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NESTED CHARACTER OF ARCTIC THERMOHALINE INTRUSIONS

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1. INTRODUCTION

During the 1994 Arctic Ocean Section survey (AOS94), Swift et al. (1997) observed an extensive array of thermohaline intrusions extending across the Arctic basin. CTD data from the AOS94 cruise shows the intrusions have a characteristically jagged profile in T/S space (figure 1), and that they migrate downward across density surfaces as they spread from warmer to cooler water. This behavior is consistent with the notion that the intrusions are driven primarily by diffusive convection, although it is possible that other factors such as baroclinic shear (May and Kelley, 1997) and cabbeling also play a role. The Arctic intrusions appear to be long-lived, as very similar structures were observed during the *Henry Larsen* cruise in 1993 (Carmack et al., 1996), and in the Eurasian Basin in 1981 (Perkin and Lewis, 1984).

The Arctic intrusions were found to be very uniform in scale (vertical scales of 40-50m) and remarkably coherent over large horizontal distances, as is demonstrated by the fact that temperature-salinity (T/S) anomalies nearly 2000 km apart line up almost perfectly in the T/S plane. Their remarkable coherence demonstrates that they are a basin-scale phenomenon, and it has been speculated by Carmack et al. (1998) that they are an important mechanism of Arctic climate change, closely linked to recent thermohaline transitions within the Arctic Ocean. The intrusions may also provide an effective means of mixing warm Atlantic water from narrow boundary and ridge currents into basin interiors.

2. "NESTEDNESS"

The intrusions exhibit a peculiar "nested" structure in T/S space in which vertical and horizontal T/S gradients in salt-finger layers have the same slopes in T/S space, and finger layers in adjacent profiles line up in the T/S plane. There is a strong tendency for the water column to "select" certain preferred vertical gradients (figure 1), and finger layers appear to describe a series of "mixing lines" in T/S space. This alignment of intrusions in the T/S plane shows that vertical T/S variations are precisely matched to lateral variations, suggesting that large-scale lateral variation within the Atlantic layer has a strong influence on local vertical gradients within intrusions.

The nestedness of the intrusions is reminiscent of the observation (Iselin, 1939) that T/S slopes of late-winter surface mixed-layer properties closely match T/S slopes of vertical property gradients in the thermocline. The longevity of the Arctic intrusions suggests that such nested structures are robust, resistant to disruption by vertical and horizontal mixing. Here we discuss the character of this nestedness, and speculate on consequences for mixing in the interior of the Arctic ocean.

Each intrusion consists of a "warming" layer (temperature increasing with depth) and a corresponding "cooling" layer (temperature decreasing with depth). The stratification within cooling layers is generally favorable for salt fingering, and that in warming layers is suitable for diffusive convection. Much weaker gradients of both T and S are observed in cooling layers, suggesting these layers may be more susceptible to various types of mixing. Thus, while the stratification in cooling layers is nominally favorable for salt fingering, their weak density stratification and their thickness suggests turbulent diapycnal fluxes may be relatively large, perhaps dominating double-diffusive fluxes. We estimate roughly 90% of the water column between 100m and 250m lies within cooling layers, so factors regulating their behavior may have a profound effect on the structure of mid-depth Arctic waters.

The nested character of intrusions is shown schematically in figure 2. The lower panel shows T/S curves for three hypothetical profiles P_1, P_2, and P_3, and the corresponding spatial structure is shown in the upper panel (contour lines show temperature-anomaly ampli-

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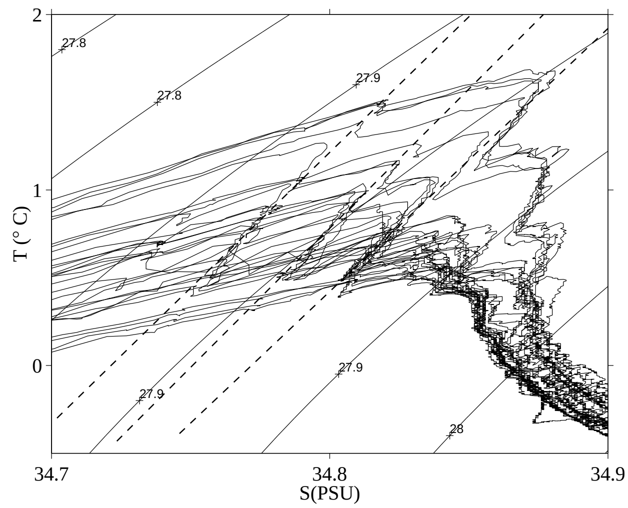

Figure 1: T/S plot showing AOS94 data with strong intrusive activity near the core of the Atlantic water layer (∼100-300m). Cusps are the signature of intrusions; contours show σ_t values. Note the tendency for the curves to line up along lines in T/S space, demonstrating a high degree of coherence. Dashed lines show least-squares best-fit lines for three lines, which have a mean slope of $15.4°\mathrm{C}\cdot\mathrm{PSU}^{-1}$.

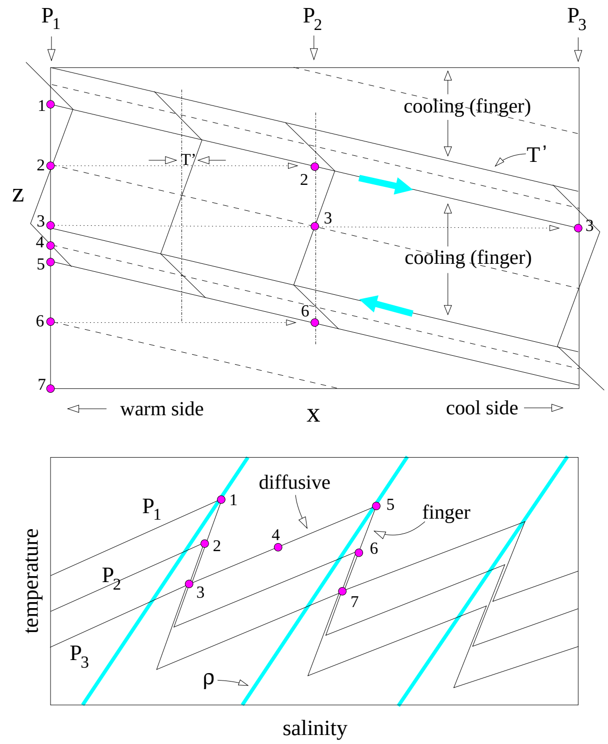

Figure 2: Structure of nested intrusions in physical space (top panel) and in the T/S plane (bottom panel).

tude, with profiles of temperature overlain to aid visualization). The top panel shows a warm and salty intrusion descending to the right across a front, and a cool and fresh intrusion rising as it advects to the left. Finger-stratified layers are drawn thicker than diffusive layers to mimic the AOS94 data.

Lateral interleaving motions of the Arctic intrusions are presumably driven primarily by double-diffusive fluxes through thin diffusive interfaces. These fluxes lead to an increase in the density of the rightward-moving warm intrusion shown in figure 2, consistent with its sinking across the front. In contrast, fluxes within finger-stratified layers are in the opposite sense, tending to make downward moving warm intrusions *lighter*. Therefore, buoyancy fluxes in finger and diffusive layers are in opposition, but the fact that the overall stratification above the Atlantic water layer is diffusive (and consequently diffusive interfaces thinner and diffusive fluxes stronger) causes diffusive fluxes to dominate. This argument is shown diagramatically in figure 3, using T/S flux vectors to represent the effects of mixing and advection on a descending warm intrusion. Based on the above discussion, the diffusive (warming) layers may be considered the "driving force" for the Arctic intrusions, with finger layers tending to retard growth.

The character of the nesting may be illustrated by considering the numbered points in profile P_1 (figure 2). Point 2 is in the center of a finger-stratified layer, while the point in P_2 with the same values of T and S is at the top of the finger layer. Similarly, point 3 (at the bottom of a finger layer in P_1) is in the middle of the layer in P_2, and at the top in P_3. It is important to note that, while the upper panel shows only temperature, the nested curves in the lower panel imply that salinity must have a similar structure. In this way, a point such as point 2 in profiles P_1 and P_2 will have the same temperature *and* salinity (and hence density), resulting in the nested structure shown in the lower panel.

For the Artic intrusions nestedness is associated with cooling (finger) layers only – the diffusive layers don't "nest." This can be understood by considering two points within a vertical profile: one near the center of a cooling layer (e.g., point 2 in profile P_1), and another near the center of a diffusive layer (point 4 in P_1). Starting at point 4 and moving a small distance to the right, we see that both the basic-state temperature gradient and that associated with the intrusive disturbance lead to a decrease in temperature. As a result, isolines of *total* temperature and salinity in diffusive layers slope more steeply than the layers themselves (figure 4). This leads to a divergence or widen-

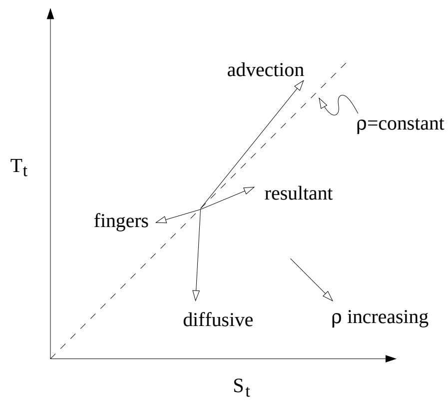

Figure 3: T/S tendency vectors giving an Eulerian picture of the effect of mixing and advection on a warm, descending intrusion. Diffusive fluxes dominate in density terms, making the intrusion heavy, although finger and advective fluxes tend to counteract diffusive buoyancy fluxes.

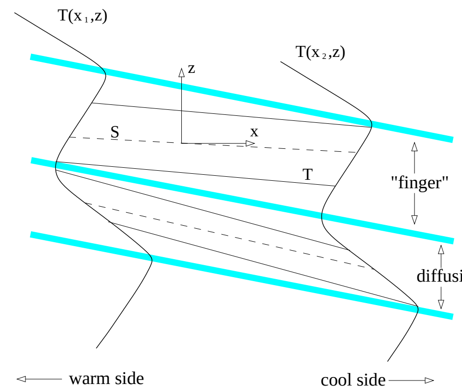

Figure 4: Vertical profiles of temperature and the associated temperature (solid) and salinity (dashed) isolines. Isolines slope more steeply than the intrusions in diffusive (warming) layers and less steeply in finger (cooling) layers.

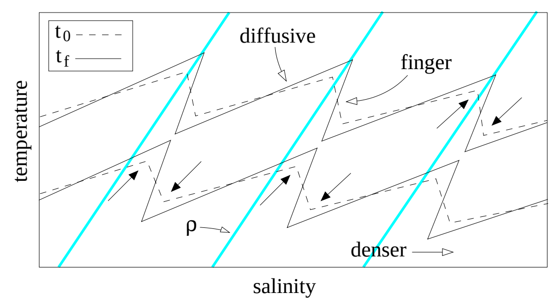

Figure 5: Schematic showing intrusions evolving from a small-amplitude state at time t_0 to a large-amplitude nested configuration at time t_f.

ing of the "T/S distance" separating diffusive layers in adjacent profiles. In contrast, starting at point 2 and moving to the right, we find compensating contributions from basic-state and intrusion temperature fields. This causes isolines of temperature within finger layers to slope less steeply than the intrusions, and leads to a convergence in T/S space between cooling layers in adjacent profiles. This mechanism may explain the tendency (apparent in figure 1) of the intrusions to nest along T/S lines parallel to cooling layers. The evolution of small-amplitude, non-nested intrusions toward a large-amplitude nested state is illustrated in figure 5. We note that the above argument implies that intrusions driven by salt-finger fluxes in finger-stratified regions may instead nest along their diffusive interfaces.

Each anomaly profile has an identical T/S structure, but underlying background temperature gradients cause a "spreading out" in T/S space. The structure suggests that lateral and vertical T/S variations are strongly linked, and raises the question of whether large-scale T/S gradients exert a regulating influence on intrusion amplitude, whether intrusions in some way feed-back onto and modify larger-scale T/S gradients, or perhaps some combination of these possibilities. Recent work by Walsh and Carmack (2001) suggests that intrusions may "select" natural horizontal decay scales (independent of externally imposed length scales), and it is possible that this may affect large-scale T/S gradients when their amplitude becomes sufficiently large.

The previously described deformation of density surfaces by intrusions may have an important effect on their advective behavior. As amplitude increases, density surfaces within finger layers become increasingly horizontal. Since lateral density gradients in finger layers tend to retard growth, decreasing these gradients should enhance growthrates (all other things being equal). In the limiting case in which density surfaces become horizontal, vertically sheared horizontal currents need not work against gravity. In this way, thick finger layers may serve to "lubricate" interleaving motions when intrusions reach a large-amplitude state.

The nested character of the cooling layers is consistent with a steady advective-diffusive balance in these layers, assuming turbulent diapycnal fluxes dominate over double-diffusive fluxes. The steady advective-diffusive equations for T and S are then:

$$u\frac{\partial T}{\partial L} = K\frac{\partial^2 T}{\partial z^2} \qquad (1)$$
$$u\frac{\partial S}{\partial L} = K\frac{\partial^2 S}{\partial z^2}\ ,$$

where u represents along-layer velocity and L denotes along-layer distance. Dividing equations (1a,b) leads to the expression

$$\frac{\beta}{\alpha}\frac{\partial S/\partial L}{\partial T/\partial L} = R_\rho + \frac{\partial R_\rho}{\partial z}\frac{\partial T/\partial z}{\partial^2 T/\partial z^2} , \qquad (2)$$

where α and β are the thermal expansion and haline contraction coefficients, and the "density ratio" R_ρ is defined as

$$R_\rho = \frac{\beta}{\alpha}\frac{\partial S/\partial z}{\partial T/\partial z} .$$

The term on the left-hand-side of (2) may be considered to be an along-layer density ratio. Equation (2) suggests that for profiles with piecewise-constant R_ρ (i.e., $\partial R_\rho/\partial z = 0$) gradients should satisfy

$$\frac{\beta}{\alpha}\frac{\partial S/\partial L}{\partial T/\partial L} \approx R_\rho . \qquad (3)$$

In words: the T/S slope of along-intrusion T/S gradients should match that of vertical T/S gradients, for intrusions governed by the steady advective-diffusive balance (1). This may be appropriate for the Arctic intrusions, since the piece-wise linear character of the T/S curves in figure 1 suggests that R_ρ is roughly constant within any given layer, and we hypothesized earlier that turbulent fluxes within the cooling layers may be dominant. Any deviation from the balance (1) (i.e., from nested structure) might then indicate intrusions in a disequilibrium state. Replacing the mixing term in (1b) with the "standard" diffusive-convection parameterization:

$$u\frac{\partial S}{\partial L} = \gamma K \frac{\alpha}{\beta}\frac{\partial^2 T}{\partial z^2} \qquad (4)$$

gives a different version of (2)

$$\begin{aligned}\frac{\beta}{\alpha}\frac{\partial S/\partial L}{\partial T/\partial L} &= \gamma \qquad (5)\\ &\approx 0.15 ,\end{aligned}$$

suggesting no direct connection between lateral and vertical gradients. It seems clear that (2) provides a better model for the T/S structure within cooling (finger) layers than (5), although reality probably lies somewhere between these limiting cases.

Nested structures may be efficient mechanisms of lateral and vertical mixing. Thick, weakly stratified cooling layers within Arctic intrusions may facilitate vertical mixing, and the lateral velocity field of intrusions can then advect mixed fluid laterally. Furthermore, nested structures may be quite robust, consistent with the apparent long lifetimes of the Arctic intrusions. Once established, neither vertical nor lateral turbulent mixing within the thick, finger-stratified cooling layers can alter their nested structure. This follows from the fact that turbulent mixing leads to movement *along* the T/S curve. Therefore, if the T/S curve is approximately straight over a range of T and S (as in figure 1), then sub-layer-scale turbulent mixing cannot produce movement perpendicular to the T/S curve. It follows that T/S signatures of nested features like those seen in figure 1, where horizontal and vertical T/S slopes are precisely matched, should be highly resistant to disruption by turbulent mixing.

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