Observational and Laboratory Insights into Salt Finger Convection

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Abstract: Improving observational capabilities in the ocean are revealing a substantial body of evidence that the double-diffusive instability known as salt fingers is widely present and plays a significant role in oceanic mixing. This evidence includes unique fine- and microstructure features in particular regions and distinct patterns in the temperature and salinity variations over large areas. Laboratory experiments have also advanced our understanding of salt fingers. The insights gleaned from both laboratory and ocean are reviewed and related to large-scale ocean structure and climate modeling.

Keywords: Mixing, Turbulence, Double-diffusion, Salt Fingers

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1. Introduction

In much of the subtropical ocean, evaporation exceeds precipitation at the same time that heating exceeds cooling. This produces a warm, salty water mass at the surface. It overlies cooler, fresher water from higher latitudes. If the temperature contrast could be removed there would be a large-scale overturning of the water column, releasing the substantial energy available in the salt distribution. However, this does not happen except on a small scale, where the greater diffusivity of heat can establish thermal equilibrium in adjacent water parcels that still have strong salt contrasts. The "salt finger" instability (Stern, 1960) appears as a close-packed array of up-and downward flowing convection cells which exchange heat laterally but diffuse little salt. This results in an advective transport of salt and, to a lesser extent, heat, in the vertical. Typical cell widths in the ocean are 2-3 centimeters. The salt finger instability is "direct", in the sense that initial displacements are accelerated, and can be modeled accurately with an exponential growth rate. When most intense, the fingers exist within high gradient interfaces separating well-mixed layers in the adjacent fluid, forming a “thermohaline staircase” when a series of such layers and interfaces are found.

The role of salt fingers in oceanic mixing has been controversial. Some ascribe a significant role to salt fingers in maintaining the tightness and shape of the temperature-salinity relationship (Schmitt, 1981; Schmitt, 1994a; Stern, 1967); others emphasize the smallness of the net buoyancy flux (Gregg, 1988; Gregg & Sanford, 1987). Much depends on the analysis methods used to interpret the available microstructure measurements. The issue has gained in importance with a number of numerical modeling studies which suggest a pronounced sensitivity of the thermohaline circulation to unequal mixing rates for heat and salt (Gargett & Ferron, 1996; Gargett & Holloway, 1992; Ruddick & Zhang, 1989; Zhang ,Schmitt & Huang, 1998; Zhang &

Schmitt, 2000). These show that meridional heat fluxes, water mass structure and the transition points for "thermal" to "haline" mode circulation are all dependent on the nature of the heat and salt diffusivities. Given the sensitivity of the thermohaline circulation to mixing, and its significant role in heat sequestration in the climate system, development of accurate parameterization schemes for double-diffusive vertical mixing has become increasingly important.

2. The Evidence for Salt Fingers

2.1 Finestructure

The propensity toward salt-fingering is a strong function of the unstable vertical salinity gradient. The instability can grow at extremely weak values of the salinity gradient, because the diffusivity of salt is two orders of magnitude less than the thermal conductivity. Thus, it is rather easy for heat and salt to develop distinctly different microscale distributions, even when they are well-correlated at large scales. When expressed in terms of the effects on density, all that is required is a top-heavy density gradient due to salt that is only about one-one hundredth of the gradient due to temperature. That is, the density ratio, R_ρ, must be less than the diffusivity ratio:

$$1 < R_\rho \equiv \alpha T_Z / \beta S_Z < \kappa_T / \kappa_S \approx 100 \qquad (1)$$

where α, β are the thermal expansion and haline contraction coefficients, T_Z, S_Z are the vertical gradients of temperature and salinity, and κ_S, κ_T are the molecular diffusivity for salt and the thermal conductivity. This criterion is met over vast regions of the tropical and subtropical thermocline. However, while the required salt gradient is very small, the growth rate of salt fingers does not become "large" until R_ρ approaches one. Using the exact similarity solutions for salt fingers in uniform gradients, Schmitt (1979, 1983) finds that the growth rate of oceanic fingers becomes of order $N / 2\pi$ (where N is the buoyancy frequency) when R_ρ is less than two. (Figure 1).

The heat/salt buoyancy flux ratio, defined as: $\gamma = \frac{\alpha \overline{T' w'}}{\beta \overline{S' w'}}$, must be less than 1 to satisfy energy requirements; that is, the density flux of heat cannot exceed that of the oppositely signed density flux of salt. The flux ratio of the fastest growing finger displays good agreement with laboratory data in both the heat-salt and salt-sugar regimes (Schmitt, 1979; Kunze, 1987), which differ by two orders of magnitude in both Prandtl number and diffusivity ratio. The physics of salt fingers dictates a close relationship between horizontal wavenumber and flux ratio (Schmitt, 1979). That is, narrow fingers lose nearly all their thermal contrast and thus advect little heat and have low flux ratio, while wide fingers retain most of the temperature contrast, advect more heat and have a flux ratio near one. In the similarity solutions, an intermediate wavenumber is found to have the fastest growth, it has a flux ratio of 0.6-0.7. This indicates that most of the energy extracted from the salt field is used to mix the temperature field, and rather less is dissipated as turbulent kinetic energy. This is an important point for the interpretation of dissipation measurements (discussed below). It also bears on the many observations of salt fingers in oceanic towed data (Gargett & Schmitt, 1982; Lueck, 1987; Mack & Schoeberlein, 1993; Magnell, 1976; Marmorino, 1987; Marmorino, Brown & Morris, 1987). All of these investigators report limited amplitude, narrow-band temperature gradient structure at a dominant wavelength around 5-6 cm . These observations indicate that the fastest-growing finger determines the dominant scale in the horizontal wavenumber spectra. Thus, the oceanic fingers are likely to have a flux ratio similar to those in the laboratory, though Kunze (1990, 1994), has suggested that the action of vertical shear may tilt fingers and lower their flux ratio. Interesting plume-like fingers are reported in horizontal microstructure obtained near the surface with a submarine by Osborn (1991). Schmitt (1994b) finds that these observations are consistent with asymmetric planform solutions to the unbounded salt finger equations and Renardy & Schmitt (1996) suggest that a non-linear near-surface temperature profile may offer a selective advantage to such asymmetric fingers.

Fingers transport more salt than heat in the vertical and have a net up-gradient buoyancy flux. Since the growthrate and fluxes increase with the strength of the stratification, high gradient regions will harbor greater fluxes than adjacent weak gradient intervals. This leads to a flux convergence that can cause the weaker gradient region to overturn and mix. The resulting structure has thin interfaces separating thicker, well mixed, layers. The layers are continuously mixed by the downward salt flux, and the convective turbulence of the layers serves to keep the interface thin and limits the length of the fingers. Observations of the "thermohaline staircase" have been reported from several sites with strong salinity gradients. A necessary condition for an organized salt finger staircase seems to be that the density ratio is less than 1.7 (Figure 2). Such conditions are found occasionally near the surface, where evaporation produces the unstable salinity gradient (Gordon, 1981), but more often at depth where the presence of isopycnal gradients of temperature and salinity can lead to a minimum in R_ρ, provided there is a component of differential advection (shear) acting on the isopycnal gradients of T and S (Schmitt, 1990). Examples of staircases are found beneath the Mediterranean water in the eastern Atlantic (Elliot & Tait, 1977; Williams, 1974), within the Mediterranean (Krahman, 1998) and Tyrrhenian Seas (Molcard & Tait, 1977), and beneath the Subtropical Underwater (salinity maximum) of the western tropical Atlantic (Boyd, 1989; Lambert & Sturges, 1977;

Schmitt, Perkins, Boyd & Stalcup, 1987).

In 1985, a detailed examination of one particular staircase system was made in the C-SALT (Caribbean Sheets And Layers Transects) program (Schmitt, 1987; Schmitt *et al*., 1987). Over a large area in the western tropical North Atlantic (~1 million square kilometers) a sequence of ~10 mixed layers, 5-40 m thick, can be observed. Data from the 1960's to the 1990's indicates that the layers are a permanent feature of the region, despite layer splitting and merging, and a moderately strong eddy field (Mazeika, 1974). One of the most remarkable features from C-SALT was the observed change in layer properties across the region. Layers got colder, fresher and lighter from north to south (Figure 3), the inferred flow direction for the upper layers, which appear to be losing salt to the layers below. This water mass transformation is strong evidence for salt fingers. That is, it can only be due to a flux convergence by salt fingers, which transport more salt than heat; turbulence transports the two components equally, and isopycnal mixing, by definition, transports them in density compensating amounts (Schmitt, 1988). The specific value of the lateral density ratio of ~0.85 is slightly above that expected by salt fingers alone (~0.7). This elevation is readily understood as the effect of nonlinearities in the equation of state on the vertical flux convergence (McDougall, 1991). But it is also consistent with an interpretation of the staircases as fundamentally intrusive structures (McDougall, 1985; Marmorino, 1991; Merryfield, 2000), or as a combination of salt-fingering and turbulence (Marmorino, 1990; Fleury & Lueck, 1991).

2.2 Microstructure and Dissipation Signatures

An important early observation of oceanic salt fingers was provided by Williams (1974), who designed an optical shadowgraph system to directly image refractive index variations. He found centimeter-scale parallel bands in the interfaces separating the mixed layers of the thermohaline staircase associated with the Mediterranean water in the eastern Atlantic. The close correspondence of the oceanic images with similar laboratory shadowgraphs was an important breakthrough, especially since towed microstructure measurements by Magnell (1976) on the same interfaces showed the narrow- band, limited amplitude conductivity signals expected of salt fingers. Later shadowgraph deployments found a close correlation of optical microstructure with R_ρ near one, which was also a strong indicator of a double-diffusive origin (Schmitt & Georgi, 1982). Larger aperture optics used in the 1985 C-SALT project revealed horizontally banded structure, which was suggestive of fingers tilted by shear (Kunze, Williams & Schmitt, 1987).

Microstructure measurements taken in the C-SALT staircase revealed limited amplitude, narrow band temperature structure within the interfaces (Gregg & Sanford, 1987; Lueck, 1987; Marmorino *et al*., 1987). The dominant horizontal wavelength was ~5 cm, in excellent agreement with the theoretical finger scale. The slope of the gradient spectra for wavenumbers less than the peak was about +2, consistent with previous towed observations of oceanic salt fingers (Marmorino, 1987; Mack, 1989; Magnell, 1976). This feature provides a useful discriminator from turbulence, which has a +1 slope for temperature gradients between the Kolmogorov and Batchelor wavenumbers. Mack & Schoeberlein (1993) and Marmorino & Greenewalt (1988), employ both the spectral slope and the kurtosis (fourth moment) of the microstructure records. Consistent with the proposal of Holloway & Gargett (1987), the narrow-band, limited amplitude character of salt fingers provides a distinctly lower kurtosis signal than the broad–band, high amplitude nature of turbulence. The combined use of spectral slope and kurtosis allows an efficient classification scheme for towed microstructure data, with the fingers having high spectral slope and low kurtosis, turbulence having low spectral slope and high kurtosis.   Recently, a model of salt finger spectra at an interface has been introduced that is able to explain the +2 slope of the temperature gradient spectra observed in the oceanic salt finger regions and in numerical models as well (Shen & Schmitt, 1996). It would be useful to have the slope/kurtosis classification technique more widely applied to data sets obtained with towed instrument packages fitted with microstructure sensors.

These differences in the character of microstructure due to salt fingers and turbulence reflect their quite different physics. A good way to appreciate this difference in mechanisms is to compare the formulae for estimating the vertical diffusivities from microstructure measurements of the dissipation rates of turbulent kinetic energy (ε) and thermal variance (χ), which are commonly obtained from dropped microstructure profilers. These relations are due to Osborn & Cox (1972) and Osborn (1980) for turbulence and McDougall (1988) and Hamilton *et al* (1989) for salt fingers. Derivation of the formulae is directly from the turbulent kinetic energy equation and the equations for thermal and salt gradient variance. The formula are contrasted as follows:

For Turbulence:

(with flux Richardson number R_f~0.17)

$$K_\theta = K_S = K_\rho = \left(\frac{R_f}{1-R_f}\right)\frac{\varepsilon}{N^2} \approx 0.2\frac{\varepsilon}{N^2}$$

$$K_\theta = K_S = \frac{\chi_\theta}{2\theta_Z}$$

For Salt Fingers:

(with R_ρ= 1.6 and γ =0.7)

$$K_S = \left(\frac{R_\rho - 1}{1-\gamma}\right)\frac{\varepsilon}{N^2} \approx 2.0\frac{\varepsilon}{N^2}$$

$$K_S = \frac{R_\rho}{\gamma}\frac{\chi_\theta}{2\theta_Z} \approx 2.3K_\theta$$

$$K_\theta = \frac{\chi_\theta}{2\theta_Z}$$

In these equations the K s represent the eddy diffusivities of temperature (θ), salinity (S) and density (ρ) and the local buoyancy frequency is represented by N. The "flux Richardson number" (R_f) indicates the ratio of the buoyancy flux to the turbulent kinetic energy production by the mean shear. McDougall & Ruddick (1992) suggest a method for using microstructure data in combination with the above formulae to estimate the eddy diffusivity in mixed turbulence/salt finger regimes. St. Laurent & Schmitt (1999) have examined the microstructure data from the North Atlantic Tracer Release Experiment (NATRE) in an effort to distinguish the two types of mixing. For NATRE a broad-scale microstructure survey of fine-and microstructure stations was performed in a 100 station, 10x10 grid, 400 km on a side, just prior to the tracer injection. The basic answer, that the mixing rate was O 0.1 x 10^{-4} m^2/s in the thermocline, was obvious after about ten dives, since the profile-to-profile variability was small. This preliminary estimate, reported in Toole, Polzin & Schmitt (1994) agreed fairly well with the subsequent tracer dispersion as given by Ledwell, Watson & Law (1993). However, the NATRE region of the North Atlantic thermocline is susceptible to salt fingers, and shadowgraph imagery verified that they were frequently present. In addition, it was obvious in the raw data that there were many occurrences of the "high χ, low ε" signature of salt fingers, that contrasted with the high epsilon signatures of turbulence. Accordingly, St. Laurent & Schmitt performed a parametric sorting of the mixing events, classifying the stronger microstructure patches by the value of the local gradient Richardson number ($Ri = S^2/N^2$, where S= local vertical shear of the horizontal velocities) and density ratio. The Richardson number indicates the susceptibility of the water column to overturning forced by shear, with values less than ¼ deemed necessary for production of turbulence. Statistically significant variations in the value of the "scaled dissipation ratio" of Oakey (1985) (Γ) were observed in this parameter space (Figure 4). This ratio is defined as $\Gamma = \frac{\chi N^2}{2\varepsilon\theta_Z^2}$, for fully developed turbulence it is expected that

$\Gamma = \left(\frac{R_f}{1-R_f}\right) \approx 0.2$; for salt fingers we expect $\Gamma = \left(\frac{R_\rho - 1}{R_\rho}\right)\left(\frac{\gamma}{1-\gamma}\right) \approx 0.4 - 0.9$ (St. Laurent & Schmitt, 1999). The sorting in Richardson number and density ratio space reveals the expected values of $\Gamma \sim 0.2$ for turbulence in the non-double diffusive regimes and at high density ratio, and values of $\Gamma \sim 0.7$ in the high Richardson number and low density ratio. Since much of the thermocline in the NATRE data set has $R_\rho < 2.0$, the dissipation data indicate that salt fingers are making a substantial contribution to mixing at this site. When translated into a flux ratio for salt fingers, the data are in agreement with laboratory data on salt fingers (Figure 5). This sorting in parameter space helps provide very stable statistics, because it combines similar regimes of hydrodynamic forcing (shear and unstable salinity gradient), whereas block averaging over larger scales tends to mix hydrodynamic regimes, which change over a few meters in the vertical.

This parametric approach to the microstructure allows a classification of the mixing events as either turbulent (with low efficiency) or salt-fingering (with high efficiency). With each process occurring at different frequencies in the water column, this translates into differences for the net vertical eddy diffusivities for heat and salt. Moreover, the flux divergences estimated can be use to infer the profile of diapycnal velocity produced by the mixing (Figure 6). At the depth range of the tracer, the salt fingers provide enough mixing to produce a downward diapycnal velocity that is in agreement with the observed tracer movement of 2-4 meters per year (Ledwell, Watson & Law, 1998). Also, the diffusivity estimated taking salt fingers into account agrees with the tracer value. Analysis using the conventional turbulence formula yields a diffusivity that is 50% low and a diapycnal velocity of the wrong sign.

Thus, it is important to reach a more quantitative understanding of salt fingers in the ocean. The observed failure of turbulence models to explain the microstructure data, tracer dispersion and migration in NATRE is consistent with a significant salt finger flux at that site, which implies that fingers should be contributing to vertical exchange in all of the Central Water masses as has often been suggested (Schmitt & Evans, 1978; Klein & Siedler, 1995; Tsuchiya & Talley, 1998).

3. Recent laboratory work

Early laboratory work established the basic features of the fluxes and flux ratio in heat-salt fingers. Turner (1967) and Schmitt (1979) showed how the salt flux varied as the 4/3 power of the salinity difference in two-layer tank experiments. They also found a flux ratio for salt fingers in the 0.5-0.8 range (figure 4). Later work by McDougall & Taylor (1984) extended the experimental range to lower density ratios, where fluxes continued to increase. They found that the nondimensional ratio of net density flux to the product of viscosity and density gradient in the fingering interface (known as the Stern number) ($A = \frac{\beta F_S - \alpha F_T}{\nu \rho_z}$) strongly increases as the density ratio approaches one. This was also reported by Schmitt (1979); it suggests that different stability criteria apply to the fingers at low density ratios; the Stern number is generally interpreted in terms of the stability of the fingering interface. Kunze (1987) has argued that the Stern number is equivalent to a Richardson number stability criteria, but finds no means for it to vary with R_ρ. in his models. This lack of variation is the likely reason his proposed flux laws fail to mimic the sharply increasing fluxes as R_ρ. → 1 reported in the laboratory experiments of McDougall & Taylor (1984).

3.1 Salt fingers and turbulence

The interaction of salt fingers and turbulence has been nicely documented by Taylor (1991). He found that fingers reform quickly after turbulent disruption, reestablishing fluxes within 4-10 e-folding periods of the fastest growing fingers as given by the long-finger theory of Schmitt (1979) (Figure 1). He suggests that with turbulence patches in the ocean occurring only 1-5% of the time, there is sufficient time for fingers to become well established. This idea has been expanded on by Wells (2001) who has generated intermittent turbulence in a tank of salt fingers by stirring rods. His results indicate that if turbulence is present more than 6% of the time for $R_\rho > 2$ then the fingers do not have time to equilibrate. If turbulence is present less than 2% of the time for R_ρ>2 then the finger fluxes remain high. For lower density ratios, the fingers more easily dominate the fluxes and form convective mixed layers and thermohaline staircases.

3.2 Anisotropy

Taylor (1993) has also investigated the anisotropy of salt fingers in the laboratory. That is, the vertical and horizontal gradients on the microscale are expected to be different, because of the tall aspect ratio of the fingers. He found that for $R_\rho < 5$, the vertical and horizontal temperature gradients were close to isotropic, with the fingers only being about twice as long as they were wide. There was trend for the fingers to be more isotropic as R_ρ approached 1, where growth rates are higher. This is consistent with the low vertical coherence observed in the C-SALT fingers by Lueck (1987), though this may also be explained by vertical shear. Also, Taylor & Veronis (1996) found that the traditional picture of long-thin fingers really only applies to high

R_ρ conditions in sugar-salt experiments. Faster growing fingers at low R_ρ are shorter and much less organized, an observation consistent with numerical simulations (e.g. Shen ,1989). Thus, a new picture has emerged of short, chaotic, salt blobs being nearly isotropic in scalar gradients at low R_ρ , where significant fluxes are realized. The relationship of these results to the traditional long-thin vertical fingers, and the apparently sheared fingers reported by Kunze *et al* (1987), remains to be determined.

4 Larger-Scale Impacts

4.1 Regional impact of the CSALT Staircase

The magnitude of the fluxes in the C-SALT staircase is an issue of some importance. Whereas the turbulent dissipation estimates were smaller than had been expected from simple extrapolation of some laboratory flux laws (Gregg & Sanford, 1987; Lueck, 1987), the rate of dissipation of thermal variance was substantial. Schmitt (1988) and Kunze (1990) estimate an eddy diffusivity for salinity of 1-2x10^{-4} m^2/s within the staircase, based on the observed thermal and turbulent dissipation rates, which are consistent with a Stern number constraint on the observed finger interfaces. Though the staircase occupies about 1/4 of the area of the Atlantic between 10-15^{o}N, the vertical salt flux there is predicted to be 3-4 times as large as the flux in the remaining area of this latitude band (Schmitt, 1998). This is because the rest of the area is expected to have diffusivities ten times smaller as well as a weaker salinity gradient (Schmitt & Evans,1978). Thus, the staircase areas appear to be sites of enhanced diapycnal exchange. A proposed balance between lateral advection of salt and the vertical flux convergence was offered in this area by Lambert & Sturges (1977). Their flux estimates may be considered high but the basic balance seems likely to hold, and an ongoing tracer release experiment should quantify the mixing rates.

4.2 Global Impacts of Salt Fingers

In addition to being of regional importance as an enhanced flux site in the tropical North Atlantic, salt fingers may be important in all of the other oceans and many marginal seas. In the Atlantic at 24 N, 95% of the upper kilometer of the ocean is salt finger favorable (Schmitt, 1990). Indeed, conditions are favorable for fingering in all of the Central Waters of the subtropical gyres. As noted above, the observed dependence of fingering on the density ratio, and the fact that salt is transported at a greater rate than heat, leads to a mechanism for maintaining the shape of the T-S curve. Since density compensated T-S anomalies are prominent in the mixed layer (Rudnick & Ferrari, 1999), some such mixing mechanism is required to explain the tightness and shape of the T-S relation of the subducted waters in the thermocline (Schmitt, 1999). Without double-diffusion, the thermocline would be characterized by numerous salinity-compensated temperature inversions, produced by stirring along isopycnals by mesoscale and submesoscale eddies. Substantial evidence is available that salt fingers are the dominant mixing mechanism operating on finescale intrusions at fronts. Double-diffusive intrusions are a mechanism for accomplishing lateral mixing of water masses at the finescale. Since it acts preferentially on high gradient regions, it may be responsible for a sizeable fraction of the global dissipation of thermal and haline variance, despite modest eddy diffusivities. This is supported by the generally low turbulence levels in most of the thermocline (Gregg, 1989) and the recent discovery that enhanced open ocean turbulence is most prominent in the weakly stratified abyss (Polzin *et al*, 1997), where the contribution to dissipation of scalar variance is necessarily small, even though the eddy diffusivities may be large.

But there are even broader implications of salt fingers to consider. It has been well-established that the strength of the thermohaline circulation depends directly on the magnitude of the vertical (diapycnal) mixing coefficient (Bryan, 1987; Zhang, Schmitt and Huang, 1999), which can be changed by the presence of salt fingers. Gargett & Holloway (1992) first investigated the effects of a simple double-diffusive parameterization in a coarse-resolution primitive equation ocean model. They found that major features of the steady-state solutions are sensitive to the ratio of the vertical eddy diffusivities for salinity and temperature. Since their mixing scheme was rather simple, a more realistic parameterization of double-diffusion for OGCMs was investigated by Zhang, Schmitt & Huang (1998). This study suggests a sensitivity of the thermohaline circulation to a density ratio-dependent mixing rate but without the radical reorganization of the flow suggested by the uniformly unequal diffusivity scheme used by Gargett & Holloway. A 22% decrease in the strength of the meridional overturning was realized when salt fingers were added to the model. A similar study in a global model with realistic topography and forcing found that double-diffusion helped to bring deep temperature and salinity fields into closer agreement with observations (Merryfield, Holloway & Gargett, 1999).

Other work has shown a sensitivity of box models of the thermohaline circulation to double diffusive effects. Ruddick & Zhang (1989) found that the "salt oscillator" mechanism could be completely stabilized by incorporating salt fingers into the model. Most recently, Gargett & Ferron (1996) found that multi-box models with non-equal heat and salt diffusivities exhibited extended ranges of multiple equilibria, a different mode transition near present-day values of freshwater forcing and the possibility of quasi-periodic oscillatory states compared to an equal diffusivity run.

The relative influence of interior mixing and surface freshwater flux on the stability of the thermohaline circulation was examined in a scaling analysis and numerical simulation by Zhang *et al* (1999). They found that for a given diffusivity, there was a critical freshwater flux above which only the haline mode of overturning can be realized. Zhang & Schmitt (2000) have examined the effect of salt-fingering in this context and found that fingering, by lowering the net interior density diffusivity, makes the circulation more susceptible to collapse of the thermal mode. In this regard, it has long been suggested that the diffusive-convective form of double-diffusion may play a significant role in bottom water formation, as it permits heat loss without much freshening of salty water and thus can yield a denser water mass than air-sea interaction alone (Carmack & Aargaard, 1973; McDougall, 1983). Subsurface, warm and salty "Atlantic" waters in the Arctic Ocean recently have displayed a substantial warming (Carmack, *et al*. 1997), with a heat content sufficient to melt much of the sea-ice separated from it by the Arctic halocline (Melling, 1998). If the halocline weakens, or the warming continues, enhanced upward heat fluxes due to double-diffusive convection are to be expected. If the heat fluxes become sufficiently strong to melt the sea ice, the resulting change in Arctic albedo would have dramatic consequences for global climate.

5. Summary

Much evidence is now available to show that salt fingers are a significant element of oceanic mixing. Laboratory and oceanic data have refined our picture of salt fingers from the long, organized, laminar, but weak structures found at high R_ρ, to more isotropic, chaotic, salt blobs providing high fluxes at low R_ρ. Optical shadowgraphs, towed microstructure data, and dropped dissipation measurements have detected the signatures of salt fingers in the expected (low R_ρ) parameter range. Solid data are available to confirm that the transfer rates of heat and salt are different and that the intensity of mixing is a strongly increasing function as $R_\rho \rightarrow 1$. These two conditions are sufficient to assure that there will be feedbacks of salt fingers on the mean temperature - salinity structure. However, we have only begun to attempt to quantify the rates of such mixing in the ocean. Theoretical models (Kunze, 1994) are unable to reproduce the flux behavior observed in the laboratory at low density ratio. Similarly, the dynamics of thermohaline intrusions and staircase layers remain controversial, with numerical models (Merryfield, 2000) failing to simulate the one-dimensional staircases so easily generated in the laboratory. Much remains to be done to understand the interplay between the variance destroying vertical mixing processes and the variance producing horizontal stirring processes of eddies, waves and intrusions. Little is known about how double-diffusive convection affects the vertical transport of momentum in the ocean.

Recent model results have made it clear that the large-scale thermohaline circulation has a first-order dependence on variations in mixing, since mixing modifies the stratification and thus the pressure gradients that drive ocean currents. Mixing is an important driving mechanism for all deep and intermediate flows. As the thermohaline circulation plays a central role in the transport and sequestration of heat in the ocean, progress in understanding oceanic double-diffusion contributes to knowledge of the climate system. Indeed, given the overwhelming heat capacity of the oceans compared to the atmosphere, uncertainties in oceanic mixing now appear to be as central to the climate problem as questions concerning cloud physics are in the atmosphere.

New capabilities in observational oceanography and numerical modeling promise to reveal much about these important problems in the near future.

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Figure Captions.

Figure 1. The exponential growth rate of salt fingers as a function of density ratio (R_ρ). The growth rate has been scaled with the buoyancy frequency, N, and multiplied by 2π for expression in "e-foldings per buoyancy period". Most of the main thermocline of the subtropical gyres has $R_\rho \sim 2$, while the regions with strong salt finger staircases have R_ρ closer to one.

Figure 2. The occurrence of thermohaline staircases as a function of density ratio. The strong staircases of the Tyrrhenian Sea, beneath the Mediterranean water in the eastern Atlantic, and the Subtropical Underwater of the western tropical North Atlantic, have $R_\rho < 1.7$. Irregular steppiness characterizes the Central Waters of the subtropical gyres, where $R_\rho \sim 2$. (From Schmitt, 1981).

Figure 3. Potential temperature - salinity values of the mixed layers observed during C-SALT. The solid circles are from mixed layers more than 10 m thick; the open circles are from layers 5-10 m thick. Temperature-salinity relationships from the northwest and southeast corners of the survey are also shown (----). Layers become warmer, saltier and denser from southeast to northwest, as would be expected from the vertical convergence of salt finger fluxes. The layer properties cross isopycnals (the 26.8, 27.0 and 27.2 potential density surfaces are shown) with an apparent heat/salt density flux convergence ratio of 0.85. (From Schmitt *et al*, 1987; reproduced by permission of Elsevier Press.)

Figure 4. The "scaled dissipation ratio" as a function of Density Ratio and Richardson number. Data from a region of the Pacific that is double-diffusively stable is consistent with turbulence (left panel), whereas data from the North Atlantic thermocline show high thermal dissipation at low density ratio and high Richardson number. This is a clear indication of salt-fingering, in a parameter regime which characterized much of the water column at this site. (Figure adapted from St. Laurent & Schmitt, 1999.)

Figure 5. Conversion of the oceanic dissipation ratio estimates to a salt finger flux ratio (solid line, with gray error bars) shows the data to be consistent with previous laboratory work. (From St. Laurent & Schmitt, 1999).

Figure 6. Vertical profiles of the density ratio (left), the vertical diffusivities of heat and salt (center) and buoyancy (right) from the North Atlantic Tracer Release Experiment microstructure measurements of St. Laurent & Schmitt (1999). The vertical eddy diffusivities are different for heat and salt due to salt-fingering. The observed dispersion of the tracer over the six months following the microstructure measurements is shown at 300 m depth. The estimate of the diffusivity for buoyancy is negative at the level just above the tracer, which contributes to an estimate of a downward diapycnal velocity, consistent with the tracer movement. (From St. Laurent & Schmitt, 1999.)