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

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LONG TERM GOAL

Long term goal of our research is to identify and evaluate key processes responsible for the generation, maintenance, and decay of oceanic turbulence. Enhancement of vertical mixing by bottom topography in deep oceans and in coastal regions is a problem of our top priority.

OBJECTIVES

The current project is focused on studying the decay of turbulence downstream of seamounts and analyzing the statistics of topography-induced mixing in different oceanic layers. We also plan to quantify the influence of vertical shear on the nature of turbulence on shallow shelves. The impact of background shear on the generation of density fine-structure induced by boundary forcing appears to be an important phenomenon that should be considered in parameterization of ocean mixing processes, and our current work delves into this aspect using numerical modeling.

APPROACH

The study is based on comprehensive analyses of field measurements and numerical modeling. During the past year we continued processing and analysis of field data obtained in the eastern subtropical Atlantic, near the seamount Erving (32N, 28W; 48th cruise of r/v AKADEMIK KURCHATOV, 11 stations) and seamount Ampere (35N, 13W; 48th cruise of r/v AKADEMIK KURCHATOV, 9 stations, and 13th cruise of r/v AKADEMIK MSTISLAV KELDYSH, 6 stations). The measurements were carried out using the Neil Brown CTD profiler and the microstructure profiler BAKLAN [Paka et al., 1998]. BAKLAN measured the small-scale shear by an airfoil probe and the conductivity microstructure by a single-electrode capillary probe. Turbulence measurements taken in the undercurrent wake of a small equatorial island (Howland Island, western Pacific, 51st cruise of r/v AKADEMIK KURCHATOV, 10 stations) were also used for comparison. Work on shear-induced turbulence in shallow regions was continued using the Black Sea data discussed in Lozovatsky et al. [1998a], and Lozovatsky and Fernando [1998]. Note that the part of this shelf turbulence study was included in the 1997 report of the present project. Improved algorithms for the calculation of kinetic energy and scalar dissipation rates were introduced recently.

Numerical modeling was used to understand the influence of sustained background shear on stratified turbulent boundary layers, in particular, the formation and evolution of density fine-structure by boundary stresses and background rotation.

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WORK COMPLETED

The decay of turbulence generated above summits and at the rims of seamounts Erving and Ampere was investigated. We found a decrease of the kinetic energy dissipation rate over a 30 km section downstream of seamount Erving. This decay can be reasonably approximated by an inverse function of the horizontal distance normalized by the buoyancy mixing scale (Ozmidov scale) at the site of turbulence generation.

Our analysis of turbulence in topographically influenced flows in the vicinity of seamount Erving and at a shallow Black Sea shelf revealed a strong dependence of mixing efficiency on both the mixing Reynolds number and the gradient Richardson number [Lozovatsky et al., 1998a].

An advanced numerical model on the evolution of stratified and rotating turbulent boundary layer was developed. We reproduced quasi-homogeneous fine-structure layers and showed that their generation and decay are governed not only by the ambient stratification, surface stress and rotation but also by background vertical shear.[Lozovatsky et al., 1998b].

In cooperation with Prof. Tom Dillon (OSU), we quantified the characteristics of microstructure probes used in the BAKLAN profiler, which was used in our field experiments [Paka et al., 1998].

SCIENTIFIC RESULTS

A. *The decay of turbulence downstream of seamounts.*

The kinetic energy dissipation rate and turbulent diffusivities obtained along sixty-miles NW - SE transect, centered at the summit of Erving, revealed an enormous enhancement of turbulent mixing above the summit (the depth of which is 260 m) of the seamount (Fig.1). A "turbulent column" more than two hundred meters of height was generated in a vicinity of the local frontal zone associated with an anticyclonic topographic eddy (the slope of isopycnal surfaces of the eddy exceeded 0.005). A turbulent region of approximately the same height was also found above the Fieberling Guyot [Kunze and Tool, 1997]. Such powerful mixing events, with the mean kinetic energy dissipation rate of $\bar{\varepsilon} = (6 \pm 1) \times 10^{-8}$ W/kg in our case, may significantly elevate the turbulent diffusivity in the area. The cumulative distribution functions of mass K_N and scalar K_{sc} diffusivities (Fig.2), calculated for the depth range of 40-200 m along the transect, ensured that the bootstrap estimates of the mean are in the range of $(3.8 - 5.1) \times 10^{-4}$ m^2/s with 90% confidence limits of $(3.1 - 6.1) \times 10^{-4}$ m^2/s. This implies that the averaged mixing rate in a 60-mile diameter and 150 m high region surrounding the seamount is 30-60

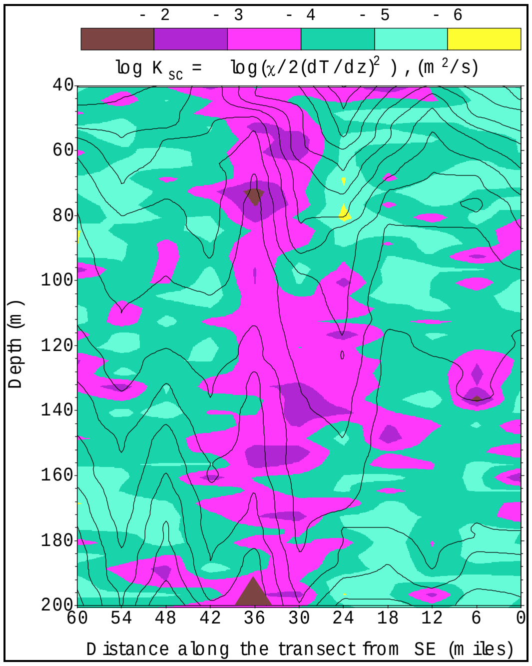

Fig. 1. A cross-section of the scalar diffusi-vity. The top of seamount Erving (z = 260 m) is in the middle of the section (a black triangle).

times than that of the far field value. At the place of generation, the diffusivities, averaged over the stratified water column were as high as $(1-2)\times 10^{-3}$ m^2/s; a similar result was reported by Kunze and Tool [1997].

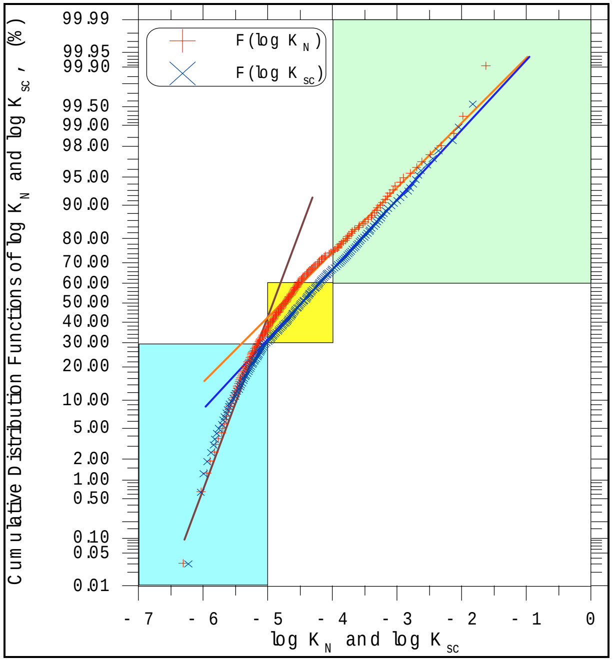

Fig. 2 Cumulative probability distributions of turbulent diffusivities at the transect across the seamount Erving in the depth range 40 - 200 m (below the upper thermohalocline). The straight lines show possible log-normal fits for the upper ($K > 10^{-5}$ m^2/s) and lower ($K < 10^{-5}$ m^2/s) portions of the distributions.

Turbulent "columns" above seamounts seem to be skewed toward the rim area. Our observations at seamount Erving and those of Kunze and Tool [1997] at Fieberling seamount showed that the turbulent "columns" are possibly detached from the bottom. Their origin appears to be related to the internal-wave shear, rather than to the bottom-roughness induced turbulence. More regular, frictional boundary layers occupy about 30 % of the water column above the summit of the Ampere seamount (Fig. 3). The dissipation rate within these stratified, non-fully mixed layers was high, $(1-9)\times 10^{-7}$ W/kg, and corresponding scalar diffusivities ranged $(5-70)\times 10^{-4}$ m^2/s.

The variation of $\overline{\varepsilon}$ along the Erving transect is shown in Fig. 4. The results correspond the depth range 90-140 m which has weak and relatively undisturbed mean stratification. It is clear, that turbulence upstream of the seamount is almost unaffected by the topography, showing a low background level of 6×10^{-10} W/kg. Downstream of the summit, $\overline{\varepsilon}$ decreases from 6×10^{-10} to about $(1-2)\times 10^{-9}$ W/kg, over a distance of 36 miles. This trend was approximated by a power lows $\overline{\varepsilon} = \overline{\varepsilon}_o(\widetilde{x}-\widetilde{x}_o)^{-n}$, similar to the methodology used for laboratory grid-generated turbulence; $\overline{\varepsilon}_o$ is the dissipation rate at the normalized location $\widetilde{x}_o$ of the topography-induced mixing (summit, rim or flank), $\widetilde{x} = x/\overline{L}$ and the Ozmidov scale $\overline{L}$ is based on $\overline{\varepsilon}_o$.

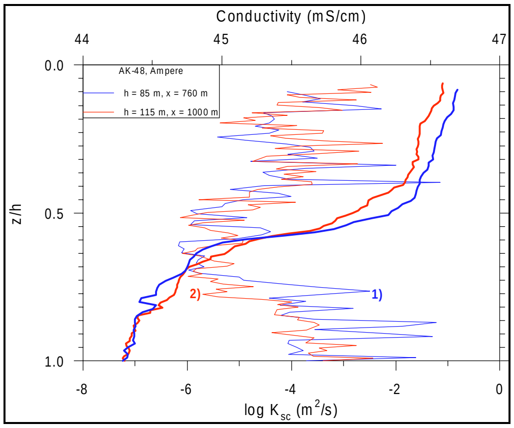

Fig. 3. Scalar diffusivities and mean conduc-tivity profiles near the rim of Ampere sea-mount plotted as a function of the normalized depth z/h, h - the depth of the bottom.

Note that the grid turbulence in stratified tunnels shows $\varepsilon(x)$ dependence close to x^{-2}. The least-square fitting applied for the Erving data (circles) gives $n = 1$ and $\overline{\varepsilon}_o = 3.5\times10^{-8}$ W/kg.

The data taken from other regions, e.g. turbulent wakes downstream of the Ampere seamount (triangles) and Howland Island (diamonds), also follow the power law trend x^{-1}, showing the versatility of the results obtained. This suggests that vertical shear induced by internal waves and topographic eddies supports turbulence far from the turbulence source. The decay of $\overline{\varepsilon}$ according to $\overline{\varepsilon} \sim \tilde{x}^{-1}$ is typically superimposed with smaller scale fluctuations induced by inhomogeneities. It appears that, turbulence first decays rapidly over distances o the order few hundreds of meters from the source, then grows owing to the interaction with strong shear and finally decays more gradually. This preliminary scenario must be verified by future research.

B. *Mixing Activity*

The ratio between turbulent buoyancy flux and kinetic energy dissipation rate, known as the mixing efficiency γ, is significantly affected by topographically-induced turbulence. We found $\gamma < 0.2$ for almost all depths above the seamount Erving. Since the activity parameter, $A_G \sim \gamma^{-1/2}$, exceeded 0.6 while the buoyancy Reynolds number $Re_b \equiv \varepsilon / 30\nu N^2$ exceeded 1, the turbulence in the upper 200 meter layer appears to be active based on Gibson's fossil turbulent theory [1986]. However, the least-squared fit to A_G - Re_b data indicated $A_G = 0.2\times Re_b^{1/3}$, which deviates from Gibson prediction, $A_G \sim Re_b^{1/2}$. This shows that some other governing parameters are significant for mixing activities close to solid boundaries.

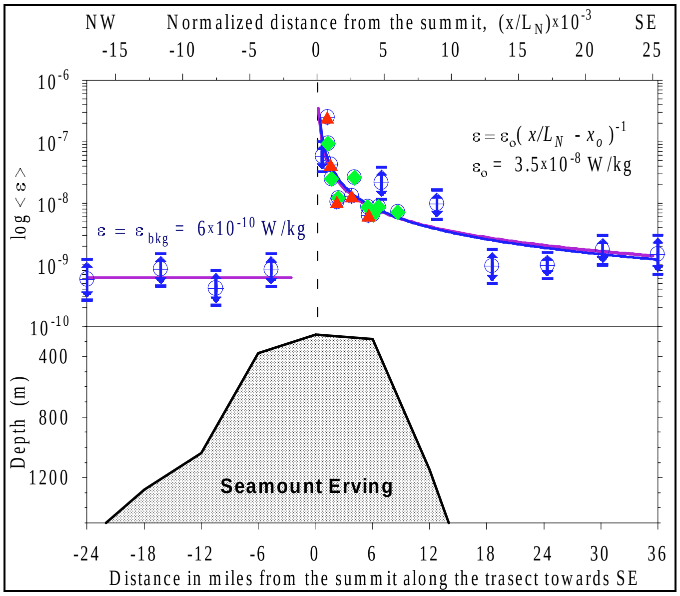

Fig. 4. The averaged dissipation rate at the transect above Erving (z = 90-140 m, blue circles) and downstream of Ampere (30-70 m, red triangles) and Howland Island (120-170 m, green diamonds). An inverse-power trend is fitted for the decrease of $\varepsilon(x/L_N)$.

Measurements on the Black Sea shelf showed that A_G is substantially dependent on both Re_b, and the gradient Richardson number Ri, at least at high Re_b. In relatively weakly-stratified layers, these dependencies for averaged variables can be given as $\hat{R}e_b \approx c_{Re} / \hat{R}i$ and $\hat{A}_G \approx c_{ARi} \times \hat{R}i^{-0.2}$, where c_{Re} and c_{Ari} are empirical constants [Lozovatsky et al., 1998]. The approximation obtained for $\hat{R}e_b(\hat{R}i)$ leads to the following expression for ratio of buoyancy and momentum diffusivities, $K_b / K = Ri^{-1}$, if a stationary balance of the turbulent kinetic energy is in existence. The later formula is in general agreement with the parameterizations used for the turbulent Prandtl number K/K_b in our numerical modeling efforts discussed in [Lozovatsky and Ksenofontov, 1998 and Lozovatsky et al., 1998b].

C. *Step-Structure Modeling*

During the first year of the project, we developed an advanced numerical model of a rotating, stratified and sheared turbulent boundary layer. This model can produce a series of fine-scale quasi-homogeneous layers in a pycnocline of constant buoyancy frequency N_o. Numerical experiments with the small-scale parameterizations described above showed that a small, but sustained, background shear is required to generate the steps [Lozovatsky et al., 1988b]. This minimal shear, sh_o, corresponds to a background bulk Richardson number of $R_o \equiv N_o^2 / sh_o^2 \approx 7$, and this criterion limits the steps generation in the model. It may indicate that, only in the regions with pre-existing global $Ri < Ri_o$, intermittent step-like structure can be generated in stably stratified waters under synoptic variations of wind stress (or tidal-induced bottom stresses).

IMPACT/APPLICATION

The inverse dependence of turbulent kinetic energy dissipation rate on normalized horizontal distance away from seamounts and small islands can be used to estimate the impact of topographical sources on regional-averaged turbulent transports. Quantification of the enhancement of turbulent mixing near Ampere and Erving seamounts provides estimates of the basin-averaged turbulent diffusivities for the North Atlantic, thus complementing the works reported recently for Pacific [Toole et al, 1997; Lueck and Mudge, 1997; Kunze and Toole, 1997] based on measurements near Fieberling and Cobb seamounts.

Functional relationships between turbulent activity on the Black Sea shelf and Richardson and Reynolds numbers appear to be close to those found for sheared stratified layers in open ocean. This provides clues to develop simple parameterizations of turbulent mixing for rotating boundary layers and hence to model the generation of vertical microstructure of shallow shelves influenced by short term atmospheric forcing.

TRANSITIONS

The new model of fine-structure formation developed under this grant was transferred for detailed testing and possible application for stably-stratified atmospheric layers to Dr. A. Ksenofontov (Russia, Nalchik) who is an expert in numerical methods in geophysical flows.

The estimates of turbulent diffusivities in regions of abrupt topography have been used by Dr. Eugene Morozov (Russia, Moscow) in his study of global oceanic mixing induced by tidal internal waves. It is expected to continue joint efforts in this direction by submitting a proposal to the COBASE Program of NSF.

RELATED PROJECTS

The P.I. has established close collaboration with oceanographers from the Former Soviet Union (Drs. Shapiro, Shapovalov, Navrotsky, Lilover) who are active in studying turbulence, internal waves and meso-scale dynamics in the coastal zones and semi-enclosed seas. We plan to continue research on this topics by employing extensive data sets collected by our foreign counterparts over the past 20 years.

The P.I. maintains contacts with Dr. Don Delisi of NWRA (Bellevue, WA) in 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 sensor, that are expected to be used for extensive 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" dealing with laboratory investigations on turbulent transport in wave boundary layers and stratified shear layers.

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