Some results of a study of the distribution of internal waves (IW) off the Iberian Peninsula based on ERS SAR observations are presented. In particular we show observations of very large amplitude internal solitary waves (ISWs) propagating in the deep ocean West of the Galicia Bank, and explain their generation as resulting from semi-diurnal frequency internal tides emanating from the bottom slopes. We determine possible generation sites of these internal tidal waves and their propagation pathways. The most energetic internal tide generation sites are calculated from the distribution of the internal tidal forcing, adapted from a model proposed by Baines [1]. This method is being used to map the internal wave activity off the Iberian Peninsula, identifying the most energetic IW generation sites assuming that the internal tidal waves are generated by the interaction of the semi-diurnal (barotropic) tide with the bottom topography. In addition we reveal SeaWiFS observations of large internal tides with a clear signature of enhanced levels of near-surface chlorophyll in the Bay of Biscay.

In the Northern Bay of Biscay (47-48° N, 6-8° W), internal waves of semi-diurnal tidal period result from climate studies. They may also be important from a biological point of view, since their impact on the development and transport of plankton is significant [6]. Non-linear IWs produce a net transport of in-water particles (phytoplankton, zooplankton and even small fish), which in the upper surface layer is usually in the same direction as the IW propagation. Typical distances reached by such transport have been modelled by Lamb [7] and are of the order of several km for a train of Internal Solitary Waves (ISWs, nonlinear asymmetric IWs). Some of the early work suggested that IW slicks are correlated with shoreward transport of pelagic larvae [8]. IWs have the ability to turn scattered distributions of fish and zooplankton into structured distributions, causing aggregation of organisms in slicks [9]. We note that very little research has been done in this field, in particular off the coast of Portugal and we hope the results of the present study may stimulate further work.

It is generally accepted that one of the main causes of IWs is the interaction between the barotropic tide and submarine topography [10, 1]. Once sufficiently accurate definitions of stratification, topography and amplitude of the tidal currents are known, one should expect that, on average, the size of predicted and observed internal tides should match quite well. These internal tides may disintegrate, subsequently, into non-linear ISWs, if the local seasonal stratification is appropriate [11]. In this paper we show ERS SAR observations of very large amplitude ISWs propagating in the deep ocean (West of Galicia Bank) and explain their generation based on the distribution of the internal tidal forcing, adapted from a model proposed by Baines [1]. Here we propose a method that could, in the future, be used to refine estimates of the global internal tide budget. The large swath scan mode of ENVISAT ASAR (400km wide) could be used to validate the results of our model.

1. INTRODUCTION

The standing question about IW generation has always been not what processes could generate them, but rather their relative importance. Even with decades of research on IWs, it is still not possible to quantify their generation sources accurately. One of the objectives of the project SPOTIWAVE was to explore the distribution of IW activity off the Iberian Peninsula, ultimately identifying the most energetic IW generation sites and their likely mechanisms. The capability of Synthetic Aperture Radars (SARs) on satellites to observe on a regular basis ocean IWs is now widely accepted [2, 3]. Over a decade of ERS SAR data is available today, and is being used for detailed studies of IW generation sites and mechanisms.

IWs are considered to be the most significant factor for explaining vertical mixing in the open ocean, to such a large extent that they may be a major factor in ocean circulation [4, 5]. Consequently they are important in...
the interaction of the surface tide with the steep shelf slope bottom topography, and can propagate both onto the shelf, and into the deeper ocean. In the upper water column, these internal tides are manifested as long wavelength (30-50 km) depressions and elevations of the thermocline of up to 30 m in amplitude. Pingree & New [12] revealed that these internal tides were also visible in remotely-sensed sunglint imagery as long-crested features extending for several hundreds of km's in a direction parallel with the shelf break. More recently da Silva et al. [13] showed that these internal tides are capable of producing a “colour” signature in SeaWiFS chlorophyll data (an issue that will be briefly explained in section 4).

Large amplitude ISWs near the sea surface are thought to be generated by the interaction of a beam of internal tidal energy with the seasonal thermocline [14]. This beam of internal tidal energy follows characteristic pathways and has a slope c to the horizontal given by

\[
c = \pm \sqrt{\frac{\sigma^2 - f^2}{N^2 - \sigma^2}} \quad (1)
\]

where σ is the frequency (corresponding to semi-diurnal tides), N is the Brünt-Väisälä frequency and f the Coriolis parameter.

We have developed two IDL (Interactive Data Language) programs as auxiliary tools for the interpretation of the generation sites/strength of the internal solitary wave trains observed in a data set of the ERS SAR mission. The primary goal of the first method/program was to determine possible generation sites of internal tidal waves, and their propagation pathways. This program calculates critical slopes where generation may take place at semi-diurnal tidal frequencies. It is also able to calculate the pathways of the “rays” of internal tidal energy and the corresponding intersections with the seasonal thermocline. The bottom slopes were calculated using available global bathymetry [15]. The ocean stratification was calculated based on a series of CTD stations of the study region. CTD profiles were obtained from the WOCE Hydrographic Program.

Assuming that the internal tidal waves are generated by the interaction of the semi-diurnal tide (barotropic) with the bottom topography, a second program was developed to determine the regions where the driving body force of the internal wave motion was strongest.

Following Baines [1], the equations governing the internal tides are those of a rotating stratified inviscid fluid, and linearity can be assumed. Subtracting out the barotropic tidal motion (corresponding to an unstratified ocean) from the linearized equations, the internal wave motion is driven by a body force F, that can be found from the following equations:

\[
\frac{\partial u}{\partial t} + f \times u + \frac{1}{\rho_0} \nabla p + \frac{\rho g z}{\rho_0} = -\rho_1 \frac{d \rho_0}{dz} \quad (2)
\]

where

\[
\frac{\rho_1}{\rho_0} = w_t \quad (3)
\]

Variables \( u \) are the fluid velocity (components of the velocity vector) for the internal wave motion; \( t \) the time; \( f \) the Coriolis parameter; \( \rho_0 \) the mean density in static equilibrium; \( p \) the pressure; \( \rho \) the density for the wave motion; \( \rho_1 \) is the density perturbation caused by the barotropic motion; \( w_t \) is the vertical component of the velocity vector of the barotropic motion; \( g \) the acceleration due to gravity; \( \hat{z} \) the unit vector in the upward vertical direction.

As the barotropic tide is hydrostatic, \( w_t \) can be expressed in terms of a mass flux vector \( Q(x,y) \). For the general case \( Q_x = u \) and \( Q_y = v \), where \( u \) and \( v \) are the zonal and meridional components of the velocity vector, respectively and \( h \) is the mean depth over \( \frac{1}{2} \) cell. The components of the barotropic velocity vector were obtained by using the tidal model OTIS [16], from which we can retrieve the tidal current ellipses for

\[\text{FIG. 1. Map of the study region.}\]
each grid point of the study region. FIG. 1. shows the study region (42°-44°N Latitude; 7°-13°W Longitude with ½º cells) where the model was used. Assuming no phase change for the barotropic tide in the study region, we can define the velocity vector to be equal to the semi-major axis of ellipse at some time \((t=0)\), everywhere in the domain. The procedure includes measuring the axis of the tidal ellipses for barotropic currents \((U_{max} \) is the semi-major axis and \(V_{max} \) is the semi-minor axis) and the angle \(\alpha\) between the semi-major axis and the Eastward direction.

We have computed the components of the mass flux vector \((Q_x \) and \(Q_y \)) for a complete tidal cycle. Hence, when \(Q\) has been determined for the study region the internal tidal forcing for each level of the water column, \(F\), can be calculated, where,

\[
F = \frac{g N^2(z)}{h^2} \left[ \left( \int Q_x \, dt \right) \frac{\partial h}{\partial x} + \left( \int Q_y \, dt \right) \frac{\partial h}{\partial y} \right] \tag{4}
\]

here \(z\) corresponds to depth; \(h\) the mean depth over ½º cell; \(N\) the Brunt-Väisälä frequency; \(Q_x \) and \(Q_y \) the components of the mass flux vector.

The body force shown in FIG. 2 corresponds to \(F\) integrated for the water column one quarter through the tidal cycle. This shows the strongest positive body force at any time in the tidal cycle West of Galicia Bank, which is situated at 42.7°N, 11.8°W. The strongest forcing is located on the steep slopes to the West of the Bank.

3. GENERATION OF ISW

Gerkema [11] studied how the characteristics of the thermocline could influence the propagation of internal tidal rays. He showed that depending of the “strength” of the thermocline, internal solitary wave generation can be forced directly by the interfacial internal tide or rather by internal tidal (IT) rays such as those described by equation (1). In this work we assume that the generation of trains of ISWs in the study region is similar to that of the Bay of Biscay, where the interaction of the IT rays with the seasonal thermocline is believed to be responsible for the short-period IW generation [11, 14].

FIG. 3 shows a bathymetry map of the study region and an interpretation sketch of two ERS SAR images showing strong signatures of ISWs. Based on the information of the body-force map presented in FIG. 2 we chose to analyze in detail the cross section marked with a dark line in FIG. 3. FIG. 4 shows this cross section and the possible generation zones as well as the corresponding ray pathways. Note also that the cross section presented in FIG. 4 was defined along the direction of propagation of the ISWs observed in the SAR image (see FIG. 5). The geographic coordinates of this section lie in between 42.3°N-13.2°W and 42.5°N-12°W. The rays in FIG. 4 emanate from the points on the topography which are critical in the sense that the bottom slope is equal to the ray slope in equation (1).

The generation sites, according to Baines theory [1] of critical slopes, are identified with red squares in FIG. 3.

![FIG. 2. Map of the forcing due to the barotropic tide M2 for the study region.](image-url)
The positions of the intersection of the internal tidal ray paths with the thermocline (taken to be at 50 metres depth) are also shown and marked with black squares. We note that the critical slopes predicted by the ray-tracing model, which determines both critical slopes and “rays” of internal tidal energy, are consistent with the position of one forcing maximum located at 42.4ºN-12.2ºW, approximately (see FIG. 2).

FIG. 3. Map of the study region showing the frames of the ERS SAR images and the ISWs packets presented as red lines. Along the section: Red squares represent the deep generation sites; black squares represent the intersections of "rays" with the seasonal thermocline.

FIG. 4. Section from FIG. 3 showing the internal tidal “rays” along which energy propagates.

FIG. 4 show “ray” trajectories for the section marked in FIG. 3. In FIG. 4, the generation sites are on the Galicia Bank slope and the beams intersect the thermocline about 50-60 km West from the generation site. These solutions correspond to rays generated at the slope between 2000m and 4000m depth, and which propagate directly upwards.

Despite the fact that the ISWs observed in the SAR images are situated 40 km to the West of the position of the intersection of the internal tidal energy “beam” with the seasonal thermocline, we are convinced (given that the ISWs usually need some 10’s of km’s to become well developed [14]) that they were generated by the internal tidal rays originating from the critical slopes shown in FIG. 4, perhaps 11h before (assuming that they propagate with a velocity of 1m.s$^{-1}$, a typical velocity for this type of wave).

FIG. 5. An extract of ERS SAR image (orbit: 15891, frame 2763) dated 30 July 1994 in full resolution, showing part of the ISWs packet.

FIG. 5 exhibits an extract of the full ERS SAR scene dated July 30, 1994. The curvature and the diminishing
of the ISWs wavelength, from the front to the rear of the packet, suggests they propagate towards the West, away from the Galicia Bank. We also note that, considering the depth of the ocean in this region, approximately 5000 m, the ISWs are depression type and present a double sign type of signature. This is easily seen in FIG. 6, which shows a backscatter profile taken from the image in the region identified by the rectangle in FIG. 5, and normalized by the mean backscatter level taken from the region identified by the box.

FIG. 6. Internal wave signature retrieved from profile as indicated in FIG. 5 (rectangle), normalized by the background backscatter (square box).

4. OCEAN COLOUR SIGNATURES OF INTERNAL TIDES.

Another goal of project SPOTIWAVE was to study a variety of ways in which phytoplankton interact with internal waves in shelf seas. Optical remote sensing has an advantage over microwave sensors which is the capability to observe in depth, down to several tens of meters in the ocean depending on the water case. In a recent paper, da Silva et al. [13] discussed bands of enhanced levels of near-surface chlorophyll in the central Bay of Biscay in remotely-sensed images from the SeaWiFS ocean colour sensor. They were able to explain the observations as likely to result from the uplifting of a subsurface chlorophyll maximum by the passing internal tides, to such a level as may be “seen” by the satellite sensor. In this section we show one more example of the kind of bands described in [13], supported by ERS SAR observations.

FIG. 7 shows a SeaWiFS image dated 14 August 2002 processed in levels of chlorophyll concentration. Overlaid on the image there is an interpretation sketch of an ERS-1 SAR image showing strong signatures of trains of internal solitary waves that were found to propagate towards the SE direction (North is up in FIG. 7). Although the SeaWiFS data is “LAC” (“local area coverage”, with a 1km resolution), it is unable to detect the presence of the ISWs, but the SAR (with a 25 m resolution) is able to image them. It is important to note here that the ISWs that can be readily seen in SAR images are usually co-located with the internal tidal troughs, where the thermocline is usually depressed to more than 100m deep. The ISWs typically have wavelengths between 1-2 km, and periods of 20-40 minutes, and result from the action of nonlinear and dispersive forces on the internal tides themselves [17]. Here, we assume that the ISWs can be considered as marking the positions of the internal tidal troughs. Correspondingly, the internal tidal crests are in between the positions where the ISWs are observed, and there the thermocline rises to about 30 m deep.

A Deep Chlorophyll Maximum (DCM) often occurs in the summer when levels of surface nutrients, phytoplankton and chlorophyll have become depleted following the spring bloom, leaving behind a subsurface maximum near the thermocline. This “chlorophyll layer” is typically observed in the northeast Atlantic, centred at the thermocline and reaching thickness of 40 m (A. Poulton, pers. comm.). In these circumstances the top of the DCM would be sufficiently lifted upwards to be within the effective depth of penetration of light, and thus could produce a measurable response to the satellite sensor. This was certainly true in the modelling and similar observations presented by da Silva et al. [13].
The interpretation sketch of the ERS-1 SAR image (dated 5 August 1992), is based on the assumption that the internal wave trains are generated always at the same phase of the semi-diurnal tide, where we phase shifted the ISW trains according to the tidal cycle and propagation speeds, to predict their positions at the time in the tidal cycle of the SeaWiFS image. Thus, assuming that the phase speed of the solitary wave trains are very close to the internal interfacial tide (approximately 1m/s), it is reasonable to compare both the SAR and SeaWiFS images after accounting for the IW displacements relative to the image acquisition times and tidal phase shifts.

Analysis of FIG. 7 indeed shows that the bands of enhanced chlorophyll concentration are correlated with the internal tidal crests, that are in between the ISW trains. This is in accordance with the mechanism proposed by da Silva et al. [13], where the uplifting of a DCM by the passage of the internal tidal crests is capable of producing a measurable response to the SeaWiFS sensor.

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5. REFERENCES


