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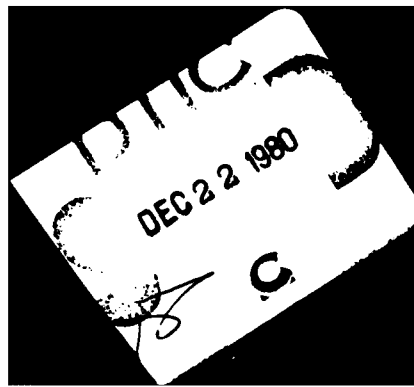
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REFRACTIVE MICROSTRUCTURE FROM DIFFUSIVE
AND TURBULENT OCEAN MIXING

by

Albert J. Williams 3rd

WOODS HOLE OCEANOGRAPHIC INSTITUTION
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December 1980

TECHNICAL REPORT

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                            Department of Ocean Engineering

Refractive microstructure from diffusive and turbulent ocean mixing

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Abstract. Small scale fluctuations in refractive index can affect visibility and image quality in ocean optics. Such fluctuations are a result of temperature and salinity microstructure. Ocean mixing proceeds by the stirring together of dissimilar water types at finer and finer scales until diffusion creates a water type intermediate to the original components. Optically, the most important scale in the mixing cascade is microstructure because it consists of the highest gradient and smallest scale structures. Two classes of mixing process have been distinguished by shadowgraph images made in conjunction with profiles of temperature, salinity, and velocity shear. One class is diffusive and depends on the vertical distribution of temperature and salinity. The other class is turbulent and depends on velocity shear.

I. INTRODUCTION

Ocean mixing is a consequence of global variations in surface heat and water flux. Heat loss at high latitudes causes relatively fresh water to sink and flow towards low latitudes where it rises to compensate for excess evaporation at the surface. The salt left behind in the form of excess salinity does not build up until the surface layer is gravitationally unstable but mixes into the rest of the ocean by a variety of mechanisms including vertical mixing, advection as a slowly sinking and spreading layer, and transport in a current. The latter two mechanisms are only the first stage in a long train of mixing processes that stir the salty water into the fresher water. Entrainment, intrusion, eddy formation, and frontogenesis are manifestations of the stirring processes. Eventually the scale of intermingling becomes small enough that molecular diffusion begins to play a role, and this scale is the finest scale that can sustain significant contrasts. It is called the microstructure scale.

The scenario described for excess salinity at the surface works as well for excess cold at the surface in the Arctic or excess salt in the deep outflow from the Mediterranean. There are a few source regions for major ocean water masses, regions where surface cooling in winter causes massive sinking. These are places of separation. Surface input of heat or fresh water or of excess evaporation are also sources of separation. Almost everywhere else is potentially a region of mixing.

The ocean is stratified except for relatively thin boundary layers at the surface and the bottom and occasional mixed layers in the interior. Generally a greater contrast exists over 1000 meters vertically than 1000 Km horizontally. Thus, advection of water by currents moving horizontally over great distances may bring water into proximity of a dissimilar water type less effectively than vertical mixing over short distances. Even when major cur-

rents transport water into dissimilar environments, the last stages of mixing before diffusion generally involve vertical mixing. For one thing, the surface of contact between the water masses is much greater for vertical mixing than for horizontal mixing. For this reason, a layered structure frequently precedes vertical mixing at a scale significantly larger than the diffusion scale. This scale, about 10 to 100 meters, is called finestructure.

II. VERTICAL MIXING

Vertical mixing of heat and salt occurs by two basically different processes. Each of these processes produces a characteristic optical microstructure. The obvious process is mechanical stirring. This can occur in the boundary layers at the surface and the bottom by wind friction and bottom friction which supply mechanical energy. However, mechanical stirring also occurs far from ocean boundaries by velocity shear associated with internal wave motion.

The other process, double-diffusion, is less obvious. The diffusivity of heat is two orders of magnitude greater than that of salt. This provides a means by which a gravitationally stable gradient in density, but one in which the temperature or the salinity gradient alone contributes an unstable density gradient, can convect. The differential diffusivities provide a natural heat exchanger that permits the density contributions of temperature to be separated from those of salinity. The result is that the gravitational energy in the unstable density field of one component can be released to drive convection and mix fluids vertically.

Double-diffusion

There are two forms of double-diffusion. Where warm, salty water overlies cool, fresh water, the convective cells called salt fingers form. A small volume of water perturbed downward in such a gradient is surrounded on all sides by cool water and loses heat faster than salt. It thus becomes heavy and sinks. A volume of

water perturbed upward gains heat and rises. A steady state equilibrium involves a regular array of counterflowing cells exchanging heat laterally and transporting salt and some heat downward. The regular array consists of square packed cells in quiet water and vertical lamellae in the presence of shear.[1] The height of the cells or lamellae is limited by instabilities that develop at their ends. The laminar flow within the fingering interface changes to a turbulent convective flow at the ends involving many fingers in the formation of plumes of anomalously light water at the top ends and anomalously heavy water at the lower ends. The removal and resupply of fluid to the end region is an unsteady process that is difficult to observe or model and has been largely ignored.

The optical signature of a salt finger interface is a vertical band pattern in horizontal shadowgraph. A shadowgraph from an interface in the Mediterranean Outflow shows this pattern in Figure 1. From above, a square pattern aligned 45° to the edge of the

vations of microstructure extending beyond the fingering interface and to chaotic shadowgraph images observed just outside the fingering interface.

The important process going on in the interface is the generation of positive and negative buoyancy by the separation of heat from salt. Even though salt and heat are transported across the interface 100 times as fast as by direct diffusion,[2] the biggest contribution to vertical mixing is the production of this buoyancy. The gravitationally unstable arrangement of fluid in the region adjacent to the interface drives turbulent convection in a layer typically 10 meters thick on either side. Another fingering interface may form on the other side of each layer if the gradient region is thick enough and a staircase of layers and interfaces develops. Figure 2 is such a staircase observed in the Mediterranean Outflow. Irregularity in the temperature structure of the layers possibly associated with convection can be seen.

Figure 1. Shadowgraph of salt fingers from an interface in the Mediterranean Outflow. The image is formed by refraction of a horizontal light beam, 160 cm long and 5 cm in diameter. The vertical structure of the salt fingers produces vertical bands in the image.
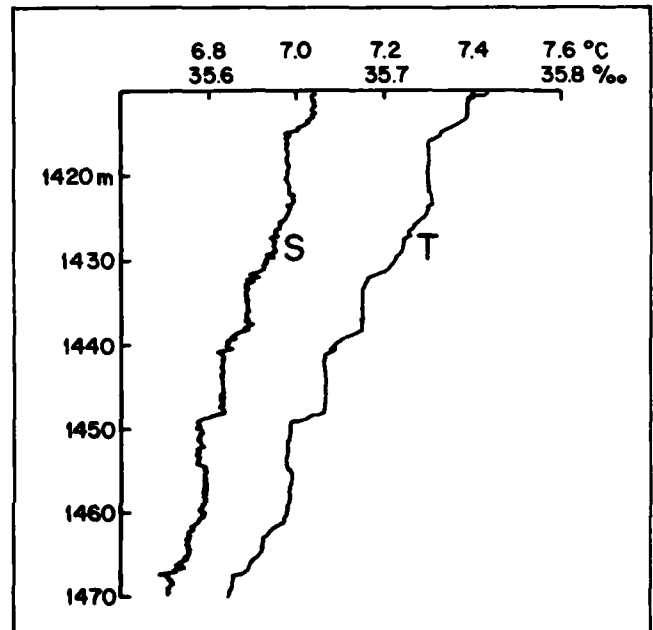

Figure 2. Thermohaline staircase from the Mediterranean Outflow. At the interfaces between warm salty layers and cool fresh layers, vertical structure is observed in the shadowgraph images.

A second case of double-diffusion occurs where cool, fresh water overlies warm, salty water. A thin interface forms, called a diffusive interface, across which heat diffuses more rapidly than salt. A density inversion develops on either side just as it does in the salt finger interface with a similar result. Staircase structure beneath ice islands[3] has been supposed to reflect this process, but no clear case of direct observation has been reported. Presumably, the optical signature would be a sharp horizontal line with vertical structure on either side. The temperature would be expected to be discontinuous across the interface.

Mechanical stirring

A stratified fluid may overturn locally if subjected to sufficient velocity shear. The stability can be expressed as a gradient Richardson number,

cells is observed. Lamellae produce lines parallel to themselves. The interface is rarely more than 10 cm thick and the cell diameter is 7 to 14 mm (band spacing 10 to 20 mm).

The temperature structure through the interface is a steep gradient, typically 100 millidegree C in 10 cm. The salinity gradient has not been resolved. On either side of the interface, a mixed layer develops; but within 1 meter of the interface, fluid is often sensed with temperature either higher or lower than that in the interior of the mixed layer. This corresponds with laboratory obser-

$$R_i = \frac{g}{\varrho} \frac{\frac{\Delta \varrho}{\Delta z}}{\left(\frac{\Delta u}{\Delta z}\right)^2} \tag{1}$$

where g is gravity, ϱ is density, u is horizontal velocity, and $\Delta/\Delta z$ is the gradient over a finite depth interval. When R_i drops below 1/4, overturning rolls develop. In the surface and bottom boundary layers, the stratification disappears and the Richardson number becomes zero. However, within these boundary layers there are generally no large gradients in temperature and salinity either, a consequence of the mixing that has already taken place. Only at the edge of the boundary layer, where entrainment of new fluid by overturning occurs, are there large gradients. Within the layer, there is much velocity microstructure and dissipation of energy by viscosity, a continuous process, the energy source being the wind or bottom current. Fluid entrained at the edge is distributed through the boundary layer by turbulent eddies, mixing with the existing fluid as it is stretched and thinned. The edge of the boundary layer is marked by a sharp density gradient which is the protection against unlimited erosion of the fluid outside the layer. In the steady state, only an occasional instability occurs at the edge of the layer resulting in entrainment and subsequent mixing.

In the ocean interior, the situation is somewhat different. The principal velocity shear source there is internal waves, possibly added to some mean shear due to advection. Again, mixing from this source is an intermittent and patchy event. The internal wave field consists of many components. Occasionally the sum of the shears due to all the components lowers the Richardson number locally below 1/4 and an overturning event occurs. However, it causes mixing only in a limited region where the superposition of the internal wave shears add, and it lasts for only a short time.

In an overturning event, the inertial effects are larger than the gravitational effects. As the roll increases, the inertial effects become greater yet. Thus the structure of the contorted interface between the two fluids is not dominated by gravity and is not constrained to be vertically or horizontally aligned. Microstructure interfaces in an overturning roll may have any orientation. Herein lies the optical signature of a mechanical stirring event; the structure is not aligned vertically. An example of this is shown in Figure 3 from near the surface of the Caribbean Sea.

Figure 3. Shadowgraph of mechanically stirred structure near the surface of the Caribbean Sea. The interfaces at orientations other than vertical are the result of shear-induced mixing.

A mechanical stirring event removes the overall temperature and salinity gradients in a layer with the thickness of the roll. This is observable in temperature profiles as a 1/2 to 2 meter thick mixed layer. Within this layer there are microscale gradients responsible for the optical structure which can be detected with fast thermistor probes but not with slower sensors. The velocity microstructure within the layer can be detected with small scale sensors designed to measure velocity dissipation. However, only the mean shear driving the overturning event can be sensed with large velocity sensors.

III. REFRACTION

The index of refraction of seawater varies with salinity, temperature, and pressure; but the effect of refraction on optical microstructure depends only on small differences in salinity and temperature. The coefficient of index of refraction variation with salinity is $\eta_S = 1.9.10^{-4}/^{o}/_{oo}$. The coefficient of variation with temperature is not a constant as it is for salinity, and thus varies as a function of temperature and to a lesser degree pressure. The coefficient varies from $\eta_T = 5.4.10^{-5}/^{\circ}C$ at 1 atmosphere to $\eta_T = -13.4.10^{-5}/^{\circ}C$ at 20°C and 200 atmospheres.[4]

For the purpose of estimating the effect of mixing on optical microstructure, it is necessary to know the temperature and salinity anomalies as well as the coefficients of index of refraction. These values can be estimated in each case from the profile, but one can do quite well by noting that, in most cases, the effect of temperature difference on density is approximately compensated by salinity difference. Using the salinity coefficient of density $\beta = 7.8.10^{-4}$ gm/cm^3 $^{o}/_{oo}$ and the thermal coefficient of density $\alpha = -5.7.10^{-5}$ gm/cm^3°C at 0°C, 35 $^{o}/_{oo}$, and 8 atmospheres, and $\alpha = -29.0.10^{-5}$ gm/cm^3°C at 20°C, 35 $^{o}/_{oo}$, and 200 atmospheres, one can estimate the index of refraction change from:

$$\Delta n = \eta_T \Delta T + \eta_S S \qquad (2)$$

and

$$\Delta \varrho = \alpha \Delta T + \beta \Delta S = 0 \qquad (3)$$

where Δn is the index of refraction difference associated with temperature and salinity differences ΔT and ΔS, respectively. Substituting Eq. (3) into Eq. (2) gives for the neutral density case

$$\frac{\Delta n}{\eta_S \Delta S} = 1 - \frac{\eta_T/\alpha}{\eta_S/\beta} . \qquad (4)$$

The range of values for $\Delta n/\eta_S \Delta S$ is from -2.9 for 0°C at the surface to -0.66 for 10°C at 200 atmospheres. (η_T/α has a minimum near 10°C.) Thus the index of refraction effect of an interface in which the contribution of salinity on density is compensated by the contribution of temperature is between three times as great and 2/3 as great as the uncompensated salinity interface.

There is the possibility of matching index of refraction across an interface and so making the mixing invisible optically. However, this condition would change as soon as some of the heat diffused from the warm to the cool fluid and changed the index of refraction match.

Observational vehicle

A program to study mixing processes through optical sensing developed a free-sinking vehicle carrying a shadowgraph camera in 1972 (Figure 4). The original instrument used a 5 cm diameter beam which passed horizontally through 160 cm of seawater, leaving the pressure housing through one window and returning, after two reflections, through a second window. The sampling volume was open and unobstructed at the bottom so that the volume observed was undisturbed by the slow sinking of the vehicle. The instrument measured and recorded temperature, salinity, and pressure as well as photographing the shadowgraph screen.[5]
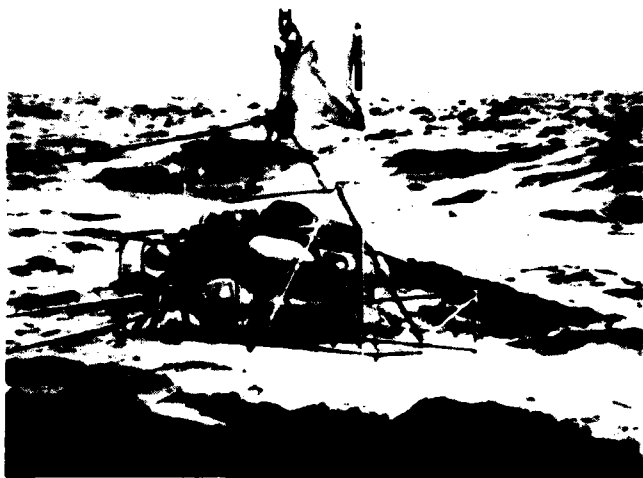
Figure 4. SCIMP, a self-contained imaging microprofiler. In the configuration shown, Autoprobe, a variable displacement vehicle, controlled the descent and ascent of the instrument.
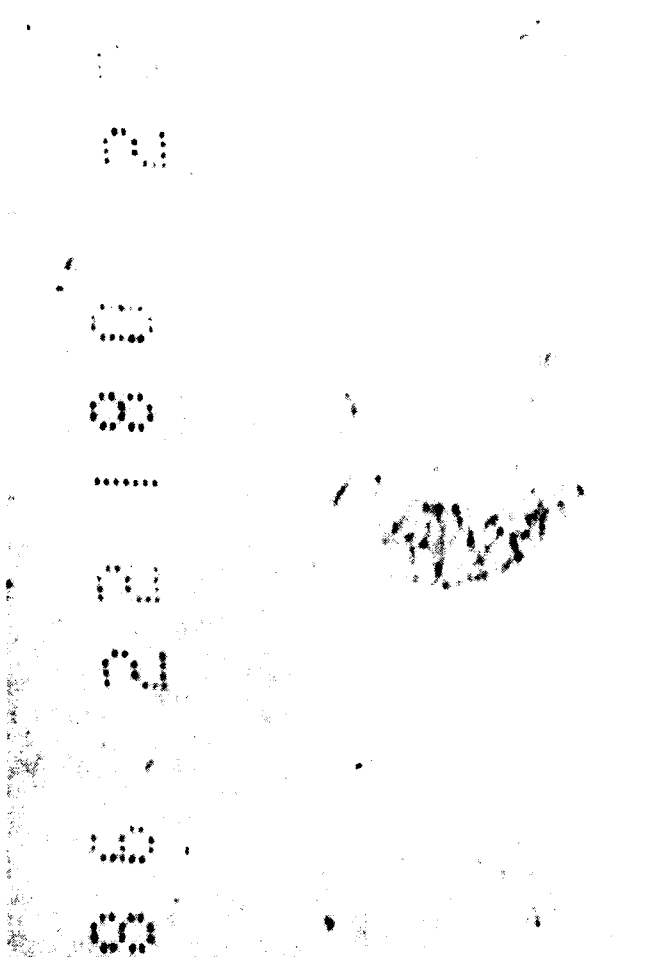

Figure 5. Shadowgraph from 8-mm film of a Gulf Stream Ring intrusion, a region where dissimilar water types mingle in a high shear environment. The outside diameter of the image is 15 cm in water. A shadow of the mirror support and of the hyperbolic mirror of the Cassagrain beam expander obstructs much of the image. However, the large aperture is necessary to permit 5 cm or larger structure to be detected; none has yet been observed.

The vehicle adjusted its ballast to maintain a constant sink rate, generally 6 cm/sec. With a frame of film exposed each 3/4 second, 700 meters of the ocean could be photographed on 400 feet of 16-mm film.

A new vehicle and optical system has been used since 1975. A velocity shear measurement has been added to the temperature, salinity, and pressure measurements. The optical system is more compact, occupying a 6-inch inside-diameter pressure cylinder and using a single high pressure window. Larger optics and smaller film are used, with some loss of photographic quality but improved instrument handling. With a 15-cm aperture, sinking at 12 cm/sec, and a frame rate of once per second, 800 meters of ocean can be photographed on 100 feet of 8-mm film. Figure 5 shows microstructure from an intrusion in a Gulf Stream Ring imaged by the Cassagrain telescope system.

Optical instrumentation

In a typical microstructure feature, the temperature anomaly is 30 to 100 millidegrees and the salinity anomaly 0.01 to 0.03 ‰, so that the variation in index of refraction is from 0.3 to 10 ppm. Structures with so small a refractive inhomogeneity are difficult to detect with a simple shadowgraph system. The one described here uses a spatially filtered and expanded beam from a low powered HeNe laser. A schlieren quality glass window separates the collimator from the seawater path. In the present shadowgraph system the beam is further expanded by a wet Cassagrain telescope. The beam is reflected back on itself, separated from the outgoing beam with a splitter, and brought to a focus inside the pressure case. The region near the focus at which the structures form an image is enlarged and projected on a screen where it is photographed (Figure 6).

A shadowgraph system is characterized by its screen distance, the distance from the test section to the projection screen. Refractive objects with a focal length equal to this distance produce the greatest contrast shadows. In this sense, the shadowgraph described is characterized by an effective screen distance of 20 meters.
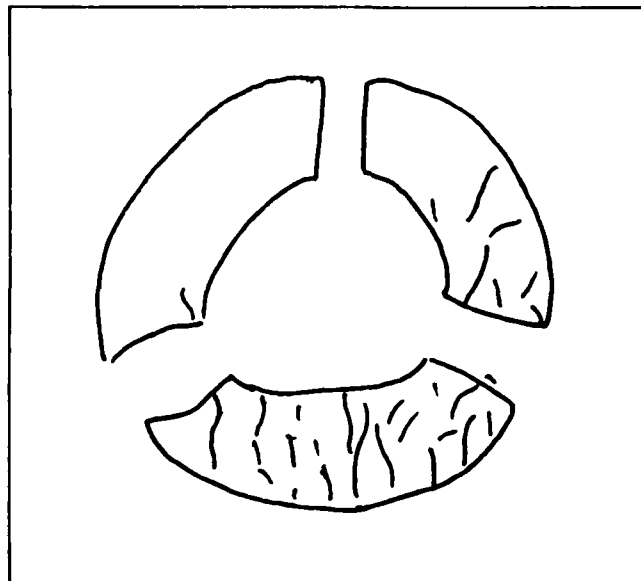

Figure 5 Sketch. The photograph of the Cassagrain telescope image is underexposed and difficult to see in a print of the movie film, so a sketch is provided to show the features visible upon viewing the original. The opaque center of the 15 cm diameter image is the shadow of the hyperbolic mirror, the three legs are shadows of the mirror support, and the three sectors show irregular vertical structure.
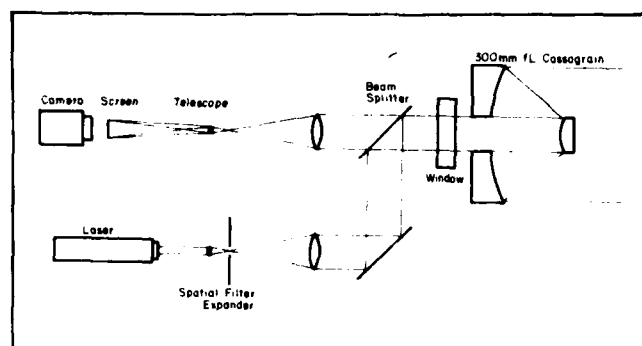
Figure 6. Underwater Cassagrain shadowgraph system.

Quantitative results are obtained with a shadowgraph system, but the quantities are positions, shapes, and locations of objects in the water column. Exact index of refraction anomalies cannot be obtained. Rough approximations are possible, however, based on image contrast and structure size. For example, an image of a structure with a contrast of 10% probably has a focal length roughly 10 times the effective screen distance. This can be worked back to an index of refraction anomaly with some assumptions of thickness of the structure in the optic axis direction. A rough estimate is that for a cylindrical object the index of refraction anomaly is the diameter over 8 times the focal length.[6]

Diffusive microstructure

Mixing in the interior of the ocean may be dominated by double-diffusion. Thermohaline gradients in most temperate and tropical ocean regions are more than adequate and sources of high velocity shear are far away. One such location is the Mediterranean Outflow where the warm salty water of the Mediterranean, which has mixed with North Atlantic Central Water in the Straits of Gibralter and has sunk to 1200 meters, spreads west. There, it forms an intrusion of warm, salty water, detectable across the Atlantic. It has been noted for a decade that a staircase can often be found beneath the salinity maximum of this water. Indeed, salt fingers are found in more or less pure form on the interfaces of the staircase.[7] Figure 2 is a portion of a staircase on which salt fingers were observed.

A larger staircase is always observed in the central part of the Tyrrhenian Sea although the temperature and salinity contrasts are reduced there. The layers are 60 to 100 meters thick and the temperature steps between layers is only 100 millidegrees. Again, salt fingers are observed on the interfaces although they are of very long focal length.

The Atlantic Ocean east of the Caribbean has a staircase with 1°C steps beneath the salinity maximum at 100 meters. This too is a large feature produced by the contact between Subtropical Underwater and Antarctic Intermediate Water. The salinity maximum is the result of surface water evaporation in the Sargasso Sea followed by sinking and spreading. It is not yet known if fingering is present on this staircase and an expedition is planned to this area soon.

Turbulent microstructure

Near the surface, near shore, and near frontal surfaces, there is often a high rate of mixing by mechanical stirring. In the upper 150 meters in the Caribbean, in the high velocity rim of cold core Gulf Stream Rings, near the edge of the Gulf Stream, and along the New England Slope Front, most of the water column exhibited turbulent microstructure. The experiments in which a velocity shear measurement was carried indicate that for intervals as long as 100 meters, the 2-meter-interval Richardson number re-

mains below 1, frequently reaching 1/4 or less. This confirms the suggestion from the images that mechanical stirring has recently occurred or is occurring.

Figure 7 is a section of a profile from the Caribbean several kilometers off the Puerto Rican shelf. There may well be boun-
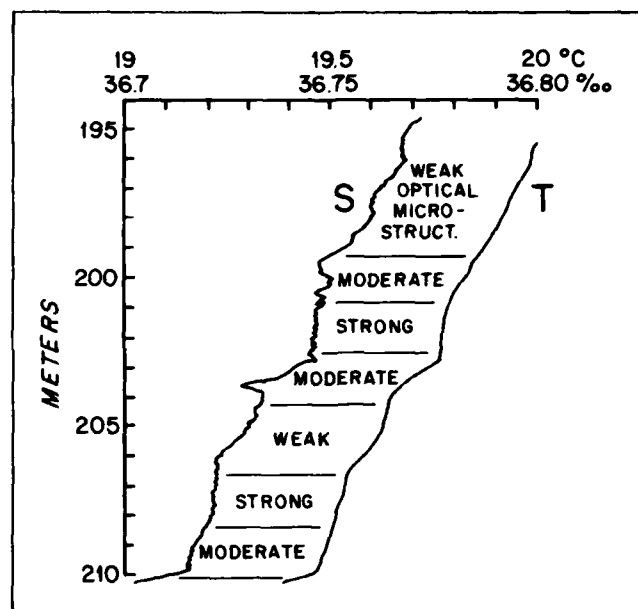

Figure 7. Profile from the Caribbean. The regions of strongest optical microstructure correspond to the minimum gradients in this case. The source of the structure is thought to be incomplete mechanical mixing.

dary effects responsible for high shears, either internal wave shears or intrusions, in this location. In the profile, the optical microstructure has been indicated. Two strong microstructure regions at 202 and 207 meters imply recent or active overturning events. There is little gradient in salinity and temperature in the 2 meter thick optically inhomogeneous regions while high gradients bound these regions but show lower optical contrasts and structure. On an irregular steppy profile such as this the low gradient regions may be the actively mixing layers at which the optical microstructure is strongest.

Patterns of optical microstructure

Patterns of microstructure are the key to interpreting mixing processes. Buoyant processes, particularly double-diffusive processes, create vertical patterns. Salt fingers are the most regular because of their uniform cell size and regular packing. They have a well-defined height and fit the temperature and salinity profile in an unambiguous way. A staircase with warm, salty water overlying cool, fresh water and with little shear is likely to be a fingering region.

In the opposite, diffusive-interface, case the situation should be equally clear. A sharp interface should exist with cool, fresh water over warm, salty water. Vertical plumes of water should be visible through their anomalous index of refraction on either side of the interface, becoming less visible as the distance from the interface increases. Mixed layers should bracket each sharp interface and form a staircase. A clear example of the diffusive-interface has yet to be observed optically. It seems unlikely that a horizontal shadowgraph viewing system could succeed in photographing a single interface without any relative tilt. One must hope for the plume signature, instead.

Chaotic structure with little vertical orientation results from

mechanical stirring, at least in its early stages. This may occupy a region 1/2 to 2 meters thick. The Richardson number across this region will be low, below 1/4 if the mixing is very recent. Temperature and salinity gradients on the large scale will be low although the optical signal implies they are still large at the microscale. A source region for the velocity shear is required if mixing is frequent and widespread. This might be the surface, the bottom, or a front.

ACKNOWLEDGMENT

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