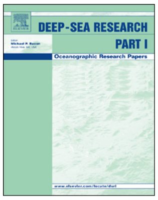
Deep-Sea Research I 99 (2015) 87–104

Contents lists available at ScienceDirect

Deep-Sea Research I

journal homepage: www.elsevier.com/locate/dsri



# Internal waves on the upstream side of a large sill of the Mascarene Ridge: a comprehensive view of their generation mechanisms and evolution

J.C.B. da Silva [a],*, M.C. Buijsman [b], J.M. Magalhaes [a]

[a] CIMAR/CIIMAR – Interdisciplinary Centre of Marine and Environmental Research & Department of Geosciences, Environment and Spatial Planning, University of Porto, Rua dos Bragas 289, 4050-123 Porto, Portugal
[b] University of Southern Mississippi, Department of Marine Science, 1020 Balch Blvd, Stennis Space Center, MS 39529, USA

ARTICLE INFO

*Article history:*
Received 2 May 2014
Received in revised form
23 December 2014
Accepted 7 January 2015
Available online 4 February 2015

*Keywords:*
Internal solitary waves
Lee waves
Multimodal bore
Local generation
Mode-1 mode-2 internal solitary wave ressonance
Synthetic aperture radar

ABSTRACT

In this paper we aim to clarify the generation of Internal Solitary Waves (ISWs) at work to the east of the Mascarene Plateau (Indian Ocean) using Synthetic Aperture Radar (SAR) imagery and MITgcm fully nonlinear and nonhydrostatic simulations. Realistic representations of stratification and bathymetry are used with asymmetric tidal forcing (including the steady South Equatorial Current which is assumed barotropic in the model) along a 2D transect aligned with the propagation direction of the wave signatures identified in the SAR. The combined flow (i.e. steady and tidal currents) is subcritical with respect to first-mode Internal Waves (IWs), but supercritical with respect to higher wave modes. Different types of nonlinear wave trains with distinct origins (i.e. tidal phase and location) have been identified with the combined aid of model and SAR: (1) large-scale primary mode-1 ISWs evolve from the disintegration of a multimodal baroclinic structure that appears on the upstream side of the sill; (2) mode-2 ISW-like waves that evolve from this same baroclinic structure and are arrested over the sill before being released upstream at the change of flow condition; (3) a large mode-2 lee wave is generated downstream of the sill (i.e. on the west side), which is trapped there during maximum westward tidal flow and released upstream when the tide relaxes; and (4) mode-2 ISW-like waves whose length-scales are O (20 km) appear some 50 km upstream of the sill, after an Internal Tide (IT) beam scatters into the pycnocline, itself originating from critical topography on the leeward (i.e. westward) side of the sill. The underwater sill being investigated is in the mixed-tidal-lee wave regime, where the internal tide release mechanism, lee wave generation and IT beams can coexist. The large-scale mode-2 ISW-like waves that form far upstream from the sill are long-lived features and can be identified in the SAR due to associated short-scale mode-1 ISWs which propagate with the same phase speed, i.e. in resonance. This coupling is also seen in the model, and here it is argued that the formation of those mode-2 ISW-like waves appears to originate from the IT beam after it reflects from the sea surface and interacts with the pycnocline, a generation mechanism referred in the literature as "local generation of ISWs". This IW generation process may be easily overlooked and could be at work in many more regions of the world than previously thought.

## 1. Introduction

The generation of nonlinear internal waves or Internal Solitary Waves (ISWs) in the ocean is generally recognized as a complex phenomenon that after 40 years of research (see e.g. Lee and Beardsley, 1974; Maxworthy, 1979; Lai et al., 2010) still remains a subject of active investigation. Some of the most common generation mechanisms of ISWs are associated with stratified strong tidal flows over large amplitude sills or submarine ridges, which generate ISWs close to the area of topographic interaction. These Internal Waves (IWs) are usually documented as nonlinear wave trains, internal undular bores, or ISWs, and may arise from the relaxation of internal hydraulic (supercritical) flows (Maxworthy, 1979; Apel et al., 1985; Brandt et al., 1997; Farmer and Armi, 1999a, 1999b), the release of internal lee waves (Haury et al., 1979; Farmer and Smith, 1980), intrusions created by collapsing mixed layers (Maxworthy, 1980), or some form of upstream influence (Baines, 1984; Grimshaw and Smyth, 1986; Melville and Helfrich, 1987; Grue

---

* Corresponding author. Tel: +351 2204 02476; fax: +351 220402490.
*E-mail address:* jdasilva@fc.up.pt (J.C.B. da Silva).

http://dx.doi.org/10.1016/j.dsr.2015.01.002
0967-0637/

**Table 1**
Non-dimensional parameters used to characterize tidal flow over bottom topography in the ocean. The densimetric and topographic Froude numbers ($Fr$ and $Fr_t$, respectively) are given together with the tidal excursion length ($\delta$). $U_{max}$ is a representative value of the maximum flow velocity over the topography (with characteristic width $L$ and height $H$), $c$ is the phase speed for long linear internal waves (modes-1 and 2), $N_{max}$ is the maximum value for the buoyancy frequency, and $\omega$ is the semi-diurnal tidal frequency ($M_2$).

| Study region | $Fr=U_{max}/c$ | | $Fr_t=N_{max}/U_{max}$ | $\delta=U_{max}/L\omega$ |
|---|---|---|---|---|
| | Mode 1 | Mode 2 | | |
| Mascarene Ridge (near-field) | $\approx 0.5$ | $\approx 1.0$ | $\approx 200$ | $\approx 0.1$ |
| Luzon Strait After Buijsman et al. (2010) and Ramp et al. (2012) | $\approx 0.4$ | $\approx 1.0$ | $\approx 500$ | $\approx 0.04$ |
| Knight Inlet After Farmer and Smith (1980) | $< 1.0$ | $\approx 2.4$ | $\approx 1.4–5.0$ | $\approx 1–2$ |

et al., 1997; Cummins et al., 2003; Lai et al., 2010) – just to name a few generation mechanisms, which would clearly benefit from a unifying theory.

A particular issue that has recently regained interest (see e.g. Scotti et al., 2007; Lai et al., 2010) concerns the ambiguity regarding the precise location (i.e either upstream or downstream) and tidal phase of the exact physical feature (i.e. isopycnal perturbations) from which IW trains eventually originate. While Lee and Beardsley (1974), indicated as L.B. in what follows proposed that the IWs are formed on the upstream side of the sill that originates the disturbance, Maxworthy (1979) concluded that the blocking effect of an obstacle on an oncoming stratified tidal flow would only result in a quasi-stationary lee wave on the downstream side of the obstacle, with a phase velocity opposite to the flow direction. This "lee wave" mechanism is based on the theory of supercritical flows, which uses the densimetric (or internal) Froude number ($Fr$, formally introduced later in Section 3) to characterize the hydraulic state of a stratified flow (i.e. subcritical, critical or supercritical) with regard to the linear long IW phase speed.

It is important to note that in Maxworthy (1979) the flow clearly reached supercritical speeds ($Fr>1$ with regard to all IW modes) during a significant period of the experiment – which may not always be the case. This means that information can only propagate downstream (i.e. in the same direction of the flow), because the fluid velocity is greater than the IW phase speeds. During the accelerating phase of the tidal flow, when the Froude number reached a critical value ($Fr=1$), a disturbance on the interface (downstream of the sill) remains stationary and accumulates energy through resonance. Such a lee wave cannot propagate against the flow in the upstream direction until the relaxation of the tidal stream over the sill, i.e. when its phase velocity exceeds the slackening current. Subsequently, the pycnocline depression advances over the sill's crest and a packet of ISWs is formed. The model proposed by Maxworthy (1979) successfully explained the generation of nonlinear IW trains in various regions of the world's oceans (see e.g., Apel et al., 1985 and Brandt et al., 1997).

Subsequent studies concluded that both L.B. and Maxworthy's (1979) mechanisms could apply depending on the flow criticality (see e.g. Haury et al., 1979; Farmer and Smith, 1980; Chereskin, 1983; Matsuura and Hibiya, 1990), although they have never been found simultaneously at work. We note however that the flow may be subcritical with respect to the fundamental mode but supercritical with respect to higher modes (e.g. mode-2). In this case, as reported by Farmer and Smith (1980), a mode-2 lee wave is formed downstream while at the same time, mode-1 ISWs are also formed upstream of the sill's crest, in what appears to be an independent process. In this last case mode-1 ISW generation has been explained in terms of partial blocking and upstream influence, which is identified in state-of-the-art numerical models as the mechanism responsible for ISW generation upstream of several ocean sills (e.g. Cummins et al., 2003; Scotti et al., 2007; Stashchuk and Vlasenko, 2007; Lai et al.; 2010; Buijsman et al. 2010), even when the flow is supercritical (with regard to all modes) over the sill's crest.

Another example of upstream influence has also been identified in the South China Sea (SCS) by Buijsman et al. (2010) who termed "internal tide release mechanism" to the generation of large amplitude ISWs from the asymmetrical flow across a large ridge (including tidal and steady currents). In this case, strong currents lift the isopycnals higher upstream of the ridge (i.e. creating an elevation wave there), allowing for a large energy density to accumulate on this side. As soon as the current slackens, this elevation wave is released upstream and ISWs form on its back slope – see Buijsman et al. (2010) for further details.

IW beams generated at critical slopes (i.e. where beam and bottom slopes match together) may also generate ISWs by means of an altogether different mechanism, termed "local generation" (New and Pingree, 1992). These ISWs are not directly related to topography, but are generated by an internal tidal beam hitting the seasonal thermocline at an oblique angle. The internal tide beam interacts with the interface and creates an interfacial wave there, which may then evolve through nonlinear steepening into ISWs (see e.g. New and Pingree, 1990, 1992; Gerkema, 2001; Akylas et al., 2007; Grisouard and Staquet, 2010; Mercier et al., 2012; Dossmann et al. 2013). Satellite imagery has confirmed the effectiveness of this generation mechanism in the Bay of Biscay (New and da Silva, 2002; Azevedo et al., 2006) as well as in other locations, such as off Portugal (da Silva et al., 2007) and in the Mozambique Channel (da Silva et al., 2009). Particularly relevant for the present study, is the work of Grisouard et al. (2011), which discusses the local generation of ISWs with a higher mode vertical structure (e.g. modes-2 and 3) in the vicinity of the beam impact. Their findings are tested in this paper to account for the generation of mode-2 ISW-like waves observed upstream of the sill, in the Mascarene Ridge region. We will also demonstrate that these ISWs are relatively long-lived, contrasting with other observations of mode-2 ISW-like waves previously reported (e.g. those in Shroyer et al., 2010, which have lifetimes of typically less than a few hours).

A particular scenario where lee waves, upstream influence and tidal beams can coexist is of key importance to our study. This generation scenario has already been discussed in the parameter space given in Garrett and Kunze (2007) (see their region 4), or alternatively in the mixed tidal lee wave regime discussed in Nakamura et al. (2000). The topographic Froude number ($Fr_t$) and the normalized tidal excursion length ($\delta$), defined as: $Fr_t=N_{max}H/Uo$ and $\delta=Uo/L\omega$ (see also Table 1), are set as two major parameters governing the different generation regimes for IWs. In particular, a large $\mathrm{Fr_t}$ and a small $\delta$ mean that significant blocking effects (owing to bathymetry) will simultaneously allow for upstream influence and lee waves to develop upstream and downstream of the obstacle (see Garrett and Kunze, 2007; Klymak et al., 2010), while still allowing tidal beams to develop in the presence of critical slopes (see Nakamura et al., 2000). Figure 4 of Buijsman et al. (2010) exemplifies precisely that, since a lee wave forms downstream of the sill together with an internal tidal beam whose energy propagates upstream and towards the surface (i.e. an upstream-leaning beam). The authors further note that, similar upstream-leaning beams have also been