SHEAR AND SALT FINGERS

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ABSTRACT

The Central Waters of the North Atlantic subtropical gyre are characterized by a remarkably constant density ratio (R_ρ) on large scales. However, when computed over smaller scales, significant finestructure in R_ρ is seen. One possible source for this finestructure is the action of inertial period shear acting on isopycnal gradients of salinity. Data from the High Resolution Profiler are examined to explore this mechanism, which appears to be viable, though it cannot explain all of the variance in R_ρ.

Given the finestructure in R_ρ, one would also expect modulation of the intensity of salt fingering, since it is a strong function of the density ratio. Evidence for such modulation is seen in the HRP data in the form of increased thermal microstructure when R_ρ is low and the stratification is strong. A distinct relationship between the theoretical salt finger growth rate and the dissipation rate of thermal variance is found in the data, which supports a simple model of intermittent fingering. Development of such relationships between microstructure and finestructure is an important step toward parameterization of the effects of salt fingers on the thermohaline structure of the ocean.

1. INTRODUCTION

The double-diffusive instabilities (salt fingers and diffusive interfaces) are thought to dominate vertical mixing in certain limited regions of the ocean (thermohaline staircases in the arctic, tropical Atlantic and Mediterranean out-flow). It is possible that elevated thermal dissipation levels in these regions make them important contributors to the global destruction of thermal variance. However, it is more probable that intermittently occurring salt fingers in the "Central Waters" (CW) of the subtropical thermocline make the larger contribution to global dissipation, by virtue of their vast extent. If salt fingers do elevate mixing levels in the main thermocline, it has been suggested that the associated nutrient fluxes could have a significant impact on biological productivity in the euphotic zone (Hamilton, Lewis and Ruddick, 1989).

The problem of assessing the role of salt fingers in the CW is potentially complex, since shear instability can also contribute to mixing there. An approach taken by Schmitt and Evans (1978) was to assume that fingers are intermittently active on the high gradient interfaces

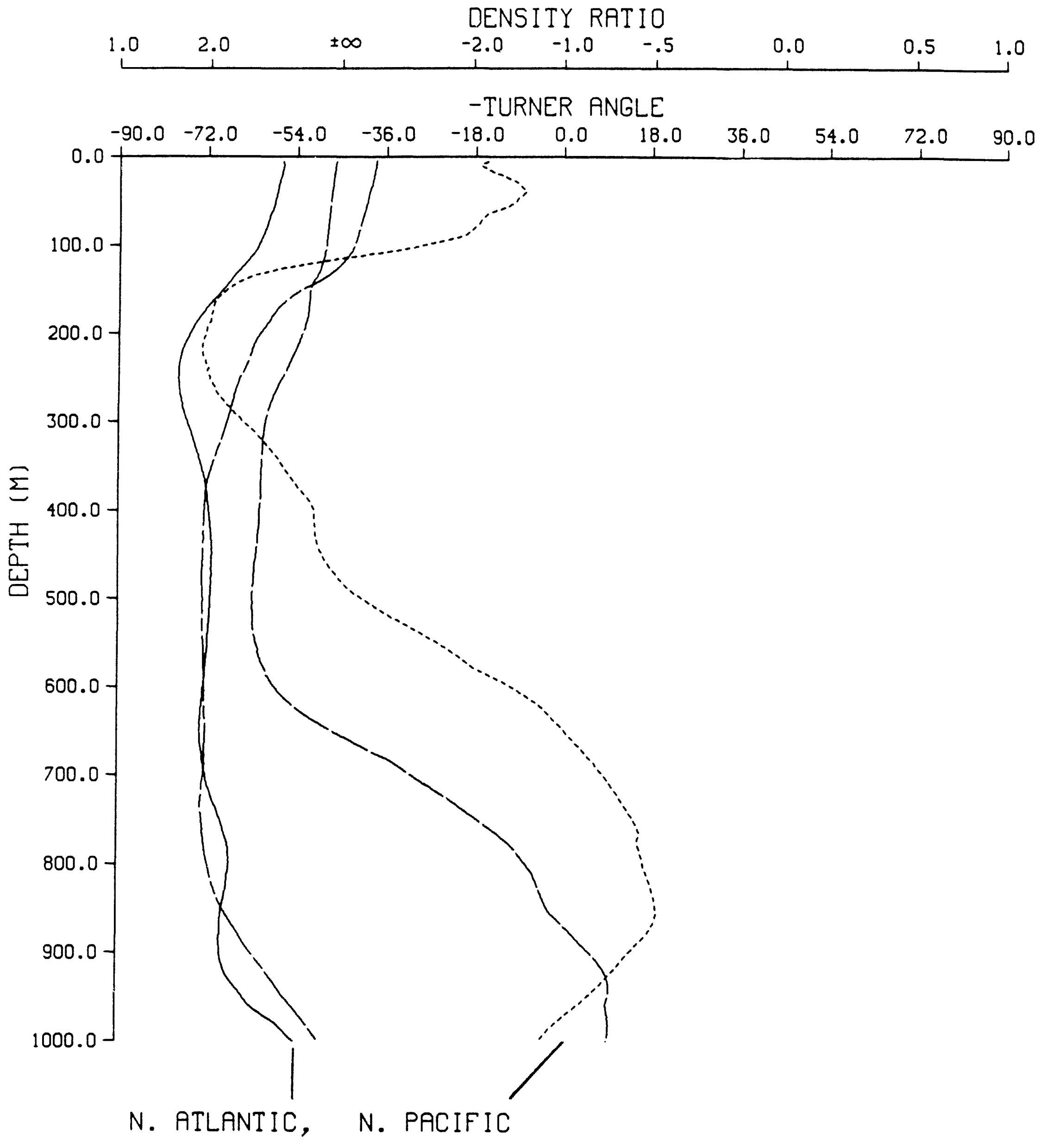


Figure 1. Density ratio (R_ρ) computed over 100 m vertical intervals for 4 CTD stations at 24°N in the eastern N. Atlantic (— = 30°W), western N. Atlantic (— - — = 70° W), eastern N. Pacific (- - - - = 140°W), and western N. Pacific (— — — = 150°E). The scale for R_ρ (top) is linear in arctan (R_ρ); the equivalent scale in the negative Turner Angle is also given. Salt fingers are possible for $1 \leq R_\rho \leq 100$, the left quadrant of the scale. The central half of the scale represents a diffusively stable stratification with $-\infty < R_\rho < 0$. The "diffusive" instability (cold, fresh over warm, salty) is possible for $0 < R_\rho \leq 1$. R_ρ profiles show less variability in the salt finger regime (North Atlantic) than in diffusively stable thermoclines (below salt minimum in the North Pacific). A value of R_ρ near 2.0 is often found in finger-favorable thermoclines, possibly a consequence of increased salt fingering for R_ρ below 2.0 (Schmitt, 1981).

produced by internal wave strain. Presumably, unstable buoyancy fluxes do not become sufficiently large to maintain a thermohaline staircase in the constantly strained and sheared internal wave field. Schmitt and Evans (1978) estimated the salt flux by applying the laboratory 4/3 power law to the "interfaces", a procedure which must be viewed as suspect since measurements from C-SALT (Lueck, 1987; Gregg and Sanford, 1987; Schmitt, 1988) indicate that this will overestimate the flux. However, an alternative flux law, based on the "Stern number" (Stern, 1969) or interface thickness (Kunze, 1987) is consistent with the C-SALT fluxes. This would reduce the Schmitt and Evans estimates for the Central Waters modestly, but would make a more dramatic difference to flux estimates in thermohaline staircases (Schmitt, 1981). Even with this revision in flux estimates the staircases have a salt diffusivity (K_s) of **O** 10^{-4} m^2/s, and in the central waters K_s would still be **O** 10^{-5} m^2/s. Since recent estimates of mixing rates in a diffusively stable regime (Gregg and Sanford, 1988) have a diffusivity of only $\sim 10^{-6}$ m^2/s, even these reduced finger fluxes may still be significant.

How then, do we go about developing a more sophisticated understanding of Central Water salt fingers? In this paper we examine two aspects of the problem. 1) the effect of finescale shears on the local density ratio and 2) an apparent finescale predictor of microscale dissipation in fingering-favorable regions. Both aspects result from the examination of fine-and microstructure data acquired with a recently developed instrument, the High Resolution Profiler (HRP, Schmitt *et al.*, 1988). Section 2 treats the shear effect, which is more fully developed elsewhere (Schmitt, Polzin and Toole, in preparation). Section 3 examines the relationship between the finescale salt finger potential and the observed thermal dissipation. The apparent relationship is an important step toward the development of a parameterization of salt finger fluxes. In Section 4 we estimate the vertical diffusivity from the observed thermal dissipation rate. Results are summarized in section 5.

2. THE EFFECT OF SHEAR ON THE DENSITY RATIO

The Central Waters of the world's subtropical gyres are characterized by a remarkable constancy of the large scale density ratio $R_\rho = \alpha\theta_z/\beta S_z$,

$$\text{where } \alpha = \frac{-1}{\rho}\frac{\partial\rho}{\partial\theta}\,|\,p,s, \quad \beta = \frac{1}{\rho}\frac{\partial\rho}{\partial S}\,|\,p,\theta$$

and θ_z, S_z are the vertical gradients of temperature and salinity. Schmitt (1981) hypothesized that this feature was due to salt fingers. The finger properties of having a greater transport of salt than heat and a strong dependence of mixing rate on R_ρ are the key elements of the mechanism. A detailed confirmation of the model will require the development of a parameterization of the effects of fingers on larger scales. However, the model is consistent with microstructure studies, and no other mechanism has been proposed to account for the dramatic difference in R_ρ profiles between salt fingering water masses and diffusively stable regimes (Figure 1). The fingering-favorable regions tend to have nearly constant R_ρ, often near a value of 2.0, while diffusively stable regions tend to have arbitrary values of R_ρ.

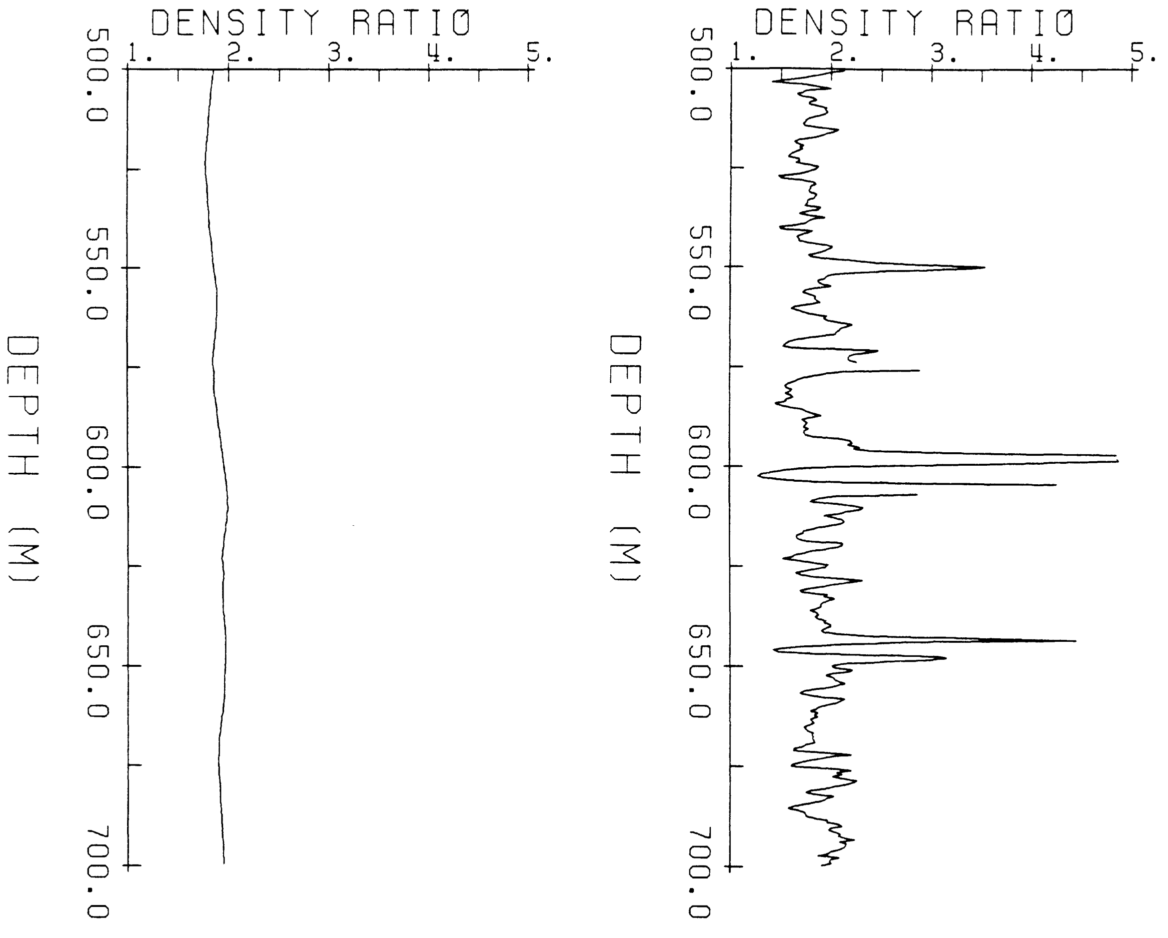


Figure 2.a. Profile of R_ρ computed using least square fits over a sliding vertical interval of 50db. Data are from HRP Dive 28, at 28° 41′N, 68° 30′W in the Sargasso Sea.

Figure 2.b. Profile of R_ρ computed using least square fits over an interval of 3db. Great variability in R_ρ is seen at small scales which should modulate the intensity of salt fingers.

While the density ratio over 50 m scales and greater is rather constant in the Central Waters, one can find sizable variations in R_ρ when the scale of the computation is reduced (Figure 2). Given that R_ρ is the ratio of two gradients, it is hardly surprising that variance increases with a decreasing computation scale, especially given the potential problems with sensor lag corrections and variable fall rate for a wire lowered CTD. However, free fall profilers have a steady fall rate and there are processing techniques for accurately matching the data from temperature and conductivity sensors (Horne and Toole, 1980). We have used such a profiler in the Sargasso Sea during the Frontal Air-Sea Interaction Experiment (FASINEX). The instrument, the High Resolution Profiler (HRP) is described by Schmitt *et al.* (1988). The HRP carries a CTD, acoustic velocimeters to measure the vertical shear of horizontal currents, accelerometers to monitor body motion, and microscale temperature, conductivity and velocity sensors. This suite of sensors provides the ability to compare microstructure levels with finescale Richardson numbers, density ratios, etc. With its steady fall rate and internal recording, we believe that the finescale salinity profiles obtained with the HRP approach the limits of resolution possible with standard 16 bit oceanographic sensors. The raw finescale data is recorded at 10 Hz; temperature, salinity and horizontal velocity are derived from the raw data and pressure sorted into 1/2 db intervals (about 10 raw data points per 1/2 db). In the remaining analysis we use a vertical interval of 3 db to compute gradients and averages from the pressure sorted data.

The variability in R_ρ seen in Figure 2 is most likely real and not due to noise in the measurement. What, then, is its origin? If the Schmitt (1981) mechanism is operative then such fluctuations should decay with time, and should not be remnants of mixing processes that occurred at the boundary of the water mass. The most likely source of finescale variability in R_ρ is the finescale vertical shear due to inertial-internal waves acting on horizontal gradients in water mass properties. That is, shear can readily change R_ρ by advecting warmer, saltier (or colder, fresher) water over a given parcel of water, if there are gradients in temperature and salinity on density surfaces. A detailed treatment of this effect is given in Schmitt, Polzin and Toole (in preparation). Using the "neutral surface" formalism of McDougall (1987) it is possible to derive the following expression for the rate of change of R_ρ.

$$\frac{\partial R_\rho}{\partial t} + \mathbf{V}^{n} \cdot \nabla_n R_\rho + \mathbf{e}\frac{\partial R_\rho}{\partial z} = \frac{(R_\rho - 1)}{S_z} \mathbf{V}_z^n \cdot \nabla_n S + \text{diffusive terms}, \qquad (1)$$

where $\mathbf{V}^n$ is the neutral surface (isopycnal) velocity, $\mathbf{V}_z^n$ is its vertical shear, and $\mathbf{e}$ is the diapycnal velocity. Some of the diffusive terms are treated in Schmitt (1981) and will not be the focus of the present discussion. The term of interest is the shear term on the right hand side of the equation. It neatly expresses the potential for vertical shear acting on isopycnal gradients of salinity for changing the density ratio.

As seen in Figure 1, large scale vertical and horizontal gradients of R_ρ are weak in the North Atlantic Central Water, so the advective terms should be small. If we disregard mixing, then there is no diapycnal velocity. Thus, we can examine the (reversible) effects of inertial-internal waves on R_ρ with the simpler equation:

$$\frac{\partial R_\rho}{\partial t} = \frac{(R_\rho - 1)}{S_z} \mathbf{V}_z \cdot \nabla S \qquad (2)$$

where we have dropped the neutral surface notation, though it still applies.

R_ρ has the inconvenient range of $\pm\infty$ making the calculation of variances, etc., unduly influenced by large R_ρ values. Alternative transformations of equation 2 are possible. One is to rearrange (2) as:

$$\frac{\partial \ln\,(R_\rho - 1)}{\partial t} = \frac{\mathbf{V}_z}{S_z} \cdot \nabla S$$

for $R_\rho > 1$, and (3)

$$\frac{\partial \ln(1 - R_\rho)}{\partial t} = \frac{\mathbf{V}_z}{S_z} \cdot \nabla S$$

for $R_\rho < 1$. Another option is to use the Turner Angle of Ruddick (1983) defined by the two-component arctangent:

$$Tu = \arctan\left(\alpha\frac{\partial\theta}{\partial z} - \beta\frac{\partial S}{\partial z},\ \alpha\frac{\partial\theta}{\partial z} + \beta\frac{\partial S}{\partial z}\right).$$

So that $R_\rho = -\tan\,(Tu + 45°)$. Equation 2 can be expressed as:

$$\frac{\partial Tu}{\partial t} = \frac{(R_\rho - 1)}{2R_\rho^2\, S_z}\mathbf{V}_z \cdot \nabla S \qquad (4)$$

Since equation 3 is simpler, we will use the natural logarithm of the absolute value of $R_\rho - 1$ as our variable, i.e., $\ln | R_\rho - 1 |$.

Our hypothesis is that near-inertial frequencies are the primary source of finescale vertical shear. If we separate the salinity and velocity fields into mean ($-$) and fluctuating components ($'$) we obtain the following expression for fluctuations in $\ln | R_\rho - 1 |$:

$$\frac{\partial(\ln | R_\rho - 1 |)'}{\partial t} = \frac{1}{\overline{S}_z}\left(\overline{\mathbf{V}}_z \cdot \nabla S' + \mathbf{V}'_z \cdot \overline{\nabla S} + \mathbf{V}'_z \cdot \nabla S'\right)$$

$$-\frac{S'_z}{\overline{S}_z^2}\left(\overline{\mathbf{V}}_z \cdot \overline{\nabla S} + \mathbf{V}'_z \cdot \overline{\nabla S} + \overline{\mathbf{V}}_z \cdot \nabla S' + \mathbf{V}'_z \cdot \nabla S'\right) \qquad (5)$$

We expect the mean vertical shear to be small on the finescale wavelengths of interest here (~ 10 m) and assume $\overline{V}_z = 0$. For this analysis we will also neglect terms of higher order in the fluctuating quantities since there appears to be no reason to expect correlation between them. Thus, the dominant effect should be due to the action of finescale shears on the mean horizontal salinity gradient:

$$\frac{\partial \ln \mid R_\rho - 1 \mid'}{\partial t} \simeq \frac{\mathbf{V}_z'}{\overline{S}_z} \cdot \nabla\overline{S}. \tag{6}$$

If we assume that the shears have an inertial period so that the components are given by:

$$u_z = V_z^0(z) \sin(ft), \quad v_z = V_z^0(z) \cos(ft)$$

we can integrate (6) over one inertial period to obtain an expression for perturbations in $\ln \mid R_\rho - 1 \mid$:

$$(\ln \mid R_\rho - 1 \mid)' = \frac{1}{f\overline{S}_z} V_z^0(z) \left[\cos(ft)\frac{\partial \overline{S}}{\partial x} - \sin(ft)\frac{\partial \overline{S}}{\partial y}\right]. \tag{7}$$

Squaring equation 7 and time averaging leads to an expression for the variance in $\ln \mid R_\rho - 1 \mid'$:

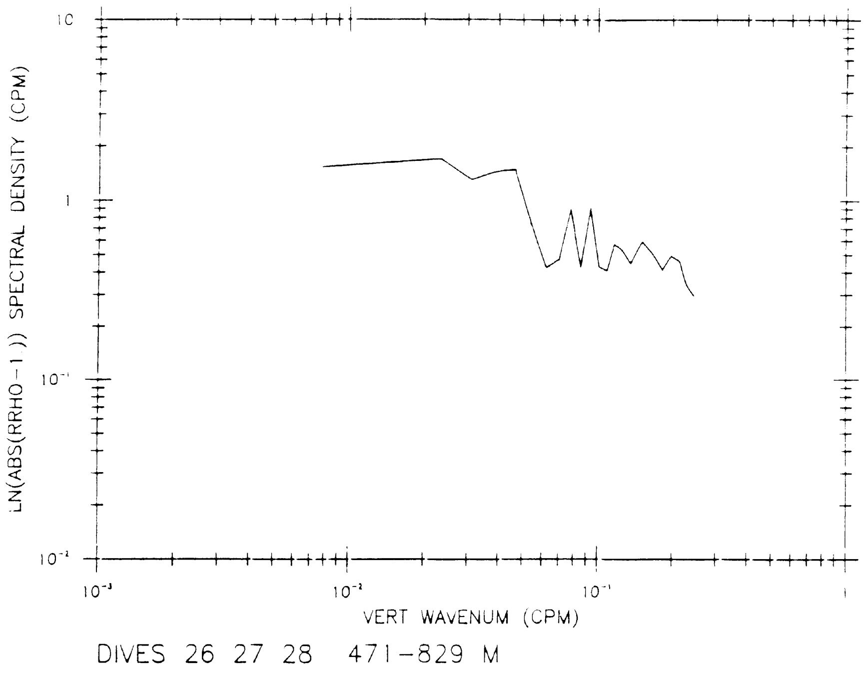
$$\overline{(\ln \mid R_\rho - 1 \mid)'^2} = \frac{1}{f^2 \overline{S}_z{}^2} \frac{\overline{(V_z^0(z))^2}}{2} \left(\frac{\partial \overline{S}}{\partial x}^2 + \frac{\partial \overline{S}}{\partial y}^2\right). \tag{8}$$

This indicates that the vertical wavenumber spectra of vertical shear and $\ln \mid R_\rho - 1 \mid$ should have similar structure, and be related in magnitude by the factor $\frac{\overline{\nabla S}^2}{2f^2\overline{S}_z^2}$.

We have examined the spectra of shear and $\ln \mid R_\rho - 1 \mid$ for dives of the High Resolution Profiler during FASINEX. These profiles were obtained in the Sargasso Sea near an upper ocean front. The region of interest for this analysis is well below the strong variability near the surface, in the depth range of near uniform R_ρ between 300 and 800 m. However, modest variations in salinity along isopycnals lead us to believe that the above mechanism should be operative.

The vertical wavenumber spectra of $\ln \mid R_\rho - 1 \mid$ and vertical shear are shown in Figure 3 a,b. Both have a similar shape, flat from low wavenumbers up to $\sim$ 20 m wavelength beyond which the spectral densities decrease. The shear spectra falls off more sharply than the usual K^{-1} (Gargett *et al.*, 1981) at wavelengths smaller than 10 db. This is due to the 3 db least square fit used to estimate the shear; a first difference operator is more commonly used.

How does the observed variance in $\ln \mid R_\rho - 1 \mid$ compare with that expected from equation 8? For the latitude of these dives (28°N) and a mean vertical salinity gradient of 2.6×10^{-3}°/₀₀/m, a horizontal (isopycnal) salinity gradient with a magnitude of 0.03°/₀₀/km would appear to be necessary, given the spectral levels of $\ln \mid R_\rho - 1 \mid$ and shear for vertical wavelengths between 100 and 20 m. We can examine the variation of salinity vs. density for



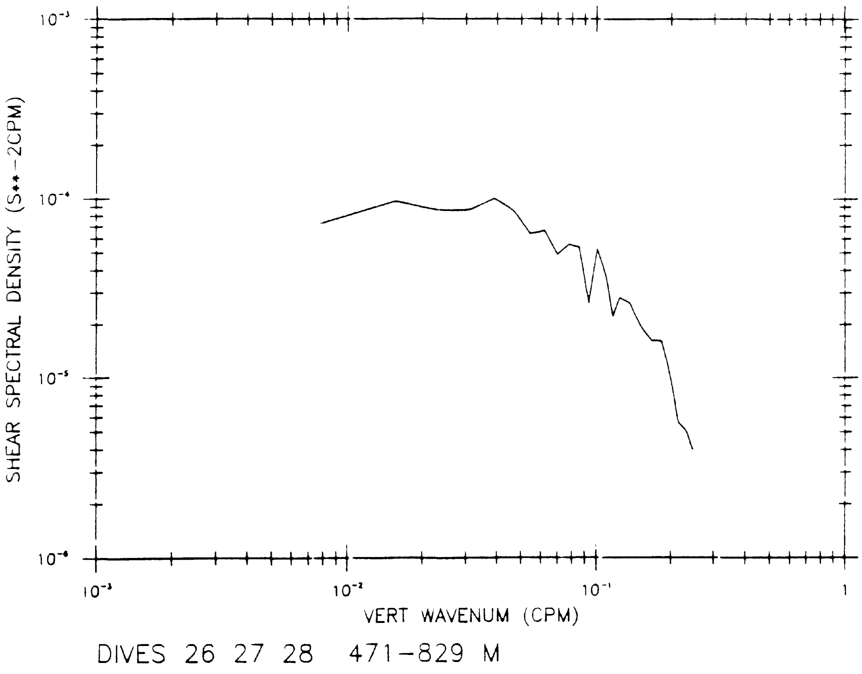


Figure 3.a. Vertical wavenumber spectrum of ln | R_ρ − 1 | for the pressure range 471-829 db for three HRP dives. R_ρ was computed from least square straight line fits over 3 db.

Figure 3.b Vertical wavenumber spectrum of vertical shear (both components) computed by least squares regression over 3 db, for the same intervals as Figure 3.a.

the three dives used in the spectral estimates (Figure 4). Variations of about $0.05°/_{oo}$ are seen on potential density surfaces. These dives are separated by as much as 30 km, suggesting that the observed salinity gradients may be a factor of 20 too low. However, other dives in the area, which are more closely spaced, show that $0.01°/_{oo}$ variations over 1 km or less are quite common. Thus, the salinity gradients on density surfaces are not smooth, but rather streaky. This fluctuation in intensity could easily be caused by the horizontal stirring of mesoscale eddies. Even if the maximal gradient is of order $0.01°/_{oo}$/km it still suggests that the inertial wave shears are inadequate to explain more than about 1/3 - 1/2 of the variance in R_ρ. A lack of coherence between V'_z and $\ln \mid R_\rho - 1 \mid$ is also found; this could be due to streakiness in the salinity field, varying salt gradient direction with depth, and the bandwidth of inertial-internal waves which contribute to the vertical shear. Spectra from other dives with weaker horizontal salinity gradients have reduced variance in $\ln \mid R_\rho - 1 \mid$ but only by a factor of 2 or so. This suggests that the other terms in equation 5 beside the $V'_z \cdot \overline{\nabla S}$ term, as well as the advective terms in equation 1, must also be contributing to the finestructure in R_ρ. These results are reminiscent of the Georgi (1978) estimate that internal wave displacements were inadequate to explain thermohaline intrusions. However, it is unclear whether these modest R_ρ fluctuations could be caused by the double-diffusive intrusion mechanism of Stern (1967) and Toole and Georgi (1981).

3. THE MODULATION OF MICROSTRUCTURE BY R_ρ.

Having identified some plausible mechanisms for generating finestructure in the density ratio, we can ask whether such fluctuations lead to variations in the intensity of microstructure, since theory (Schmitt, 1979a) and experiment (Schmitt, 1979b) indicate that salt fingers are strongly dependent on R_ρ. There is ample precedent for expecting that it will; Schmitt and Georgi (1982) found a correlation of optical microstructure with R_ρ, and Mack (1985) found an increase in the occurrence of temperature gradient zero crossings when R_ρ approached one. We first examine some profiles in detail before looking at the parametric dependence of microstructure indicators.

Using a 3db vertical window for averaging and gradient calculations we have plotted vertical profiles of buoyancy frequency (N), density ratio (R_ρ), Richardson number (Ri), thermal dissipation rate (χ)and theoretical salt finger growth rate (Figure 5). The data are from the interval 800-900 db in Dive 28. N, R_ρ and Ri are computed from the finescale CTD and velocity data from the HRP. The finger growth rate is computed from the formula given by Schmitt (1979a) for the fastest growing finger; an approximate form is

$$\lambda = (\kappa/\nu)^{1/2} N[(1 - 1/R_\rho)^{-1/2} - 1] \quad (9)$$

(Schmitt and Evans, 1978; Stern, 1975). Thus, the growth rate increases when N is high and when R_ρ approaches 1. Schmitt and Evans (1978) argued that internal wave strain caused variations in N (in a constant R_ρ thermocline) which modulated the salt finger intensity. Given the finestructure in R_ρ (possibly caused by the previously described shear mechanism) and the non-linear dependence of growth rate on R_ρ, it seems in fact, that N variations are of

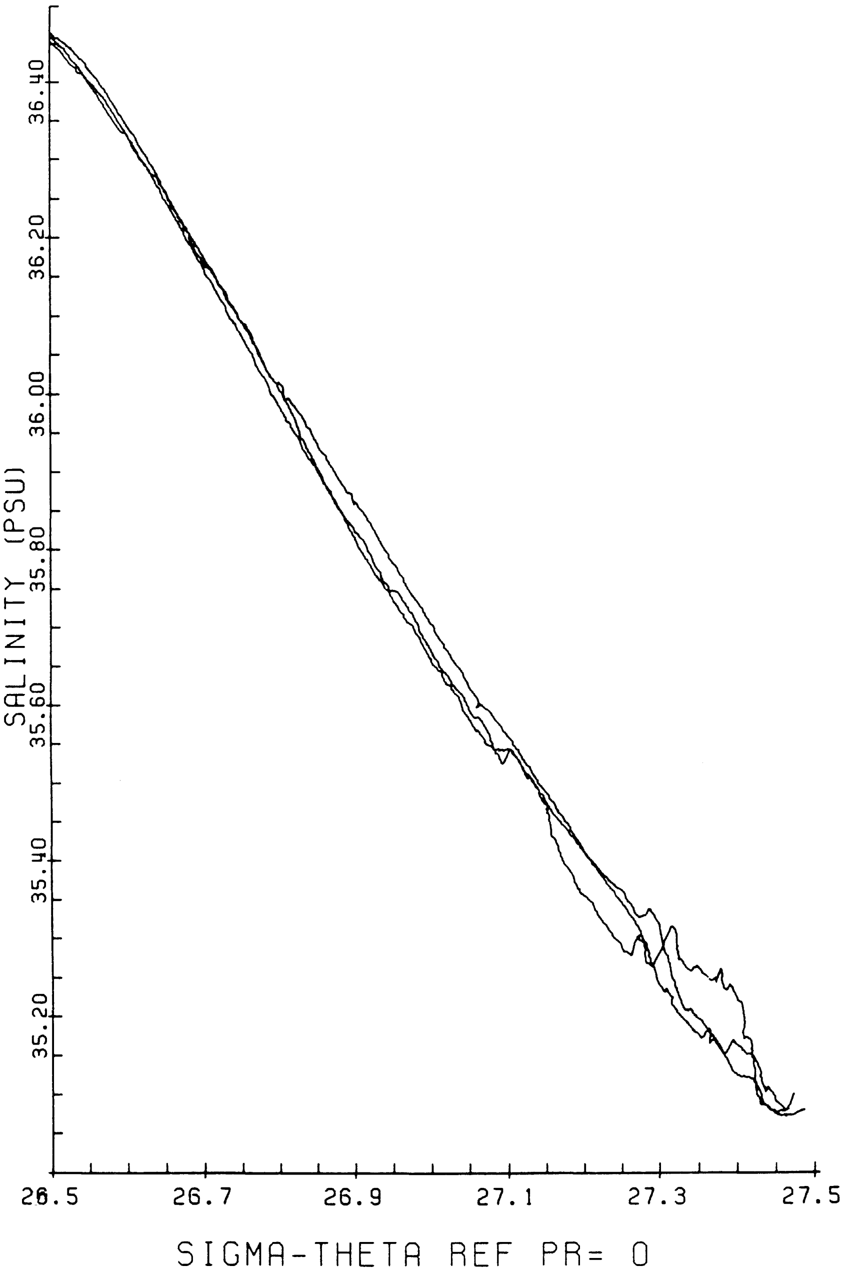


Figure 4. Salinity versus potential density for High Resolution Profiler dives 26, 27 and 28.

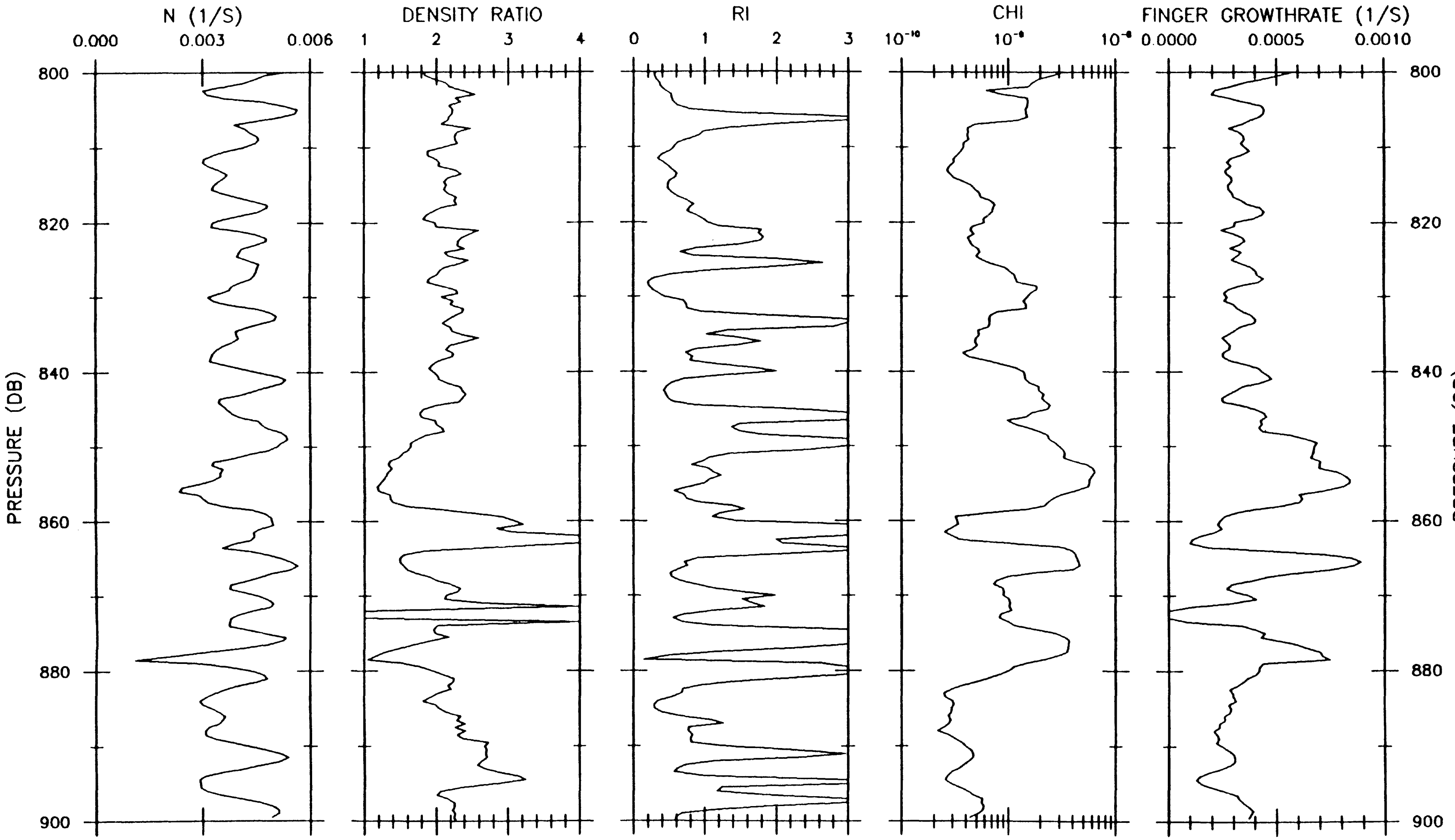


Figure 5: Vertical profiles of buoyancy frequency (N), density ratio (R_ρ), Richardson number (Ri), vertical component of thermal dissipation rate (χ, K^2/s) and salt finger growth rate, for the interval 800-900 db in HRP dive 28. A 3 db window is used for gradient calculations and averaging.

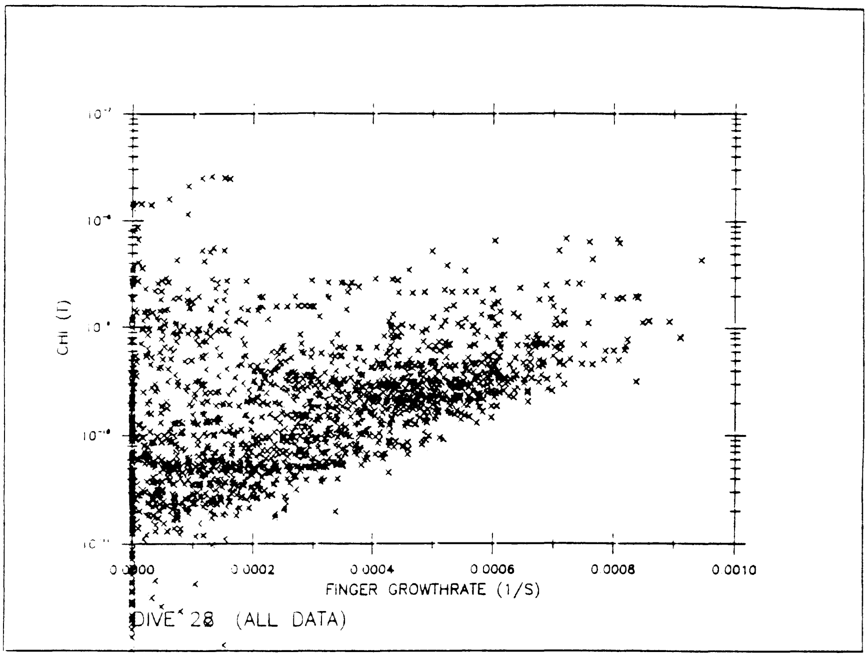
secondary importance. Close examination of the profiles reveals incidences of both positive and negative correlation between N and λ.

The contribution of vertical gradients to the thermal dissipation rate (χ_z, K^2/s) was computed from the conductivity microstructure probe by using a local regression against CTD temperatures. A similar profile is obtained with the temperature probe; the conductivity was used because it resolves more of the thermal variance spectrum. The profile of χ_z can be compared with the other variables to identify probable sites of shear instability and salt fingering. For instance, at 828 db the Richardson number drops below 1/4 and there is a corresponding increase in χ_z. Deeper in the water column, at 854, 866 and 878 db, we find sites with higher salt finger growth rate and χ_z elevated by an order of magnitude. The deeper of these also has a low Richardson number, so the mechanism is ambiguous at that site. The others, though, have Richardson numbers in the range of 0.5 - 1.0, the usual range for the median value of Ri on these scales. Thus, in this 100 m segment of North Atlantic Central Water we find only a few meters which have Ri $<$ 1/4, while nearly the whole segment is unstable to salt fingering. The sections of the profile with the strongest microstructure generally have large salt finger growth rates, so it appears that fingering may be the more important mixing mechanism.

To further explore the apparent relationship between dissipation rate and finger growth rate we have generated scatter plots of the two variables (Figures 6.a, 6.b). The first, Figure 6.a shows the relationship between 3 db averaged thermal dissipations (as computed from the fast response thermistor) and the salt finger growth rate, for all the data from Dive 28 which went to 1000 m depth. There is considerable scatter, especially at low salt finger growth rates, but a clear positive correlation is seen. Part of the scatter may be due to shear instability events which could occur at any finger growth rate. Accordingly we have selected a subset of the data which have a Richardson number greater than 1.5; this corresponds roughly to the upper quartile of Richardson number observations. A scatter plot of conductivity derived χ_z estimates against salt finger growth rate for the high Richardson number data from Dives 25-30 is shown in Figure 6.b. The cluster of points suggests a linear relationship between the log of χ_z and the finger growth rate. The evidence perhaps favors a minimum χ_z level for a given growth rate; points are more likely to scatter above the main grouping than below it. This might be due to prior shear instability events or tilting of fingers by vertical shear, thus increasing the variance seen by a vertical profiler (Kunze, Williams and Schmitt, 1987).

Why should the log of χ_z be proportional to the finger growth rate? A very simple model that allows this is one in which the time allowed for finger growth is fixed by processes external to the fingering, that is, by the internal wave strains and shears which modulate the intensity of the salinity gradient. In such a situation, the amplitude of the fingers will be proportional to exp $(\lambda\tau)$, where τ is the time allowed for growth. This is exactly the model used by Gargett and Schmitt (1982) to generate salt finger spectra from the Schmitt (1979a) theory for comparison with towed microstructure observations. The fluxes (and the dissipation) scale as exp $(2\lambda\tau)$. If applied to the data of Figure 6.b we expect to see a relation between χ_z and λ such that

$$\chi_z = \chi_0 \exp(2\lambda\tau). \qquad (10)$$



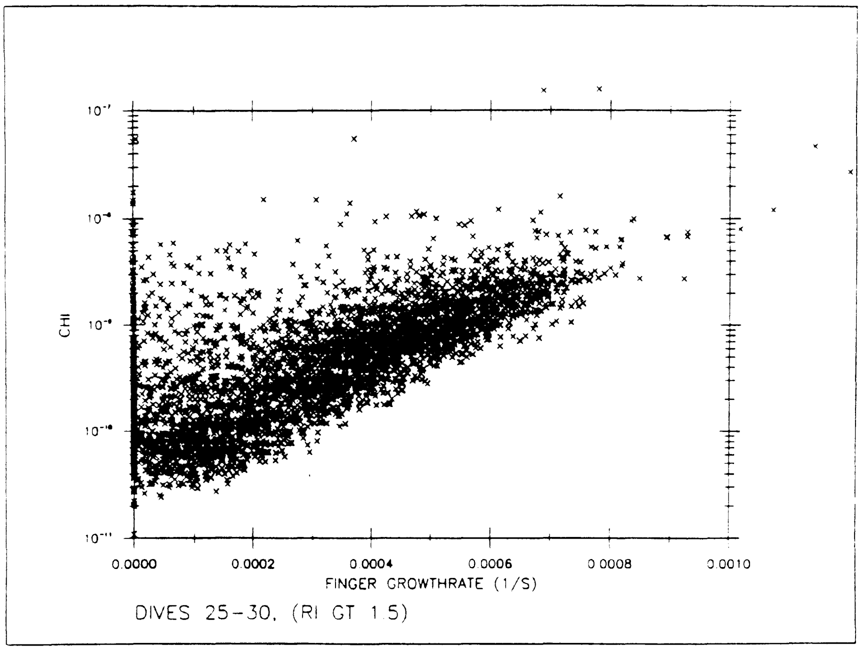


Figure 6.a. χ_z (K^2/s) as derived from the fast response thermistor plotted against salt finger growth rate. A log scale is used for χ_z and a linear scale for the growth rate. All data from overlapping 3 db intervals from HRP dive 28 are shown.

Figure 6.b. χ_z (K^2/s) as derived from the micro-conductivity probe plotted against salt finger growth rate. Only those 3 db intervals with a Richardson number greater than 1.5 in dives 25-30 are shown.

Values for χ_0 of 3 x 10^{-11} K^2/s and for τ of $\sim$ 1 hour give a reasonable fit to the main trend in the data. Since the mean buoyancy period is about 1/2 hour in the main thermocline, it appears that these data are consistent with the spectral level reported by Gargett and Schmitt (1982), where a few buoyancy periods of growth were required to match theoretical and observed spectra.

The foregoing simplistic model for the salt finger intensity can surely be improved upon. An approach we are taking with the FASINEX HRP data is to search for a general dependence of χ upon N, R_ρ and other variables for comparison with salt finger models such as that of Kunze (1987). It seems likely that a purely kinematic explanation for the correlation seen in Figure 6 can be ruled out, as χ_z is poorly correlated with N, yet well correlated with R_ρ. The complex issues of appropriate averaging intervals and conditional sampling of the data set carry this task beyond the scope of the present paper and we reserve these discussions for future publications.

4. IMPLICATIONS FOR MIXING IN THE CENTRAL WATER

The thermal dissipations derived from the HRP data can be used to estimate the vertical eddy diffusivities. The Osborn and Cox (1972) model can be used for the thermal diffusivity, however, there are two caveats for its application to salt fingering portions of the water column. The first problem is uncertainty in the orientation of the fingers; if the fingers are perfectly vertical then a vertically traversing probe could underestimate the dissipation by an order of magnitude. However, the shears that are present in the thermocline should tilt the fingers (Kunze, Williams and Schmitt, 1987), so that the normal assumption of isotropy may be reasonable. The second problem arises if the fingers are not in a steady state, but growing, as the foregoing analysis implies. Gargett and Schmitt (1982) estimate that the flux could be underestimated by as much as 56% because of the unsteady terms in the growing finger model. Since both of these uncertainties would increase the vertical diffusivity, the following estimates should be considered lower bounds.

The vertical contribution to χ can be related to the vertical diffusivity for heat by the relation:

$$K_\theta = \frac{3\chi_z}{2(\bar{\theta}_z)^2}, \tag{11}$$

where the factor of 3 assumes isotropy and the factor of 1/2 is required from the definition of χ. The diffusivity for salt (and nutrients) is obtained from the definitions of the salt finger flux ratio,

$$\gamma = \frac{\alpha F_\theta}{\beta F_s}$$

and the density ratio, $R_\rho = \alpha\theta_z/\beta S_z$. The effective diffusivities for heat and salt are obtained by dividing the fluxes by the mean gradients, thus the ratio of salt to heat diffusivities is:

$$\frac{K_s}{K_\theta} = \frac{R_\rho}{\gamma} \tag{12}$$

In salt finger theory and experiments, $\gamma = 0.5 - 0.7$ at low density ratios. Thus, we expect the salt diffusivity to be 3–4 times as large as the heat diffusivity for R_ρ near 2.

For the present data set, $\overline{\chi}_z \approx 2 \times 10^{-9}$ K$^2/s$ in the low $\overline{R}_\rho$ portion of the main thermocline. The mean vertical temperature gradient is about 2 x 10^{-2} K/m. Equation (11) yields a thermal diffusivity estimate of $K_\theta \simeq 7.5 \times 10^{-6}$ m^2/s; the corresponding salt diffusivity is $K_s \simeq 2.25 - 3 \times 10^{-5}$ m^2/s. The actual diffusivity could be higher if the isotropy factor is greater or if time dependent effects are important. Given that the estimate of vertical diffusivity in a diffusively stable thermocline is only 3 x 10^{-6} m^2/s (Gregg and Sanford, 1988), it appears that salt fingers could easily be the dominant mixing mechanism in the North Atlantic Central Water. Note that the salt diffusivity estimate of Schmitt and Evans (1978) was also $\sim 10^{-5}$ m^2/s for this water mass, despite an uncertain estimation technique.

5. SUMMARY

We have examined two aspects of salt finger mixing in the Central Waters: the effects of finescale shear on the density ratio in the presence of horizontal salinity gradients, and the relationship between thermal dissipation and salt finger growth rate. We have also estimated the effective vertical diffusivity due to salt fingers, finding it to be notably higher than estimates in non-double-diffusive regions. These investigations were made possible by the small scales resolvable by the High Resolution Profiler. It appears that a parameterization of salt fingering based on finescale CTD data may be possible. However, to be effective, a vertical resolution of 0 1 m should be retained in processed CTD data.

Identification of the shear mechanism as a source of finestructure in R_ρ, and therefore the salt finger intensity, raises some interesting questions about the relationship between vertical mixing and isopycnal stirring. The mechanism is an example of shear dispersion in which vertical gradients are intensified by the action of shear on horizontal gradients (Young, Rhines and Garrett, 1982). In this case we can see that the vertical mixing achieved will depend on the value of R_ρ, with more mixing when R_ρ is driven toward 1, less mixing when R_ρ is increased. One can imagine that this would lead to a rectification of the shear dispersion, in which more horizontal mixing is achieved during the low R_ρ portion of an oscillatory excursion than during the high R_ρ portion. Also, a thermohaline intrusion, in which a salinity compensated temperature inversion is found, can be viewed merely as a case of R_ρ being driven through unity. Intrusions are relatively rare in the Central Water and it seems likely that the increased salt fingering found when $R_\rho \rightarrow 1$ is a significant factor in limiting their occurrence.

The shear mechanism is also important for maintaining relatively low $\overline{R}_\rho$ in the CW on large scales. That is, aside from air-sea interaction effects (Schmitt and Olson, 1985; Gordon, 1981) and particular vertical variations in the intensity of horizontal mixing, the action of the mean vertical shear on the mean isopycnal salinity gradient is the only mechanism for decreasing R_ρ. This is required to balance the tendency for salt fingers to increase R_ρ. It appears that estimates of the shear term from mean hydrographic survey data may be used to place an upper bound on the eddy diffusivity for salt in a suitably "constant R_ρ" portion of the Central Water (Schmitt, in preparation).

The Central Waters of the World Ocean, in which the large scale density ratio is rather constant, may represent a situation in which the small scale physics controls the thermohaline stratification for a vast portion of the main thermocline. Much remains to be done to understand the mechanism; however, there seems to be sufficient evidence to suggest that it has global significance. One can argue that Central Water salt fingers play a role in regulation of climate, since modification of evaporation and precipitation patterns is a likely consequence of global warming. This affects the surface buoyancy flux (Schmitt, Bogden and Dorman, 1989) and could change the rate of salt finger mixing in the thermocline. The modified heat and salt transports themselves may have feed-back effects as would any change in biological productivity due to increased nutrient transport rates (Hamilton, Lewis and Ruddick, 1989).

Thus, there is ample motivation for further study of salt fingering in the Central Water. There is an obvious need for improved theoretical, numerical and laboratory modeling of the process, especially with regard to the effects of internal waves. The problem also provides a clear focus for a coordinated field program. Large scale surveys, direct microstructure measurements, and novel tracer release techniques (J. Ledwell, this volume) would be valuable components of such a program.

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