Journal of Marine Systems 77 (2009) 428–440

Contents lists available at ScienceDirect

Journal of Marine Systems

journal homepage: www.elsevier.com/locate/jmarsys

The structure of dissipation in the western Irish Sea front

John H. Simpson [a,*], J.A. Mattias Green [a], Tom P. Rippeth [a], Thomas R. Osborn [b], W. Alex M. Nimmo-Smith [c]

[a] School of Ocean Sciences, College of Natural Sciences, Bangor University, UK
[b] Department of Earth and Planetary Sciences, The Johns Hopkins University, Baltimore, MD, USA
[c] School of Earth, Ocean & Environmental Sciences, University of Plymouth, UK

ARTICLE INFO

Article history:
Received 6 December 2007
Accepted 29 October 2008
Available online 11 November 2008

Keywords:
Tidal mixing front
Turbulence
Dissipation
Autosub
Irish Sea

ABSTRACT

We report on an intensive campaign in the summer of 2006 to observe turbulent energy dissipation in the vicinity of a tidal mixing front which separates well mixed and seasonally stratified regimes in the western Irish Sea. The rate of turbulent dissipation ε was observed on a section across the front by a combination of vertical profiles with the FLY dissipation profiler and horizontal profiles by shear sensors mounted on an AUV (Autosub). Mean flow conditions and stratification were obtained from a bed mounted ADCP and a vertical chain of thermistors on a mooring. During an Autosub mission of 60 h, the vehicle, moving at a speed of ~1.2 m s^{-1}, completed 10 useable frontal crossings between end points which were allowed to move with the mean flow. The results were combined with parallel measurements of the vertical profile of ε which were made using FLY for periods of up to 13 h at positions along the Autosub track. The two data sets, which show a satisfactory degree of consistency, were combined to elucidate the space–time variation of dissipation in the frontal zone. Using harmonic analysis, the spatial structure of dissipation was separated from the strong time dependent signal at the M_4 tidal frequency to yield a picture of the cross-frontal distribution of energy dissipation. A complementary picture of the frontal velocity field was obtained from a moored ADCP and estimates of the mean velocity derived from the thermal wind using the observed density distribution. which indicated the presence of a strong (0.2 m s^{-1}) jet-like flow in the high gradient region of the front. Under neap tidal conditions, mean dissipation varied across the section by 3 orders of magnitude exceeding 10^{-2} W m^{-3} near the seabed in the mixed regime and decreasing to 10^{-5} W m^{-3}. in the strongly stratified interior regime. The spatial pattern of dissipation is consistent in general form with the predictions of models of tidal mixing and does not reflect any strong influence by the frontal jet.

1. Introduction

Tidal mixing (TM) fronts are the boundaries between seasonally stratified and well-mixed regimes. They occur widely in regions of the continental shelf which experience a combination of high tidal dissipation and a large seasonal heat exchange. The shelf seas of north-western Europe satisfy both of these conditions and are host to a number of prominent frontal features which have been the subject of extensive study. The basic theory of the heating–stirring competition which underlies the formation of these fronts and controls their geographical positions (Simpson and Hunter, 1974) has been utilised in combination with numerical models of tidal flow to predict the positions of fronts (e.g. Pingree and Griffiths, 1978; Garrett et al., 1978; Lie, 1989; Glorioso and Simpson, 1994). Tidal mixing theory has been extended to allow for the influence of the fortnightly cycle in tidal stirring and the contribution from wind mixing (Simpson and Bowers, 1981) as well as the effects of the Earth's rotation (Simpson and Sharples, 1994; Simpson and Tinker, in press). The internal dynamics of fronts have also been

* Corresponding author. School of Ocean Sciences, Bangor University, Menai Bridge, Anglesey, LL59 5AB, UK. Tel.: +44 01248 38 28 44.
E-mail address: j.h.simpson@bangor.ac.uk (J.H. Simpson).

0924-7963/$ – see front matter © 2008 Published by Elsevier B.V.
doi:10.1016/j.jmarsys.2008.10.014

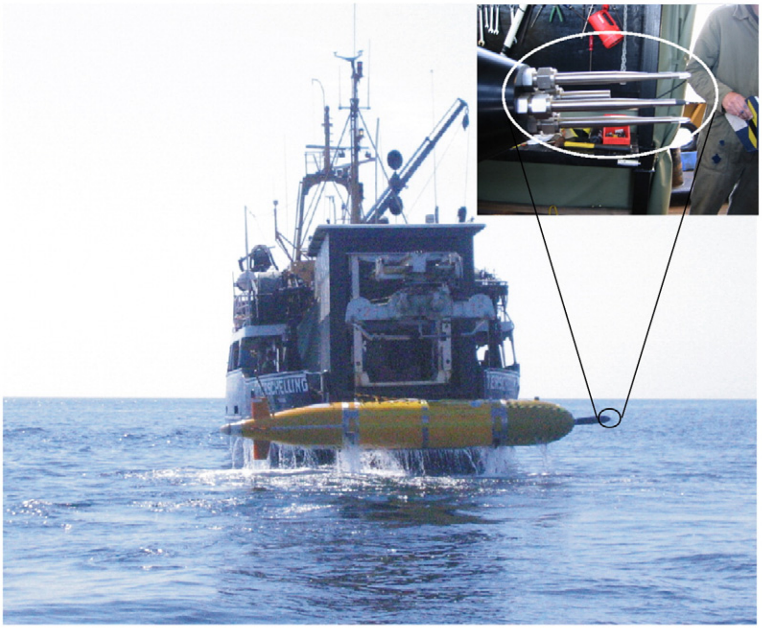

Fig. 1. Autosub at the end of mission in the recovery gantry on MS Terschelling. Insert shows the nose-mounted airfoil shear probes which sense transverse velocity on a scale of <1 cm. Autosub is 7 m long and has a diameter of 0.9 m.

explored in numerical models (e.g. Garrett and Loder, 1981; James, 1984) which indicate the presence of a frontal jet and a weak cross-frontal circulation. Direct observations of the frontal jet have been obtained in a number of tidal mixing fronts (e.g. Lwiza et al., 1991; Brown et al., 2003) while evidence of the cross-frontal circulation has been obtained from dye dispersal experiments by Houghton, 2002. More generally the contribution of the density driven-flows produced by heating and tidal stirring to the summer circulation in shelf seas has been elucidated by Hill et al. (1997).

Direct measurements of the gradients in tidally forced turbulence which are responsible for generating and maintaining TM fronts became practical with the advent of shear profilers (Oakey, 1982; Dewey et al., 1987). An extensive series of measurements with the FLY profiler have elucidated the structure of turbulent dissipation and mixing in the characteristic mixed and seasonally stratified regimes of the European shelf seas (Simpson et al., 1996; Rippeth, 2005; Rippeth et al., 2005). Generally there is a pronounced M_4 cycle in dissipation in the tidally-driven bottom boundary layer (bbl) which, in the mixed regime, extends up to the surface where it merges with the surface mixed layer. In the seasonally stratified regime, the bbl is limited to a fraction of the water depth, and dissipation shows a marked phase lag increasing with height above the bed (Simpson et al., 2000). Most of the observed profiles of dissipation can be understood in terms of energy inputs at the top and bottom boundaries of the water column, although in strongly stratified conditions there are clear indications of additional energy inputs in mid-water whose origin remains uncertain and is the subject of ongoing investigations (e.g. Rippeth et al., 2005).

While the seasonally stratified and well-mixed regimes have now been extensively studied through vertical profiles, there have been very few measurements of the horizontal variability of turbulent processes. In particular, determining the structure of turbulence in the tidal mixing fronts between stratified and mixed regimes has proved difficult with vertical shear profilers because of complicated space–time pattern of dissipation in these structures. In addition to the time evolution on M_2 and M_4 time scales the whole frontal structure is subject to tidal advection with an excursion of ~5 km or more. Observing a TM front therefore requires an extended sampling scheme as in the pioneering measurements by Oakey and Pettipas (1992) based on a series of 98 anchor stations on a section through the Georges Bank TM front.

In this contribution we report a series of observations of the turbulent dissipation rate ε in a TM front based on a new approach in which we used a combination of horizontal transects across the front combined with vertical profiles of dissipation and mooring measurements of the vertical structure of density and velocity. The measurements are combined and analysed to give as full a picture as possible of the space–time evolution of dissipation in the frontal zone. The paper is structured so that in Sections 2 and 3 we briefly describe the measurement methods and the observational campaign before describing the density and velocity fields (Section 4) which set the physical context for the turbulence measurements. We then present the main results in Sections 5–8, and conclude with a summary and a brief discussion of their implications in Section 9.

2. Measurement methods

The measurements reported here were obtained through a two ship campaign in the Irish Sea during the period July 11–23 2006. The M. S. Terschelling carried the Autosub team and acted as mother vessel to the autonomous underwater vehicle (AUV)