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Chlorophyll enhancement in the central region of the Bay of Biscay as a result of internal tidal wave interaction

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ABSTRACT

A multi-sensor satellite approach based on ocean colour, sunglint and Synthetic Aperture Radar imagery is used to study the impact of interacting internal tidal (IT) waves on near-surface chlorophyll-a distribution, in the central Bay of Biscay. Satellite imagery was initially used to characterize the internal solitary wave (ISW) field in the study area, where the "local generation mechanism" was found to be associated with two distinct regions of enhanced barotropic tidal forcing. IT beams formed at the French shelf-break, and generated from critical bathymetry in the vicinities of one of these regions, were found to be consistent with "locally generated" ISWs. Representative case studies illustrate the existence of two different axes of IT propagation originating from the French shelf-break, which intersect close to 46°N, −7°E, where strong IT interaction has been previously identified. Evidence of constructive interference between large IT waves is then presented and shown to be consistent with enhanced levels of chlorophyll-a concentration detected by means of ocean colour satellite sensors. Finally, the results obtained from satellite climatological mean chlorophyll-a concentration from late summer (i.e. September, when ITs and ISWs can meet ideal propagation conditions) suggest that elevated IT activity plays a significant role in phytoplankton vertical distribution, and therefore influences the late summer ecology in the central Bay of Biscay.

1. Introduction

Tidal flow over irregular bottom topography forces vertical motions at the tidal frequencies, and generates Internal Waves (IWs) with a tidal period, which under stratified conditions will then propagate along the thermocline as interfacial waves and are often referred to as Internal Tides (ITs). While propagating away from their generation site, ITs can steepen and generate IWs of much shorter period that are usually termed Internal Solitary Waves (ISWs) or "trains of solitons". These shorter IWs, whose periods can reach several tens of minutes, are termed 'solitary' since they tend to occur in individual packets (usually trapped in the troughs of the ITs), and have often been identified with the soliton solutions of nonlinear wave theory.

Large ITs and ISWs have already been extensively studied in the Bay of Biscay (see Fig. 1 for location) and are amongst the most energetic anywhere in the world (see e.g. Baines, 1982). In this region, the internal tidal energy generated at the shelf-break has been documented to radiate away horizontally in the form of interfacial ITs, and to form internal tidal beams that propagate into the deep stratified ocean below. Therefore, large interfacial ITs will form in the thermocline directly above the shelf-break, and evolve (through nonlinear processes) to higher-frequency ISWs packets that propagate both offshore and inshore (see e.g. New and da Silva, 2002). However, the IT energy propagating downward into the deep ocean may also originate a second generation mechanism known as "local generation" (Akylas et al., 2007; da Silva et al., 2009; Gerkema, 2001; Grisouard et al., 2011; Mercier et al., 2012; New and da Silva, 2002; New and Pingree, 1992). In this case, a beam (or ray) of IT energy is generated at the shelf-break where the bottom slopes match the characteristic slopes of the IT beams (i.e. critical slopes), and then propagates into the deep ocean. In the Bay of Biscay, it is well known that these rays reflect from the seafloor (Pingree and New, 1989, 1991) and interact with the thermocline from below, causing large IT oscillations there, and "locally" generating ISWs some 150 km offshore from the shelf-break where the beam is initially generated. This process is also known as "beam scattering" into the pycnocline.

Previous studies using remote sensing data (Pingree and New, 1995) and in situ measurements (Pingree et al., 1986) have documented the

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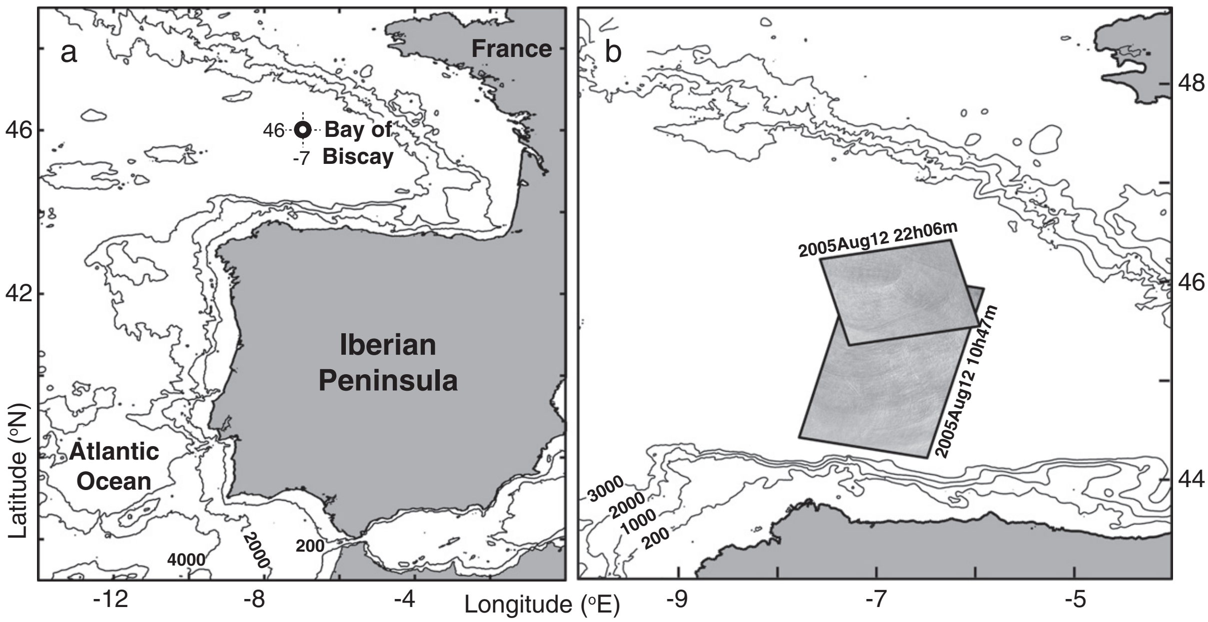

Fig. 1. (a) Study area for the present work in relation to the western Iberian Peninsula. The contours mark isobaths in metres (200, 2000 and 4000 m). The crossed filled circle in black marks the central location of the 'elliptical eye' described in the text. (b) Detailed bathymetry of the Bay of Biscay. Grey areas represent land and the isobaths for 200, 1000, 2000, and 3000 m, are shown in black contours. For reference, two black rectangles are used to frame the Envisat-ASAR images discussed in the text.

presence of ITs in the central region of the Bay of Biscay, especially during late summer and after spring tide events. In the upper water column, the ITs appear as coherent features with wavelengths reaching from 30 to 50 km, and produce vertical oscillations of the seasonal thermocline of up to 30 m in amplitude. During the summer, they have been observed by Pingree et al. (1986) to travel from the northern shelf-break of the Bay of Biscay into the deep ocean with typical propagation speeds of around 1.0 ms^{-1}.

Also important, is the geometry of the Bay of Biscay (when considering the region's isobaths), where the form of an elliptical "eye" was first noted by Pingree and New (1995), centred near 46 °N and −7 °E (see Fig. 1). This was recognised as suggesting the presence of enhanced and localized IT waves. They conjectured that this "elliptical eye" could result from the intersection between ITs generated by an almost elliptical shelf-break arc, which is located either north or south at about 170–200 km from its centre. Based on in situ observations and modelling results, Pichon et al. (2013) reinforced this idea by revealing IT interactions consistent with the "eye's" location (around 46 °N, −7 °E), which involved IT beams coming from different generation spots sited over the northern (French) shelf-break.

The existence of large ITs and their possible interaction may be particularly relevant from a biological point of view, since their propagation induces a natural vertical motion within the water column, focused mainly near the pycnocline, which forces water particles to undergo upward and downward motions. This means that neutrally buoyant phytoplankton cells, which are usually passive in relation to these waves' time scales, can be significantly displaced vertically. It is also important to note that, under typically stratified conditions, levels of surface nutrients may become depleted, following the spring bloom, and thus leaving behind a chlorophyll subsurface maximum near the thermocline (see Harlay et al., 2010, 2011). Therefore, in the Bay of Biscay, as well as many other locations in the North Atlantic Ocean, a Deep Chlorophyll Maximum (DCM) often occurs in the summer. This in turn means that the presence of IT activity may displace the top of the DCM and lift it upwards where the effective light is just enough to produce a measurable response in ocean colour satellite sensors (see da Silva et al., 2002; Vázquez et al., 2009).

Significant coupling between ITs and phytoplankton dynamics has already been reported using in situ measurements (e.g., Gaxiola-Castro et al., 2002; Sangra et al., 2001). The use of satellite SAR images and chlorophyll-a concentration products from the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) in the central region of Bay of Biscay, also lead da Silva et al. (2002) to document the synergetic surface expressions of IT crests both in the SAR and in chlorophyll-a surface images. More recently, in-situ and Moderate-resolution Imaging Spectroradiometer (MODIS) data presented by Wang et al. (2007) and Pan et al. (2012) showed increased levels of chlorophyll-a in two different regions of the South China Sea, which were explained as a result of IT activity. Finally, Muacho et al. (2013) also reported the same phenomenon in the Nazaré Canyon (west of the Iberian Peninsula), where the role of large-amplitude ITs in increasing primary production was verified using both in situ and satellite data together with an analytic model.

This paper aims to present a typical case study, where SAR surface expressions of locally generated ISWs (i.e. by beam scattering into the thermocline) can be seen propagating in two separate directions, and thus be associated with distinct IT beams originating from the northern shelf break of the Bay of Biscay. These ISWs are used to infer the locations of their corresponding IT troughs and crests within the central Bay of Biscay, where ITs are already known to be amplified because of their nonlinear interactions (see Pichon and Correard, 2006; Pichon et al., 2013). Interestingly, the location of this interaction is also consistent with the location where Pingree and New (1995) observed their elliptical "eye" (approximately at 46 °N, −7 °E and marked with a filled circle in Fig. 1a). Therefore, the main aim of the paper is to assess the impact of this region's elevated IT activity (and the interactions therein) on surface chlorophyll-a concentrations, measured by ocean colour remote sensors, both via daily (level 2) images and climatological data (from 2002 to 2011).

This paper is organized as follows. A SAR analysis begins by describing the 2D surface spatial structure of the IW field in the central region of the Bay of Biscay. A particular case study is used to highlight a region where ITs are likely to interact. The most probable generation mechanism is identified for two different families of ISWs, one of which has not yet been reported in the literature. We then investigate the influence of IT interactions on surface chlorophyll-a satellite data, and compare our findings with those coming from modelling results. The paper ends with some relevant discussions and conclusions.