Large amplitude internal tides, solitary waves and turbulence in the central Bay of Biscay

X. H. Xie\textsuperscript{1*}, Y. Cuypers\textsuperscript{1}, P. Bouruet-Aubertot\textsuperscript{1}, B. Ferron\textsuperscript{2}
A. Pichon\textsuperscript{3}, A. Lourenço\textsuperscript{1}, N. Cortes\textsuperscript{2}
\textsuperscript{1}LOCEAN, UMR7167, Université Pierre et Marie Curie, 75252 Paris, France.
\textsuperscript{2}LPO, Ifremer, UMR 6523 CNRS-IFREMER-IRD-UBO, Plouzané, 29280 Brest, France
\textsuperscript{3}SHOM, Centre Militaire d'Océanographie, 29603 Brest, France

Abstract

Microstructure and fine-scale measurements collected in the central Bay of Biscay during MOUTON experiment are analyzed to investigate the dynamics of internal waves and associated mixing. Large amplitude internal tides (ITs), that excite internal solitary waves (ISWs) in the thermocline, are observed. ITs are dominated by modes 3 and 4, while ISWs projects on mode-1 that is trapped in the thermocline. Therein, ITs generate a persistent narrow shear band, which is strongly correlated with the enhanced dissipation rate in the thermocline. This strong dissipation rate is further reinforced in presence of ISWs. Dissipation rates during the period without ISWs largely agree with the MacKinnon-Gregg scaling proposed for internal wave fields dominated by a low frequency mode. On the opposite, they show poor agreement with the Gregg-Henyey parameterization valid for internal wave fields close to the GM model. The agreement with the MacKinnon-Gregg scaling is consistent with the fact that turbulent mixing is here driven by the low-frequency internal tidal shear.

*Email: xiaohuihh\_2006@yahoo.com.cn
1. Introduction

It is well known that the Bay of Biscay (BB) is a marginal sea with large amplitude internal tides (ITs). Therein, ITs are mainly generated on the slope via interaction between the barotropic tide and the steep topography [e.g. Pingree and New, 1991; Gerkema et al., 2004; Pichon et al., 2011]. Once generated, they propagate both seaward and shoreward. Linear internal-wave theory and observations show that the seaward traveling ITs propagate along a beam or ray path with a slope to the horizontal given by:

\[ c = \pm \left[ \frac{(\omega^2 - f^2)}{(N^2 - \omega^2)} \right]^{1/2}, \]  

(1)

where \( \omega \) is the semidiurnal frequency, \( f \) is the local inertial frequency and \( N \) is the buoyancy frequency [Pingree and New, 1991]. The theory also predicts that the offshore propagating beam first reflects at the bottom and next at the sea surface in the central BB [Gerkehma et al., 2004; Pichon et al., 2011] (Fig.1.a). Using temperature and velocity records obtained from the central BB, New and Pingree [1990] observed large internal interfacial tides and internal solitary waves (ISWs) in the thermocline. These waves were as large as those observed at the shelf edge, and they were thus conjectured to be locally aroused in the central BB, where internal tidal beams hit the seasonal thermocline near the sea surface. This hypothesis was confirmed by satellite imagery [New and Da Silva, 2002]. Theoretical framework for this process was given by Gerkema (2001) (hereafter referred to as G01) who showed that scattering of IT beams in the thermocline leads to the local generation of large ITs and ISWs. This scenario was retrieved in other numerical models [Grisouard et al., 2011] and reproduced in laboratory experiments [Mercier et al., 2012].

While there are numerous insights on ITs and ISWs in the BB, there have never been measurements in the BB allowing a fine characterization of ITs and ISWs.
Another aspect that has never been quantified is the turbulent mixing induced by these internal waves. In this paper, we report on joint fine-scale and microstructure measurements performed for the first time in the central BB. We first characterize vertical structures of ITs and ISWs and next dissipation rate ($\varepsilon$) of turbulent kinetic energy and turbulent mixing induced by ITs and ISWs. Eventually, fine-scale parameterizations are tested against microstructure measurements.

2. Data

Data were collected at a location (45.75°N, 7.38°W) in the central BB during the MOUTON experiment in summer 2008, where the water depth is about 4800 m (Fig. 1a). This location is about 200 km away from generation area of internal tidal beams on the northern slope of BB (Fig. 1a) [Pichon et al., 2011]. From Sept. 18th, 01(h):10(min) until Sept. 19th, 04:00, combined CTD/LADCP yo-yoing was performed. Sixteen profiles were collected with an effective depth range from 6 to 2663 m. From 04:50 to 21:20 on Sept. 19th, two microstructure instruments, VMP (Vertical Microstructure Profiler) and SCAMP (Self-Contained Autonomous Microstructure Profiler), were alternatively deployed. Dissipation rate estimates with Scamp are based on Batchelor fitting of the temperature gradient spectrum measured by high frequency temperature sensors [Ruddick et al., 2000], whereas VMP estimates are based on measurements of microscale vertical shear. While 19 VMP profiles were obtained from the surface to depths of 400-500 m, 15 Scamp profiles were collected from the surface to depths of 70-110 m. Data above 10 m were removed due to the contamination by the ship’s wake. Current velocities were inferred from two 150-kHz and 38-kHz broadband shipboard ADCPs. Measurement range of the former ADCP is from 18 m to 162 m with a 2-min time-average interval and 4-m bin, while that of the
latter is from 55 m to 1231 m with the same time-average interval and 24-m bin. We used here the 150-kHz ADCP data to compute 4-m shear ($S_z$) during microstructure measurements.

CTD data were de-spiked and averaged into 1-m bins, while $\varepsilon$ is computed from VMP and Scamp data using 1m bins. Since Scamp was not equipped with conductivity sensors, salinity during Scamp measurements was estimated by a linear interpolation of VMP salinity data.

3. Results

3.1 Mean stratification and semidiurnal IT ray path

The time-averaged CTD data were used to compute the buoyancy frequency $N(z)$. The climatological temperature and salinity data at the measurement location obtained from the World Ocean Atlas 2009 were used to complete the profile below 2663 m depth (Fig. 1b). The $N(z)$ profile showing the largest value at 40-70 m (seasonal thermocline) and a small peak near 800 m (permanent pycnocline) (Fig. 1b) is typical for the central BB during summer [G01]. An internal tidal beam path is computed using $N(z)$ and a typical model topography in the BB. The surface reflection site of internal tidal beams in the central BB is ~140 km away from their generation location and ~60 km away from our observation site (Fig. 1a, embedded panel).

3.2 Internal interfacial tides and ISWs

Time series of temperature show large thermocline depressions with a semidiurnal period, so called as internal interfacial tides (Fig. 2a). Their amplitude from crest to trough is in the range 40-70 m. Note that the largest isotherm displacements are often observed below 1800 m (not shown). These large displacements are likely induced by the descending beam, which intersects the mooring position at large depth (see
During the second observation period, that of VMP/SCAMP measurements, the isotherms slope in the thermocline depressions become steeper, implying the enhancement of IT nonlinearity. As a result, high-frequency ISWs are generated in troughs and surface velocities are increased (Figs. 2b and 3a). Note that the averaged time interval between two ISWs events is equal to 25-min, therefore ISWs could not be identified from temperature data due to their low temporal resolution (about 20-min) but only from ADCP data.

We determine in the following the directions of propagation of ITs and ISWs as well as their vertical structure. The large thermocline depressions often cause southward velocity in the surface layer (Figs. 2c and 2d), implying a southward propagation of ITs. These large southward interfacial tides likely result from the scattering of the seaward traveling internal tidal beams generated on the northern slope [G01]. However, a more complex pattern can be observed on Sept.19th, 6h-12h. During this period, two oppositely travelling troughs are observed in the large thermocline depression: the first one generates southward surface velocity while the second one induces northward surface velocity. The trough propagating northward may be associated with internal tidal beams originating from the southern slope [Pichon et al., 2011]. Since the velocity direction caused by ISWs is the same as that of thermocline depressions (Fig. 2c), their propagating direction is consistent with that of internal tides.

To investigate the vertical structure of ITs and ISWs, we have computed vertical modal functions of displacement Φ(z) and horizontal velocity Π(z) at semidiurnal and 1/25 min\(^{-1}\) frequencies following equations 6.10.2, 6.10.3 and 6.10.6 from Gill [1982]. Modal structures of waves with these two frequencies show large difference (Figs. 1c and 1d), as the high frequency is larger than N below the thermocline (see Fig. 1b). As
a result, the high-frequency modes are trapped in the thermocline (Figs. 1d and 2b). To distinguish mode functions of high-frequency waves from that of low-frequency waves, we refer to the former as trapped mode structures and to the latter as IT mode thereafter. In order to infer IT mode structures, we compute time series of isopycnal vertical displacement from CTD measurements. Then we extract the semidiurnal amplitude for each depth using a harmonic analysis of the displacement time series. The resulting normalized displacement profile at the semidiurnal frequency is plotted in Figure 1c. The mode-3 structure roughly reflects depth variation of IT displacement except for depths below 1800 m (Fig. 1g), where more modes may be present due to the downward IT beam. A mode projection on IT displacements by the least square method indicates that mode-3 (mode-4) explains about 61% (23%) of total potential energy above the depth of 500 m. Accordingly, the sum of the projected mode-3 and mode-4 reproduces well the variation of semidiurnal displacement above 500 m depth (Fig. 1c). Meanwhile, measured velocity profiles when ISWs pass the fixed point are well fitted by trapped mode-1 (Fig. 1i). Note that as vertical advection of velocity signals by thermocline displacements is strong (see Fig. 2c), Eulerian depth of velocity profiles in Figures 1h and 1i was transformed to semi-Lagrangian depth. Interestingly, the vertical structures of IT mode-4 and trapped mode-1 are very similar within the thermocline (Fig. 1e), which suggests that the observed ISWs are likely to result from mode-4 ITs.

3.3 Microstructure measurements

Time series of dissipation rates is shown in Figure 3b. The largest $\varepsilon$ values often occur near the surface, which may be directly associated with wind stirring in the mixed layer. Enhanced $\varepsilon$ values are also encountered in the thermocline with a mean $\varepsilon$ value of $2.3 \times 10^{-8}$ Wkg$^{-1}$. Diapycnal diffusivity, $K_p$, was computed according to the
relationship established by Shih et al. (2005) who distinguished different regimes as a function of turbulent intensity: $K_\rho = \lambda \varepsilon / N^2$, where $\lambda = 2[\varepsilon/(\nu N^2)]^{1/2}$ ($\nu$ is the molecular viscosity) when $\varepsilon/(\nu N^2) > 100$ otherwise $\lambda = 0.2$. Enhanced $K_\rho$, also occur in the thermocline (Fig. 3c) with a mean value equal to $1.5 \times 10^{-5} \text{m}^2 \text{s}^{-1}$, slightly larger than background values found in the open ocean thermocline. Below the thermocline, mixing becomes quite weak ($\varepsilon < 10^{-9} \text{W Kg}^{-1}$, $K_\rho < 10^{-5} \text{m}^2 \text{s}^{-1}$) except for a few patches. The time-mean profiles along isotherms also display the above depth variations of $\varepsilon$ and $K_\rho$ (inserted panels in Figs. 3b and 3c).

In the 4-m shear field, a narrow band of strong shear caused by ITs is clearly identified within the thermocline with the strongest stratification (Fig. 3e). Because of the large thermocline displacement caused by interfacial tides, the strong shear band is vertically elevated and depressed in a semidiurnal period. The time-averaged $S^2$ and $N^2$ show the same variation with decreasing temperature/depth (inserted panel in Fig. 3d). However, $S^2$ is smaller than $N^2$, implying that the Richardson number $Ri = N^2 / S^2$ is larger than 1 and that the large-scale waves are stable toward shear instability. Since the strong stratification in the top of the thermocline (Fig. 3d) inhibits the penetration of surface turbulence into the thermocline, the enhanced $\varepsilon$ inside the thermocline is likely to be associated with strong shears in the thermocline (Fig. 3e). Below the thermocline, weaker $\varepsilon$ is associated with smaller shear and stratification. In addition, dissipation rates as well as $K_\rho$ in the troughs are elevated relative to those in the crests. This may be associated with disintegration of IT troughs into a group of ISWs that further enhances turbulent mixing.

### 3.4 Mixing Parameterization

In order to investigate further the relationship between dissipation rates and shear/stratification, the observed dissipations rate were averaged into logarithmic bins...
of $N^2$ and $S^2$. Two parameterizations, MacKinnon-Gregg (M-G) and Gregg-Henyey (G-H), are tested. The former was found to be relevant in situations where shear of large-scale waves and energy of small-scale waves do not maintain a particular relationship through the Garrett-Munk (GM) spectrum as illustrated for internal wave mixing in the coastal ocean [MacKinnon and Gregg, 2003], while the latter applies for internal wave fields with the GM spectral shape and is widely encountered in the open ocean [Gregg, 1989]. These two parameterizations are given by

$$\varepsilon_{GH} = 1.8 \times 10^{-6} f \cosh^{-1}(N_0 f)(S/S_{GM})^4(N/N_0)^2$$

$$S_{GM}^4 = 1.6 \times 10^{-10}(N/N_0)^2$$

and

$$\varepsilon_{MG} = \varepsilon_0 (N/N_0)(S/S_0),$$

where $N_0=S_0=0.0052s^{-1}$ and $\varepsilon_0$ is an adjustable constant. This constant was set as $2.2 \times 10^{-9}$ Wkg$^{-1}$ using profiles without ISWs so that the mean $\varepsilon_{MG}$ matches the observed mean dissipation rate. Data within the mixed layer, namely those above the thermocline (T>17.3°C), were removed for the comparison. Since ADCP data in the lower layer have many gaps, only data above the depth of 110 m were used. Meanwhile, 150-kHZ ADCP data were movingly averaged onto 30-min resolution before computing shear, as we do not focus on high-frequency shear. Stratification data were smoothed by an 8-m Bartlett filter to agree with the spatial response of ADCP. The dissipation rates were vertically averaged over 4-m. Since results measured by different microstructure instruments may have bias, VMP and Scamp data were calculated independently. The results are displayed in Figure 4.

During VMP measurements, high dissipation values are encountered in strong sheared and stratified regions (Fig. 4a). The distribution of the measured $\varepsilon$ in the space of $N^2$ and $S^2$ is qualitatively more consistent with the M-G parameterization (Fig. 4b),
while it is evidently different from the G-H parameterization (Fig. 4c). The
distribution pattern of the observed \( \varepsilon \) in the space of \( N^2 \) and \( S^2 \) during Scamp
measurement is also better reproduced by the M-G parameterization (Figs. 3d to 3f).
However, in the regions of \( 7 \times 10^{-5} \text{s}^{-2} < N^2 < 3 \times 10^{-4} \text{s}^{-2} \), the observed \( \varepsilon \) are evidently
larger than those predicted by the parameterization. This may be associated with
nonlinear waves, whose mixing cannot be described by the above two
parameterizations [Mackinnon and Gregg, 2003]. Note that most of ISWs appear
during Scamp measurements (see Fig. 3). In addition, \( Ri \) is partly found to be
between 0.25 and 1, but no evident correlation between this parameter and dissipation
rate is identified.

To obtain the trend of dissipation rates versus \( S^2 \) and \( N^2 \) alone, the bin-sorted
dissipation rates are averaged along \( N^2 \) and \( S^2 \), respectively (Figs. 4g-4j). The two
parameterizations show large difference in the trend of dissipation rates versus shear
(Figs. 4g and 4i), while the M-G model during VMP measurements successfully
reproduces the slope of the observed dissipation rates with increasing \( S^2 \). During
Scamp measurements, the M-G model also captures the essential relationship of
dissipation rate versus shear, although the dissipation rates are larger for \( 6 \times 10^{-6} \text{s}^{-2} < S^2 < 1 \times 10^{-4} \text{s}^{-2} \) due to the effect of nonlinear waves. Regarding the relationship
between dissipation rate and stratification (Figs. 4h and 4j), both models reflect the
main variation of dissipations rates with stratification.

4. Discussion

In the previous section, we showed that the elevated turbulent mixing in the
thermocline mainly resulted from strong low-frequency (IT) shears. There large ITs
do not directly cause mixing because of their stability (\( Ri > 0.25 \)), but they are likely to
directly promote energy transfers toward smaller scale waves that ultimately become unstable leading to mixing. These conditions are consistent with the simple assumption behind the M-G scaling. As a result, we find that the observed dissipation rate is largely reproduced by the M-G model. The simple assumption behind the M-G scaling is that the large-scale shear providing the environment for scattering and breaking of smaller waves results from a few low-frequency waves (ITs or near-inertial waves) rather than from a steady state background GM spectrum on which the G-H scaling applies. This assumption is generally fulfilled in shallow coastal seas such as New England Shelf [MacKinnon and Gregg, 2003, 2005] and the Baltic Sea [van der Lee and Umlauf, 2011], where dissipations were also well parameterized by the M-G model. Therefore, the M-G scaling is mostly known as a shallow water parameterization. However, our observations in the deep sea that fulfill the M-G assumptions, with an internal wave field dominated by a few vertical modes at the semidiurnal frequency, show that the M-G scaling has a wider range of applications than coastal seas.

The large ITs that we observe in the thermocline propagate southward and mostly project on mode-3 and mode-4. It is quite likely that they result from scattering of IT beams generated in the northern slope of BB when beams propagate upward from the deep water and hit the thermocline following the scenario described by G01. In this course, nonlinear steepening of ITs further excites ISWs which are as well observed at the mooring location. Since the frequency of ISWs exceeds the buoyancy frequency except in the thermocline, these waves are trapped in this region where they may further increase local mixing. However because of the limited number of microstructure profiles during ISW’s events and the long time interval between two
adjacent profiles, it was difficult to give evidence of the impact of ISWs on mixing. Additional data are required for this purpose.

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Reference


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Captions

Figure 1: (a) Map showing bathymetry in the BB and the observation site (the black point). The slash line indicates the possible propagation path of the seaward traveling internal tidal beams generated on the northern slope. Their characteristic path is given in the inserted panel (blue line with arrows). The red curve is typical model topography in the BB along the cross-slope direction. The vertical line indicates the observation location. (b) Profile of $N(z)$: The vertical line indicates a frequency of 1/25 min$^{-1}$. Vertical structures of displacement $\Phi(z)$ for the mode-1 (blue), mode-2 (green), mode-3 (red) and mode-4 (pink) waves with (c) semidiurnal and (d) 1/25 min$^{-1}$ frequencies. In (c), the black solid line is the measured IT displacement profile around 3h/19th (black solid line). The dashed line is sum of projected mode-3 and mode-4. (e) Observed velocity profiles (red and blue lines) during two ISWs (marked by arrows in Figure 3a) in a semi-Lagrangian frame and velocity profiles of IT mode-4 (black dashed line) and trapped mode-1 (black solid line). Note that both displacements and velocities have been normalized.

Figure 2: (a) Temperature. White vertical lines indicate the times of CTD profiles. (b) Current Velocity amplitude. Time series of meridional velocities obtained from (c) 150-kHZ and (d) 38-kHZ ADCPs. Data in (d) have been movingly averaged to 10-min resolution. Two black lines in (c) are isotherms of 17.3°C and 12.9°C, indicating depths of the thermocline, similar for Figures 3b to 3e (white lines in Figures 3d and 3e).

Figure 3: (a) Velocity amplitudes during VMP/Scamp observation. The arrows indicate ISWs plotted in Figure 2b. (b) Dissipation rate. (c) Diacynal diffusivity. Isotherms whose interval is 0.5°C (white lines) are over-plotted on (b) and (c). (d) $N^2$. 
(e) $(S_4)^2$. A 4-m running average is used for (b) and (c). Data in (e) have 30-min resolution. The embodied panels in (b), (c) and (d) is time-averaged $\varepsilon$, $K_\rho$ and $N^2$ (blue) and $(S_4)^2$ (red) along the isotherms.

**Figure 4:** Distribution of dissipation rates in bins of $N^2$ and $S^2$ from observations (a and d) and the M-G (b and e) and G-H (c and f) parameterizations. The averaged dissipation rate in bins of $S^2$ (g and i) and $N^2$ (h and j), respectively. (a), (b), (c), (g) and (h) for the observation period of VMP. (d), (e), (f), (i) and (j) for the observation period of Scamp. The red, blue and green curves in the latter 4 panels are the results of the observation, M-G model and G-H model, respectively. The grey shading indicates 95% confidence interval. The oblique solid and dashed lines in (a) to (f) are the boundaries of $Ri=0.25$ and $Ri=1$. 
Figure 1
Figure 2
Figure 3
Figure 4