SAR IMAGING OF WAVE TAILS: RECOGNITION OF SECOND MODE INTERNAL WAVE PATTERNS AND SOME MECHANISMS OF THEIR FORMATION

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ABSTRACT

Mode-2 internal waves are usually not as energetic as larger mode-1 Internal Solitary Waves (ISWs), but they have attracted a great deal of attention in recent years because they have been identified as playing a significant role in mixing shelf waters [1]. This mixing is particularly effective for mode-2 ISWs because the location of these waves in the middle of the pycnocline plays an important role in eroding the barrier between the base of the surface mixed layer and the stratified deep layer below. An urgent problem in physical oceanography is therefore to account for the magnitude and distribution of ISW-driven mixing, including mode-2 ISWs. Several generation mechanisms of mode-2 ISWs have been identified. These include: (1) mode-1 ISWs propagating onshore (shoaling) and entering the breaking instability stage, or propagating over a steep sill; (2) a mode-1 ISW propagating offshore (antishoaling) over steep slopes of the shelf break, and undergoing modal transformation; (3) intrusion of the whole head of a gravity current into a three-layer fluid; (4) impingement of an internal tidal beam on the pycnocline, itself emanating from critical bathymetry; (5) nonlinear disintegration of internal tide modes; (6) lee wave mechanism. In this paper we provide methods to identify internal wave features denominated "Wave Tails" in SAR images of the ocean surface, which are many times associated with second mode internal waves. The SAR case studies that are presented portray evidence of the aforementioned generation mechanisms, and we further discuss possible methods to discriminate between the various types of mode-2 ISWs in SAR images, that emerge from these physical mechanisms. Some of the SAR images correspond to numerical simulations with the MITgcm in fully nonlinear and nonhydrostatic mode and in a 2D configuration with realistic stratification, bathymetry and other environmental conditions. Results of a global survey with some of these observations are presented, including: the Mascarene Ridge of the Indian Ocean; South China Sea; Andaman Sea; tropical Atlantic off the Amazon shelf break, Bay of Biscay of the western European margin; etc. The survey included the following SAR missions: ERS-1/2; Envisat and TerraSAR-X.

INTRODUCTION

Reference [2] reported, for the first time, the existence of long-lived mode-2 internal waves coupled with "wave-tails" composed of mode-1 smaller-scale ISWs in the Mascarene Ridge of the Indian Ocean. Similar findings and interpretation were reported in [3] in the northern South China Sea. The transference of internal wave energy from the seasonal thermocline through a weakly stratified layer to the main thermocline is known since the 1960s [4]. This phenomenon may be reversible, i.e. energy may be transferred back to the seasonal thermocline in a resonance process known as Eckart's resonance or tunneling in an analogy to quantum mechanics. Tunneling occurs for pairs of modes that have comparable frequency and wavenumber, hence nearly the same phase speed. This coupling (or resonance) between internal wave modes propagating in different ducts is relevant to remote sensing of the ocean, since ISWs propagating in the near surface duct are more likely to be detected in SAR images while those internal waves propagating in the deeper duct would be hardly identified if they were not coupled with short-period mode-1 ISWs in the upper duct. Hence, our ability to understand and identify internal wave coupling in different horizontal ocean ducts is of considerable importance and worth investigating. In addition, interaction of ISWs with mesoscale eddies is also a problem receiving considerable attention in recent years [5], and currently under investigation. In this paper we address the problem of small scale internal waves trailing large ISWs of the fundamental, in regions where these large scale ISWs have been documented in recent years, such as: South China Sea, Andaman Sea and the tropical Atlantic off the Amazon shelf break.

DATA ANALYSIS

Our first case study refers to February 2004 in the Northeastern South China Sea (SCS), over the steepest slopes between the SCS deep basin and the continental shelf to the Southwest (Figure 1). Altimeter data revealed the existence of an Anticyclonic Eddie (AE) over this area of the SCS during the whole month of February (see Figure 1). ERS-2 SAR image dated 25 February 2004 acquired at 02:42 UTC, whose frame is marked as a white rectangle in Figure 1, shows signatures of various ISW features which include both mode-1 and mode-2 internal waves (Figure 2).

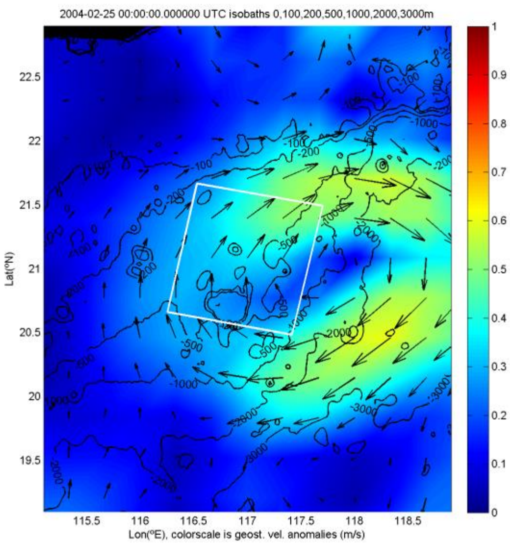

Figure 1. Geostrophic velocity anomalies in an Anticyclonic Eddie computed from altimeter data. White rectangle refers to ERS-2 SAR frame dated 25.02.2004.

Mode-1 and mode-2 ISWs can be discriminated in SAR images due to their surface signature. While mode-1 waves show as bright bands followed by dark bands in the direction of phase propagation, mode-2 waves are detected with reversed patterns, i.e. dark bands precede bright bands in the propagation direction [6]. In addition, separation between consecutive wave packets in the same image can be used to infer wave phase speed on the assumption of tidal period generation. The measured phase speed can then be compared with linear phase speed computed from a standard Boundary Value Problem (BVP), assuming we know the average ocean stratification. In Figure 2 several features are identified with different letters: M1 refers to a mode-1 ISW, M2 refers to mode-2 internal waves, T is a trailing wave train of the fundamental mode that evolves due to wave focusing produced by the AE, and F is a disintegrated ISW also resulting from defocusing effects produced by the presence of the AE. The interpretation of these features is based on [5].

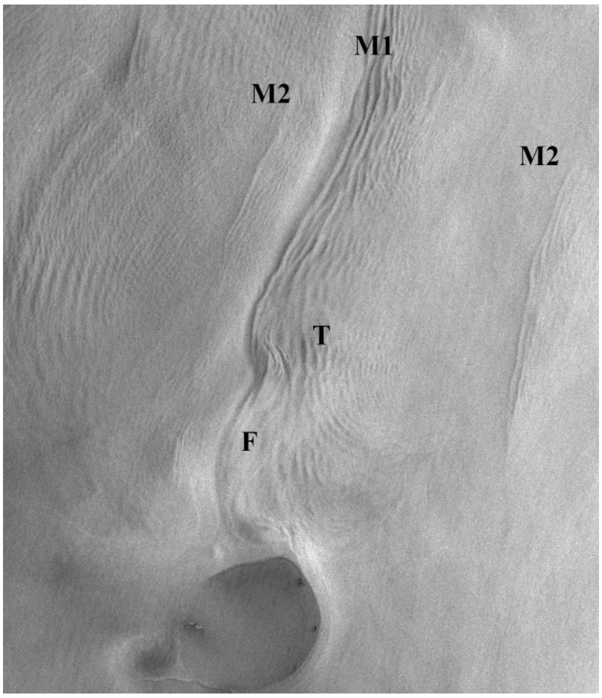

Figure 2. ERS-2 SAR image dated 25.02.2004 acquired at 02:42 UTC over the South China Sea. See text for label description.

The appearance of the first (i.e. earliest) mode-2 internal wave train coincides with the region of steep shelf break bottom slopes. Scrutiny in data analysis reveals that the mode-2 ISW train visible in the ERS-2 SAR image occurs immediately to the west of a bottom bump with some 200m height above the sloping sea floor at about 700m depth. Previous work reported the influence of bottom bumps in mode-2 internal wave generation [7]. In Figure 3 the location of the mode-2 ISW signatures clearly suggests the influence the bottom bump may have in their formation or evolution. Note that the mode-2 internal waves are long lived features with lifetimes greater than a semi-diurnal tidal cycle (12.42 hours). This can be inferred from the image in Figure 2 because two consecutive mode-2 wave trains are separated by more than 35km, the distance expected to be travelled by the internal waves based on their average linear phase speed.

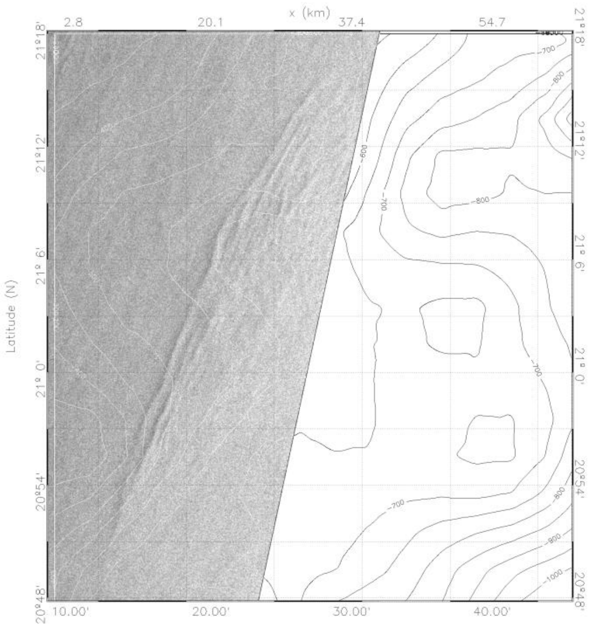

Figure 3. Zoom into the ERS-2 SAR image shown in Figure 2. Note the mode-2 internal wave train to the West of a bottom feature visible on the right hand side of bottom contours (depth contours in meters).

The second case study addressed in this paper reports mode-2 short-period internal waves propagating along the Ten Degree Channel of the Andaman Sea. The mode-2 SAR signatures are again identified by their dark and bright stripes along the propagation direction, from West to East. We investigate the generation mechanism of these mode-2 waves by using ray tracing techniques based on our knowledge of average stratification and the bottom topography. The bottom topography is characterized by a double ridge system relatively shallow compared to other bottom features of the Andaman Sea whose depth is some 800m. Figure 4 shows an Envisat ASAR image dated 16.01.2005 acquired at 15:51 UTC in Precision Image mode. The mode-2 SAR signatures present in this image appear to the East of the Eastern Ridge, whose crests are aligned with the Ridge but some 40-50 km to the East. The Eastern Ridge is also characterized by the strongest tidal currents in the study area, with values of approximately 20cm/s. Body force calculations (not shown) also confirm the Eastern Ridge as the most likely candidate to explain internal wave generation [8].

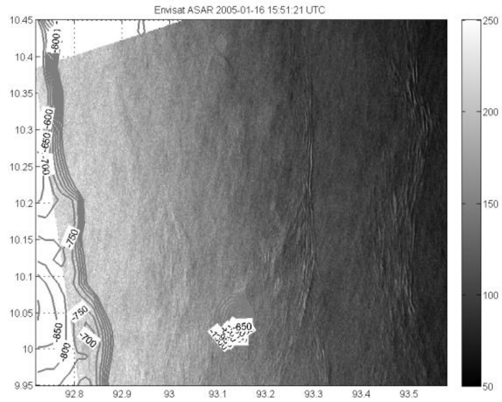

Figure 4. Envisat ASAR PRI dated 16.01.2005 acquired at 15:51 UTC over the Andaman Sea. Two wave trains with mode-2 structure are identified.

The Internal Tide (IT) ray paths calculated in our model are presented in Figure 5 and illustrate a possible generation mechanisms for these mode-2 internal wave trains. IT rays may form near critical bathymetry, i.e. bathymetry whose slope is nearly the same as the IT ray characteristics, and energy propagates upwards from the Eastern Ridge. The energy eventually impinges the pycnocline from below and is thought to give origin to the mode-2 wave trains visible in the SAR image in Figure 4.

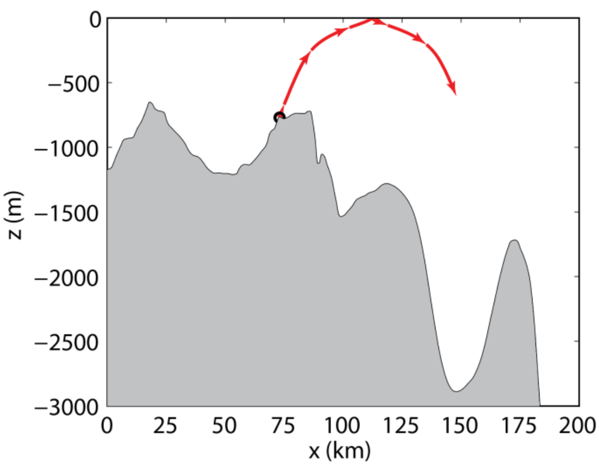

Figure 5. Bottom topography along the Ten Degree Channel of the Andaman Sea and IT rays emanating from critical slopes on the Eastern Ridge. For details see text.

Our last case study in this paper concerns a region recently explored for ISWs with Earth Observation data: the Tropical North Atlantic Ocean off the Amazon shelf break [9]. Preliminary analysis of SAR images from the study region have shown the possible existence of both mode-1 and mode-2 ISWs emanating from the shelf break into the deep ocean [9]. We have computed the Ursell number along the propagation paths of these waves based on available climatological hydrographic records, which result from a standard BVP solution and methods developed in [10]. The procedure was carried out using climatology data from June and results are presented in Figure 6. Sites A and B are as in [9].

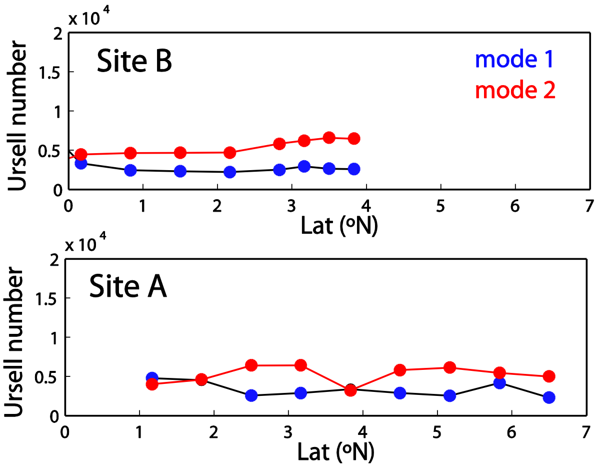

Figure 6. Ursell number calculated along ISW propagation direction off the Amazon shelf break for June climatology. For detailed procedure see [10].

The mode-2 solitary waves are long lived, possibly surviving several days, and are revealed in SAR images by their wave tails (i.e. mode-1 short-period ISWs coupled with mode-2 waves in a deeper duct). One can see from Figure 6 that the Ursell numbers are comparable for both modes, but that mode-2 seems to dominate specially for Site B. The Ursell number gives a measure of the comparative strengths of nonlinear and nonhydrostatic dispersive effects in the evolution of internal waves for given amplitudes and length scales [10].

DISCUSSION AND CONCLUSION

For the case of mode-2 ISWs in the SCS three different mechanisms may be at work: IT beam scattering into the pycnocline; desintegration of a mode-2 interfacial IT, which needs further investigation; and pycnocline deepening may be favored by the presence of the AE. In any case the role of the bottom bump discussed in this paper seems to play a fundamental role in the generation of mode-2 ISWs.

In the Andaman Sea our results indicate that the generation mechanism is consistent with the beam scattering of an IT beam into the seasonal thermocline according to the work in [11].

Mode-2 ISWs off the Amazon shelf break are currently being investigated. Generation mechanisms that need to be tested include the disintegration of the internal tide and multimodal evolution of solitary waves over the steep slopes. Other generation and propagation mechanisms may also be at work in the tropical Atlantic.

In conclusion, generation mechanisms of mode-2 solitary waves are complex and vary in nature. Some large O(20km) mode-2 solitary waves can be identified in SAR due to resonance / coupling with mode-1 near-surface ISWs as recently reported in [2]. The recently predicted beam scattering generation mechanism for mode-2 internal waves [11] may be active in the Andaman Sea and in many other tropical seas (e.g. Mascarene Ridge of the Indian Ocean) [2].

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