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On instability and mixing on the UK Continental Shelf

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ABSTRACT

The stability of stratified flows at locations in the Clyde, Irish and Celtic Seas on the UK Continental Shelf is examined. Flows are averaged over periods of 12–30 min in each hour, corresponding to the times taken to obtain reliable estimates of the rate of dissipation of turbulent kinetic energy per unit mass, ε. The Taylor–Goldstein equation is solved to find the maximum growth rate of small disturbances to these averaged flows, and the critical gradient Richardson number, $\mathrm{Ri_c}$. The proportion of unstable periods where the minimum gradient Richardson number, $\mathrm{Ri_{min}}$, is less than $\mathrm{Ri_c}$ is about 35%. Cases are found in which $\mathrm{Ri_c} < 0.25$; 37% of the flows with $\mathrm{Ri_{min}} < 0.25$ are stable, and $\mathrm{Ri_c} < 0.24$ in 68% of the periods where $\mathrm{Ri_{min}} < 0.25$. Marginal conditions with $0.8 < \mathrm{Ri_{min}}/\mathrm{Ri_c} < 1.2$ occur in 30% of the periods examined. The mean dissipation rate at the level where the fastest growing disturbance has its maximum amplitude is examined to assess whether the turbulence there is isotropic and how it relates to the wave–turbulence boundary. It is concluded that there is a background level of dissipation that is augmented by instability; instability of the averaged flow does not account for all the turbulence observed in mid-water. The effects of a horizontal separation of the measurements of shear and buoyancy are considered. The available data do not support the hypothesis that the turbulent flows observed on the UK shelf adjust rapidly to conditions that are close to being marginal, or that flows in a particular location and period of time in one sea have stability characteristics that are very similar to those in another.

1. Introduction

Turbulent mixing on the continental shelf is a significant component of global tidal dissipation and contributes to the process known as the 'continental shelf pump' related to the oceanic storage of carbon dioxide (Rippeth, 2005). Turbulence is generated by wind, buoyancy flux and surface waves at the sea surface, by tidal stress at the seabed and, in mid-water, by instability resulting mainly from shear. The latter is the subject of this investigation.

In a recent study, Liu (2010) (hereafter referred to as L10) examines the stability of baroclinic tidal flow in the Clyde Sea and its relation to dissipation and mixing. Hourly averaged density and velocity data are incorporated into the Taylor–Goldstein (T–G) equation to find the structure and rate of growth of the fastest growing small disturbances. The mean velocity, $U(z)$, is then scaled by a factor $(1 + \Phi)$, where Φ is a non-dimensional parameter, and the T–G equation is solved with successively decreasing values of Φ to find the conditions, at a value $\Phi = \Phi_c$, in which the maximum disturbance growth rate is zero. We define $\mathrm{Ri_{min}}$ as the smallest gradient Richardson number, $\mathrm{Ri} = N^2/S^2$, of the observed (un-scaled) flow, where $N(z)$ is the mean buoyancy frequency and $S = dU/dz$. The critical gradient Richardson number, $\mathrm{Ri_c}$, is then $\mathrm{Ri_c} = \mathrm{Ri_{min}}/(1 + \Phi_c)^2$. The critical gradient Richardson number determined in this way is sometimes close to the often-assumed critical value of $\frac{1}{4}$, but not always; the smallest value found is 0.06. A measure of whether or not the flow is in a state of marginal stability is determined from the proximity of $\mathrm{Ri_{min}}/\mathrm{Ri_c}$ to 1 or of Φ_c to 0.

The analysis of L10 involves some pragmatic compromises that are all tested in that paper. For example, interpolation onto a 0.2 m vertical grid is found necessary in solving the T–G equation using the matrix method (Monserrat and Thorpe, 1996). A limit is set for the range of unstable wavelengths, to reduce computer time. The upper and lower parts of the water column affected by bed- or surface-generated turbulence are excluded from the analysis.

Here we apply the same analysis to examine the stability of flows in two other seas on the UK Continental Shelf, each strongly affected by the tides. This allows us to have a more general understanding on characteristics of shear instability and its role in generating turbulence in shelf seas. It is found that instability of the averaged flow does not account for all the turbulence observed in mid-water;

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Table 1
Values characterising the three seas: dates of observations, water depth, latitude, Coriolis parameter, location in the spring-neap tidal cycle and the maximum depth averaged tidal flow.

Parameter	Clyde Sea	Irish Sea	Celtic Sea
Dates	July 1–2 2002	July 16–18 2006	August 10–11 2003
Depth, H (m)	58	103	95
Latitude	55°21′N	53°42′N	51°28′N
Coriolis parameter, f (s^{-1})	1.196×10^{-4}	1.172×10^{-4}	1.138×10^{-4}
Days after spring tide	5	2	8
Maximum mean tidal flow (m s^{-1})	0.21	0.47	0.37

processes possibly vortical modes or internal waves of relatively small period provide a background level of turbulence augmented by flow instability. We also test (and then refute) the hypothesis that the turbulent flows observed on the UK shelf adjust rapidly to conditions that are close to being marginal. In Section 2 data from the three seas, the Clyde (that already examined by L10), Irish and Celtic, are briefly described. Data analysis and the results are described in Section 3. This includes a general discussion of 'marginal stability', which takes into account the study by D'Asaro and Lien (2000) of the existence of a transition at the 'wave–turbulence boundary' from a flow in which mixing is dominated by interactions between internal waves to one dominated by turbulence. The main conclusions are summarized in Section 4.

2. The data

Some details of the sites in the three seas are given in Table 1. At each site velocity profiles are obtained by a bottom-mounted

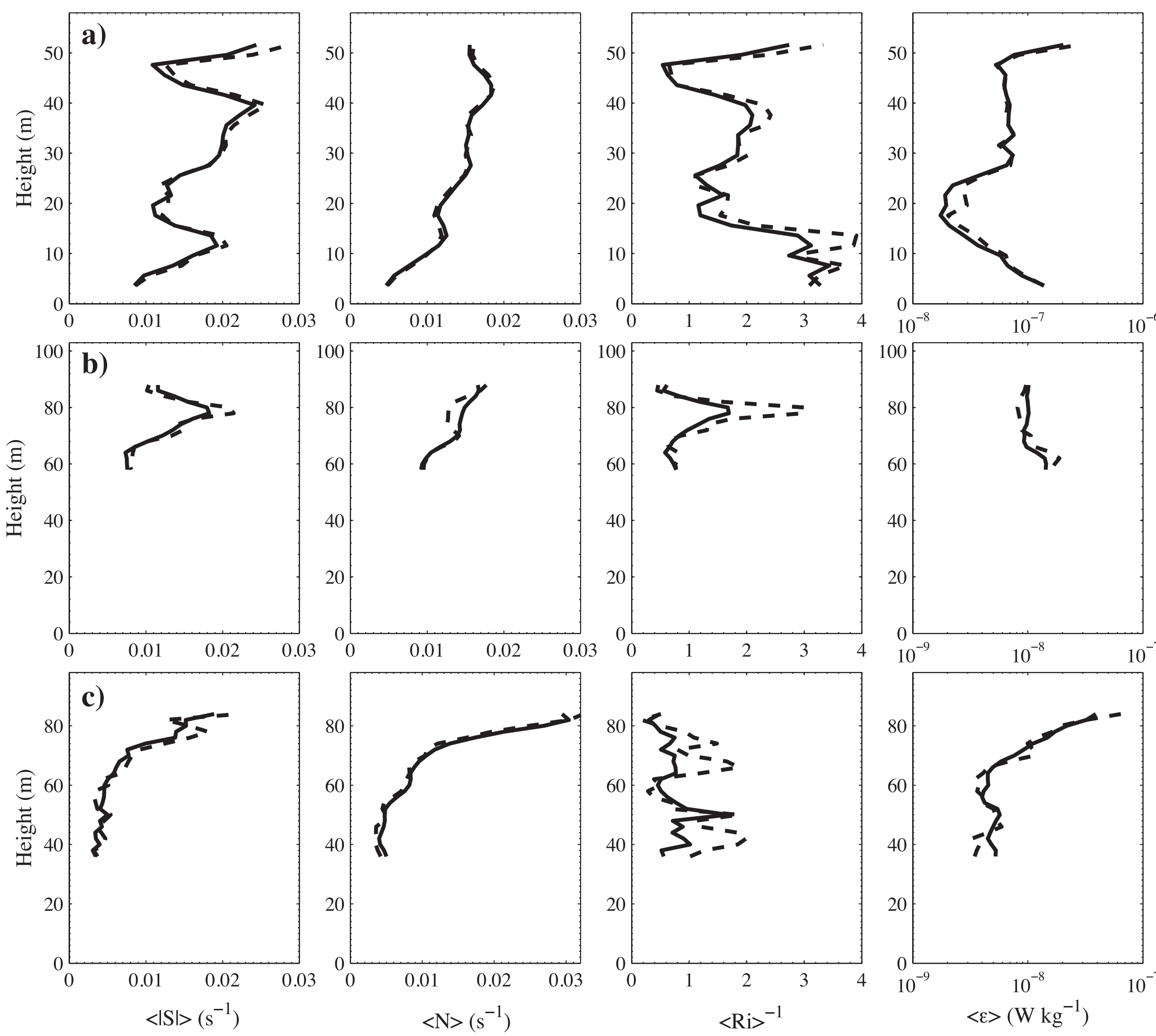

Fig. 1. Mean profiles for the three seas. (a) The Clyde, (b) the Irish and (c) the Celtic Sea. Left to right: the modulus of the mean shear, $<|S|>$; the modulus of the buoyancy frequency, $<N>$; the inverse mean Ri where $<\mathrm{Ri}> = <N^2>/<|S|^2>$; and the rate of dissipation of turbulent kinetic energy per unit mass, $<\varepsilon>$. Solid lines indicate the means of all the data, and the dashed lines indicate data in unstable conditions ($\mathrm{Ri}_{min} < \mathrm{Ri}_c$).