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Exploring the vertical extent of breaking internal wave turbulence above deep-sea topography

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ABSTRACT

A mooring equipped with 200 high-resolution temperature sensors between 6 and 404 m above the bottom was moored in 1890 m water depth above a steep, about 10° slope of Mount Josephine, NE-Atlantic. The sensors have a precision of less than 0.5 mK. They are synchronized via induction every 4 h so that the 400 m range is measured to within 0.02 s, every 1 s. Thin cables and elliptical buoyancy assured vertical mooring motions to be smaller than 0.1 m under maximum 0.2 m s^{-1} current speeds. The local bottom slope is supercritical for semidiurnal internal tides by a factor of two. Exploring a one-month record in detail, the observations show: 1/semidiurnal tidal dominance in variations of dissipation rate ε, eddy diffusivity K_z and temperature, but no significant correlation between the records of ε and total kinetic energy, 2/a variation with time over four orders of magnitude of 100-m vertically averaged ε, 3/a local minimum in density stratification between 50 and 100 m above the bottom, 4/a gradual decrease in daily or longer averaged ε and K_z by one order of magnitude over a vertical distance of 250 m, upwards from 150 m above the bottom, 5/monthly mean values of $<[\varepsilon]> = 2 \pm 0.5 \times 10^{-7}$ m^2 s^{-3}, $<[K_z]> = 8 \pm 3 \times 10^{-3}$ m^2 s^{-1} averaged over the lower 150 m above the bottom.

1. Introduction

The impact of mechanical turbulent mixing in the ocean is considerable: without it there will be no life, no redistribution of nutrients and matter, and, typical for the deep-sea, no stable stratification in density as it also governs the downward transport of heat (Munk, 1966). Since Munk's suggestion, with follow-ups by Armi (1978, 1979), that most ocean mixing occurs in the vicinity of sloping bottom topography, efforts have been made to establish the dominant processes until to date, see for example a recent overview by Sarkar and Scotti (2017) focusing on modelling of internal waves generated by barotropic flow over topography.

Turbulent frictional effects by steady flows are quite different over topography compared to flat bottoms, (e.g., Weatherly and Martin, 1978; MacCready and Rhines, 1991). Topography is also a primary source and sink of internal waves supported by the stable density stratification (LeBlond and Mysak, 1978). In particular the breaking of internal waves that have amplitudes O(10–100) m, (e.g., van Haren, 2005; Levine and Boyd, 2006), may dominate turbulent mixing in the lower 100 m above the bottom to such extent that it is sufficient to maintain the entire ocean stratified, without the need of further mixing in the interior. This only holds if near-boundary mixing is efficient (Garrett, 1990), with the necessity to transport the homogeneous waters into the interior and replace them by stratified waters.

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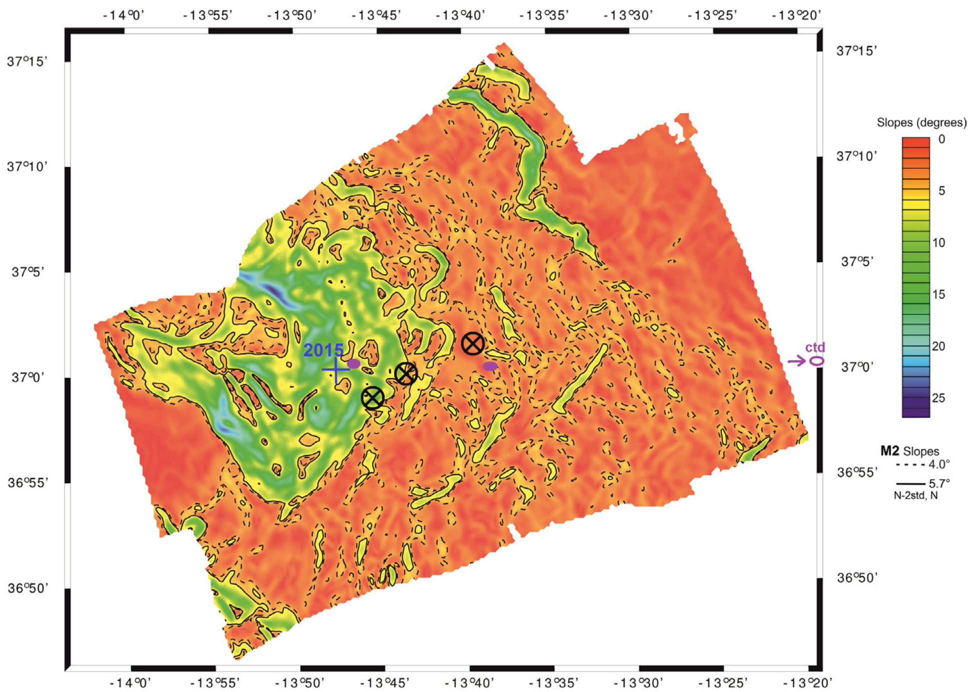

Fig. 1. Mooring area to the East of the southern sub-summit (37°02′N; 13°58′W) of Mount Josephine. The present site (blue) is shallower than three previous ones (black circle crosses) deployed in 2012–2013. Nearby and far CTD stations are indications by purple ellipses, one outside the page. Critical M_2 internal tidal slopes are computed for mean (N) and weak stratification (N-2 standard deviations). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Detailed ocean temperature observations have demonstrated near-boundary turbulence in the deep-sea above sloping topography (Thorpe, 1987; van Haren et al., 1994). The latter experiment included microstructure profiler data down to 0.15 m from the bottom. Long-term mooring experiments above the Hawaiian Ridge, project 'HOME', established estimates of turbulence parameters monitoring 10–200 m vertical scales in 1500 and 2500 m water depth starting about 10 m from the bottom (Levine and Boyd, 2006; Aucan et al., 2006). These authors used SeaBird temperature sensors with an accuracy of several mK sampling at rates of 2–3 min in areas where the temperature-density relationship was sufficiently tight. In such areas temperature is an appropriate tracer for density so that the method of reordering vertical density profiles into stable ones can be used, as proposed by Thorpe (1977). During HOME, mean turbulence dissipation rate ε of 10^{-8} m^2 s^{-3} and vertical eddy diffusivity K_z of 10^{-3} m^2 s^{-1} were estimated for the lower 100 m near the bottom. Higher up, more than 100 m above the bottom, one tenth of these values were estimated.

Meanwhile and inspired by the instrumentation described in (Thorpe, 1987), the Royal Netherlands Institute for Sea Research NIOZ developed moorable high-resolution temperature sensors that were ten times more precise than SeaBird sensors (van Haren et al., 2001). As their power consumption was made very low, they could sample at a rate of 1 Hz, 100 times faster than the moored sensors in (Levine and Boyd, 2006; Aucan et al., 2006). Initially, such sampling rate could be maintained on one power supply for the duration of a month, later of a year (van Haren et al., 2009). This sensor set-up and the use of many, typically 100 sensors at 0.2–2 m vertical distances depending on the local stratification, became to reveal details of near-bottom internal wave-induced turbulence over sloping topography (van Haren, 2005; van Haren et al., 2015). Thus far over ranges of up to 100 m, such observations have shown high-frequency internal wave breaking is accompanied by the moving up and down of larger scale internal tidal waves that result in continual and rapid restratification to within a few meters from the bottom, (e.g., van Haren et al., 2015). In that study, moored data were compared from three different slope sites of Mount Josephine (black sites in Fig. 1), a large seamount in the NE-Atlantic Ocean. Most intense internal wave breaking was observed above slopes steeper, 'supercritical', than the slope of rays of the most energetic internal waves, at the semidiurnal lunar tidal M_2 frequency. The importance of steep bottom topography has recently been acknowledged in numerical modelling (Sarkar and Scotti, 2017). It contrasts with numerical simulations of internal wave breaking above concave and convex topography, showing intense turbulence at all slopes (Legg and Adcroft, 2003).

Over a distance of 100 m from the bottom, i.e. the intense mixing layer height over sloping topography suggested by (Armi, 1979; Garrett, 1990), considerable difference in turbulence temperature statistics was found between tidal phases and height above the bottom (Cimatoribus and van Haren, 2015). Turbulence was much stronger during the upslope tidal phase. In the lower 50 m, the temperature statistics were consistent with those of shear driven turbulence and inertial subrange. In the upper 50 m, the temperature statistics deviated from those of shear turbulence, and also evidence of turbulent convective activity was found.