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The role of double diffusive interleaving in mesoscale dynamics: An hypothesis

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ABSTRACT

It is hypothesized that double diffusive interleaving can act to enhance the temperature, salinity and buoyancy signatures of some mesoscale structures. The hypothesis is founded on theoretical results showing that the fluxes produced by double diffusive interleaving can have counter-gradient components, and on the observations that isolated mesoscale rings have a long lifetime and that there is intense interleaving in the frontal zone typically surrounding the ring. Quantitative examples for a warm and a cold core ring demonstrate the feasibility of the hypothesis. Some suggestions are given for extending the hypothesis to include other mesoscale features. Also theoretical investigations and field experiments to test further the hypothesis are suggested.

1. Introduction

In regions with large scale epipycnal *T-S* gradients and with diapycnal gradients suitable for salt fingering, the salt fingering drives double diffusive interleaving (DDI) which undergoes unstable growth (Stern, 1967). Posmentier and Hibbard (1982) and McDougall (1985) have noted that the DDI can cause large fluxes of salt, heat, and mass, and that these fluxes can have up-gradient components. This "negative diffusion" phenomenon, it was suggested, may result in feedback to larger-scale structures. They did not, however, propose a specific example in which such a process may be significant.

Among the many larger-scale structures which conceivably could be enhanced by DDI, mesoscale rings often have enigmatically long lives and intense fine- and microstructure in their frontal boundary zones. This latter feature is often indicative of DDI. As a first, preliminary test of the potential of DDI to enhance larger-scale structures, we therefore select mesoscale rings.

Motions on the mesoscale are among the most energetic in the complete spectrum of ocean currents. They play an obvious and key role in the transport of momentum, salt and heat between geographic regions. They also play a key but much subtler role in transfer of energy between different scales. In regard to the latter issue there are two

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competing effects. Conservation of kinetic energy and enstrophy suggest that the mesoscale should transfer energy to less energetic large scales. On the other hand it is widely believed that internal friction passes energy from the mesoscale to smaller scales. Moreover, mesoscale dynamical processes can sap the energy of rings. For example, Flierl (1977) has shown that rings can lose energy through Rossby wave radiation. Also, Stern (1975), Flierl *et al.* (1980), and Mied and Lindemann (1982) have demonstrated that mesoscale eddies can generate energetic modons.

Observations from POLYMODE (Robinson, 1982) indicate that the mesoscale motions indeed pass energy to both larger and smaller scales. Nevertheless, a curious aspect of the observations cited by Robinson is that the decay of the cold core rings in the Sargasso Sea is of the order of a year or more, if they don't interact with other rings or with the Gulf Stream. In a classic set of observations Richardson *et al.* (1973) have documented the existence of a single anticyclonic ring in the Sargasso Sea for twenty months. Also from observations of the available potential energy of rings, Barrett (1971) speculated that typical lifetimes are of the order of 3 to 5 years if they don't re-enter the Gulf Stream or interact with bottom topography.

Theoretical studies of ring decay can be divided into two types. Molinari (1970) and Schmitz and Vastano (1975) have employed diffusion models, while Flierl (1977), Csanady (1979) and Mied and Lindemann (1979) have emphasized entrainment and quasi-geostrophic dynamics. The former give decay estimates which are in good agreement with the observations cited above. However, as discussed by Schmitz and Vastano (1975) the model parameters are adjusted to agree with the observed decay times. The latter studies are tuned to observed currents and thermocline displacements. Often when the rings are young they give much shorter decay times, of the order of six months and less. This suggests that as yet unidentified mechanism(s) may be operating to maintain the distribution of available potential energy within rings.

We hypothesize that the fluxes of salt, heat, and buoyancy caused by DDI within the front surrounding a mesoscale ring may be adequate to refresh the ring's available potential energy, salinity anomaly, and heat anomaly, at least once within the lifetime of the ring. No theoretical framework adequate to "prove" the viability of this hypothesis exists presently. However, there is some basis to demonstrate its feasibility. The purpose of this paper is to provide two realistic, quantitative examples in support of the hypothesis. It is recognized that not all scenarios produce fluxes which are capable of refreshing a ring. Our thesis is that some can on the time scales of ring decay.

The radical nature of this proposal is acknowledged. Our concern is not with this but with critical testing of the conjecture. Regardless of the outcome, application of the scientific method to this hypothesis should lead to better understanding of both mesoscale exchange processes and double diffusive phenomena.

The observational and theoretical basis of the hypothesis is given in the next section, and some calculations which demonstrate the feasibility are presented. The last section discusses its consequences, and suggests some extensions of present theory and field tests which will be necessary to establish further the viability of the hypothesis.

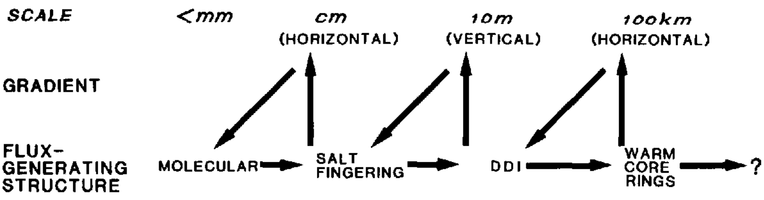

Figure 1. Interactions among gradients, structures, and double diffusive fluxes over eight decades of scale.

2. A preliminary test of the hypothesis

Our argument begins with some recent theoretical results of Posmentier and Hibbard (1982). That study showed how Stern's (1967) original model for DDI can be used to calculate the epipycnal buoyancy flux from warm saline water to cold fresh water. Moreover, the sense of the diapycnal velocities in the interleaving is such that flux of buoyancy is upward toward lower density. Hence DDI can act to maintain the existing distribution of available potential energy! Thus, molecular diffusive processes cause microscale diffusive processes (salt fingering), which produce a finescale interleaving, which, in turn, can produce a feedback to the mesoscale. Figure 1 is a schematic of these interactions. It is interesting that this feedback transfers energy from less than a mm scale to a 100 km scale—more than 8 decades of scale.

The second item in the argument is the general impression that the frontal zone separating either warm salty water or cold fresh water from the ambient ocean is an actively intrusive region which can be conducive to DDI. For example, Mied and Lindemann (1984) found that intense fine- and microstructure is found in a narrow zone between the ring edge and the ambient fluid. Demonstrating that frontal zone interleaving is DDI requires a very intensive observational program. Williams (1981) photographed intense double-diffusive intrusions along the Gulf Stream front, and Toole (1981) demonstrated that the intense intrusions observed along the Antarctic Polar Front are driven by salt fingering.

As a preliminary test of the hypothesis, a quantitative example of the positive feedback from DDI to a mesoscale ring is examined here. First we set forth some features of a hypothetical mesoscale warm core ring illustrated in Figures 2 and 3. Then we calculate the properties of DDI in the ring front, including the fluxes produced by the DDI. Finally, we evaluate the reciprocal effects of the DDI fluxes on the ring.

a. Hypothetical mesoscale structure. We assume the idealized ring geometry and properties in Figure 2 and Table 1. A *T-S* plane depiction of this hydrography is shown in Figure 3.

Each of the three scales considered here—salt fingers, DDI, and rings—is best described in a different coordinate system. These three coordinate systems are illustrated in Figure 2B. The *x-z* coordinates are horizontal (positive outward from the

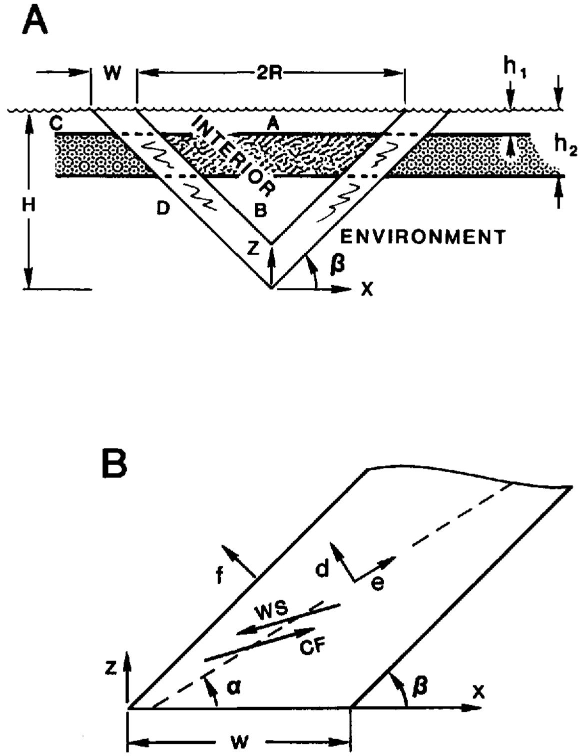

Figure 2. (A) Sketch of the idealized ring representation, defining R, W, and H. The near-surface thermocline is in the depth range h_1 to h_2, which is also the depth range of active DDI in the ring front. (B) Sketch of a section of the front. Orientations are shown for the x and z (horizontal and vertical), e and d (epipycnal and diapycnal), and f (cross-frontal) axes. Dashed line is isopycnal. The isopycnal slope is tan α, and the front slope is tan β. *WS* and *CF* are the DDI velocities in the warm salty and cold fresh intrustions, respectively.

ring center) and vertical (positive upward). The e-d coordinates, used tó describe the DDI within the ring front, are epipycnal (positive outward from the ring center) and diapycnal (positive upward toward lower density). The f coordinate is normal to the ring front (positive toward the ring interior). Note that z, d, and f are nearly coincident, and directed upward. Directions x and e are also nearly coincident, and directed outward from the ring center. McDougall (1984) has discussed these systems in more detail. In summary, all three systems use the same sign conventions: positive upward, and positive outward from the ring center.

Referring to Figure 2, it is seen that the horizontal and vertical derivatives of any scalar Q, within the front between depths h_1 and h_2, are given by

$$Q_x = (Q_C - Q_A)/W \tag{1a}$$

$$Q_z = (Q_A - Q_B)/h_2 - R(Q_C - Q_A)/WH \tag{1b}$$

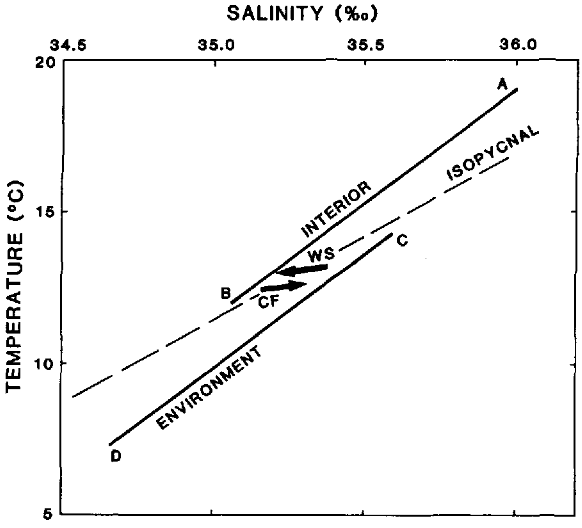

Figure 3. Temperature-salinity relationship of water inside ring and outside ring. Same symbols as Table 1 and Figure 2B.

where subscripts x and z represent partial derivatives, and subscripts A, B, C represent values in the regions defined in Figure 2A and Table 1. The resulting gradients are listed in the first two rows of Table 2. The densities listed are based on a thermal expansion coefficient $a = 1.5 \times 10^{-4}(°C)^{-1}$, and a haline contraction coefficient $b = 7.5 \times 10^{-4}(‰)^{-1}$, which are used throughout this report.

The horizontal change in density across the front is 4×10^{-4} g-cm^{-3}. From the Margules equation this gives a velocity difference of 40 cm-s^{-1} for Coriolis $= 10^{-4}$ s^{-1}, and a corresponding shear of 0.016 s^{-1}. The vertical thickness of the front is $HW/R = 25$ m. The vertical density gradient within the 25m-thick front, anywhere within the depth range h_1 and h_2, is 1.99×10^{-7} g-cm^{-4}. Using $g = 980$ cm-s^{-2} and $\rho = 1.025$ g-cm^{-3}, the corresponding Richardson's number is $980 \times (1.99 \times 10^{-7})/1.025 \times (0.016)^2 = 0.74$, which is large enough to disregard Kelvin-Helmholtz instabilities.

Table 1. Geometry and hydrographic properties of idealized ring.

$2R = 100$ km	$h_1 = 50$ m
$H = 500$ m	$h_2 = 140$ m
$W = 2.5$ km	$\beta = \arctan(H/R) = 9.9997 \times 10^{-3}$

	Property		
Location	S(‰)	T(°C)	$\rho - \rho_A$(g-cm^{-3})
A. Surface Interior	36.00	19.0	0
B. Deep Interior	35.07	12.0	3.53×10^{-4}
C. Surface Environment	35.59	14.3	3.98×10^{-4}
D. Deep Environment	34.66	7.3	7.50×10^{-4}

b. Finescale DDI. The model used here to calculate the DDI properties and fluxes within the front is the model for inviscid, hydrostatic motion on an f-plane, with salt fingering causing vertical T, S, and density fluxes, as described by Stern (1967). This linear model is not applicable after T-S inversions occur, nor is it strictly applicable in baroclinic regions or after viscous effects become significant. The possible effects of these limitations are discussed in the following section. We proceed here with the application of Stern's (1967) linear DDI model, and postpone the development of a relevant, nonlinear, baroclinic, viscous model of DDI to the near future.

The gradients in x-z coordinates, listed in the first two rows of Table 2, can be expressed in the e-d coordinate system by using

$$Q_e = Q_x \cos \alpha + Q_z \sin \alpha \tag{2a}$$

$$Q_d = Q_z \cos \alpha - Q_x \sin \alpha \tag{2b}$$

where α is the direction cosine between the x and e directions (or the z and d directions), and represents the slope of the isopycnals, given by arctan (ρ_x/ρ_z). See McDougall (1984). The results of this coordinate rotation on the T, S, and e gradients are given in the third row of Table 2. Note that while the signs of the x-derivatives of T and S are negative (cold, fresh water outside the ring), their e-derivatives are positive for the example discussed here. This is because of the isopycnal slope (see Fig. 3).

Following Stern (1967), it is assumed that perturbations of salinity, temperature, pressure and density, and the velocity components in the e, y, (along front) and d directions, are modulated by exp $(i(ke + jy - \delta d) + \lambda t)$ and have amplitudes of S', T', p', ρ', U, V, and W, respectively. The parameter λ is the growth rate of the DDI. The seven amplitudes are governed by the equations of motion, the hydrostatic equation, continuity, conservation of salt and heat, and a linear equation of state:

$$\lambda U - fV + (ik/\rho)p' = 0 \tag{3a}$$

$$fU + \lambda V + (ij/\rho)p' = 0 \tag{3b}$$

$$-gbS' + gaT' + (i\delta/\rho)p' = 0 \tag{3c}$$

$$ikU + ijV - i\delta W = 0 \tag{3d}$$

$$\overline{S}_e U + \overline{S}_d W (\lambda + K\delta^2)S' = 0 \tag{3e}$$

$$\overline{T}_e U + \overline{T}_d W + (\gamma b K \delta^2/a)S' + \lambda T' = 0 \tag{3f}$$

$$bS' - aT' - \rho' = 0 \tag{3g}$$

where the overbar represents the unperturbed state which includes constant gradients, and subscripts denote partial derivatives. The constant ρ is a reference density, g is gravitational acceleration, f is the Coriolis' acceleration, K is the salt diffusivity in salt fingering, and γ is the heat-to-salt buoyancy flux ratio in salt fingering.

Table 2. Gradients within ring front. (See Fig. 2B for sign conventions.)

	S(‰-cm^{-1})	T(°C-cm^{-1})	ρ(g-cm^{-4})
horizontal	-1.64×10^{-6}	-1.88×10^{-5}	1.59×10^{-9}
vertical	2.67×10^{-4}	2.66×10^{-3}	-1.99×10^{-7}
epipycnal	4.93×10^{-7}	2.45×10^{-6}	0
diapycnal	2.67×10^{-4}	2.66×10^{-3}	-1.99×10^{-7}

Note: The vertical and diapycnal gradients differ in the 5th decimal place.

This set of equations, equivalent to Stern's (1967) Eq. 2, leads to a characteristic equation for the eigenvalues of λ. According to Posmentier and Hibbard (1982), the largest positive eigenvalue (fastest growth rate) is obtained for j and k given by

$$j = \frac{-\delta^3 K(1 - \gamma)b\overline{S}_e f}{2\lambda_m(\lambda_m(a\overline{T}_d - b\overline{S}_d) + \delta^2 K(a\overline{T}_d - \gamma b\overline{S}_d))} \tag{4a}$$

$$k = \lambda_m j/f \tag{4b}$$

where λ_m, the optimum DDI growth rate, is the largest real root of

$$4g\lambda_m^2(\lambda_m + \delta^2 K)(\lambda_m(a\overline{T}_d - b\overline{S}_d) + \delta^2 K(a\overline{T}_d - \gamma\overline{S}_d)) - ((1 - \gamma)\delta^2 Kgb\overline{S}_e)^2. = 0 \tag{5}$$

(The 2 in the denominator of Eq. (4a) was erroneously omitted from Posmentier and Hibbard's (1982) Eq. 2a.)

Using Posmentier and Hibbard's (1982) equations with $a = 1.5 \times 10^{-4}$(°C)$^{-1}$, $b = 7.5 \times 10^{-4}$(‰)$^{-1}$, $\gamma = 0.56$ (Turner, 1967), $K = 0.5$ cm^2-s^{-1}, and $2\pi/\delta = 25$ m, the fastest DDI growth rate λ_m is 2.75×10^{-6} s^{-1}. This growth rate occurs for an along-front intrusion tilt of (j/δ) of 6.44×10^{-3} and a cross-front tilt (k/δ) of 1.77×10^{-4}. The latter tilt, however, which would be apparent in the plane of Figure 2, is not critical to the growth rate. McDougall (1985) has shown that with friction the range of these tilts can be greatly reduced. Nevertheless, projection of the velocity component into the cross-front plane, which does not necessarily appear to be parallel to the cores of the intrusions, will always cross isopycnals toward lower density.

Returning to the calculations for the interleaving at the fastest growth rate, for a density amplitude of $\rho' = -.0788 \times 10^{-3}$ g-cm^{-3} (which is not so large as to cause hydrostatic instabilities!), we find that Eq. (3) yields the results that: the diapycnal velocity W in the core of the warm salty intrusion is 8.83×10^{-4} cm/s "upward"; the epipycnal velocity U is -5.00 cm/s; T' is 2.41°C; and S' is 0.377‰. The negative sign of U denotes velocity toward the ring center. It is, however, opposite the epipycnal salinity gradient, as should be expected in a warm, salty intrusion.

The diapycnal and epipycnal components of the corresponding fluxes of salt, heat, and mass are listed in Table 3. The epipycnal fluxes of salt and heat are both negative, i.e.—toward the ring center, which is antiparallel to the epipycnal S and T gradients.

Table 3. Fluxes generated by double-diffusive interleaving (DDI) and by salt fingering (SF) within the frontal zone.

	Salt ($mg\text{-}cm^{-2}\text{-}s^{-1}$)	Heat ($cal\text{-}cm^{-2}\text{-}s^{-1}$)	Mass ($g\text{-}cm^{-2}\text{-}s^{-1}$)
DDI diapycnal	1.66×10^{-4}	1.06×10^{-3}	-3.48×10^{-8}
DDI epipycnal	-9.43×10^{-1}	-6.03	1.97×10^{-4}
DDI cross-frontal	2.06×10^{-3}	1.32×10^{-2}	-4.31×10^{-7}
SF*	-1.33×10^{-4}	-3.74×10^{-4}	-4.39×10^{-9}

*SF fluxes are vertical, but are nearly identical to their diapycnal or cross-frontal components.

The epipycnal density flux is positive, i.e.—away from the ring center. The three diapycnal fluxes are parallel (not antiparallel!) to their respective gradients, as noted by Posmentier and Hibbard (1982).

c. DDI effects on the mesoscale ring. The components of these DDI fluxes toward the ring center across the ring front, parallel to direction f in Figure 2B, may be calculated by

$$F_f = F_d \cos(\beta - \alpha) - F_e \sin(\beta - \alpha) \tag{6}$$

where F represents any flux, and the subscripts denote components in the appropriate directions. The three resulting cross-frontal components of the DDI fluxes are listed in the third row of Table 3.

These cross-frontal DDI fluxes can be multiplied by the surface area of the cone section between depths h_1 and h_2 in Figure 2A to find total fluxes. The DDI mechanisms under consideration here would produce no effect outside the depth range h_1 to h_2 because the epipycnal T/S gradients are zero.

The times required by the DDI total fluxes to produce (not dissipate!) the ring's anomalies of 0.41‰, 4.7°C, and -3.98×10^{-4} $g\text{-}cm^{-3}$ through the entire volume of the 500 m-deep cone, are 132 days, 236 days, and 611 days, respectively. Interleaving in the ring front thus acts to double the ring's hydrographic signature and anticyclonic baroclinicity on a 4–20 month time scale. The magnitude and direction of DDI fluxes is clearly more than adequate to supply a ring with significant salt, heat, and potential energy, at least for this one representative case.

The vertical fluxes directly produced by salt fingering within the front (see Table 3) were calculated using K, γ, a, and b. The direction cosines for converting these to diapycnal or cross-frontal fluxes are very close to 1. In comparison with the cross-frontal fluxes caused by the DDI, the salt fingering fluxes are negligible. Only density is carried in the same direction (downward) by both scales of fluxes. These salt fingering fluxes are not considered further here. However, it is interesting to note that the density flux due to salt fingering, although small, is in the correct direction to enhance the available potential energy of the ring. This observation provides intuitive support for our result, that all three cross-frontal DDI fluxes enhance the hydrographic properties of the mesoscale ring.

d. A second example. A second quantitative example representing a cold core ring may also be examined. For this example, all quantities are the same as in the warm core ring example, with two exceptions: The "Interior" and "Environment" in Table 1 are reversed; the conical ring front is concave downward, with a surface diameter of 50 km and a 150 km diameter at 500 m depth. The gradients, DDI amplitudes, and fluxes in the active part of the front are therefore the same as in the warm core ring example. However, the fluxes act over a smaller surface area and affect a larger volume. The resulting time required to produce the cold core ring's salinity, temperature, and buoyancy anomalies are 502, 898, and 2329 days, respectively. Although longer than their counterparts for the warm core ring, these times are still short enough to suggest that DDI can supply the cold core ring with a significant amount of salt, heat, and potential energy for this case.

Among further examples, similar results would be likely for positive feedback between DDI and a subsurface, isolated "meddy" (T. McDougall, personal communication, 1984).

3. Discussion

The fluxes in our examples are only suggestive since Posmentier and Hibbard's (1982) extensions of Stern's (1967) linear theory are limited to the domain which exists only before the interleaving gradients approach the mean gradients. In contrast, most observations of interleaving have been made after the interleaving has become nonlinear, since this phenomenon usually escapes notice until it becomes significantly nonlinear. However, once the interleaving exists, both salt fingering and diffusive regimes will exist, and will continue to drive the interleaving, probably even more vigorously than during the earlier linear process. Our linear DDI flux estimates are therefore conservative; a DDI model valid in the nonlinear domain would predict faster feedback to the mesoscale. This gap between the observation and theory of double-diffusively driven interleaving suggests the need for the development of nonlinear theory. Both numerical and analytic work in this area is progressing with one of us (ESP).

Another respect in which the theory used here is not strictly applicable to our examples is Stern's (1967) assumption that the mean fields are barotropic. While this assumption is not essential to the validity of the mechanism proposed here, it does affect quantitatively the DDI properties. Since baroclinic effects have not yet been included in DDI models, it is not yet possible to estimate quantitatively the role that baroclinicity can play in the DDI fluxes. In addition, theory must be extended to include DDI with horizontal scales comparable to or greater than frontal widths.

Finally, future models of feedback between DDI and mesoscale gradients should include viscous effects on DDI, as considered by Toole and Georgi (1981).

In the warm salty intrusions of the DDI, buoyancy is increased by salt fingering. As noted by Stern (1967), this causes the velocity in the warm salty intrusions to have positive (upward) diapycnal components, as sketched for the intrusion labelled *WS* in Figure 2B. Therefore, the diapycnal components of DDI fluxes always contribute to the amplification of the ring's properties.

Epipycnal DDI fluxes, however, must be opposite the epipycnal derivatives of T and S, which may be of either sign depending on the isopycnal slope (even though the x-derivatives of T and S are always negative in the front around a warm core ring). In the example given here, the epipycnal derivatives are positive, so the epipycnal fluxes are negative, and contribute further to the positive feedback caused by the diapycnal fluxes. In contrast, scenarios with negative epipycnal derivatives of T and S would cause the core velocities to reverse their epipycnal components. The epipycnal fluxes will therefore not necessarily cause positive feedback across all fronts.

It is of interest to examine the general conditions under which double-diffusive interleaving will cause positive feedback. We consider here the slightly narrower question of when positive feedback will occur in fronts of the same geometry as in Figure 2—a trapezoidal front in which gradients are constant. Our criterion for positive feedback is that, within the frontal region, the buoyancy flux must have a component normal to the oblique boundaries of the frontal region (parallel to f in Fig. 2B) which is toward the warm, salty, more buoyant side of the front. That is, F_f for buoyancy, given by Eq. (6), must be positive, or

$$F_e/F_d < \cot(\beta - \alpha). \tag{7}$$

Since there is no generally accepted model describing F_e and F_d in fully-developed baroclinic interleaving, condition (7) cannot be further explored at this time.

Based on a model of an eddy field not directly comparable with ours, and on the laboratory results of Ruddick and Turner (1979), Garrett (1982) argued that, while F_d may be significant in some regions, and may be negative for heat, the probable dominance of F_e would prevent observable consequences of F_d. Since our eddy model and interleaving model are different from Garrett's, his results are not necessarily irreconcilable with our conclusions that both F_d and F_e may contribute to the growth of mesoscale gradients. Even in cases where the sense of F_e opposes this mechanism the cross-frontal components of F_d may be greater than those of F_e.

We do not attempt here to describe thé mechanism for continuing the fluxes, caused by DDI within the front, into the interior or exterior water masses. However, it is clear that some such mechanism must exist; otherwise, extremely large convergences at the boundaries of fronts would produce structures unable to escape notice in the field. This is analogous, on a larger scale, to the question of how microscale fluxes within 1 m steps are continued into the 20 m layers—it is clear that the fluxes are continued, but the mechanisms are still unknown.

As to field observations, attempts should be made to test the predictions of the along-front tilts of intrusions made by various models. Previous experiments have not focused on this along-front tilt. Also careful salt, heat and buoyancy budget studies could provide a practical test of the hypothesis.

The evolution of individual layers of interleaving is difficult to document. Nevertheless the statistical properties of interleaving and their relation to mesoscale gradients can be assessed by judicious use of theory and observation. There is considerable scope for immediate work and results in this area.

The hypothesis and consequent testing can be extended to include feedback between DDI and any mesoscale or larger features which have enigmatically large persistence. For example, DDI may also operate to maintain quasi-permanent fronts between warm salty water and cold fresh water such as the subtropical front in the North Pacific (Roden, 1975). Here the DDI could feed back potential energy to maintain the gyre circulation; a transfer of energy across even larger scales than the ring case.

If testing of the hypothesis suggested here supports the significance of DDI in feedback to mesoscale and larger-scale features, it may become necessary to study further the parameterization of both epipycnal and diapycnal fluxes due to DDI, and to consider the inclusion of such results in numerical models of mesoscale through global scale circulation.

In conclusion we have quantitatively demonstrated the feasibility of the hypothesis that fluxes caused by DDI within a ring front in some cases may be adequate to enhance the temperature, salinity, and buoyancy signatures of some mesoscale features. Models of DDI used to study further this feedback should include viscosity, nonlinearity, mean baroclinicity, and mean thermohaline gradients of limited spatial extent. Field tests of both the DDI concept and the feedback to mesoscale structure hypothesized here should be possible. It may be necessary to include fluxes caused by DDI in mesoscale and larger-scale numerical models.

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