascending slopes can be found in Gostiaux *et al.* (2006).

3 Internal tide generation

Internal tides are a specific form of monochromatic internal gravity waves, generated by barotropic tidal flow over oceanic bottom topography. They propagate in the flow under the form of localized wave beams, emitted from shelf break or, more generally, from the upper part of the topography, where the vertical velocity of the barotropic tide is the strongest. Except a very preliminary attempt by Baines & Xin-Hua (1985), there were no experimental studies of this very important oceanographic phenomenon.

The experiment was performed in a tank with a linear stable stratification, pure water at the free surface while highly salted water at the bottom, resulting in a constant Brunt-Vaisälä buoyancy frequency $N \simeq 0.79$ s^{-1}. We introduced a curved thin PVC plate to play the role of the continental slope while a tidal current was created by a second PVC plate, oscillating like $A\cos(\omega t)$ and localized far from the continental slope. We took of course a tidal frequency ω satisfying the condition $0 < \omega < N$, so that internal tides may be freely radiating. Experimental data were obtained with the standard synthetic Schlieren technique by acquiring successive side views (see Gostiaux & Dauxois (2007) for experimental details).

Figures 3 show successive snapshots of the vertical density gradient. To facilitate the visualisation, a narrower domain centered on the shelfbreak is shown. To increase the visibility, we filtered at the excitation frequency ω the experimental images over one experimental tidal period (see Gostiaux *et al.* (2006) for more details about this method). More precisely the n-th picture corresponds to the result around $t_n = nT/2$, which means a filtering procedure over the interval $[(n-1)T/2, (n+1)T/2]$. Such a method allows to emphasize the development of the internal tides as a function of time.

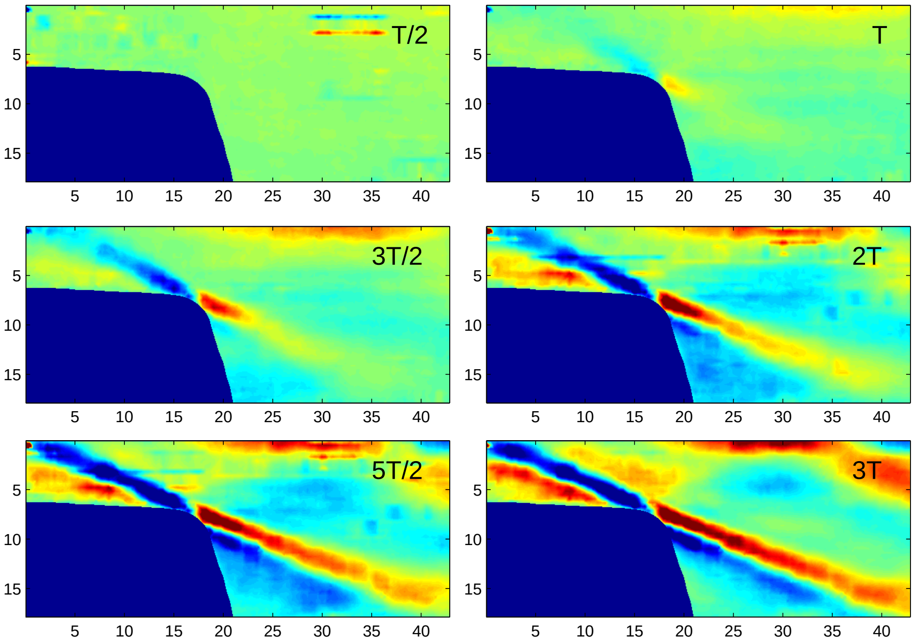

Figure 3: Two-dimensional vertical density gradient averaged over one tidal period of excitation around $t_n = nT$ for $n = 1, 2, 3$. The excitation amplitude was $A = 0.5$ cm. Horizontal and vertical distances are in cm.

Several comments are in order. No transmission transverse to the slope can be detected from these results, contrary to previous theoretical predictions (Baines (1982)). On the contrary, a clearly identified beam is emitted tangentially to the slope from a specific point. As emphasized by Fig. 4, the phase propagates in opposite directions from the generation point: this is consequently an amphidromic point, around which the phase turns, and where the amplitude vanishes.

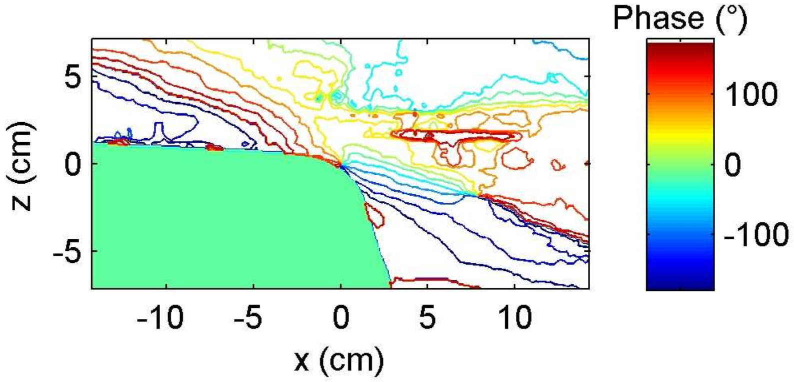

Figure 4: Phase around the generation point: this is an amphidromic point.

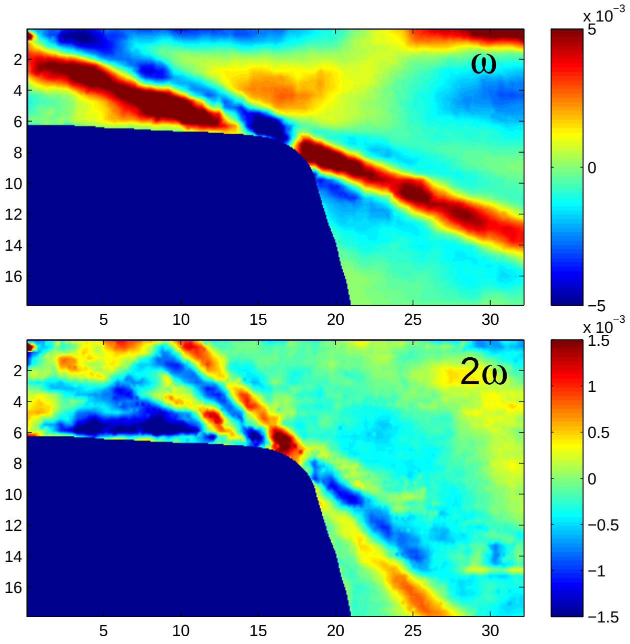

Figure 5: Two-dimensional vertical density gradient of the first two harmonics averaged over one tidal period of the experiment: respectively ω around $t = 3T$ and 2ω around around $t = 4T$. The excitation amplitude A was set to 0.5cm. Note that the colorbars plotted on the right are different. Horizontal and vertical distances are in cm.

To get further insight into the generation mechanism at the critical amphidromic point, we have filtered not only the experimental data around ω as shown in Figs. 3 but also around its harmonics $n\omega$. As shown in Figs. 5, harmonics are generated although their amplitudes are much reduced (as emphasized by the colorbars). As the propagation angle of the second harmonic is steeper (this is a consequence of the internal waves dispersion relation), a careful inspection reveals that the location of the generation point is slightly shifted to the right.

In Gostiaux & Dauxois (2007), we have shown that a fruitful analogy with an oscillating cylinder in a static fluid (Hurley & Keady (1997)) might provide interesting results for a static slope in an oscillating fluid. The key point is to study the emission of internal waves from the cylinder with a radius defined by the local curvature of the slope around the amphidromic point. Figure 6 emphasizes that theory and experiment not only agree from the qualitative point (left panel) of view but also from the quantitative point of view.

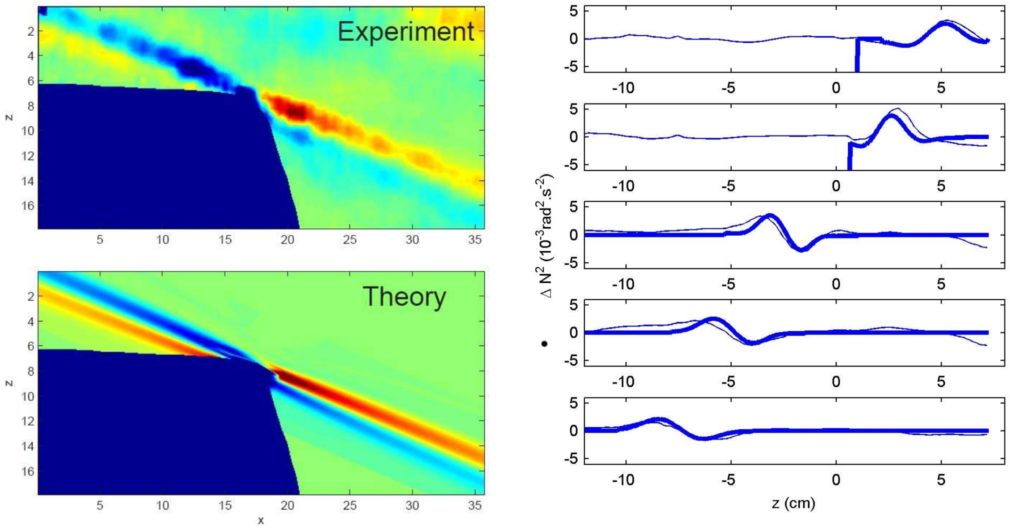

Figure 6: Panel a presents the comparison between experimental and theoretical results for the vertical density gradient at $t = 3T/2$. Panel b shows several vertical density gradients at x =22, 24, 26, 28 and 30 cm. The thin line corresponds to the experimental results, while the thick one to the theoretical prediction.

4 Conclusions

We have briefly reviewed several experiments we devised in order to study the interaction of internal gravity waves with topography. We would like to emphasize the design of a new kind of internal waves generator capable of selecting a single direction of emission of the waves. They are purely monochromatic, both spatially and temporally, which is of first importance for the study of nonlinear processes involved in internal waves dynamics.

This possibility opens new perspective for future studies of the dynamics of internal waves in stratified fluids. Let us mention not only quantitative measurements of internal wave reflection as discussed in this paper, but also the reflection in a rotating tank. Interesting new effects have been found in preliminary experiments of gravito-inertial waves reflection.

Last but not least, let us stress the first experiment of internal tide generation, and a simple analogy which leads to a nice theoretical predictions of the wave beam emitted from an amphidromic point. Experiments and theory nicely agree.

5 Acknowledgments

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