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Turbulence and finestructure in a deep ocean channel with sill overflow on the mid-Atlantic ridge

Sandra Tippenhauer [a,*], Marcus Dengler [a], Tim Fischer [a], Torsten Kanzow [b,c]

[a] GEOMAR Helmholtz Centre for Ocean Research Kiel, Düsternbrooker Weg 20, D-24105 Kiel, Germany
[b] Alfred-Wegener-Institut, Helmholtz-Zentrum für Polar- und Meeresforschung, Bussestraße 24, 27570 Bremerhaven, Germany
[c] Universität Bremen, Department of Physics and Electrical Engineering, Otto-Hahn Allee, Geb. NW1, 28334 Bremen

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ABSTRACT

Diapycnal mixing in the deep ocean is known to be much stronger in the vicinity of rough topography of mid-ocean ridges than above abyssal plains. In this study a horizontally profiling microstructure probe attached to an autonomous underwater vehicle (AUV) is used to infer the spatial distribution of the dissipation rate of turbulent kinetic energy (ε) in the central valley of the Mid-Atlantic Ridge. To the authors' knowledge, this is the first successful realization of a horizontal, deep-ocean microstructure survey. More than 22 h of horizontal, near-bottom microstructure data from the Lucky Strike segment (37°N) are presented. The study focuses on a channel with unidirectional sill overflow. Density was found to decrease along the channel following the mean northward flow of 3 to 8 cm/s. The magnitude of the rate of turbulent kinetic energy dissipation was distributed asymmetrically relative to the position of the sill. Elevated dissipation rates were present in a segment 1–4 km downstream (north) of the sill with peak values of 1×10^{-7} W/kg. Large flow speeds and elevated density finestructure were observed within this segment. Lowered hydrographic measurements indicated unstable stratification in the same region. The data indicate that hydraulic control was established at least temporarily. Inside the channel at wavelengths between 1 m and 250 m the slopes of AUV-inferred horizontal temperature gradient spectra were found to be consistent with turbulence in the inertial-convective subrange. Integrated temperature gradient variance in this wavelength interval was consistent with an $\varepsilon^{2/3}$ dependence. The results illustrate that deep-reaching AUVs are a useful tool to study deep ocean turbulence over complex terrain where free-falling and lowered turbulence measurements are inefficient and time-consuming.

1. Introduction

The deep water masses in the world ocean are formed at high latitudes in both hemispheres and spread equatorward along deep isopycnals (Dickson and Brown, 1994). To close the circulation, the amount of downwelled water has to be balanced by an equal amount of water rising elsewhere such that the deep meridional mass transport is compensated by an opposing upper ocean transport (Munk, 1966; Kanzow et al., 2007). The upwelling of deep water masses is closely related to the global ocean energy budget (Bryden and Imawaki, 2001). Tides and the global wind field represent by far the most important sources of mechanical energy input into the oceans (Wunsch and Ferrari, 2004). The energy input is balanced by irreversible dissipation of turbulent kinetic energy and by diapycnal mixing, representing a transfer of kinetic to potential energy. In contrast to relatively low mixing rates in the open ocean or above abyssal plains (Ledwell et al., 1993; Toole et al., 1994), greatly enhanced levels of mixing are found above rough topography, such as mid-ocean ridges (Polzin et al., 1997; Toole et al., 1997; Ferron et al., 1998; Kunze et al., 2006). Recent findings support the view that the strongest mixing does not occur *above* rough topography but *inside* deep ocean channels (St. Laurent et al., 2001; Thurnherr et al., 2005; Thurnherr, 2006; St. Laurent and Thurnherr, 2007). However, the dynamics underlying the circulation and mixing processes in such channels are currently not fully understood. The observations that exist to date in the vicinity of or inside channels on mid-ocean ridge flanks, suggest that the flow is directed "uphill" with bottom-intensified along-valley currents (Ledwell et al., 2000; Thurnherr and Speer, 2003; St. Laurent and Thurnherr, 2007; MacKinnon et al., 2008). All of these studies show an along-channel decrease of density in the direction of the flow indicating strong mixing. MacKinnon et al. (2008) report strong mixing in a channel without sills but with a strong along-channel flow. They argue that the elevated mixing is the result of the interaction between the mean current and small-scale internal gravity waves and internal tides. In contrast, studies

* Corresponding author. Tel.: +49 431 600 4159.
E-mail address: stippenhauer@geomar.de (S. Tippenhauer).

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in channels with sills report particularly elevated mixing rates and large horizontal density gradients associated with the flow over the sills (Polzin et al., 1996; Ferron et al., 1998; St. Laurent and Thurnherr, 2007; Alford et al., 2013). St. Laurent and Thurnherr (2007) present evidence for hydraulically controlled sill-overflow but do not find a downstream maximum of turbulent dissipation which would be expected in such a regime (Alford et al., 2013). For their study, St. Laurent and Thurnherr (2007) used a vertically profiling microstructure probe to infer the dissipation rate of turbulent kinetic energy inside the channel. They found increasing dissipation rates toward larger depths, reaching values of nearly 10^{-6} W/kg close to the sea floor. The absence of a downstream maximum of turbulent dissipation may either be due to limited horizontal and temporal data coverage or due to other processes involved in the dynamics of the overflow leading to elevated mixing upstream.

In this study, we present high-resolution horizontal dissipation data to advance the understanding of the cross-sill structure of mixing at Lucky Strike which is prerequisite to identify the dominant mixing regime (hydraulic control, internal waves or both). In August 2010, a near-sea-floor circulation and mixing experiment was carried out on R/V Poseidon in the Lucky Strike area. The key instrument was a horizontally operated microstructure probe (MicroRider, MR) attached to an autonomous underwater vehicle (AUV) which is standard-equipped with conductivity–temperature–depth sensors (CTD). Lowered acoustic Doppler current profiler (LADCP) and CTD measurements as well as mooring-based observations completed the survey. The data base provided by the study of St. Laurent and Thurnherr (2007) offers a good opportunity to compare the results obtained from the new instrument combination of AUV and MR for the deep ocean.

Microstructure probes have already been successfully used aboard a range of AUVs but limited to the upper ocean (Levine and Lueck, 1999; Lueck et al., 2002; Thorpe et al., 2003; Goodman et al., 2006; Steele et al., 2012). The detection limits of these studies were similar to the one of the AUV–MR system described in this study. To our knowledge, horizontal, AUV-based dissipation measurements in the deep ocean (sub-thermocline) in the vicinity of rough topography have not been accomplished in the past.

Details regarding the study site, the AUV dives as well as all other measurements are given in Section 2. Section 3 introduces the method of inferring the dissipation rate from microstructure data obtained with the AUV *Abyss*. The distribution of observed dissipation rates, small scale density variability, the average background density and flow field, spectral analyses of horizontal temperature records and average dissipation rates are presented in Section 4. Possible mechanisms driving the mixing at Lucky Strike and the direct comparison of our results with those obtained by St. Laurent and Thurnherr (2007) are discussed in Section 5.

2. Study site and data

The Lucky Strike segment is located in the rift valley of the Mid-Atlantic Ridge near 37°N. It contains two basins separated by a volcano (Fig. 1). The basins are connected via two meridional channels at each side of the volcano. This study focuses on the eastern channel which is blocked by a zonally-extending sill (Figs. 1 and 4). The depth of the sill is approximately 2050 m. The channel is zonally confined below 1800 m by the rift-valley wall in the east and by the eastern flank of the volcano in the west. Near the sill the channel is approximately 3 km wide with a mean slope of the channel walls of 17° (St. Laurent and Thurnherr, 2007).

2.1. AUV and payload

The AUV *Abyss* is an extended Remote Environmental Measuring UnitS (REMUS) vehicle manufactured by Hydroid Inc. that can be operated in water depths up to 6000 m. It is 4 m long and has a diameter of 0.66 m. A pumped CTD (Seabird SBE 49 FastCat) is mounted to the side of the AUV. The CTD was operated at a sampling rate of 5 Hz. For navigation, the AUV is equipped with a GPS, an Inertial Navigation System, a Doppler Velocity Log (DVL) for bottom tracking, an altitude sensor for measuring the distance from the sea floor, and a pressure sensor. The DVL and pressure sensors used for navigation were operated at 1 Hz. For underwater positioning, the AUV is equipped with a long baseline positioning transponder (LBL, Hydroid). At the beginning of the cruise two bottom-mounted transponders were deployed as a reference frame (Fig. 4). The AUV was operated at a speed of 1.5 m/s.

2.2. Microstructure profiler, mounting and vibrations

The microstructure package used in this study was a MicroRider (MR) manufactured by Rockland Scientific International (RSI). The MR was equipped with two airfoil velocity shear probes (Siddon, 1971; Osborn, 1974; Osborn and Crawford, 1980; Lueck et al., 2002), two fast-responding thermistors (FP07), a pressure sensor (Pa-10L/600Bar from Keller), and a three-dimensional accelerometer. The latter was used in data processing to reduce the AUV-induced noise in the velocity shear data (Section 3). During the missions, microstructure shear and temperature as well as the acceleration sensors were configured to sample at 512 Hz. The MR pressure sensor sampled at 64 Hz.

The MR consists of two separate pressure cases to equally distribute the weight on each side of the AUV. One pressure case houses the sensor electronics while the other contains the data storing unit. The power for the MR was supplied by the AUV.

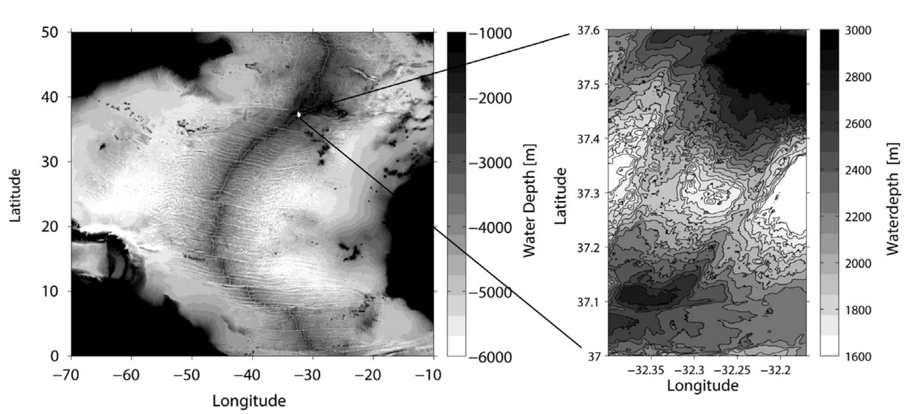

Fig. 1. Topography of the North Atlantic Ocean (left), and the Lucky Strike segment (right). The Lucky Strike volcano is located in the middle of the segment, with meridional channels east and west of the volcano that connect the deep southern and northern basins.