

Contrasting the interleaving in two baroclinic ocean fronts

Brian D. May^{a,*}, Dan E. Kelley^b

^a *Large Lakes Observatory, University of Minnesota Duluth,
10 University Drive, Duluth, MN 55803, USA*

^b *Department of Oceanography, Dalhousie University, Halifax, NS, Canada B3H 4J1*

Received 7 September 2000; received in revised form 27 March 2002; accepted 2 April 2002

Abstract

To investigate the effects of baroclinicity on frontal interleaving, we contrast the interleaving characteristics of two fronts, one in the Arctic Ocean and the other surrounding a Mediterranean salt lens (Meddy). The Meddy is broken into two parts based on the vertical temperature and salinity structure, so our comparison involves three sets of interleaving observations. The cross-front slopes of intrusions relative to horizontal and isopycnal surfaces are taken to be key diagnostics of the interleaving dynamics. Assuming the observed slopes match those that were present during the initial growth of interleaving, we use an instability theory to infer the dominant form of double diffusion that was active during the growth stage. Then, to investigate the observed interleaving, we use a steady-state model to infer the dominant form of double diffusion at the time of observation. In the Arctic Ocean front, it appears that different forms of double diffusion dominated the two stages of interleaving (salt fingering during the growth stage and diffusive convection at steady state). In contrast, in the Meddy, the same form of double diffusion appears to have dominated both stages of interleaving (salt fingering in the lower part of the Meddy, diffusive convection in the upper part). In the Arctic Ocean front, the observations suggest that interleaving was driven by baroclinicity as well as double diffusion. In both parts of the Meddy, however, driving was by double diffusion only. Motivated by these differences, we suggest a new intrusion classification scheme, based on the slopes of intrusions relative to horizontal and isopycnal surfaces.

© 2002 Elsevier Science B.V. All rights reserved.

Keywords: Oceanic fronts; Oceanic eddies; Water mass intrusions; Finestructure; Double diffusion; Water mixing; Atlantic Ocean; Arctic Ocean

* Corresponding author.

E-mail addresses: bmay@d.umn.edu (B.D. May), dan.kelley@dal.ca (D.E. Kelley).

1. Introduction

Thermohaline intrusions are often observed in vertical profiles of temperature and salinity in the ocean. They are made visible by large fluctuations, or inversions, in the profiles and as zig-zag patterns in temperature–salinity plots. These features typically have vertical scales of 10–100 m and horizontal scales of 1–100 km (Stommel and Fedorov, 1967; Joyce et al., 1978; Perkin and Lewis, 1984; Ruddick and Hebert, 1988). In the presence of horizontal gradients of temperature and salinity, the intrusive signature may be produced by vertically-alternating lateral currents across ocean fronts. These interleaving motions are thought to be driven by buoyancy forces arising from perturbations in the density field, e.g. produced by differential mixing of heat and salt by double diffusion (Stern, 1967; Ruddick and Turner, 1979).

Most theoretical studies of double-diffusive interleaving are based on instability models, which predict the growth of interleaving from random perturbations in a front (Stern, 1967; Toole and Georgi, 1981; McDougall, 1985a). Early models of double-diffusive interleaving were developed for barotropic thermohaline fronts, which have density-compensating horizontal gradients of temperature and salinity and no vertical shear. Effects of baroclinicity were first considered by Kuzmina and Rodionov (1992), who predicted that double-diffusive interleaving would be diminished in baroclinic fronts due to an increase in shear-driven turbulence. The combined effects of turbulence and double diffusion have been considered further by Walsh and Ruddick (2000) and Kuzmina and Zhurbas (2000). In addition, Kuzmina and Rodionov (1992) found two different mechanisms for intrusion growth in baroclinic fronts: double-diffusive forcing and baroclinic forcing. Baroclinicity will act as a driving mechanism if the intrusion slope lies in the “wedge” of baroclinic instability, i.e. between horizontal and isopycnal surfaces (May and Kelley, 1997). After the growth stage, interleaving is thought to evolve toward a steady state in which advective fluxes of temperature and salinity along intrusions are balanced by double-diffusive fluxes between intrusions. Models of steady-state interleaving have been developed by McDougall (1985b), Walsh and Ruddick (1998) and Merryfield (2000).

In a recent study of thermohaline intrusions in the Arctic Ocean, May and Kelley (2001) applied instability and steady-state models to intrusions observed north of Svalbard (Perkin and Lewis, 1984). Based on observed intrusion slopes, it was suggested that the interleaving was likely driven by salt fingering during the growth of the intrusions, but that diffusive convection was likely the dominant form of double diffusion at steady state. An outstanding question is whether this is a common occurrence, i.e. whether one form of double diffusion often dominates the instability stage with a second form of double diffusion dominating at steady state. In addition, May and Kelley (2001) found that the Arctic interleaving was likely driven by baroclinicity as well as salt fingering during the growth stage. It is not yet known whether this behavior is common in other interleaving fronts.

In this study, we extend the analysis of May and Kelley (2001) to intrusions observed in a Mediterranean salt lens (i.e. Meddy). Meddy Sharon is a warm, salty lens of Mediterranean water that was observed in the eastern North Atlantic from 1984 to 1986 (Armi et al., 1989). During the period of observation, its heat, salt and velocity characteristics were gradually eroded away by lateral interleaving (Ruddick and Hebert, 1988; Hebert et al., 1990). The Meddy has been well-studied and evidence has been presented that the thermo-

haline intrusions were double-diffusively driven (Ruddick, 1992). Based on the slopes of intrusions relative to isopycnal surfaces, Ruddick used a steady-state model to infer that the double-diffusive fluxes between intrusions were dominated by salt fingering in the lower part of the Meddy and by diffusive convection in the upper part. Ruddick noted a link between the dominant form of double diffusion and the background stratification, which was appropriate for salt fingering in the lower part of the Meddy and diffusive convection in the upper part. More recently, May and Kelley (1997) used Meddy Sharon as a test case for an instability model of interleaving in baroclinic fronts. They found the observed slopes in the lower part of the Meddy were consistent with a dominance of salt fingering during the initial growth of interleaving. There are a number of outstanding questions regarding the Meddy intrusions. Does diffusive convection dominate the growth stage of the upper intrusions, as it does at steady state? What is the role of baroclinicity in driving the intrusive motions? What are the relative magnitudes of the salt-finger and diffusive-convection fluxes at steady state? We address these questions here. In addition, a significant goal of this study is to contrast the Meddy intrusions with those observed in the Arctic Ocean front.

We begin by reviewing the relevant theory, focusing on the differences between the growth and steady-state stages of interleaving and on the role of baroclinicity in driving intrusive motions (Section 2). Then, we outline the dynamically relevant characteristics of the Arctic and Meddy fronts, especially two key interleaving parameters—the cross-front intrusion slope and the along-intrusion density ratio (Section 3). We compare the observed characteristics with those predicted by instability theory to determine the dominant form of double diffusion during the growth stage (Section 4). Then, we apply a steady-state theory to determine the dominant form of double diffusion at the time of observation (Section 5). Motivated by the results, we develop a new classification scheme for intrusions based on the slopes of intrusions relative to horizontal and isopycnal surfaces (Section 6). Finally, we consider the intensity of interleaving as it relates to frontal baroclinicity (Section 7).

2. Theory

Intrusions are thought to arise from lateral currents across thermohaline fronts in the ocean. The idea is that, in the presence of large horizontal gradients of temperature and salinity, vertically-varying lateral motions alter the profiles of temperature and salinity, which gives rise to regions of enhanced double-diffusive mixing (i.e. salt fingering or diffusive convection). The density perturbations caused by the double-diffusive density fluxes lead to buoyancy forces that can then reinforce the intrusive flow. It is thought that intrusions begin as random perturbations (whether infinitesimal or finite-amplitude) to a frontal zone. Under the influence of double diffusion, these perturbations grow, exponentially according to instability theory. Ultimately, due to the competing influences of the two forms of double diffusion (salt fingering under warm salty intrusions and diffusive convection above), the intrusion growth may be quenched and the intrusive motions approach a steady state. Thus, it is instructive to analyse two stages in the development of intrusions: a “growth” stage in which intrusions grow to large amplitude from initial random perturbations and a “steady state” stage in which the intrusions have reached their maximum amplitude (Fig. 1).

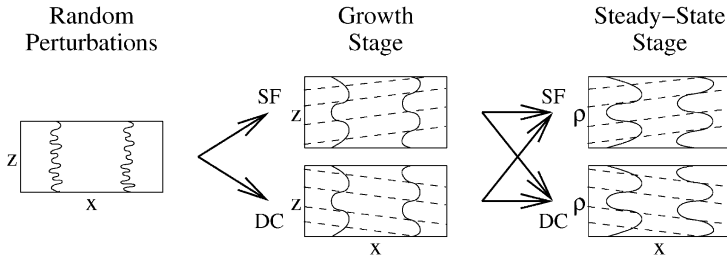


Fig. 1. Diagram illustrating the evolution of intrusions from random perturbations to the growth and steady-state stages of interleaving. During the growth stage, the dominant form of double diffusion (SF or DC) determines the slope of intrusions relative to horizontal surfaces (i.e. $z = \text{constant}$). In contrast, at steady state the dominant form of double diffusion (SF or DC) is linked to the slope of intrusions relative to isopycnal surfaces (i.e. $\rho = \text{constant}$).

2.1. Growth stage of interleaving

During the growth stage of interleaving, it is thought that one form of double diffusion dominates, so that the other form can be neglected. Thus, instability models of interleaving include parameterizations for salt fingering or diffusive convection, but not both. It is not yet established what determines the dominant form of double diffusion during the growth stage of interleaving. If the background stratification is appropriate for double diffusion, then it is likely that the type of stratification plays a role. If the background stratification is appropriate for salt fingering then salt fingering should dominate; if the stratification is appropriate for diffusive convection then diffusive convection should dominate. In these fronts, initial perturbations can be reinforced by double diffusion regardless of their size. If the background stratification is stably stratified with respect to double diffusion, then it is not at all clear which form should dominate. Regardless, in these fronts, the initial perturbations must be large enough to form inversions in the profiles of temperature and salinity upon which double diffusion can occur (McDougall, 1985a). These finite-amplitude perturbations may arise from internal waves or they may arise from instabilities dependent on differential mixing of mass and momentum (McIntyre, 1970), or differential mixing of temperature and salinity by molecular diffusion (Holyer, 1983) or low Reynold's number turbulence (Hebert, 1999; Merryfield, 2001).

During the growth stage of interleaving, the expected slope of intrusions depends on the form of double diffusion acting. If salt fingering is the dominant form of double diffusion, then the downward density fluxes below warm salty intrusions will cause them to become anomalously light. Therefore, the motions will be reinforced by the resulting buoyancy forces only if the warm salty intrusions slope upward (relative to horizontal surfaces) across the front (Fig. 1). In contrast, if diffusive convection is the dominant form of double diffusion, the motions will be reinforced only if the warm salty intrusions slope downward (relative to horizontal surfaces) across the front. Note that because gravity acts perpendicular to horizontal geopotential surfaces, it is the slope of intrusions relative to horizontal surfaces that is important during the growth stage.

We define this cross-front intrusion slope as

$$s = \left. \frac{\partial z}{\partial x} \right|_l, \quad (1)$$

where z is the vertical position relative to horizontal geopotential surfaces, x the cross-front distance along horizontal geopotential surfaces and l denotes the derivative taken along an intrusion. As a convention, we will assume that x increases toward the cold fresh side of the front, so that $s > 0$ for warm salty intrusions sloping upward across the front. Instability theories predict the range of unstable intrusion slopes. If salt fingering is the dominant form of double diffusion during the growth state, the cross-front intrusion slope should be in the range (May and Kelley, 1997)

$$0 < s < -\frac{\alpha \bar{\theta}_x - \gamma_f \beta \bar{S}_x}{\alpha \bar{\theta}_z - \gamma_f \beta \bar{S}_z}, \quad (2)$$

where $\bar{\theta}_x$ and \bar{S}_x are the mean cross-front horizontal gradients of potential temperature and salinity, respectively, $\bar{\theta}_z$ and \bar{S}_z the mean vertical gradients of potential temperature and salinity, respectively, α the thermal expansion coefficient, β the haline contraction coefficient and γ_f is the non-dimensional flux ratio for salt fingering. For salt fingering, the flux ratio is defined by $\gamma_f = \alpha F_\theta^f / \beta F_S^f$, where F_θ^f and F_S^f are the vertical fluxes of temperature and salinity, respectively. In contrast, if diffusive convection is the dominant form of double diffusion, the range of unstable intrusion slopes is

$$-\frac{\gamma_d \alpha \bar{\theta}_x - \beta \bar{S}_x}{\gamma_d \alpha \bar{\theta}_z - \beta \bar{S}_z} < s < 0, \quad (3)$$

where γ_d is the flux ratio for diffusive convection, defined by $\gamma_d = \beta F_S^d / \alpha F_\theta^d$, where F_θ^d and F_S^d are the vertical temperature and salinity fluxes due to diffusive convection, respectively.

A quantity related to the cross-front intrusion slope is the along-intrusion density ratio

$$R_l = \left. \frac{\alpha \partial \theta}{\beta \partial S} \right|_l. \quad (4)$$

The along-intrusion density ratio is the non-dimensional slope of intrusions in temperature–salinity space and is a convenient measure of intrusion slope relative to isopycnal surfaces (i.e. $R_l < 1$ for warm salty intrusions sloping upward relative to isopycnals). Noting that the density ratio is linked to the intrusion slope by $R_l = (\alpha \bar{\theta}_x + s \alpha \bar{\theta}_z) / (\beta \bar{S}_x + s \beta \bar{S}_z)$, (2) and (3) can be used to predict the range of unstable along-intrusion density ratios. If salt fingering is the dominant form of double diffusion during the growth stage, one would expect an along-intrusion density ratio in the range $\gamma_f < R_l < R_h$, where R_h is the horizontal density ratio defined by $R_h = \alpha \bar{\theta}_x / \beta \bar{S}_x$. In contrast, with diffusive convection as the dominant form of double diffusion, the along-intrusion density ratio should be in the range $R_h < R_l < 1/\gamma_d$.

Under the assumption that the intrusion slope is set during the growth stage and remains unchanged to the time of observation, these relationships yield a method for determining the dominant form of double diffusion during the initial growth of interleaving. By estimating the intrusion slope (relative to horizontal surfaces) and comparing with the predictions of (2) and (3), one may be able to infer the form of double diffusion that was dominant during

the growth stage. Alternatively, one may compare the observed along-intrusion density ratio with the predicted values.

In baroclinic fronts, double diffusion does not provide the only energy source for interleaving. If the intrusion slope lies between the slopes of horizontal and isopycnal surfaces, i.e. in the “wedge” of baroclinic instability, intrusive motions will be driven by baroclinicity as well as double diffusion (Kuzmina and Rodionov, 1992; May and Kelley, 1997). To determine the relative importance of the double-diffusive and baroclinic driving terms, one may consider the evolution of temperature and salinity in an intrusion, given by

$$\frac{\partial \theta}{\partial t} = -u \frac{\partial \theta}{\partial l} - \frac{1}{H} F_{\theta}, \quad (5)$$

$$\frac{\partial S}{\partial t} = -u \frac{\partial S}{\partial l} - \frac{1}{H} F_S, \quad (6)$$

where u is the along-intrusion velocity, $\partial \theta / \partial l$ and $\partial S / \partial l$ are the along-intrusion gradients of temperature and salinity, respectively, H is the intrusion thickness, and F_{θ} and F_S are the temperature and salinity fluxes, respectively, out of the layer due to double diffusion (i.e. either salt fingering or diffusive convection). We note that the non-dimensional ratio of the advective temperature and salinity terms is equal to the along-intrusion density ratio R_l and the ratio of the double-diffusive terms is equal to the flux ratio (γ_f for salt fingering, γ_d for diffusive convection). Under the assumption that double diffusion completely removes the advective salinity (salt fingering) or temperature (diffusive convection) perturbation, it is possible to determine the relative magnitude of the various terms in (5) and (6). These are indicated in Table 1, where the corresponding density terms were computed from $(1/\rho)(\partial \rho / \partial t) = \beta(\partial S / \partial t) - \alpha(\partial \theta / \partial t)$. The relative magnitude of the advective and

Table 1
Relative magnitude of the terms in the temperature–salinity conservation equations^a

	Salinity ($\beta(\partial S / \partial t)$)	Temperature ($\alpha(\partial \theta / \partial t)$)	Density ($(1/\rho)(\partial \rho / \partial t)$)
(a) Growth stage, salt fingering dominant			
Advection	1	R_l	$1 - R_l$
Salt fingering	-1	$-\gamma_f$	$-(1 - \gamma_f)$
Net	0	$R_l - \gamma_f$	$-(R_l - \gamma_f)$
(b) Growth stage, diffusive convection dominant			
Advection	1	R_l	$1 - R_l$
Diffusive convection	$-\gamma_d R_l$	$-R_l$	$(1 - \gamma_d) R_l$
Net	$1 - \gamma_d R_l$	0	$1 - \gamma_d R_l$
(c) Steady-state stage			
Advection	1	R_l	$1 - R_l$
Salt fingering	$-(1 - \gamma_d R_l) / (1 - \gamma_d \gamma_f)$	$-\gamma_f (1 - \gamma_d R_l) / (1 - \gamma_d \gamma_f)$	$-(1 - \gamma_f)(1 - \gamma_d R_l) / (1 - \gamma_d \gamma_f)$
Diffusive convection	$-\gamma_d (R_l - \gamma_f) / (1 - \gamma_d \gamma_f)$	$-(R_l - \gamma_f) / (1 - \gamma_d \gamma_f)$	$(1 - \gamma_d)(R_l - \gamma_f) / (1 - \gamma_d \gamma_f)$
Net	0	0	0

^a Quantities have been arbitrarily normalized to the advective salinity term.

double-diffusive density terms yields a quantitative estimate of the relative importance of baroclinicity and double diffusion in driving intrusive motions. With salt fingering dominant, this ratio is $(R_l - 1)/(1 - \gamma_f)$; with diffusive convection dominant, it is $(1 - R_l)/[(1 - \gamma_d)R_l]$.

2.2. Steady-state stage of interleaving

In order to reach a steady state, the double-diffusive fluxes of temperature, salinity and density between intrusions must balance advective fluxes along intrusions. If a warm salty intrusion slopes upward relative to isopycnal surfaces, then advection along the intrusion will lead to a local (i.e. Eulerian) increase in density. In order to maintain a steady state (i.e. $\partial\rho/\partial t = 0$), double diffusion must lead to a corresponding density decrease. This requires that the salt-finger density fluxes exceed those of diffusive convection. In contrast, if a warm salty intrusion slopes downward relative to isopycnal surfaces, a dominance of diffusive convection is required. Thus, the dominant form of double diffusion at steady state can be linked directly to the slope of intrusions relative to isopycnal surfaces (Fig. 1).

The discussion above suggests a method for inferring the dominant form of double diffusion at steady state. By estimating the observed slope of intrusions relative to isopycnal surfaces, one may be able to determine the dominant form of double diffusion at the time of observation. This technique was employed by Ruddick (1992) to infer that the intrusions in the lower part of Meddy Sharon were dominated by salt fingering while those in the upper part were dominated by diffusive convection. Here, we use the along-intrusion density ratio as an easily observed measure of the slope of intrusions relative to isopycnals. If $R_l < 1$, warm salty intrusions slope upward relative to isopycnals, which suggests a dominance of salt fingering. In contrast, if $R_l > 1$, warm salty intrusions slope downward relative to isopycnals, which suggests a dominance of diffusive convection.

To determine the relative magnitudes of the salt-finger and diffusive-convection fluxes, one may consider the steady-state temperature–salinity balance, given by

$$\frac{\partial\theta}{\partial t} = -u\frac{\partial\theta}{\partial l} - \frac{1}{H}F_\theta^f - \frac{1}{H}F_\theta^d = 0, \quad (7)$$

$$\frac{\partial S}{\partial t} = -u\frac{\partial S}{\partial l} - \frac{1}{H}F_S^f - \frac{1}{H}F_S^d = 0. \quad (8)$$

Noting that the advective terms are related by the along-intrusion density ratio R_l and the double-diffusive terms are related by the flux ratios γ_f and γ_d , it is possible to solve for the relative magnitudes of the various terms in (7) and (8). These are outlined in Table 1, where the corresponding density terms are given by $(1/\rho)(\partial\rho/\partial t) = (\beta)(\partial S/\partial t) - (\alpha)(\partial\theta/\partial t)$. The relative magnitude of the salt-finger and diffusive-convection density terms yields a quantitative estimate of the relative importance of salt fingering and diffusive convection at steady state, given by

$$\Gamma = \frac{(1 - \gamma_f)(1 - \gamma_d R_l)}{(1 - \gamma_d)(R_l - \gamma_f)}. \quad (9)$$

Note that $\Gamma > 1$ if $R_l < 1$ (i.e. salt fingering dominates if warm salty intrusions rise relative to isopycnals). Similarly, $\Gamma < 1$ if $R_l > 1$ (i.e. diffusive convection dominates if warm salty intrusions fall relative to isopycnals).

It is important to note that the dominant form of double diffusion may not be the same at steady state as it is during the growth of interleaving. In particular, if the intrusions slope between horizontal and isopycnal surfaces, then the slopes of intrusions relative to horizontal and isopycnal surfaces will be of different sign and the inferred forms of double diffusion will be different. For example, if intrusions slope upward relative to horizontal surfaces, but downward relative to isopycnals surfaces, this would imply a dominance of salt fingering during the growth of interleaving but a dominance of diffusive convection at steady state. The multiple pathways (i.e. arrows) in Fig. 1 allow for different dominant forms of double diffusion during the two stages of interleaving.

3. Observations

In order to investigate effects of baroclinicity, we compare the growth and steady-state stages of interleaving in two fronts in which interleaving has been observed in detail. One front is in the Arctic Ocean and the other is at the edge of a Mediterranean salt lens (i.e. Meddy). The Meddy front will be divided into lower and upper parts so our comparison will thus involve three sets of interleaving observations. These fronts were carefully chosen based on availability of suitable intrusion observations, in particular, observations of intrusion slopes relative to horizontal and isopycnal surfaces. Furthermore, the three cases represent examples of the three possible stratification types. The lower part of the Meddy is stratified appropriately for salt fingering, the upper part is stratified appropriately for diffusive convection, while the Arctic Ocean front is stably stratified with respect to double diffusion.

3.1. Arctic Ocean front

We consider intrusions observed north of Svalbard in the Arctic Ocean (Perkin and Lewis, 1984). Recently, we performed an analysis of the intrusions (May and Kelley, 2001) and we use the results of that study here. Background gradients are summarized in Table 2. In the depth range with observed intrusions (250–550 m) temperature increases upward and salinity decreases upward. The vertical density ratio $R_\rho = \alpha \bar{\theta}_z / \beta \bar{S}_z < 0$, indicating that the stratification is not appropriate for either type of double diffusion. Temperature and salinity both decrease horizontally moving northward across the front. The horizontal density ratio $R_h = \alpha \bar{\theta}_x / \beta \bar{S}_x > 1$, which indicates that the temperature gradient is larger (in density terms) than the salinity gradient. Density increases horizontally so the background isopycnals slope upward across the front ($s_\rho = -\bar{\rho}_x / \bar{\rho}_z > 0$).

In May and Kelley (2001), intrusions were tracked roughly 300 km across the front. The cross-front intrusion slope and along-intrusion density ratio were estimated by linear regression along the intrusions (Table 2). The cross-front slope $s > 0$, indicating that warm salty intrusions slope upward relative to horizontal surfaces across the front. In contrast, the along-intrusion density ratio ($R_l > 1$) indicates that warm salty intrusions slope downward relative to isopycnal surfaces. Thus, the intrusions slope between horizontal and isopycnal surfaces, as illustrated in Fig. 2.

Table 2
Frontal and intrusion properties^a

	Arctic Ocean front	Meddy Sharon (lower)	Meddy Sharon (upper)
(a) Background gradients			
$\bar{\theta}_x$ ($^{\circ}\text{C m}^{-1}$)	$(-2.3 \pm 0.4) \times 10^{-6}$	$(-1.3 \pm 0.2) \times 10^{-4}$	$(-5.5 \pm 0.8) \times 10^{-5}$
$\bar{\theta}_z$ ($^{\circ}\text{C m}^{-1}$)	$(1.6 \pm 0.2) \times 10^{-3}$	$(8.5 \pm 0.7) \times 10^{-3}$	$(-2.5 \pm 0.8) \times 10^{-3}$
\bar{S}_x (psu m^{-1})	$(-5.9 \pm 2.6) \times 10^{-8}$	$(-3.0 \pm 0.6) \times 10^{-5}$	$(-1.6 \pm 0.2) \times 10^{-5}$
\bar{S}_z (psu m^{-1})	$(-3.0 \pm 0.8) \times 10^{-4}$	$(1.1 \pm 0.2) \times 10^{-3}$	$(-1.9 \pm 0.4) \times 10^{-3}$
$\bar{\rho}_x$ (kg m^{-4})	$(1.4 \pm 0.3) \times 10^{-7}$	$(2.8 \pm 0.7) \times 10^{-6}$	$(-1.0 \pm 0.9) \times 10^{-6}$
$\bar{\rho}_z$ (kg m^{-4})	$(-3.7 \pm 0.6) \times 10^{-4}$	$(-7.8 \pm 0.4) \times 10^{-4}$	$(-9.9 \pm 1.0) \times 10^{-4}$
(b) Calculated background quantities			
R_{ρ}	-0.5 ± 0.2	1.9 ± 0.2	0.34 ± 0.14
R_h	4 ± 2	1.12 ± 0.04	0.92 ± 0.07
s_{ρ}	$(3.8 \pm 1.0) \times 10^{-4}$	$(3.5 \pm 1.0) \times 10^{-3}$	$(-1.0 \pm 0.9) \times 10^{-3}$
(c) Observed intrusion properties			
s	$(2.7 \pm 0.6) \times 10^{-4}$	$(5.7 \pm 2.5) \times 10^{-3}$	$(-2.4 \pm 1.3) \times 10^{-3}$
R_l	1.6 ± 0.1	0.91 ± 0.08	1.16 ± 0.09
(d) Predicted intrusion properties, salt fingering dominant			
s	$0 < s < (5.8 \pm 1.7) \times 10^{-4}$	$0 < s < (10.6 \pm 3.2) \times 10^{-3}$	$0 < s < (11 \pm 10) \times 10^{-3}$
R_l	$0.6 \pm 0.2 < R_l < 4 \pm 2$	$0.6 \pm 0.2 < R_l < 1.12 \pm 0.04$	$0.6 \pm 0.2 < R_l < 0.92 \pm 0.07$
(e) Predicted intrusion properties, diffusive-convection dominant			
s	$(-0.7 \pm 1.5) \times 10^{-4} < s < 0$	$-\infty < s < 0$	$(-7.5 \pm 1.5) \times 10^{-3} < s < 0$
R_l	$4 \pm 2 < R_l < 7.5 \pm 2.5$	$1.12 \pm 0.04 < R_l < 7.5 \pm 2.5$	$0.92 \pm 0.07 < R_l < 7.5 \pm 2.5$

^a Uncertainties indicate 95% confidence limits.

3.2. Meddy Sharon

Following Ruddick (1992), we separate our analysis for the upper and lower parts of Meddy Sharon based on the vertical temperature and salinity structure. Mean gradients were obtained by linear regression of the seven “tow-yo” CTD profiles considered by Ruddick (1992) (Table 2). In the lower part of the Meddy (1000–1300 m depth), potential temperature and salinity both increase upward, so the background vertical stratification is appropriate for salt fingering ($R_{\rho} > 1$). The horizontal density ratio $R_h > 1$, which indicates that the horizontal temperature gradient is slightly larger (in density terms) than the salinity gradient. As a result, potential density increases horizontally away from the center of the Meddy, with isopycnals sloping upward across the front ($s_{\rho} > 0$). In the upper part of the Meddy (750–950 m depth), potential temperature and salinity both decrease upward, so the background vertical stratification is appropriate for diffusive convection ($0 < R_{\rho} < 1$). In this case, the horizontal density ratio $R_h < 1$, indicating that the horizontal temperature gradient is slightly smaller (in density terms) than the salinity gradient. Potential density decreases horizontally away from the center of the Meddy, so that isopycnals slope downward across the front ($s_{\rho} < 0$).

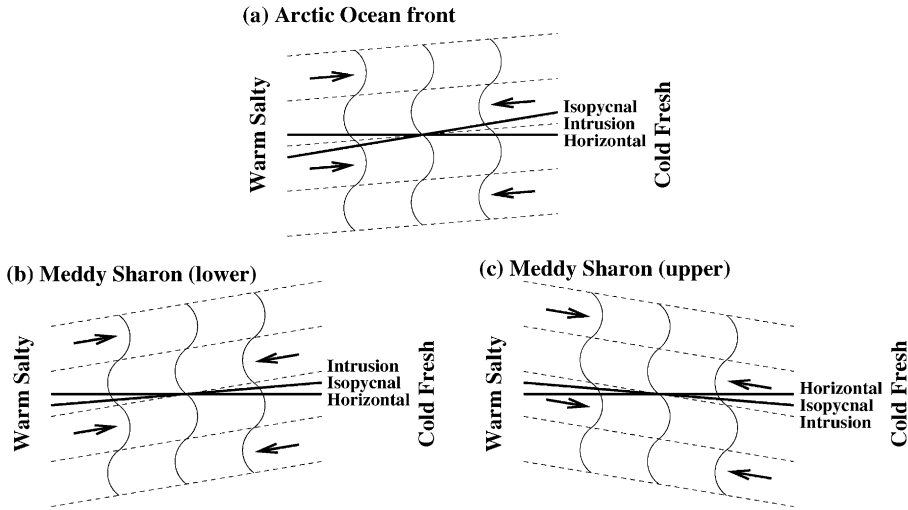


Fig. 2. Sketch of observed intrusion slopes for (a) the Arctic Ocean front, (b) the lower part of Meddy Sharon, and (c) the upper part of Meddy Sharon.

In his analysis, Ruddick (1992) tracked intrusions across the front, measuring the slope of the intrusions in density–salinity space. Taking values from his Table 1, we estimate the mean density–salinity slope of the intrusions (i.e. $\partial\rho/\partial S$) to be $0.07 \pm 0.06 \text{ kg m}^{-3} \text{ psu}^{-1}$ in the lower part of the Meddy and $-0.12 \pm 0.07 \text{ kg m}^{-3} \text{ psu}^{-1}$ in the upper part. We compute the along-intrusion density ratio from the density–salinity slope by noting that $R_l = 1 - 1/(\rho\beta) \partial\rho/\partial S$. The cross-front intrusion slopes were then calculated from the relationship $s = -(\alpha\bar{\theta}_x + R_l\beta\bar{S}_x)/(\alpha\bar{\theta}_z + R_l\beta\bar{S}_z)$. In the lower part of the Meddy, $s > 0$ and $R_l < 1$, indicating that intrusions slope upward relative to horizontal and isopycnal surfaces away from the center of the Meddy (Table 2). In the upper part of the Meddy, $s < 0$ and $R_l > 1$, which is consistent with intrusions sloping downward relative to horizontal and isopycnal surfaces across the front. In both cases, the intrusions slope in the same direction but more steeply than the background isopycnals (Fig. 2).

4. Growth stage of interleaving

As discussed in Section 2, the dominant form of double diffusion during the growth stage is thought to determine the slope of intrusions relative to horizontal surfaces. These slopes are illustrated in Fig. 2 for the three test cases. Warm salty intrusions slope upward relative to horizontal surfaces in the Arctic Ocean front and in the lower part of the Meddy. Thus, these slopes are consistent with a dominance of salt fingering during the growth stage. In contrast, in the upper part of the Meddy, warm salty intrusions slope downward relative to horizontal surfaces, which is consistent with a dominance of diffusive convection.

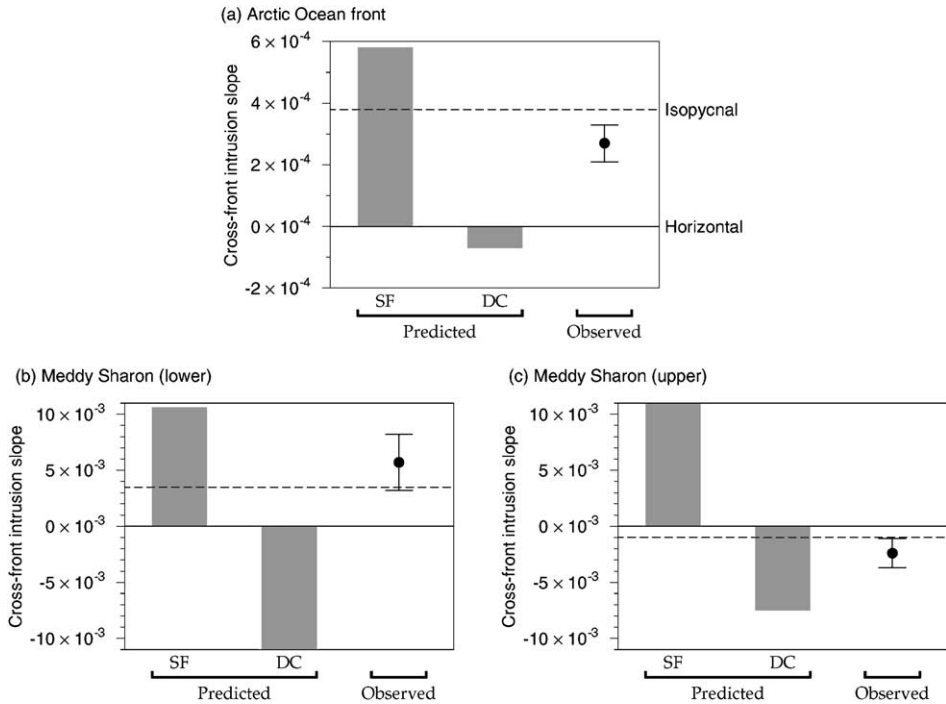


Fig. 3. Comparison of observed and predicted cross-front intrusion slopes for (a) the Arctic Ocean front, (b) the lower part of Meddy Sharon and (c) the upper part of Meddy Sharon. Unstable ranges (shaded) are illustrated for the salt-finger (SF) and diffusive-convection (DC) forms of double-diffusive interleaving. Bullets indicate the observed values. Solid and dashed lines indicate horizontal and isopycnal surfaces, respectively.

To put these ideas into a more quantitative context, we compare the observed slopes with those predicted by instability theory. For the predictions, we use background frontal properties from Table 2. We specify the salt-finger flux ratio $\gamma_f = 0.6 \pm 0.2$ (McDougall and Ruddick, 1992) and the diffusive-convection flux ratio $\gamma_d = 0.15 \pm 0.05$ (Kelley, 1990). For each front, we calculate the expected range of unstable slopes and along-intrusion density ratios assuming salt fingering dominates and assuming diffusive convection dominates (Table 2). In the Arctic Ocean front and in the lower part of Meddy Sharon, the observed slopes agree with the salt-finger predictions, but not with the diffusive-convection predictions (Fig. 3). In the upper part of Meddy Sharon, the observed slope agrees well with the diffusive-convection prediction, but not the salt-finger prediction. Thus, the comparison suggests that salt fingering was the dominant form of double diffusion during the growth of interleaving in the Arctic Ocean front and in the lower part of the Meddy, but that diffusive convection was the dominant form in the upper part of the Meddy.

In the Arctic Ocean front, the intrusions slope between horizontal and isopycnal surfaces, i.e. in the wedge of baroclinic instability (Figs. 2 and 3). In contrast, in both parts of the Meddy, the intrusions do not slope between horizontal and isopycnal surfaces. This suggests

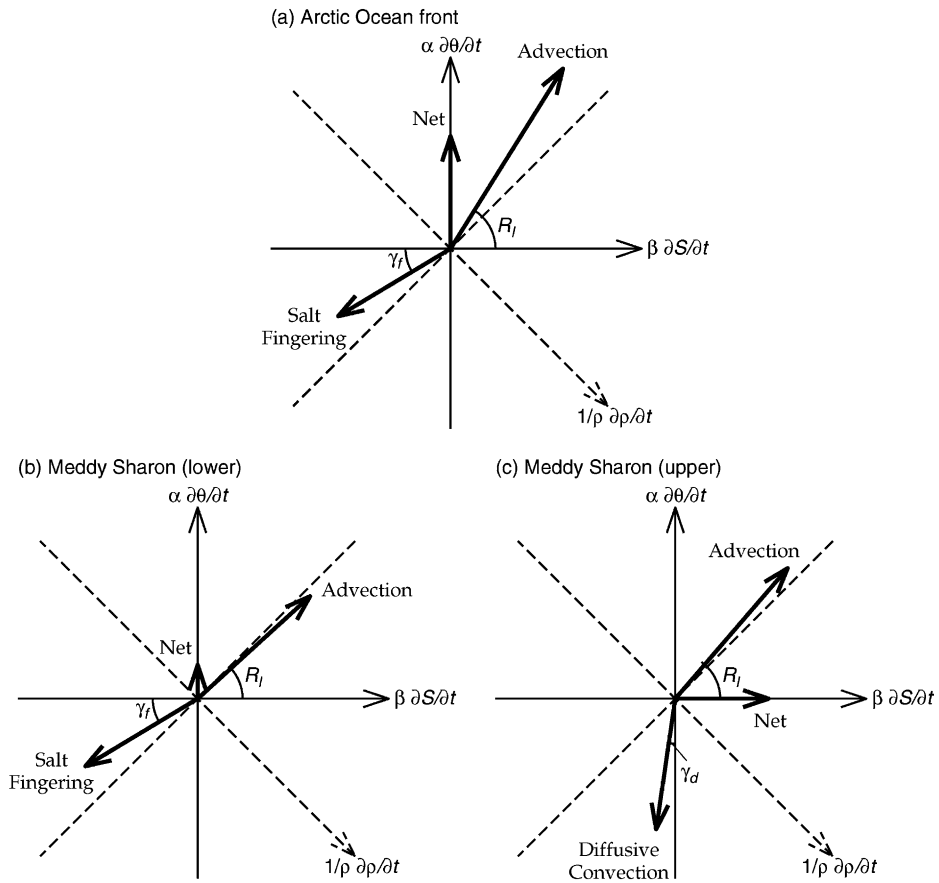


Fig. 4. Schematic illustrating the relative contributions of advection and double diffusion to the net growth of temperature–salinity perturbations in (a) the Arctic Ocean front, (b) the lower part of Meddy Sharon and (c) the upper part of Meddy Sharon.

that the intrusive motions were driven both by baroclinicity and by double diffusion in the Arctic front but that driving was by double diffusion only in the Meddy. To determine the relative importance of baroclinicity and double diffusion in each case, we calculate the relative contributions of advection and double-diffusion to the net temperature and salinity evolution using formulas in Table 1. The temperature–salinity terms are illustrated in Fig. 4 for the three interleaving cases. For the Arctic front, we estimate the ratio of the advective and double-diffusive density terms to be 1.8 ± 1.0 . The positive value is consistent with baroclinic driving of interleaving and the magnitude suggests that both baroclinicity and salt fingering contributed significantly to the growth. For the lower Meddy, we estimate the ratio to be -0.25 ± 0.25 and for the upper Meddy, we estimate the ratio to be -0.16 ± 0.08 . In both cases, the ratios are negative, indicating that the advective density perturbations oppose rather than enhance the motion.

5. Steady-state stage of interleaving

In contrast to the growth stage, at steady state it is the slope of intrusions relative to isopycnal surfaces that is linked to the dominant form of double diffusion. These slopes are illustrated in Figs. 2 and 3. As discussed by May and Kelley (2001), in the Arctic front, warm salty intrusions slope downward relative to isopycnals, which suggests that diffusive convection dominates at steady state. As discussed by Ruddick (1992), in the lower part of the Meddy, warm salty intrusions slope upward relative to isopycnals, which is consistent with a dominance of salt fingering. In the upper part of the Meddy, warm salty intrusions slope downward relative to isopycnals, consistent with a dominance of diffusive convection.

To determine quantitatively the relative importance of salt fingering and diffusive convection, we estimate the relative magnitude of the various terms in the temperature–salinity evolution equations (i.e. using formulas in Table 1). The steady state is illustrated in Fig. 5 for the three interleaving cases. We estimate the relative magnitude of the salt-finger and diffusive-convection density terms to be $\Gamma = 0.36 \pm 0.12$ for the Arctic Ocean front, $\Gamma = 1.5 \pm 0.5$ for the lower part of the Meddy and $\Gamma = 0.5 \pm 0.2$ for the upper part of the Meddy. In the lower Meddy, $\Gamma > 1$, which is consistent with a dominance of salt fingering. In contrast, in the upper Meddy and Arctic front, $\Gamma < 1$, which is consistent with a dominance of diffusive convection.

6. Intrusion classification scheme

During the growth stage of interleaving, the dominant form of double diffusion determines the slope of intrusions relative to horizontal surfaces. In contrast, during the steady-state stage, the dominant form of double diffusion is linked to the slope of intrusions relative to isopycnal surfaces. Thus, it is possible to classify intrusions based on these two slopes: the slope of intrusions relative to horizontal surfaces and the slope of intrusions relative to isopycnals.

Four possible slope combinations exist (Fig. 6) and can be explained as follows:

- (I) If warm, salty intrusions rise relative to horizontal surfaces and rise relative to isopycnal surfaces (rise/rise), then we can infer that (1) salt fingering dominates during the growth phase and (2) salt fingering dominates at steady state (SF/SF).
- (II) If warm, salty intrusions rise relative to horizontal surfaces but fall relative to isopycnal surfaces (rise/fall), then we can infer that (1) salt fingering dominates during the growth phase and (2) diffusive convection dominates at steady state (SF/DC).
- (III) If warm, salty intrusions fall relative to horizontal surfaces but rise relative to isopycnal surfaces (fall/rise), then we can infer that (1) diffusive convection dominates during the growth phase and (2) salt fingering dominates at steady state (DC/SF).
- (IV) If warm, salty intrusions fall relative to horizontal surfaces and fall relative to isopycnal surfaces (fall/fall), then we can infer that (1) diffusive convection dominates during the growth phase and (2) diffusive convection dominates at steady state (DC/DC).

In cases I and IV, the dominant form of double diffusion is the same during the growth and steady-state stages of interleaving. In contrast, in cases II and III, the dominant form of

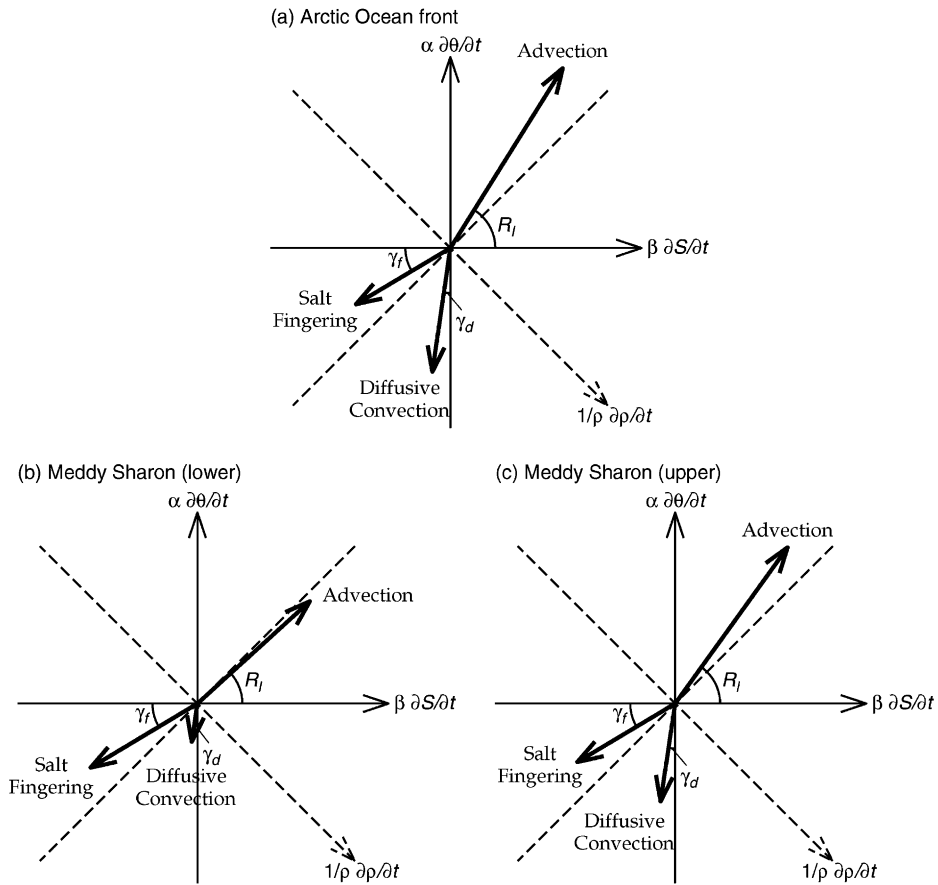


Fig. 5. Schematic illustrating the relative contributions of advection, salt fingering and diffusive convection to the steady-state temperature–salinity balance in (a) the Arctic Ocean front, (b) the lower part of Meddy Sharon and (c) the upper part of Meddy Sharon.

double diffusion during the growth stage is different than that at steady state. Also, in cases I and IV, the intrusion slope exceeds the isopycnal slope, so driving is by double diffusion only. In contrast, in cases II and III, the intrusions slope between horizontal and isopycnal surfaces so that intrusive motions are driven by baroclinicity as well as double diffusion. The test cases considered here fall into a number of these categories (compare Figs. 2 and 6). The Arctic Ocean intrusions are case II, the intrusions in the lower part of the Meddy are case I, and those in the upper part of the Meddy are case IV. We have not yet identified a set of case III intrusions.

A potential limitation of this classification scheme is that it requires detailed intrusion observations, i.e. slopes relative to horizontal and isopycnal surfaces. To address this, we construct a frontal classification scheme that can be applied without intrusion observations.

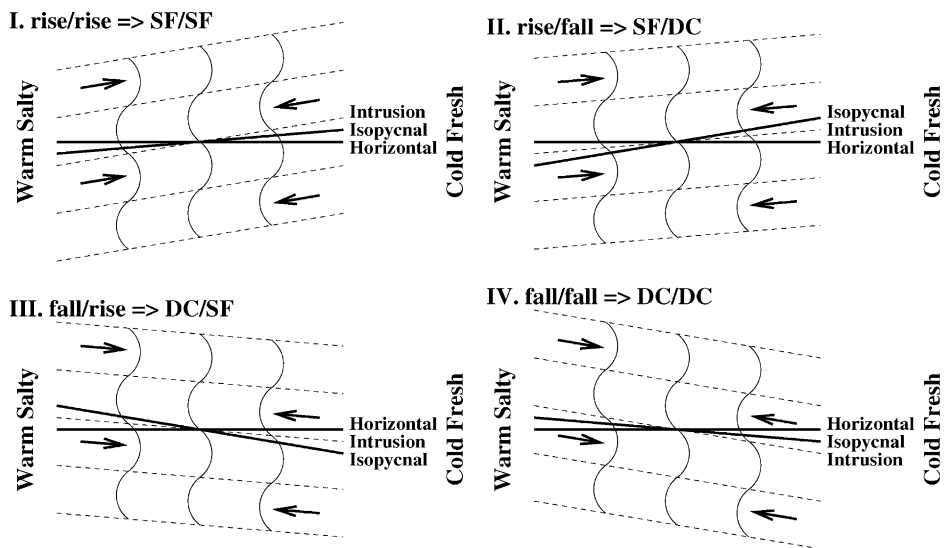


Fig. 6. Sketch illustrating the classification of intrusions based on whether warm salty intrusions rise or fall relative to horizontal surfaces and whether they rise or fall relative to isopycnal surfaces.

This scheme is based on two non-dimensional quantities describing a front, the horizontal density ratio R_h and the vertical density ratio R_ρ .

The first question is, for given values of R_h and R_ρ what form of double diffusion should dominate during the growth stage? In cases in which the background stratification is appropriate for double diffusion, we assume that salt fingering will dominate if the background stratification is appropriate for salt fingering (i.e. $R_\rho > 1$) and diffusive convection will dominate if the stratification is appropriate for diffusive convection (i.e. $0 < R_\rho < 1$). The cases in which the stratification is stable with respect to double diffusion (i.e. $R_\rho < 0$), we argue that the form of double-diffusive interleaving that dominates will be that with the fastest rate of growth. Noting that the growth rate is an increasing function of the maximum unstable slope (May and Kelley, 1997), the boundary between cases in which salt fingering dominates and diffusive convection dominates should occur roughly where the magnitudes of the maximum unstable slopes for the two forms of interleaving are equal, i.e. where

$$\left| \frac{\alpha \bar{\theta}_x - \gamma_f \beta \bar{S}_x}{\alpha \bar{\theta}_z - \gamma_f \beta \bar{S}_z} \right| = \left| \frac{\gamma_d \alpha \bar{\theta}_x - \beta \bar{S}_x}{\gamma_d \alpha \bar{\theta}_z - \beta \bar{S}_z} \right| \Rightarrow \left| \frac{R_h - \gamma_f}{R_\rho - \gamma_f} \right| = \left| \frac{\gamma_d R_h - 1}{\gamma_d R_\rho - 1} \right|. \quad (10)$$

This relationship allow a separation in R_h - R_ρ space between cases in which salt fingering dominates the growth stage (i.e. cases I and II) and cases in which diffusive convection dominates the growth stage (i.e. cases III and IV). This boundary is indicated as a solid line in Fig. 7.

The dominant form of double diffusion at steady state is linked to the slope of intrusions relative to isopycnal surfaces. Salt fingering will dominate at steady state if the intrusion slope is greater than the isopycnal slope, diffusive convection will dominate otherwise.

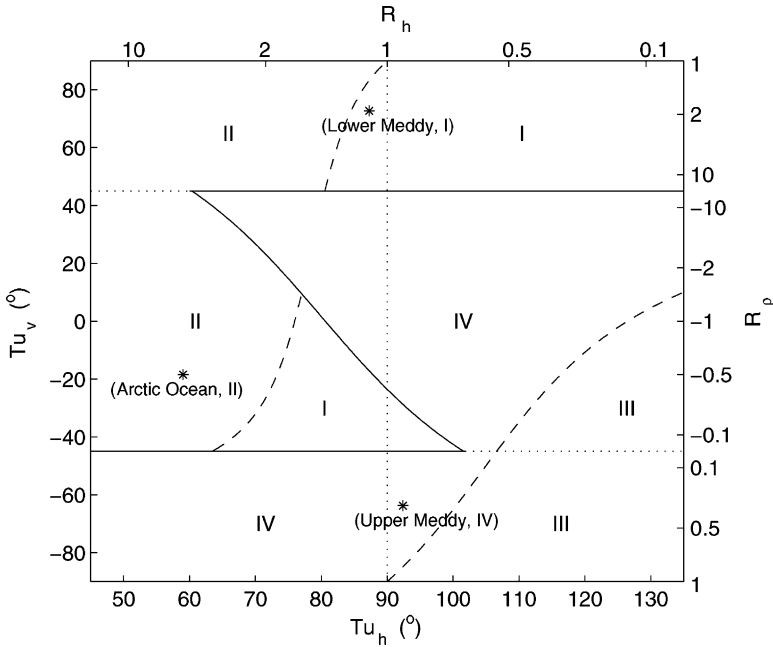


Fig. 7. Frontal classification based on horizontal density ratio R_h and vertical density ratio R_ρ . Solid and dashed lines separate regions where interleaving is predicted to be cases I–IV. Asterisks indicate test cases with classification based on observed intrusion slopes indicated in parentheses. Axes are linear in horizontal and vertical Turner angle, defined by $Tu_h = \tan^{-1}[(R_h + 1)/(R_h - 1)]$ and $Tu_v = \tan^{-1}[(R_\rho + 1)/(R_\rho - 1)]$, respectively.

But, what is the intrusion slope? We note that the optimum slope (i.e. the slope of the fastest-growing mode) is roughly half the maximum unstable slope (May and Kelley, 1997). Thus, if salt fingering dominates the growth stage (cases I and II), we take the intrusion slope to be half the maximum unstable slope given by (2). This yields a boundary between cases I and II where

$$-\frac{1}{2} \frac{\alpha \bar{\theta}_x - \gamma_f \beta \bar{S}_x}{\alpha \bar{\theta}_z - \gamma_f \beta \bar{S}_z} = -\frac{\bar{\rho}_x}{\bar{\rho}_z} \Rightarrow \frac{1}{2} \frac{R_h - \gamma_f}{R_\rho - \gamma_f} = \frac{R_h - 1}{R_\rho - 1}. \quad (10)$$

Similarly, if diffusive convection dominates the growth stage (cases III and IV), we take the intrusion slope to be half the maximum unstable slope given by (3). This yields a boundary between cases III and IV where

$$-\frac{1}{2} \frac{\gamma_d \alpha \bar{\theta}_x - \beta \bar{S}_x}{\gamma_d \alpha \bar{\theta}_z - \beta \bar{S}_z} = -\frac{\bar{\rho}_x}{\bar{\rho}_z} \Rightarrow \frac{1}{2} \frac{\gamma_d R_h - 1}{\gamma_d R_\rho - 1} = \frac{R_h - 1}{R_\rho - 1}. \quad (12)$$

These boundaries are indicated by dashed lines in Fig. 7.

Fig. 7 yields a scheme for predicting the intrusion classification (I, II, III or IV) based only on frontal-scale parameters R_h and R_ρ . This allows the prediction of (1) the dominant form of double diffusion during the growth stage and (2) the dominant form of double diffusion at steady state. As a first step in evaluating this new classification scheme, we have indicated

on Fig. 7 the position of each of our test cases (asterisks) and indicated in brackets the classification based on observed intrusion slopes. In each case, the classification based on intrusion slopes agrees with the classification predicted from frontal-scale R_h and R_ρ .

7. Intrusion intensity

While we have discussed intrusion slopes considerably, we have not made much mention of the magnitude of the intrusion perturbations. To put our observations in the context of other studies, we refer back to the analysis of Zhurbas et al. (1988) in which the intensity of interleaving was related to frontal baroclinicity. In that study, the intrusion intensity was defined by

$$J = \frac{\Delta T/H}{(T_l)_\rho}, \tag{13}$$

where ΔT is the amplitude of the observed intrusive temperature perturbation, H the layer thickness and $(T_l)_\rho$ is the cross-front gradient of temperature along isopycnals. The intrusion intensity was related to a baroclinicity parameter

$$\delta = \frac{\gamma_\rho}{f/N}, \tag{14}$$

where γ_ρ is the background isopycnal slope, f the Coriolis parameter and N is the buoyancy frequency. Using data from a number of locations, Zhurbas et al. (1988) observed an empirical relationship between J and δ , given by

$$\log J = 0.49 - 1.03 \log \delta. \tag{15}$$

Further studies have investigated these issues in detail (Kuzmina et al., 1994; Shapiro and Yemel'yanov, 1994), but the fundamental relationship discovered by Zhurbas et al. (1988) remains unchanged.

We proceed by calculating the baroclinicity parameter δ and intrusion intensity J for our three test cases. Background frontal parameters (i.e. γ_ρ , f , N , $(T_l)_\rho$) were estimated from quantities in Table 2. In the Arctic Ocean case, intrusion parameters (i.e. ΔT , H) were obtained from May and Kelley (2001), while in the Meddy cases, intrusion parameters were

Table 3
Calculation of baroclinicity parameter δ and intrusion intensity J

	Arctic Ocean front	Meddy Sharon (lower)	Meddy Sharon (upper)
γ_ρ	$(3.8 \pm 1.0) \times 10^{-4}$	$(3.5 \pm 1.0) \times 10^{-3}$	$(1.0 \pm 0.9) \times 10^{-3}$
f (s ⁻¹)	1.45×10^{-4}	7.7×10^{-5}	7.7×10^{-5}
N (s ⁻¹)	$(1.9 \pm 0.2) \times 10^{-3}$	$(2.7 \pm 0.1) \times 10^{-3}$	$(3.2 \pm 0.2) \times 10^{-3}$
δ	0.005 ± 0.001	0.13 ± 0.03	0.04 ± 0.03
ΔT (°C)	0.2 ± 0.1	0.20 ± 0.08	0.09 ± 0.04
H (m)	45 ± 35	15 ± 10	10 ± 5
$(T_l)_\rho$ (°C m ⁻¹)	$(1.7 \pm 0.4) \times 10^{-6}$	$(1.0 \pm 0.2) \times 10^{-4}$	$(5.8 \pm 1.0) \times 10^{-5}$
J	2500 ± 2000	125 ± 75	175 ± 100

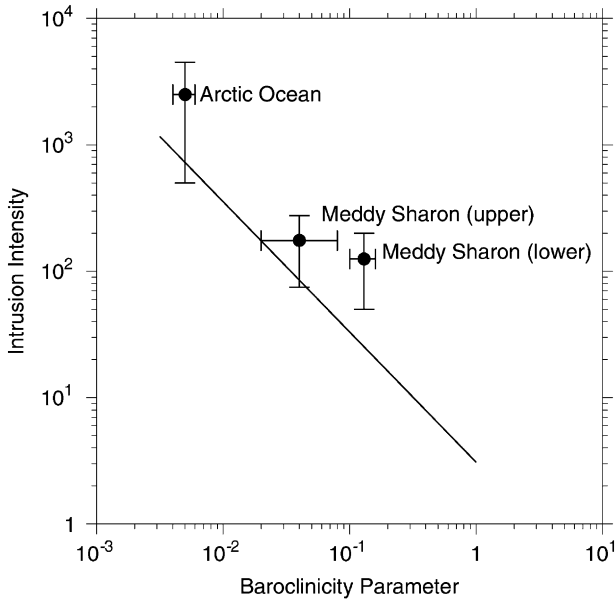


Fig. 8. Plot of intrusion intensity J as a function of baroclinicity parameter δ . Bullets indicate observed values. The straight line is an empirical relationship derived by Zhurbas et al. (1988).

obtained from Ruddick (1992). The calculations of δ and J are summarized in Table 3, with values plotted in Fig. 8. Our data agree reasonably well with the empirical fit of Zhurbas et al. (1988) (i.e. within uncertainty in two of three cases) and lie within the range of scatter of values used to generate the empirical fit (see their Fig. 3). Perhaps more importantly, the trend in our data is the same as that reported by Zhurbas et al. (1988), i.e. decreasing intensity of interleaving with increasing baroclinicity.

8. Summary and conclusions

In this study, we investigated the growth and steady-state stages of double-diffusive interleaving in baroclinic ocean fronts. Three test cases were considered: interleaving at an Arctic Ocean front and interleaving at the edge of a Mediterranean salt lens (lower and upper parts). The cross-front slopes of intrusions relative to horizontal and isopycnal surfaces were used as a key diagnostics of the intrusion dynamics.

The Arctic Ocean and lower Meddy fronts were alike in having warm salty intrusions sloping upward relative to horizontal surfaces across the front. In contrast, the upper Meddy front had intrusions sloping downward across the front. There was an important difference with regard to the slope of intrusions relative to isopycnal surfaces. In the Arctic front, intrusions sloped less steeply than isopycnal surfaces (i.e. between horizontal and isopycnal surfaces in the wedge of baroclinic instability). In contrast, in both parts of the Meddy, the intrusions sloped more steeply than isopycnal surfaces.

First, to investigate the dynamics during the growth of interleaving, the observed intrusion slopes were compared with predictions of instability theory. In both the Arctic Ocean and lower Meddy fronts, the comparison suggests that salt fingering was the dominant form of double diffusion during the growth stage. In contrast, in the upper Meddy case, the observed slopes are consistent with diffusive convection being the dominant form of double diffusion. This behavior was explained by the different slopes of intrusions relative to horizontal surfaces in each case. In addition, given intrusions sloping within the wedge of baroclinic instability, the Arctic Ocean observations suggest that the intrusions were likely driven by baroclinicity as well as double diffusion during the growth stage. In contrast, in both Meddy cases, the observations were consistent with driving of the intrusions by double diffusion only.

Next, to investigate the dynamics of the observed steady-state interleaving, the intrusion slopes were interpreted in the context of a steady-state model of interleaving. In the lower part of the Meddy, double-diffusive fluxes were found to be dominated by salt fingering. However, in both the upper Meddy and Arctic Ocean cases, the observations suggest that diffusive convection was the dominant form of double diffusion. This behavior was explained by the different slopes of intrusions relative to isopycnal surfaces in each case.

Comparing the growth and steady-state results reveals significant differences between the Arctic and Meddy cases. In the Arctic front, different forms of double diffusion dominated during the two stages (salt fingering during the growth stage and diffusive convection at steady state). In contrast, in both Meddy cases, the same type of double diffusion was dominant during the growth and steady-state stages of interleaving (salt fingering in the lower part, diffusive convection in the upper part). The differences between the growth and steady-state stages of interleaving emphasize the need to take care when interpreting observations of thermohaline intrusions. For making inferences about the growth stage, the slope of intrusions relative to horizontal surfaces is most important. In contrast, at steady state, the slope of intrusions relative to isopycnal surfaces is the key feature.

A classification scheme was developed to simplify the interpretation of intrusion slopes. Using the slopes of intrusions relative to horizontal and isopycnal surfaces, the classification scheme can be used to infer the dominant form of double diffusion during the growth and steady-state stages of interleaving. It also indicates whether intrusions will be driven by baroclinicity and double diffusion or by double diffusion alone. Noting that detailed observations of intrusion slopes are not always available, we extended our intrusion classification scheme to one based on frontal-scale parameters. The frontal classification scheme predicts the dominant form of double diffusion during the growth and steady-state stages of interleaving based only on the frontal-scale horizontal density ratio R_h and vertical density ratio R_ρ . The prediction scheme appears to work for the three test cases considered here. Testing this scheme in additional frontal zones is a challenge left for future work.

Acknowledgements

The authors thank the anonymous reviewers for many helpful suggestions, which led to significant improvement of the manuscript. The authors also thank Igor Belkin for his hard work in putting together this special issue.

References

- Armi, L., Hebert, D., Oakey, N., Price, J.F., Richardson, P.L., Rossby, H.T., Ruddick, B., 1989. Two years in the life of a Mediterranean salt lens. *J. Phys. Oceanogr.* 19, 354–370.
- Hebert, D., 1999. Intrusions: what drives them? *J. Phys. Oceanogr.* 29, 1382–1391.
- Hebert, D., Oakey, N., Ruddick, B., 1990. Evolution of a Mediterranean salt lens: scalar properties. *J. Phys. Oceanogr.* 20, 1468–1483.
- Holyer, J.Y., 1983. Double-diffusive interleaving due to horizontal gradients. *J. Fluid Mech.* 137, 347–362.
- Joyce, T.M., Zenk, W., Toole, J.M., 1978. The anatomy of the Antarctic Polar Front in the Drake Passage. *J. Geophys. Res.* 83, 6093–6113.
- Kelley, D.E., 1990. Fluxes through diffusive staircases: a new formulation. *J. Geophys. Res.* 95, 3365–3371.
- Kuzmina, N.P., Rodionov, V.B., 1992. Influence of baroclinicity on formation of thermohaline intrusions in ocean frontal zones. *Izv. Russ. Acad. Sci. Atmos. Oceanic Phys. Engl. Transl.* 28, 804–810.
- Kuzmina, N., Zhurbas, V., 2000. Effects of double diffusion and turbulence on interleaving at baroclinic oceanic fronts. *J. Phys. Oceanogr.* 30, 3025–3038.
- Kuzmina, N.P., Zhurbas, V.M., Sagdiev, A.M., 1994. Dependence of fine-structure intensity upon the mean hydrological parameters at the subarctic frontal zone of the Pacific. *Oceanology* 34, 176–179.
- May, B.D., Kelley, D.E., 1997. Effect of baroclinicity on double-diffusive interleaving. *J. Phys. Oceanogr.* 27, 1997–2008.
- May, B.D., Kelley, D.E., 2001. Growth and steady-state stages of thermohaline intrusions in the Arctic Ocean. *J. Geophys. Res.* 16783–16794.
- McDougall, T.J., 1985a. Double-diffusive interleaving. Part I. Linear stability analysis. *J. Phys. Oceanogr.* 15, 1532–1541.
- McDougall, T.J., 1985b. Double-diffusive interleaving. Part II. Finite amplitude, steady state interleaving. *J. Phys. Oceanogr.* 15, 1542–1556.
- McDougall, T.J., Ruddick, B.R., 1992. The use of ocean microstructure to quantify both turbulent mixing and salt-fingering. *Deep Sea Res. Part A* 39, 1931–1952.
- McIntyre, M.E., 1970. Diffusive destabilization of the baroclinic circular vortex. *Geophys. Fluid Dyn.* 1, 19–57.
- Merryfield, W.J., 2000. Origin of thermohaline staircases. *J. Phys. Oceanogr.* 30, 1046–1068.
- Merryfield, W.J., 2001. Intrusions in double-diffusively stable Arctic waters: evidence for differential mixing. *J. Phys. Oceanogr.*, submitted for publication.
- Perkin, R.G., Lewis, E.L., 1984. Mixing in the West Spitsbergen Current. *J. Phys. Oceanogr.* 14, 1315–1325.
- Ruddick, B., 1992. Intrusive mixing in a Mediterranean salt lens—intrusion slopes and dynamical mechanisms. *J. Phys. Oceanogr.* 22, 1274–1285.
- Ruddick, B., Hebert, D., 1988. The mixing of Meddy “Sharon”. In: Nihoul, J.C.J., Jamart, B.M. (Eds.), *Small-Scale Turbulence and Mixing in the Ocean*. Elsevier, Amsterdam, pp. 249–262.
- Ruddick, B.R., Turner, J.S., 1979. The vertical length scale of double-diffusive intrusions. *Deep Sea Res. Part A* 26, 903–913.
- Shapiro, G.I., Yemel’yanov, M.V., 1994. Relationship between characteristics of the mesoscale and fine structure in the antarctic polar front zone. *Oceanology* 34, 180–185.
- Stern, M.E., 1967. Lateral mixing of water masses. *Deep Sea Res. Oceanogr. Abstr.* 14, 747–753.
- Stommel, H., Fedorov, K.N., 1967. Small scale structure in temperature and salinity near Timor and Mindanao. *Tellus* 21, 306–325.
- Toole, J.M., Georgi, D.T., 1981. On the dynamics and effects of double-diffusively driven intrusions. *Prog. Oceanogr.* 10, 123–145.
- Walsh, D., Ruddick, B., 1998. Nonlinear equilibration of thermohaline intrusions. *J. Phys. Oceanogr.* 28, 1043–1070.
- Walsh, D., Ruddick, B., 2000. Double-diffusive interleaving in the presence of turbulence: the effect of a nonconstant flux ratio. *J. Phys. Oceanogr.* 30, 2231–2245.
- Zhurbas, V.M., Kuzmina, N.P., Lozovatskiy, I.D., 1988. The role of baroclinicity in intrusive layering in the ocean. *Oceanology* 28, 34–36.