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Dynamics of the semi-diurnal and quarter-diurnal internal tides in the Bay of Biscay. Part 2: Baroclinic tides

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ABSTRACT

A regional baroclinic model forced with several tidal constituents at different frequencies is used to investigate the internal tide of the Bay of Biscay. The regional ocean model is free surface, sigma-coordinate and it is implemented in order to accurately take into account the barotropic forcing, the strong bathymetry gradients and the temperature and salinity stratifications. In a previous paper, the barotropic component of the tides was studied in details and the boundary conditions of the three-dimensional model were extracted from the atlases. In the present paper, we focus on the baroclinic component of the tides and the simulations are validated against observations from the MINT94 experiment. The observed currents and stratification are accurately reproduced by the model. The internal tide pattern is consistent with the descriptions found in the literature. Combining wavelet and principal component analysis we extract the patterns of generation and propagation of the internal tide at the semi-diurnal and quarter-diurnal frequencies. Secondary internal wave generation areas are identified over the plain. The vertical displacements of isopycnal surfaces for the M4 internal tide are found to be locally half those induced by the semi-diurnal internal tide. A sensitivity study shows the impact of using a three-dimensional initial stratification over the direction of propagation and wavelengths of the internal tides.

1. Introduction

Research dealing with the origin of the ocean dyapicnal mixing has been given a renewed interest in the recent years since this mixing appeared to control, at least partially, the ocean stratification, the meridional oceanic circulation, heat transports and the climate response (Saenko, 2006). Among other processes, internal waves are thought to be a major contributor to the mechanical energy which is necessary for the ocean mixing (Munk and Wunsch, 1998; Garrett and St Laurent, 2002; St Laurent and Garrett, 2002; Wunsch and Ferrari, 2004). Internal waves are created by the action of the wind over the surface layer and by the interaction of the tide with the bathymetry. They feed the mixing by breaking or leading to direct instability and turbulence in the deep ocean. The energetic content of both energy sources may be roughly estimated at global scale and is likely to be comparable: the most recent estimates are between 1 and 1.5 TW for the wind and about 1 TW for the tide (Wunsch and Ferrari, 2004). Through the associated mixing, the internal tide can have a non-negligible impact over sediment transport (Cacchione and Drake, 1986) and biological growth in specific sites of the ocean (Pingree and Mardell, 1981).

A review of previous studies dealing with the internal tide in the deep-ocean can be found in Garrett and Kunze (2007). In the Hawaii Ocean-Mixing Experiment (HOME), researchers from different institutions have shared their knowledge of observations and modeling in order to quantify the tidal energy transfers over the Hawaiian ridge (Pinkle and Rudnick, 2006). It has been found that 20 GW of barotropic tidal energy were dissipated along the Hawaiian Island chain in specific sites (2% of the 1 TW global pelagic tidal dissipation) (Egbert and Ray, 2001). The generation of the internal tide is enhanced by three major forcings: a strong barotropic tidal forcing, a steep slope of the sea-floor (such as at ridges and shelf breaks) and strong stratification gradients (thermoclines). When the barotropic tidal velocity remains significantly less than the phase speed of the generated internal tide, then the linear theory prevails (otherwise higher harmonics can develop) (Vlasenko et al., 2005). Barotropic tides above steep

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topography give birth to internal tides at critical slopes, the regions where the direction of the wave beam is tangent to the slope of the topography (Baines, 1982). A large number of baroclinic tidal modes are generated, which combine into beams or ray of internal tidal energy (New, 1988). The generation of the internal tide at a continental slope has been reproduced in laboratory experiments by Gostiaux and Dauxois (2007). They also reproduced the beam-like propagation of the internal tide. Strong non-linear effects and mixing can be found in the generation region itself. In regions where the beam reflects (bottom, surface), ingoing and outgoing beams interact inducing non-linear advection of overlapping internal wave beams, as shown by the numerical work of Gerkema et al. (2006) and the experimental work of Peacock and Tabaei (2005) and Gostiaux et al. (2006).

In the Bay of Biscay, the internal tide is mainly semi-diurnal (Pingree and New, 1989) due to the dominance of the semi-diurnal M2 barotropic forcing above the shelf break. Two main generation area have been identified: the Northern shelf break near La Chapelle bank (New and Pingree, 1990; Pichon and Correard, 2006) and the Cape Finisterre region off Northwest Spain (Pichon and Correard, 2006; Azevedo et al., 2006). The beams have been observed to emanate from the upper part of the continental slope where it becomes critical (Pingree and New, 1991; Jezequel et al., 2002). The characteristics of the internal tide can be inferred from observations and model predictions through some disturbances induced by the internal waves in the oceanic density and velocity structure at the tidal frequency. Large amplitude internal tide beams were first reported from in situ observations in the Bay of Biscay by Pingree and New (1989), with values ranging from about 150 m near the upper slopes to 100 m farther out. Pingree and New (1989) have also highlighted the spatial variability in the internal tide, with a reduction of the amplitude and a spreading of the beam during the propagation from the shelf break. The wavelength associated with the propagation of the internal tide varies with the stratification. It was estimated from the sea surface signature of the vertical motion induced by the internal tide. From remotely sensed AVHRR "sunglint" imagery in the visible band (Pingree and New, 1995) and SAR imagery (New and Da Silva, 2002), values of 30–35 km were found onto the shelf in summer, against 40–50 km for the oceanward tides. The SAR images of New and Da Silva (2002) also showed that the ray that propagates downwards from the Northern shelf break reflects from the sea bottom and resurfaces some 150 km away from the shelf break. The Bay of Biscay thus shows a complex pattern with several area of internal tide generation, several directions of propagation of the waves, at different frequencies. A joint approach combining observations at sea, theoretical basis and numerical models is required. The numerical model is the only way to complete the observations in order to have a simultaneous and synoptic view of all the parameters, but it has to be set up and validated using observations.

Until recent years, nearly all tidal studies using numerical models were dedicated to the M2 internal tide. In the past decades, the models were first based on simple academic approaches and they were restricted to idealized topography in the coastal zone. Several authors have proposed analytical solutions for the generation of the internal tide by interaction of the tidal flow over topography (Garrett and Kunze, 2007), based on the ray tracing theory or the decomposition over normal modes (e.g. Rattray, 1960; Cox and Sandstrom, 1962; Baines, 1973, 1974; Bell, 1975; Prinsenberg and Rattray, 1975). These models, which are linear in the dynamics, led to other developments that give analytical expressions for the rate at which energy is input to the internal wave field (Craig, 1987; Llewellyn Smith and Young, 2002; Khatiwala, 2003). In the case of internal tides generated at shelf slopes at M2 frequency, the two-dimensional analytical model of Baines (1982), namely the body force approach, gives the energy conversion from barotropic to baroclinic tides. One of the most important energy conversion rate was found to be located at the continental shelf slope of the North Atlantic ocean centered around the Bay of Biscay and the English Channel. But there are a lot of oceanic regions in which simple analytic models cannot be used any more, as in the case of a corrugated continental slope (Legg, 2004). In order to study the influence of the variations in the stratification and bathymetry over the internal tidal field, taking into account the presence of rotation and non-linearity, numerical models have been implemented. Numerical two-dimensional models have been used in order to estimate the semi-diurnal tidal offshore energy flux in regions such as the Australian northwest shelf (Holloway, 1996; Xing and Davies, 1997). However, Munk and Wunsch (1998) have shown that the two-dimensional hypothesis in the theory by Baines (1982) is too restrictive and that three-dimensional features are likely to contribute significantly. Various studies using three-dimensional models were performed showing the influence of the barotropic forcing, the stratification and the shape of the topography on the characteristics of the internal tide in a wide range of geographical locations (Cummins and Oey, 1997; Xing and Davies, 1999; Robertson, 2001; Merrifield and Holloway, 2002; Niwa and Toshiyuki, 2004; Simmons et al., 2004; Hibiya, 2004; Munroe and Lamb, 2005). In particular, Pichon and Correard (2006) applied the three-dimensional isopycnal model MICOM to the study of the internal tide in the Bay of Biscay, focusing on the continental slope and abyssal plain (i.e. they did not model the shelf). The initial stratification was chosen horizontally homogeneous, as in a number of internal tide modeling studies (for example in Gerkema et al., 2004). The tidal forcing was restricted to the use of semi-diurnal tidal solutions from a spectral model (Lyard and Le Provost, 1997), thus neglecting the quarter-diurnal and diurnal components of the tide. The internal tide obtained with MICOM was validated against observations from the MINT94 internal tide experiment performed by the SHOM (the French hydrographic and oceanographic naval service) in September and October 1994. This study showed the capacity to approach the complexity of the beam-like propagation of the internal tide in the deep part of the Bay of Biscay with an isopycnal model. The use of isopycnal coordinates in an adiabatic way (without coupling with the mixing model) gave the opportunity to keep the stratification close to an average realistic measured profile and to focus on the vertical displacement of isopycnics (amplitude of the internal tide), but neglecting local spatial variations in the stratification due for instance to an enhanced mixing by internal tides.

In this paper, the aim is to qualify and quantify numerically the mechanisms of generation and propagation of internal tides in the abyssal plain, continental slope and shelf of the Bay of Biscay. This is achieved by using the three-dimensional regional SYMPHONIE model (Marsaleix et al., 2008). This model is particularly well adapted to the study of internal tides since it is energy conservative (Marsaleix et al., 2008) and as a consequence it does not suffer any spurious energy loss when representing energy transfers. The model uses a realistic bathymetry, which is enhanced by the use of a high horizontal resolution and generalized sigma coordinates in the vertical. A particular attention was paid to the modeling of the barotropic tide, as it is one of the three main forcings for the generation of internal tides. In a previous paper (Pairaud et al., 2008), a two-dimensional high resolution configuration of the SYMPHONIE model was embedded into the T-UGOm tidal model of the North-East Atlantic. We showed that a large amount of energy was to be transferred from the surface tide (mostly M2) to the internal tide at the semi-diurnal frequency over the shelf break, with a maximum located in southern French Brittany near La Chapelle bank (see the wave drag on Fig. 7 by Pairaud et al., 2008). The three-dimensional model is forced by