INTERMITTENCY IN STRATIFIED TURBULENCE PRODUCED BY BREAKING INTERNAL GRAVITY WAVES

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Summary Internal gravity waves nonlinear interactions lead to intermittent breaking events with density overturning and vertical turbulent mixing. We analyze the statistics of density and velocity fluctuations in this process, using direct numerical simulations.
We characterize the density and velocity gradients at different scales along the vertical direction. The velocity gradients behave in a very similar way to usual turbulence, while the density gradients are very intermittent. This can be attributed to the formation of sheets with strong stable density gradients. Unstable density gradients are rare and form intermittent patches of different scale for which we have analyzed the statistics. We discuss the link with mixing properties of the internal wave field and compare with observations in the ocean and the atmosphere.

INTRODUCTION

Internal wavebreaking is an important source of turbulence in stably stratified fluids. Because wavebreaking occurs intermittently in space and time it is important regarding the interpretation of microstructure measurements (for instance the estimate of mixing) to have a "good" knowledge of the statistical properties at small scales. To this aim process-oriented studies performed with the use of numerical simulations constitute an efficient approach. We start with a simple initial condition (a large scale internal gravity wave), so that turbulence is produced by an intrinsic sequence of instabilities, without external noise, and our calculations can be exactly reproduced and checked. We performed two-dimensional direct numerical simulations which allow better resolution. It is representative of three dimensional cases, as shown by different comparisons Bouruet-Aubertot *et al* (2001), Carnevale *et al* (2001). We analyze as well three-dimensional numerical simulations (but with a lower resolution). The purpose of this paper is to analyze statistical properties of the turbulence induced by the breaking of a large scale primary wave, characterize rare events responsible for the intermittency and discuss the link with mixing processes.

RESULTS

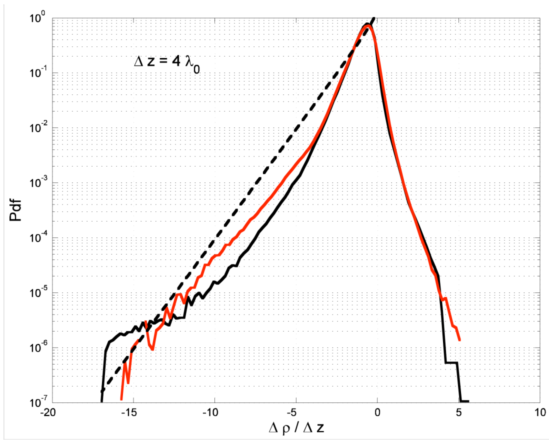
Moments and exponents

We computed the moments of the horizontal and vertical velocity, u and v, and of the density fluctuations, ρ' versus the separation δz. We obtained power laws versus δz over one decade approximately. We then looked at the behavior of the exponents ζ_n of the moments of u, v and ρ'. Both velocity components and density are intermittent. Interestingly scaling exponents for u and v are very closed suggesting that physical events responsible for the intermittency of the flow occur at very small scales where the anisotropy introduced by the stratification does not come into play. In contrast density fluctuations are more intermittent than velocity components. This point is very similar to ordinary turbulence in which the passive scalar has a more intermittent behavior than velocity. We then compared the scaling exponents for the density fluctuations with those obtained in ordinary three-dimensional turbulence. Density fluctuations are found more intermittent than passive scalar in three-dimensional turbulence. This suggests that the dynamical coupling between buoyancy and inertial forces is a crucial process for the intermittency of density fluctuations.

Pdfs of vertical density gradients at small vertical scales

We next characterized the density and velocity gradients at different scales along the vertical and horizontal directions. The velocity gradients behave in a very similar way to usual turbulence, while the density gradients at small scales are very intermittent. More precisely probability density functions (pdfs) of the density gradients at small scales are highly skewed. The pdf decreases more strongly toward unstable density gradients while the decrease is less steep toward stable stratification until the pdfs reaches almost a plateau for the highest values (Fig.1). We identified the physical events responsible for this density structure. These strongly stratified regions are correlated with breaking events. Indeed density overturnings can lead in some cases to a convergence of fluid which results in a local increase of the vertical density gradient. The resulting density structure is made of a succession of sheets with strong stable density gradients and turbulent regions of greater vertical extent.

Two processes may be responsible for the increased skewness of the pdf of density gradients at small vertical scale, either the reversible straining produced by internal gravity waves or irreversible mixing events. These two alternatives were addressed in theoretical models. We focus here on the gamma pdf model, proposed by Hayes *et al.* (1975), which describes a staircase density profile with randomly distributed steps separating mixed layers with uniform density. This model provides a reasonable fit to our numerical data at scales smaller than $30\, l_O$ (where l_O is the Ozmidov length scale defined by $l_O = \sqrt{\frac{\varepsilon}{N^3}}$, ε is the energy dissipation and N the buoyancy frequency). The probability density of the density difference $\Delta\rho$ at separation Δz is given by Eq.9 of Hayes *et al* (1975) and it is determined by a single parameter μ which denotes the mean number of steps per unit of height. The formation of sheets and layers is clearly associated with energy dissipation and vertical mixing. We therefore expect a link between the Ozmidov scale, related to energy dissipation, and the mean vertical distance between sheets, μ^{-1}. Figure 2 shows indeed that these two quantities are proportional : $\mu^{-1} \approx 5.3\lambda_0$.



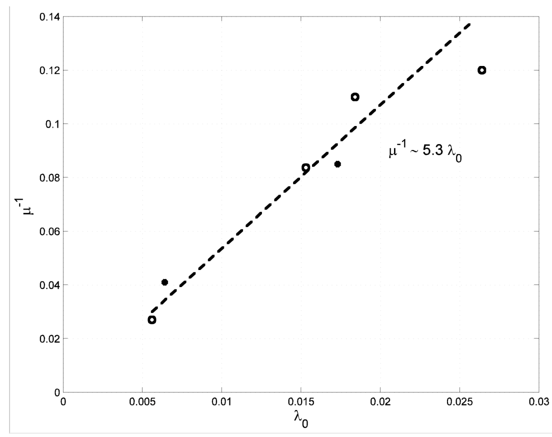


Figure 1: Pdfs of density gradient at vertical scale $\Delta z = 4\lambda_O$ function
for a wave of amplitude $A = 0.256$, 3d results are represented represented
in red and 2d results in black, theoretical prediction of the Hayes *et al* model with a dashed line.

Figure 2: Mean distance between steps μ^{-1} as a
of the Ozmidov length scale λ_O, 2d results are
with empty circles and 3d results with filled circles.

CONCLUSION

We analyzed some statistical properties of the turbulence induced by the breaking of internal gravity waves. This dynamics corresponds to the so-called buoyancy subrange and it is characterized by kinetic and available potential energy spectra that follow a k_z^{-3} power law. In the ocean such behavior is obtained in the finescale domain, in between weakly nonlinear waves and three dimensional turbulence, corresponding to vertical scales typically within the range $[1m, 10m]$. We focused on the vertical structure of the density field with the main purpose of providing a link between density intermittency, energy dissipation and mixing processes.

Density gradients are strongly intermittent at small scales. The main feature is the strong skewness of the histograms toward stable stratification that becomes evident as soon as overturning events occur. We have characterized these rare and intense events. These take the form of strongly stratified sheets of thin vertical thickness close to the Ozmidov scale and horizontal scale related to that of the large scale breaking wave. These structures are generated through strong convergent motions induced by surrounding overturning events. Indications of these structures were obtained in the atmosphere from vertical profiles of temperature as well as in the ocean in the seasonal thermocline of the Sargasso Sea.

We then checked the ability of the sheet and layer model or gamma pdf model to reproduce the shape of the histograms of vertical density gradient at small vertical scales (typically within $[\lambda_0, 30\lambda_0]$). This model, which assumes that the step-like structure is the result of mixing processes, depends on one parameter, the mean number of sheets (or steps) per unit length.
The main result of this paper is that the sheet spacing varies linearly with the Ozmidov length scale defined with the total energy dissipation rate. This thus provides a link between density statistics at finescale and energy dissipation. As a consequence, the mean eddy diffusivity that characterizes breaking events varies linearly with a dimensionless parameter defined with μ^{-1}: $\frac{\mu^{-2} N}{\nu}$ which provides a link with mixing processes. In future work we plan to further check this indirect estimate of mixing based on density statistics at finescale on a large set of in situ oceanic data and compare this estimate with direct measurements of mixing as inferred from microstructure measurements.

References

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