Mixing, Fine-Structure and Internal Waves Near Shallow-Summit Seamounts

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LONG TERM GOALS

The long term goals of our research are to identify and evaluate key processes responsible for the generation and decay of oceanic turbulence. Intermittent turbulent mixing in coastal and deep oceans and associated background meso-scale dynamics are studied by comprehensive analyses of special field measurements as well as using theoretical and numerical modeling.

OBJECTIVES

The prime objective of the current work is to acquire a better understanding of the oceanic fine-structure generated by turbulent mixing and internal-wave dynamics in regions of abrupt topography of coastal and deep oceans. This study is important, in particular, for modeling and calculation of vertical transports through the highly-stratified seasonal pycnocline in mid-latitudes. Evaluation of the influence of boundary mixing on the basin-averaged turbulent diffusivity is also one of our major objectives. It is expected to develop a parameterization for turbulent mixing in rotating, stratified, shear flows that can be used to formulate a model for thermohaline fine-structure formation in the pycnocline due to forcing at oceanic boundaries.

APPROACH

Exhaustive statistical analysis of field data obtained in coastal zones and near shallow-summit seamounts is the basis of this study. The turbulent measurements taken in the Black Sea coastal zone were used to make a detailed analysis of mixing activities from the sea surface down to the bottom at various location across the shelf. Several averaging procedures were implemented to obtain satisfactory estimates of turbulent diffusivities in different layers. The

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calculation of various turbulent quantities (dissipation rates, diffusivities, turbulent efficiency and Reynolds numbers) at cross-sections over the seamount Erving (eastern subtropical Atlantic), using the data obtained during 48th cruise of r/v AKADEMIK KURCHATOV, was initiated. Special attention was given to the error analysis of calculations and for developing new algorithms for data processing.

During the last year, our efforts were focused on theoretical and numerical studies of the generation of well-defined quasi-homogeneous mixed layers, which are often observed in strongly stratified seasonal thermoclines and in the pycnocline aloft the bottom boundary layer. A one-dimensional, non-stationary, numerical model was developed, using an advanced parameterization of turbulent mixing. To estimate the effects of stratification, boundary stresses, rotation and the local Richardson number dependence of diffusivities on the formation of the step-like structure, a series of numerical experiments was run in close collaboration with Dr. Alexander Berestov of Arizona State University.

WORK COMPLETED

Research on some of the above issues has been completed and the others are in progress. The completed work includes:

- The analysis of Black Sea data, which yielded a turbulent Reynolds-number dependent correlation between turbulent mass and scalar diffusivities at the shallow shelf.
- Development of a turbulent closure, based on theoretical hypotheses (which are corroborated by field data), for the numerical model on the evolution of vertical density structure in stratified shear flows influenced by boundary forcing.
- Carrying out of a series of numerical experiments (with fine space-time resolution) to simulate the generation of well-mixed layers separated by narrow, strongly stratified interfaces within the pycnocline under the influence of surface stress and rotation.

SCIENTIFIC RESULTS

Calculations of various turbulent quantities in the vicinity of seamount Erving showed an enormous enhancement of turbulent mixing in the thermocline over the summit (the summit depth is 260 m). It was found that over the top of the seamount the kinetic energy dissipation rate is so high that the turbulent diffusivities rise to 10^{-3} - 10^{-2} m^2/s across the whole water column.

The measurements taken at the shallow shelf showed that the normalized Thorpe scale L_{Th}/h_p in a stratified turbulent patch with the vertical size h_p is governed by the mixing Reynolds number R_m and the patch Richardson number Ri_p. When $R_m < R_{cr} \approx 150$, L_{Th}/h_p increased rapidly and approached a constant value close to 0.3 for $R_m >> R_{cr}$.

To evaluate the relationship between the eddy mass diffusivity $K_N = \gamma\varepsilon / N^2$ and the scalar turbulent diffusivity $K_{sc} = \chi / 2\overline{(dC/dz)}^2$, where ε and χ are the kinetic energy and scalar dissipation rates, γ is the mixing efficiency, $\overline{dC/dz}$ is the mean scalar gradient and N^2 is the buoyancy frequency, a large amount of field data obtained in the coastal ocean were analyzed. It was shown that the relation between K_N and K_{sc} crucially depends on the nature of space averaging and on the phase of turbulence decay. Insufficient averaging led to almost complete loss of correlation between these parameters. When the averaging was carried out over whole turbulent structure (e.g., a patch, layer, overturn) it was found that $K_N \approx K_{sc}$ and $\gamma \approx 0.2$. In weakly-turbulent stratified layers, $K_{sc} > K_N$ and γ tends to 0.5 - 0.6. The results are given in Figure 1.

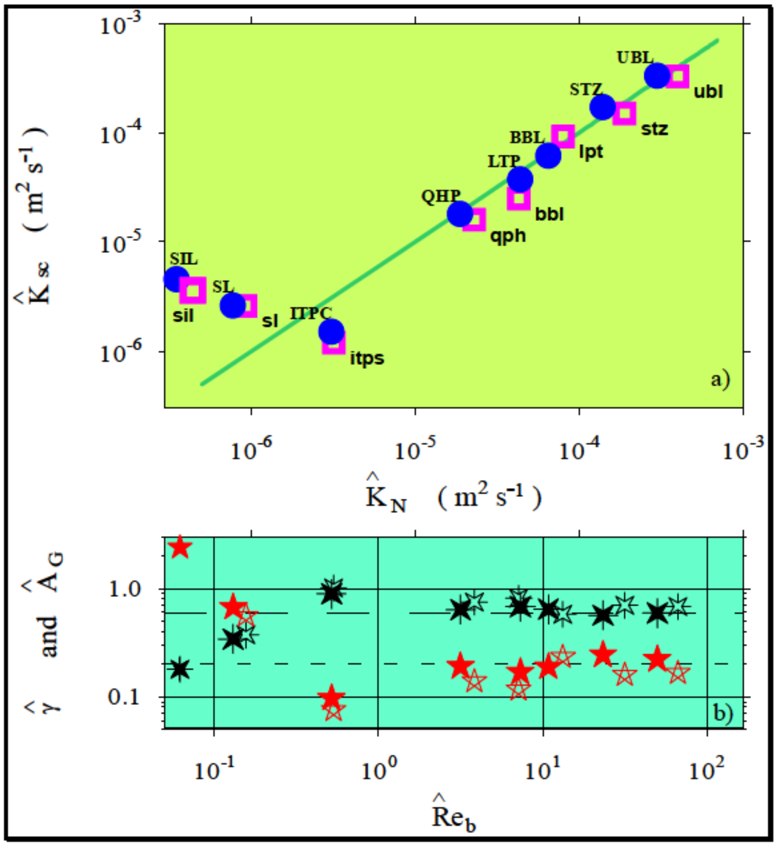

Figure 1. (a) - Averaged diffusivities in the upper marine boundary layer (UBL), stratified and weakly-turbulent inner layers (SIL and SL), quasi-homogeneous turbulent patch (QHP), sheared turbulent zone (STZ) and local turbulent patch (LTP) within the thermohalocline, intermittently turbulent pycnocline (ITPC) and near-bottom boundary layer (BBL). The straight line is a linear regression $\hat{K}_{sc} = \hat{K}_N$ (the hats over variables define the averaged estimates for particular regions);

(b) - Activity parameters $\hat{A}_G \sim \sqrt{\hat{\gamma}}$ (snow-flakes) and mixing efficiencies $\hat{\gamma}$ (stars) versus the buoyancy Reynolds numbers $\hat{Re}_b$, taken from the same regions. The light dashed line indicates $\hat{\gamma} = 0.2$, heavy dashed line marks $\hat{A}_G = 0.6$. (Solid symbols (dots, stars, and snow-flakes) show arithmetic averaged samples; open symbols indicate the maximum likelihood estimates of the mean for log-normal probability distributions of K_N and K_{sc}).

The numerical simulations clearly showed that the use of Richardson number dependent turbulent diffusivities in a sheared flow results in a formation of pycnoclines with prominent fine-structure. The model was based on non-stationary stratified planetary boundary layer equations [Mellor and Yamada, 1973], the turbulent kinetic energy equation and the turbulent closure proposed by Lozovatsky et al. [1993]; $K_M = K_{Sh} / \sqrt{1 + Ri / Ri_{cr}}$ and $K_N / K_M = 1/(1 + Ri / Ri_{cr})$, where K_M is the eddy viscosity and K_{Sh} is the shear dependent eddy viscosity in non-stratified flows. The latter parameterization ensures the instability of density gradients in a stably-stratified layer with decreasing buoyancy flux F_b, when N^2 exceeds a critical value N_{cr}^2, corresponding to a local maximum of $F_b(N^2)$. This type of instability was independently proposed by Phillips [1972] and Posmentier [1977] and has been later treated by several others. It was also found that the development and decay of fine-structure are strongly dependent on inertial oscillations! The reason for this observation is the local enhancement of vertical shear at the density interfaces between homogeneous layers. As a result, the local Richardson number decreases, thus generating shear-induced turbulence within interfaces. This is why some of the interfaces are rapidly destroyed and the fine-structure may even vanish at times. These numerical predictions are in consonance with oceanic microstructure measurements and, to our knowledge, this is the first time that the importance of inertial oscillations on the microstructure formation has been clearly illustrated numerically. The scales of the layers observed in simulations (Figure 2) are close to those observed in the seasonal ocean pycnocline.

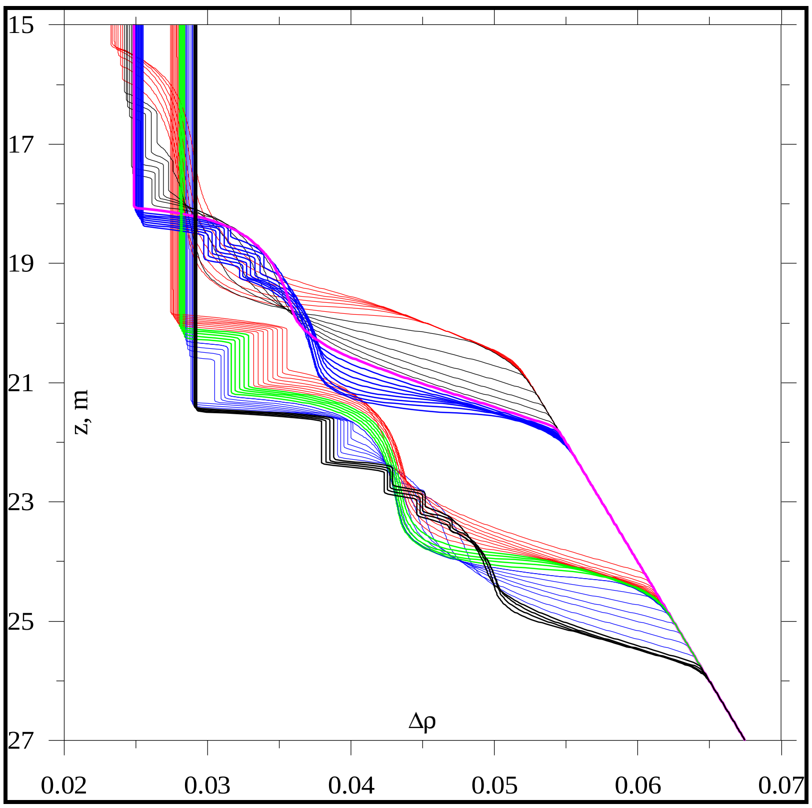

Figure 2. Modeling density profiles for the 4th (upper set) and 7th (lower set) inertial periods, counting from the beginning of the computation. The curves are given for every hour. A constant friction velocity, $u_* = 1.1$ cm/s, linear initial stratification, $N^2 = 2.5 \times 10^{-5}$ s^{-2}, and Coriolis parameter $f = 10^{-4}$ s^{-1} were used in this numerical experiment. The layering phases alternate with the "calm" periods, and at times the steps vanish completely. These "calm" stages may last up to $(0.5 - 0.9)T_{in}$, where the inertial period T_{in} is 17.45 h.

IMPACT/APPLICATIONS

The functional dependence between the normalized overturning scale and the mixing Reynolds number in a weakly mixed turbulent patch obtained in the study substantially improves existing scaling for vertical transport in highly-stratified layers.

The first direct estimates of vertical exchange coefficients of the Black Sea shelf were carried out in this study. Relatively high turbulent mass diffusivities (5×10^{-5} - 5×10^{-4} m^2/s) were found in the boundary layers and in active turbulent regions in the water interior affected by moderate wind. A comparison of present results with those obtained from other coastal studies will help to deduce climatology of coastal mixing, which is an oceanographic problem of current interest.

The new parameterization used for turbulent mixing together with classical model of a rotating boundary layer led to the formation of homogeneous mixed surface layer with an underlying pycnocline containing step-like fine-structures (the structures were developed and evolved solely by the surface stress acting on an initially linear density profile). The detailed results obtained from this study is an important achievement for the prognostic modeling of turbulent transports across strongly stratified interfaces separated by homogeneous layers. The influence of rotation on the generation and decay of step-like structure can be scrutinized in future laboratory experiments to acquire a better understanding of the physics of relevant process.

TRANSITIONS

The model of fine-structure formation can be nested into more complex models dealing with vertical transport of heat, energy, nutrients and sediments in the oceanic boundary layers.

The approach used to acquire adequate estimates of mixing in different layers at the Black Sea shelf can be applied to other shallow regions including semi-enclosed seas. To this end, we initiated a collaborative project with Russian oceanographers to study the relationship between internal waves and mixing in the Baltic Sea. A proposal on this project has been recently submitted to ONR for consideration for funding under the next year NICOP program.

RELATED PROJECTS

The P.I. have established close collaboration with Dr. Don Delisi from NWRA (Belliveu, WA), who is studying the effects of vertical shear on grid-generated turbulence in a tilting tank. The P.I. is also involved in an ongoing NWRA project, dealing with the testing of Russian-build EM velocity sensors that are expected to be used for turbulent measurements from towing platforms.

The Co-P.I. is involved in an ONR funded project entitled "Turbulent Mixing in Oceanic Surface and Benthic Boundary Layers" to investigate turbulent transport in wave boundary layers and stratified shear layers using specially designed laboratory experiments.

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