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Oceanic thermohaline intrusions: observations

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Abstract

Intrusions are commonly observed in the upper, deep and coastal oceans, and are closely linked to lateral fluxes of heat, salt and momentum. This is a review of observations of intrusions and the results of comparisons of properties such as scale, slopes, microstructure activity, and fluxes with theoretical models. A summary of estimates of lateral heat fluxes indicates a wide range of lateral diffusivities. We conclude by noting that our present knowledge is insufficient to predict the structure, length-scales and lateral fluxes of thermohaline intrusions with confidence, and list a number of unresolved questions. Suggestions are made for compilation of existing data into a database for exploratory analysis and testing of theoretical hypotheses. An outline is given of a potential collaborative field experiment using CTD, fluorescent dye, and microstructure observations.

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1. Introduction

Almost any oceanic temperature and salinity profile from anywhere in the world contains several inversions indicative of lateral thermohaline intrusions. These use the available potential energy in lateral water mass differences, released by vertical double-diffusive mixing, to drive lateral mixing. External energy from shear-driven turbulent (vertical) mixing or horizontal stirring is not required, although these processes undoubtedly interact and compete with intrusive mixing. Intrusions cause lateral fluxes of salt and heat that are often comparable to those by more 'dynamic' larger scale processes such as mesoscale eddy stirring or barotropic/baroclinic instability. In several locations they cause large lateral heat and salt fluxes, with eddy diffusivities of O(10^3 m^2 s^{-1}). Despite their probable importance, a predictive, tested parameterization of the process still eludes researchers.

Awareness of the existence of finescale thermohaline intrusions, and understanding of their production mechanism, came slowly. The advent and use of the continuously recording bathythermograph (Vine, 1952) often showed thermal inversions that would have been unresolved by discrete sampling (Robinson, 1957). Roden (1964) studied thermal inversions in several regions of the Pacific, and showed that they were usually salt stabilized—i.e. that cold water overlying warm did not necessarily indicate a density inversion. Although he noted that inversions occurred in polar, subtropical and tropical regions, he found multiple inversions are particularly likely to occur at frontal zones between different water masses, naming zones off Baja California, central Chile, and the Kuroshio-Oyashio boundary in particular. Roden was also the first to investigate the role of lateral advection in producing inversions and their possible destruction by vertical diffusion, estimating timescales for the processes.

Stommel and Federov (1967) noted the presence of temperature-compensated salinity inversions in vertical Salinity-Temperature-Depth (STD) casts in the Timor Sea, and ascribed their origin to sheared lateral advection in the presence of lateral T/S gradients. They noted that vertical mixing would blend them into their new surroundings, and estimated their lifetime to be about a few weeks for layers of 10 m thickness. Neither this work nor that of Roden (1964) recognized the possibility that intrusions can be self-driven by vertical double-diffusive fluxes, and can cause significant, self-driven, lateral mixing.

1.1. Role and importance of intrusions, links to larger scales

1.1.1. Lateral fluxes across fronts

Intrusions are important primarily because of the fact that they drive lateral mixing of heat and salt, and probably momentum, using the available 'thermoclinic' potential energy (Woods, Onken, and Fischer, 1986) of the lateral T/S water mass differences across fronts, released via double-diffusion. For this reason, intrusions are most prominent near fronts, and are thought to be most important at fronts, where water mass characteristics differ most strongly. The overwhelming majority of intrusion observations are from such frontal zones.

1.1.2. Lateral fluxes cause decay of rings, Meddies, and eddies

Observations of the decay of Meddy 'Sharon' (Armi et al., 1989; Hebert, Oakey and Ruddick, 1990) demonstrated the dominance of intrusions in blending large anomalous eddies into the background ocean, after such anomalies were produced by instability of a boundary current. This also occurs for warm-core rings (Schmitt et al., 1986).

Garrett (1982) shows how fronts can be sharpened by eddy stirring, and smoothed by intrusions. In such cases the flux is carried across the sharp frontal zone by intrusions, and across the weaker non-frontal zones by eddies.

1.1.3. Intrusions enhance rms vertical gradients, hence vertical fluxes

Garrett (1982) suggested that one role of intrusions is to enhance rms vertical gradients, and so enhance (in an rms fashion) vertical fluxes. Hebert (1988) analyzed the two-year time series of vertical CTD profiles from the Meddy center on the assumption that all changes were the result of vertical double-diffusive fluxes out of the bottom of the Meddy (i.e. non-intrusion fluxes). He concluded that the salt finger fluxes were more than an order of magnitude weaker than estimates based on laboratory experiments and the '4/3' flux laws, and were consistent with an O(1) Stern number (see the discussion and definitions by Kunze, 'Salt Finger Theories', this issue). The (non-intrusive) salt flux associated with salt fingers would cause the salinity anomaly of the Meddy to decay on a timescale of 20 years, much slower than the observed rate of decay by intrusions. In intrusive situations, vertical fluxes are further enhanced because lateral advection by intrusions cause density ratio to approach one.

Marmorino (1991) described high-resolution towed thermistor chain observations within the salt finger staircase off Barbados. His discovery of thermal inversions and diffusive interfaces in the staircase suggested the possible involvement of 'small' intrusions in the maintenance of thermohaline staircases. Merryfield (2000) argued that intrusions that fail to grow to the point of producing inversions can, in fact, explain the genesis of thermohaline staircases. Staircases have larger fluxes than smooth gradients, and so these enhanced vertical fluxes owe their origin to lateral gradients and intrusions.

1.1.4. Lateral fluxes often have a vertical component and provide a pathway for heat to escape to the sea surface, then to the atmosphere

Lateral mixing by all mechanisms, including intrusions, provides a pathway for heat to escape to the surface along sloping isopycnals, aiding air-sea interaction, and therefore playing a key role in the climate system (Robertson, Padman, and Levine, 1995; Boyd and d'Asaro, 1994). This also appears to occur in the Arctic Eurasian Basin (Rudels, Björk, Muench and Schauer, 1999; Dewey, Muench, and Gunn, 1999).

1.1.5. Fluxes cause water mass modification

The boundary currents described by Carmack, Macdonald, Perkin, McLaughlin and Pearson (1995), Carmack et al., (1997, 1998) are strongly modified in their properties as they flow along ridges and from basin to basin. Rudels, Muench, Gunn, Schauer and Friedrich (2000) described the changes in the core of the boundary current flowing north of the Siberian shelf. These changes are primarily the result of lateral mixing, and here intrusive mixing is known to play a significant role.

Garrett and Horne (1978) considered the effect of lateral (intrusive) mixing at a thermohaline front with a nonlinear equation of state. They found the mixed water to be denser than the water on either side (because of the cabbelling instability), and they computed the rate of densification and subsidence as a function of the lateral diffusivity. The resulting convergence was found to play a major role in maintaining the sharpness of the front against lateral diffusive spreading.

Talley and Yun (2001) considered the origins of the North Pacific Intermediate Water in the subtropical North Pacific via the mixing of Oyashio water with waters from the Kuroshio. They estimated that cabbeling processes accounted for about half of the estimated change in density between the two water masses. They considered the effect of double-diffusion within intrusions, and estimated that the remainder of the required density change was being accounted for by intrusive salt finger fluxes.

A useful introduction to the field of double-diffusion is in Turner (1973), and Schmitt (1994) gave an excellent and balanced review of double-diffusion in oceanography. Bianchi, Giulivi and Piola (1993) summarized a number of frontal heat flux estimates, which are included in Table 1. May (1999, table 1.1) compiled a useful list of all the intrusion observations made up until that date, and provided a map showing their locations. The present paper attempts to include all of those findings.

1.2. Dynamics of double-diffusive intrusions

Stern (1967) developed an instability theory that showed how lateral intrusions could be driven by salt finger flux convergences. The theory was groundbreaking because, in addition to discovering a new mechanism to drive lateral fluxes, Stern's vertical diffusivity parameterization (linking the heat flux to the salt flux via a flux ratio) incisively captured the major effect of salt fingers. Stern also clearly showed that turbulent mixing, with equal turbulent diffusivities for salt and heat, cannot drive intrusions. Stern's (linearized) theory did not predict the vertical scale of intrusions, nor the lateral fluxes, because linearized intrusions were predicted to grow exponentially without bound—equilibration mechanisms were not considered. The intrusive formation mechanism was demonstrated and clarified in laboratory experiments by Turner and Chen (1974), in which a variety of two-dimensional mixing effects were qualitatively explored.

The dynamical mechanism behind thermohaline intrusions is simple but subtle. Consider a situation with lateral gradients of temperature and salinity, but not density (Fig. 1), with a vertical stratification that supports salt fingering. If a perturbation consisting of alternating shear zones is superimposed, the lateral advection and lateral T/S gradients act to produce alternating warm, salty and cold, fresh layers, with vertical T and S gradients that will alternately enhance and oppose the existing salt fingers. This produces flux convergences that tend to reduce the T and S perturbations. However, because the buoyancy flux for salt fingers is upgradient and so effectively generates a negative eddy diffusivity for density, the fluxes will make the warm, salty perturbations become less dense and the cool, fresh perturbations more dense. If the initial perturbation has a slight slope (as shown) such that the warm, saline perturbations slope upwards from the warm, salty side, then the buoyancy forces will act to reinforce the initial motion. The warm, salty layers thus become anomalously light because of the flux convergence, and so 'slide upwards' to the left, with the converse occurring to the cool, fresh layers. Turner (1978) showed how the net density

Table 1
Lateral intrusive heat flux estimates, from Joyce (1977) with $K_v = 10^{-4}$ m^2s^{-1}. Adapted from Bianchi et al. (1993). (1 W/m^2 = 4.2 x 10^6 °C m s^{-1})

Location	Source	Lateral Diffusivity (m^2 s^{-1})	Heat flux (10^{-4}C m s^{-1})	Intrusion scale (m)
Northwest Atlantic (Gulf Stream)	Joyce (1976)	–	6.0[a]	2–50
Polar front (AACC)	Joyce et al. (1978)	34	8.6	3–100
Nova Scotia Shelf Break front	Horne (1978)	10	83[b]	10
Argentine Basin (NADW-CDW)	Georgi (1981)	80	4[a]	32–256
South of Africa	Piola and Georgi (1982)	–	2.5	
South of New Zealand			3.4	16–64
Argentine Basin (AAIW)			9.4	
E. N. Atlantic	Georgi and Schmitt (1983)	1500	15	O(20)
Iceland-Faero Front	Hallock (1985)	1200	120 ± 24	50
Meddy Sharon	Hebert et al. (1990)			
		4–5	10-13[b]	10–50
	Ruddick and Hebert (1988)	(salinity)		
Brazil-Malvinas Confluence	Bianchi et al. (1993)	120	76 (0-500 m)	10–100
		220	6.5 (2-3 km)	
Brazil-Malvinas Confluence	Provost et al. (1995)	300(T)	200 (0-500m)	10–100
		500(T)	50 (2-3 km)	
Arctic Ocean	Carmack et al. (1997)	3000[c]	60	40
	Walsh and Carmack (2002)	600		
Equatorial Pacific	Richards (1998); Richards and Banks (2002)	O(1000)	120	O(10)
Oyashio Front	Nagasaka et al. (1999)	1–6		O(18)

[a] Taken from Bianchi et al. (1993).
[b] Estimate from advective balance, Joyce (1977) model not used.
[c] Estimate from temporal changes, Joyce (1977) model not used (likely to be an over-estimate).

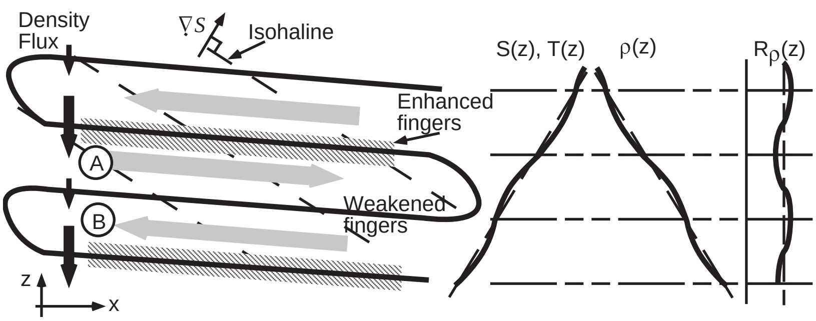

Fig. 1. Linear phase of intrusion growth, with warm, saline water above and to the right. Isohaline surfaces (dashed lines) slope upwards to the left. Isotherms also slope upwards to the left, but are not shown. Mean isopycnals are horizontal. Intrusive perturbations (dashed lines) also slope upwards to the left, but less steeply. Intrusive velocities are indicated by the gray arrows. Lateral advection by the intrusive velocities has caused the vertical salinity gradients and density flux to be enhanced above point A and decreased below. The flux convergences cause fluid parcel A to become more dense, and fluid parcel B to become less dense. The resulting buoyancy forces combine with the intrusion slope to reinforce the original motion.

change produced by double-diffusive flux convergences interacts with the intrusion slope to create a driving force. Turner showed how intrusions slope up (relative to isopycnals) from the warm salty side when salt finger buoyancy fluxes dominate, and how they slope downwards when diffusive fluxes (which cause warm, salty intrusions to become denser) dominate.

As the intrusion amplitude becomes large, inversions in T and S form, thus allowing the formation of diffusive-sense thermohaline convection above the warm, saline intrusions. The three-way balance involving finger and diffusive fluxes, and lateral advection, can allow a quasi-steady state (McDougall, 1985b; Walsh and Ruddick, 1995a).

2. Observations of thermohaline intrusions

2.1. Mid-latitude frontal intrusions

Following the early observations of intrusions that were mentioned in the introductory section, the 1970s and early 1980s saw an increasing body of observations that found intrusions occurring near ocean fronts and water mass boundaries of all types, and contributed to circumstantial evidence associating intrusions with lateral exchange.

Tait and Howe (1968) and Howe and Tait (1970) reported on an extensive series of step-like layers in temperature and salinity near the Mediterranean outflow. This initially appeared to be a double-diffusive thermohaline staircase, but a closer inspection of the salinity and temperature traces in their Fig. 1 revealed inversions that are characteristic of intrusive layers (Howe and Tait, 1972).

Pingree (1969, 1971) described intrusions in the Northeast Atlantic, and showed that the temperature and salinity perturbations were approximately compensating in their effect on density—i.e. their formation was consistent with sheared lateral advection rather than local vertical mixing.

Posmentier and Houghton (1978) described intrusions in the shelf-slope front off the eastern seaboard of the US, and discussed the possibility that apparent density inversions (loops in the T/S curve) were produced by double-diffusive flux convergences. However, CTD sensor-response mismatches could also have caused such loops, and intrusion dynamics do not create density inversions until nonlinear, finite-amplitude effects come into play (Walsh and Ruddick, 1998). Horne (1978) and Herman and Denman (1979) documented the properties of similar shelf-break frontal intrusions in the Shelf-slope water front off Nova Scotia. Horne (1978) found the intrusions to be laterally coherent for several kilometres cross-front, and at least 17 km along-front. Horne estimated the layer velocity by assuming an advection-diffusion balance, and then used the velocity and intrusive thermal anomaly to estimate a lateral temperature flux of 83×10^{-4} °C m s^{-1}. This was equivalent to a horizontal heat diffusivity of 10 m^2 s^{-1}.

Joyce (1976) documented intrusive fine-structure in the Gulf Stream front, and estimated a moderately strong lateral heat flux (see Table 1 in section 1.1.5) using the Joyce (1977) model (see section 3.5 for a description of this model and a summary of intrusive flux estimates). Williams (1981) described intrusions in the Gulf Stream, suggesting that shear may also be involved in the interleaving. The existence of intrusions in such a strongly sheared, dynamic region as the Gulf Stream is noteworthy because the observations confirm that intrusions can maintain themselves in the face of potential destruction by shear-induced instabilities, either vertical or lateral.

Ochoa (1987) showed that temperature and salinity gradients were highly coherent in the Eastern Subtropical Pacific, with S and T changes with depth in-phase in intrusive regions but out-of-phase in step structures. He discussed the underlying mechanisms but did not consider the effects of internal wave strain in producing coherent structures.

In a series of papers (Ozsoy, Top, White, and Murray, 1991; Ozsoy, Unluata, and Top, 1993; Ozsoy and Besiktepe, 1996), the descent, entrainment, and eventual mixing by intrusions of the Black Sea inflow plume were described and quantified. It appeared that the initial mixing of the plume was governed by gravity current dynamics and associated entrainment, and this controlled the depth to which the inflow reached. The eventual mixing of the water into the interior of the Black Sea was found to be driven by thermohaline intrusions.

Anderson and Pinkel (1995) documented interleaving in a front off the California coast. They found T/S anomalies that were double-diffusively unstable, laterally coherent from trace to trace, and were observed to slope upward from the warm side to the cool side of the front. The intrusion vertical lengths of 5–15 m were consistent with scales predicted by Toole and Georgi (1981). Kennan and Lukas (1996) performed detailed statistical analyses of the Hawaiian Ocean Time Series (HOTS) hydrographic data, and found the histograms of salinity at constant density to be clearly bimodal as a result of the intermittent appearance of intrusive features. These features ranged from 5 to 100 m in vertical scale; one synoptic transect gave evidence that a saline, low oxygen intrusion was a submesoscale feature about 50 m thick and 50 km across. They considered possible water mass origins for such features, but were unable to make firm conclusions. Smaller intrusions, about 10–20 m thick, had density ratios associated with potentially strong double-diffusion, but in the absence of appropriately synoptic observations or microstructure instrumentation, the fluxes could not be quantified. No clear front was identified, and so the Joyce (1977) model could not be applied.

Bianchi, Piola, Osiroff and Charo (1997) and Bianchi, Giulivi and Piola (1993) described the fourfold intensification of intrusive fine-structure in the frontal zone formed by the confluence of the southward-flowing Brazil current and the northward-flowing Malvinas current. They applied the model of Joyce (1977) using an estimated vertical diffusivity of 10^{-4} m^2 s^{-1} to estimate a cross-frontal temperature flux of $10^{-2\circ}$ C m s^{-1}, which was an order of magnitude larger than estimates from other fronts (Table 1). Bianchi et al. (1993) also considered the role of intrusive mixing in dissipating the small (70 m thick $\times$ 7 km diameter) intrusive lenses found near the front, estimating their lifetime to be ~1 week, whereas their estimated lifetime for the 100 km size meanders and cyclonic eddies that detached from the frontal zone was six months. Provost, Gana, Garçon, Maamaatuaiahutapu and England (1995) gave a detailed description of the water mass properties and circulation of the Confluence region, and computed exceptionally large intrusive fluxes (Table 1) that correspond to a lateral heat diffusivity of 300 m^2 s^{-1} and a lateral salinity diffusivity of 100 m^2 s^{-1}, the largest mid-latitude intrusive diffusivity found so far. The factor of three difference between the two diffusivities is probably related to the tendency of salt fingers to reduce the vertical salinity differences more than the temperature differences, causing unequal salt and heat vertical diffusivities that have not been accounted for in application of the Joyce (1977) model.

Bianchi, Piola and Collino (2002) estimated the diapycnal fluxes and diffusivites of salt and heat using Kunze's (1987) model for fastest growing fingers in a salt-finger sense staircase below a warm intrusion in the Brazil–Malvinas confluence. They find the effective diffusivities to be 0.7×10^{-4} m^2 s^{-1}, and 0.3×10^{-4} m^2 s^{-1} respectively. The diffusive-convective zone above the intrusion, with a 2° temperature contrast, was considered as a single, sharp diffusive interface. Heat and salt fluxes were estimated using laboratory flux laws to be two orders of magnitude larger than the finger fluxes, although closer examination of the profiles may reveal multiple interfaces with smaller temperature jumps and fluxes.

2.2. Warm-core rings and Meddies

Tang, Bennett and Lawrence (1985) and Ruddick, Bennett and Lawrence (1985) documented the evolution of an intrusive feature in a Gulf Stream warm-core ring, and tested for consistency with a variety of mixing mechanisms. They concluded that the observed slope and inferred evolution was not likely to be the result of double-diffusion, but that vertically-sheared advection was responsible for the apparent vertical migration of the feature. Schmitt, Lueck and Joyce (1986) studied a similar feature during the Warm Core Rings experiment, and found that the intrusion slope was consistent with dominance of diffusive interface fluxes, a conclusion supported by thermal and velocity microstructure evidence. However, they concluded that the intrusions were not primarily double-diffusive in origin, but were likely to have been created by vertically-sheared advection and mixed via mechanically-driven turbulence, in agreement with Ruddick et al. (1985).

Perhaps the most complete set of observations and analysis linking double-diffusion, intrusions, lateral mixing, and large-scale changes comes from the collaborative observations of Meddy 'Sharon', a lens of Mediterranean water in the Atlantic that was tracked for more than two years with SOFAR floats (Armi et al., 1988, 1989). The region outside the core of the Meddy had thermohaline intrusions that eroded laterally 30 km into the core during the first year of observation. During this period the Meddy shrank in diameter, but changed in thickness very little. The salinity front, velocity maximum, and the vorticity front moved inward with the intrusions. Thermal microstructure was notably absent from the core, strong in thin regions above and below the core, and exceptionally strong on the upper and lower boundaries of the intrusions. Armi et al. (1989) concluded that the intrusions were responsible for mixing the Meddy into the surrounding ocean. Detailed analyses of Meddy intrusion scales, slopes, and fluxes are described in section 3.

In a different Mediterranean salt lens, Zhurbas et al. (1992) investigated the radial structure of interleaving intensity (defined by intrusive salinity amplitude) versus radius, and found that the maximum intensity occurred at a larger radius than the thermohaline front. They discussed several possible reasons for this but were unable to come to any firm conclusions.

2.3. Intrusions near melting ice

Neshyba, Neal and Denner (1971) described interleaving structures in CTD measurements under Ice Island T-3. Similar structures were described by Jacobs, Huppert, Holdsworth and Drewry (1981) near the Erebus Glacier, and by Horne (1985) in an Arctic fjord. Huppert and Turner (1980) showed in a series of laboratory experiments that melting ice in salt-stratified water produces a regular sequence of intrusive layers, and found that their thickness is proportional to the temperature difference between the ice and the environment, and inversely proportional to the ambient density gradient. This result is similar to the laboratory and theoretical findings of Thorpe, Hutt and Soulsby (1969) for layers produced in a salt stratification by heating a sidewall. The difference is that in the case of a heated sidewall, the lateral salt flux is zero at the wall, while in the case of melting ice the freshwater flux and the (negative) heat flux are linked. In the laboratory experiments, and presumably in the field, such intrusions are driven by diffusive interface fluxes, and rise upwards from the cold surface.

Laboratory experiments with melting ice-blocks in unstratified seawater have shown a cold, fresh, convecting, doubly-diffusive boundary layer adjacent to the ice surface, with complicated physics as a result of the combined action of freshwater and latent heat of cooling (Josberger and Martin, 1981). Similar boundary layers occurred in the stratified experiments above, and likely in the field, and are undoubtedly involved in the formation and the driving of the intrusions. Kerr (1991) has suggested approximate boundary conditions for this situation.

2.4. Intrusions in the Antarctic

Lateral mixing by intrusions appears to be one step in the formation of Antarctic Bottom Water (AABW). Foster and Carmack (1976) delineated the water masses that form AABW, and found that mixing of Weddell shelf water with a warmer, saltier intermediate water mass (Modified Warm Deep Water) at the shelf break is the penultimate formation step. Multiple thermohaline intrusions were observed, and the possibility of double-diffusive mixing across their upper and lower surfaces was noted, among a number of other possible physical mixing mechanisms. Foster and Middleton (1979) made further observations and concluded that the mixing processes involved in AABW formation are probably intermittent in space and time. However, they also found intense interleaving at the shelf break zone, and also that some of the newly formed deep water flowing down the slope does not become true bottom water because it interleaves at intermediate depths. Foster (1987) analyzed a number of closely spaced shelf break sections and current meter records in an attempt to determine the mixing mechanisms. Tidal motions, shelf waves, shear instability of currents, and double-diffusive intrusions were implicated, but mixing rates caused by each were not quantified. Although intrusive mixing appears to occur over a broad expanse of shelf edge, it is not the key step: Foster and Carmack (1976) concluded that the rate-limiting process is brine rejection by ice formation on the shelf adjacent to the Weddell sea.

Carmack (1977) and Carmack and Killworth (1978) documented intrusions in newly formed abyssal waters adjacent to Antarctica, and suggested the process may be involved in abyssal circulation.

The investigations above noted the presence of intrusions and hypothesized their possible role in the mixing processes of AABW formation, but did not estimate quantitatively the role of the various possible mixing processes. Robertson, Padman and Levine (1995) estimated the upward heat flux from the subsurface core of the Warm Deep Water to the ice-covered surface in the Weddell Sea (the rate-limiting step) as about 3 W m^{-2}, primarily resulting from (vertically acting) double-diffusion. This was consistent with the estimated mean rate of heat transfer across the mixed layer to the ice above. Intrusions were found in the region, primarily near the frontal boundary between the warm-core current and the shelf-modified water to the east. These fluxes are significantly less than the 19 W m^{-2} required to balance the heat budget of the Weddell Gyre, and the authors suggested that shelf processes to the west and more energetic double-diffusion to the east could account for the difference. It was hypothesized that lateral mixing along sloping intrusions and upward-sloping isopycnals contributed to the heat loss, providing a lateral conduit for heat to escape across the surface (as Boyd and d'Asaro (1994) explained the heat loss by the West Spitzbergen current in the Arctic Ocean—see section 2.5). However, the process was not quantified.

Gordon, Georgi and Taylor (1977) and Gordon (1975 a, 1975b) drew attention to the prominent interleaving of temperature and salinity in the Antarctic Polar Front Zone, a subpolar convergence zone across which climatically important heat flux was thought to occur. This front was studied in more quantitative detail by Joyce, Zenk and Toole (1978), and Toole, 1980, 1981a)—see section 3.2.

2.5. *Intrusions in the Arctic*

Perkin and Lewis (1984) documented the properties of intrusions in the West Spitzbergen Current, which is the major inflow from the Atlantic into the Arctic Ocean. They were able to trace individual layers in T-S space (or, equivalently, S-sigma space) over much of the Arctic basin, and found evidence of double-diffusive layering structures lying above and below the intrusions. The lateral mixing of heat and salt, and the consequent changes of water mass properties in the Current, were hypothesized to influence the circulation of the Arctic significantly. Steele and Morison (1993) described observations of intrusions in the region made from a drifting buoy in the ice pack.

Quadfasel, Sy and Rudels (1993) noted intrusions within the Arctic Ocean in ship of opportunity temperature observations, and their possible role on the larger scale is discussed by Rudels, Jones, Anderson and Kattner (1994). Carmack et al. (1995, 1997, 1998); Anderson et al. (1994); Quadfasel, Sy and Rudels (1993), Rudels et al. (1994), and Rudels, Björk, Muench, and Schauer (1998) described a spectacular set of Arctic Ocean thermohaline intrusions associated with the mixing between water masses of Pacific and Atlantic origin. These intrusions were tracked over a distance of 2000 km (Figs. 2 and 3), and were hypothesized to be associated with major changes in deep ocean water mass properties, perhaps resulting from climatic shifts [But note that intrusions existed in the Arctic prior to this shift (Perkin and Lewis, 1984).] Water of Atlantic origin flooded the Nansen, Amundsen, and Makarov Basins (NB, AB, and MB respectively in Fig. 2a) in the years 1991–1994, flowing along the ridges that bound the basins. The cores

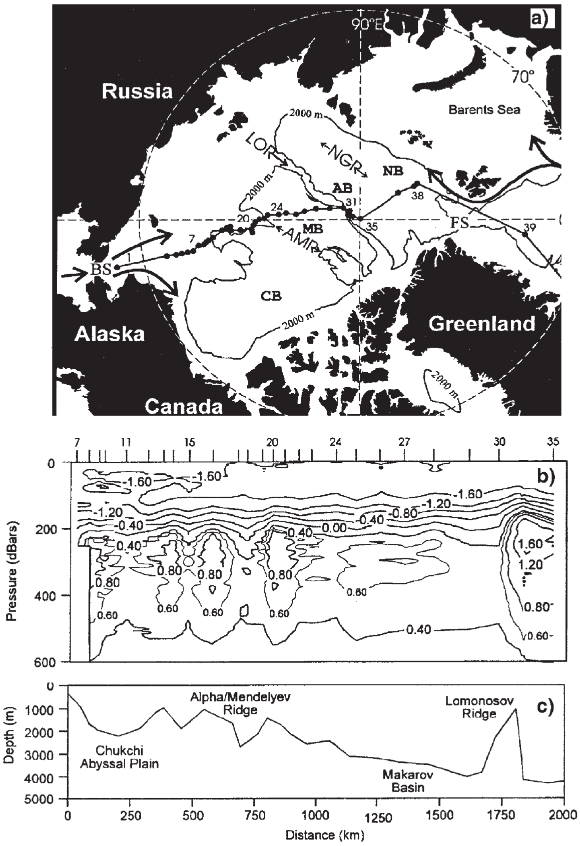

Fig. 2. (a) Map of the Arctic Ocean, showing the stations. (b) Potential temperature in the upper km along a section from the Chukchi Sea to the North Pole. (c) The bathymetry along the section in (b). (Reproduced by permission of the American Geophysical Union, From Carmack et al., 1998).

can be seen in Fig. 2b as warm cores above the ridges marked in Fig. 2c. Intrusions 40–60 m thick can be seen throughout the basins, and are laterally coherent in T-S space over the entire section (Fig. 3). Warm saline layers were observed to be successively cooler, fresher, and denser as the observations moved laterally, consistent with dominance by diffusive sense fluxes. The diffusive regions had a (vertical gradient) density ratio of 0.5, while the finger regions had a density ratio of 1.7 (Fig. 3), both of which indicate active vertically-acting double-diffusion.

Carmack et al. (1997) explored the possibility that the observed 0.05 °C warming from 1991 to 1994 could have been driven purely by intrusive fluxes, and calculated that the intrusions would need to have affected a lateral diffusivity of order 3000 m^2s^{-1}. They concluded that this was unreasonably large, and suggested that the water properties were initially spread around the periphery of the basins via fast boundary currents, and then spread into the basin interior via the intrusions. Rudels et al. (1998) discussed the formation of intrusions near Fram Strait, followed by their advection by the currents that follow bathymetric features throughout the Arctic. These intrusions then propagate from currents to interior of basins. The Joyce (1977) model was applied by Walsh and Carmack (2002) to estimate lateral diffusivities of 200 m^2s^{-1}; (600 m^2s^{-1} if the canonical vertical diffusivity of 10^{-4} m^2s^{-1} is used). McLaughlin, Carmack, Macdonald and McLaughlin (1996) found fine-scale variations in geochemical properties coherent with these intrusions, indicating that the tracers were spreading along with heat and salt in the intrusions. Rudels et al. (2000)

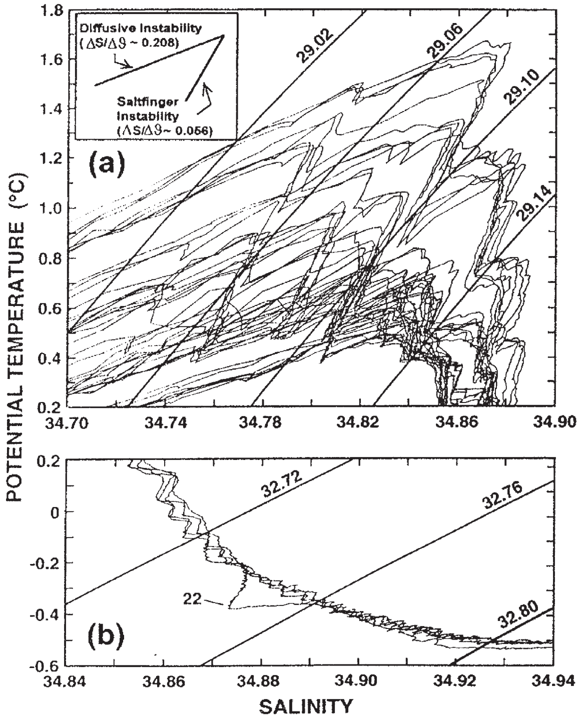

Fig. 3. (a) Expanded-scale potential temperature θ_S curves for stations 7 to 35 near the warm- water maximum of Fig. 4, showing the alignment in θ_S space of the intrusions that extended across the Makarov Basin. Inset shows the slopes of the diffusive and salt-finger regimes. Isopycnals represent potential density relative to 250 db. (b) Expanded-scale θ_S curves at stations 21-24 in and near an anticyclonic eddy at about 1000 m near station 22. Isopycnals represent potential density relative to 1000 db. Note the presence of smaller intrusive features at depth, and the anomalous (cold, fresh) properties of the eddy. (Reproduced by permission of Pergamon Press, from Carmack et al., 1997).

and Schauer, Muench, Rudels and Timokhov (1997) discussed the processes affecting water mass transformation of the boundary current and the intermediate depth layers, concluding that lateral mixing plays a key role, possibly via intrusions.

Gunn and Muench (2001) discussed the changes of the temperature of the Atlantic layer in the Arctic, and concluded that the changes were likely advected along currents above the mid-ocean ridges, then propagated into the basins, either via lateral intrusions or by an as-yet unknown advective mechanism, such as eddies or intra-basin currents. The observed warming occurred in the Makarov Basin well after the Nansen and Amundsen Basins. (In the Atlantic layer intrusions are best defined along the ridges, and become less defined away from the ridges (R. Muench, pers. comm, 2002), supporting the notion of an origin near the water mass fronts associated with the ridge currents. Recently, Walsh and Carmack (2002) noted that these intrusions became indistinct as they extended into colder water, and considered the effects of temperature variation of the thermal expansion coefficient. They concluded that the nonlinearity induces a spatial decay of intrusion amplitude toward cooler water, consistent with the observations.

Many of the observations cited above reported a deeper set of intrusions (800–100 m) that was related to the flow of water from the Barents Sea shelf beneath the Atlantic Water layer in the boundary flow north of the Kara Sea. These intrusions are much smaller in vertical length scale than those in the Atlantic Water and appear to originate through the horizontal gradient generated when the Barents Water enters

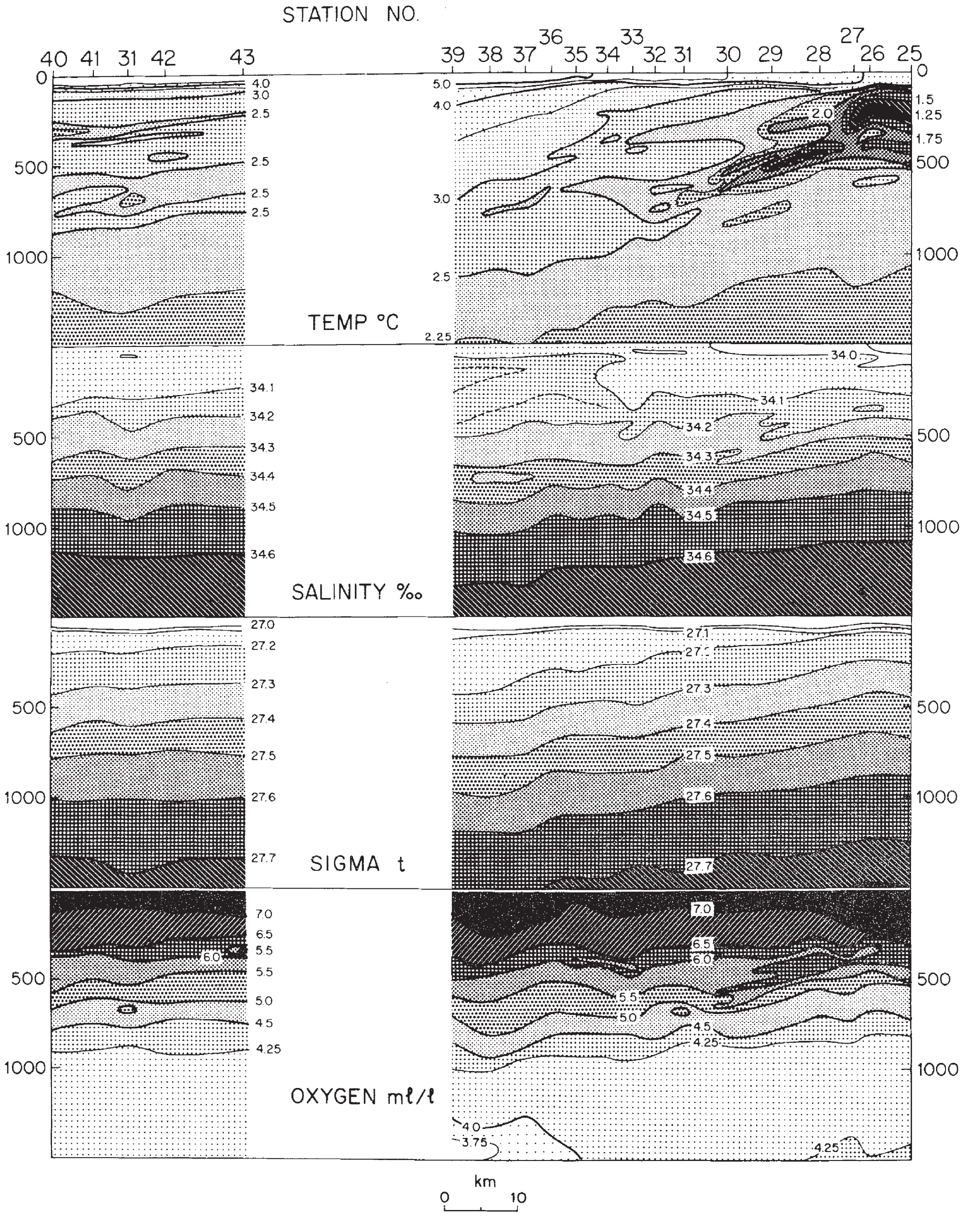

Fig. 4. Sections of temperature, salinity, sigma-t, and oxygen from a closely spaced CTD section perpendicular to (right column) and parallel to (left column) the polar front. (Reproduced by permission of the American Geophysical Union, from Joyce et al., 1978).

the Arctic Ocean. They are of smaller vertical scale and horizontal extent than the Atlantic layer intrusions, but may be important in lateral mixing between water masses.

2.6. Equatorial intrusions

Persistent intrusive structures are a feature of the thermocline in the equatorial Pacific. Because of the sharp front in water mass characteristics at the equator that spans the breadth of the Pacific, salinity proves to be a wonderful tracer of intrusive behaviour. Such features were reported by Toole, 1981b) in the eastern equatorial Pacific and later by McPhaden (1985) in the central equatorial Pacific. The lateral coherency of individual layers can be extensive. Richards and Pollard (1991), using high resolution data from the western equatorial Pacific, showed layers O(10 m) thick in the vertical which extended several hundred kilometres in the meridional direction. Later observations showed similar characteristics (see Banks, 1997; Richards, 1998). The large lateral coherency scale of equatorial intrusions greatly exceeds similar structures at mid-latitude fronts, and is (so far) matched only by the Arctic intrusions.

How important double diffusive processes are for the formation and maintenance of the equatorial intrusions is as yet an open question. Richards (1991) showed that the observed vertical and horizontal scales are consistent with linear double diffusive layering instability on an equatorial beta plane. However, the later work of Edwards and Richards (1999) demonstrated that inertial instability applied to the equatorial ocean also had very similar characteristics to the observations, making it difficult to discriminate observationally between the two formation mechanisms. Edwards and Richards (1999) developed a theory of combined double-diffusive-inertial instability. In this case a third class of instability was found with an oscillatory behaviour. This oscillatory behaviour can be attributed to differential diffusion of density and momentum, as discussed by McIntyre (1970).

Although we are uncertain as to the formation mechanism, at finite amplitude double diffusion does appear to be playing some role in maintaining the intrusions and influencing fluxes of heat and salt. When analysing a number of meridional sections in the western equatorial Pacific, Richards and Banks (2002) concluded that at least 50% of the observed intrusions had properties consistent with double diffusion dominating the vertical fluxes of salt and heat. Based on the model of Joyce (1977) they estimated the meridional fluxes of heat and salt caused by the interleaving to be comparable to those of the eddy field. Using this result Richards (1998) estimated the effective lateral diffusivity of the interleaving to be O(1000 m^2s^{-1}). Interestingly, Maes, Madec and Delecluse (1997), using an ocean GCM, found this level of lateral mixing greatly influences the large scale dynamics and thermodynamics of the equatorial Pacific. Preliminary results from numerical simulations of interleaving by Edwards and Richards (manuscript in preparation) confirm the high values of meridional fluxes and effective lateral diffusion coefficient.

The potential impact of interleaving on the large-scale structure of equatorial Pacific has prompted the development of parametrization schemes suitable for inclusion in ocean GCMs (see Richards, 1998). Modeling the effect of interleaving as an enhanced mixing in the equatorial thermocline, Pezzi and Richards (2003) show that the effect of interleaving can reduce the cold bias often found in ocean GCMs whilst limiting the speed of the EUC.

3. Properties of thermohaline intrusions

3.1. Vertical length scales

Stern (1967) parameterised vertical salt and heat fluxes via a flux ratio, and ignored viscosity. He found the growth rate to increase without bound with the vertical wavenumber—a ‘blue catastrophe’. Toole and Georgi (1981) added a constant eddy viscosity to Stern’s theory, and found the growth rate to maximize at a particular wavenumber, leading to a prediction for the scale of the fastest-growing intrusions:

$$H = 2\pi\left[\frac{4(K_S A)^{1/2} N}{g(1-\gamma)\beta \bar{S}_x}\right]^{1/2} \tag{1}$$

where N is the buoyancy frequency, γ the salt finger flux ratio, and $\bar{S}_x$ is the lateral salinity gradient, converted to density equivalent. This has the disadvantage of depending on both the unknown eddy diffusivities for salt K_S and of momentum A, both of which are very poorly known (Walsh and Ruddick, 1995a). It is also likely that the lateral salinity gradient could be weakened by the intrusions, so that comparison of formula (1) with observations may not relate to the conditions that actually caused the intrusions.

In a series of laboratory experiments, Ruddick and Turner (1979) found that the intrusion scale was proportional to the cross-frontal salinity contrast. They set out a mechanistic argument for the redistribution of heat and salt by intrusive advection followed by salt finger rundown, and considered the potential energies involved. They were able to deduce bounds for the vertical intrusion scales that were not only supported by the laboratory observations but also consistent with a variety of published ocean observations. The resulting estimate for the intrusion scale is:

$$H = \frac{3(1-\gamma)}{2}\frac{g\beta\Delta S}{N^2} \tag{2}$$

where $\beta\Delta S$ is the density contrast resulting from the cross-frontal salinity change, measured along isopycnals (and therefore equal to the density contrast resulting from the cross-frontal temperature change). This form is similar to that found by Thorpe et al. (1969) for a heated sidewall in a salt stratification, and Huppert and Turner (1980) for melting ice in salt-stratified water.

Van Aken (1982) noted that both Ruddick and Turner (1979) and Toole and Georgi (1981) formulae predict very different dependence on N, and he used observations of intrusion thickness in the Rockall Trough to test the power-law dependence on N. He found an intermediate result, perhaps because the dependence on other key parameters such as cross-frontal salinity contrast or gradient was ignored. McDougall (1986) considered their implications of the Ruddick and Turner arguments on the T/S plane, and concluded that such intrusions could not grow to a large enough amplitude to create T/S inversions. Since such inversions are commonly observed in oceanic intrusions, he suggested that the Ruddick-Turner arguments cannot be applied in estimating the scale of oceanic intrusions.

Ruddick and Hebert (1988) analyzing CTD observations from Meddy 'Sharon' calculated a vertical intrusion wavelength as 30 m, They then used the observed 30 km/year (~1 mm s^{-1}) erosion rate as an estimate of the lateral intrusion velocity. By assuming a balance between radial advection and vertical flux divergence within individual intrusions, they estimated the vertical salt diffusivity to be $K_S = 3 \times 10^{-5}$ m^2s^{-1} and the lateral diffusivity to be O(1 m^2s^{-1}). Using the vertical diffusivity, they compared the observed vertical intrusion scale from the edge of Meddy 'Sharon' with the predicted scales using Ruddick and Turner (1979) (Eq. 2, 300 m) and Toole and Georgi (1981) (Eq. 1, 25 m, assuming an effective Prandtl number of 40 (Ruddick, 1985)). Ruddick and Hebert computed a key parameter G from the linear instability theory of Niino (1986) for a finite width front. They found G $\approx 10^{10}$, which indicates that the Meddy front is a wide front. Physically, this means that the region outside the frontal zone is of little importance to the dynamics of the intrusions, and the formula (Eq. (1)) of Toole and Georgi is appropriate. Walsh and Ruddick, 1995b) considered the effect of strong dependence of the diffusivity on the density ratio on the Toole-Georgi theory, finding enhanced effective diffusivities and growth rates. The enhanced diffusivity combined with more recent estimates of turbulent double-diffusive Prandtl number of O(1) (Ruddick, Griffiths, and Symonds, 1989), to yield improved agreement with the Meddy observations.

3.2. Intrusion slopes relative to isopycnals

The apparent slope of intrusions is, as described in the introduction and shown in Fig. 1, intimately linked to their dynamics, and changes according to whether the finger or diffusive buoyancy fluxes dominate. The slope relative to isopycnals is often inferred in synoptic CTD observations by monitoring the change in density of the T-S maxima and minima as one moves laterally from one CTD station to the next. This is done because internal wave motions shift both isopycnals and the intrusions significantly from one CTD cast to the next, and destroying lateral coherence when temperature-depth plots are compared. An alternative method uses ‘stretched pressure’ as the vertical coordinated. This quantity is, in effect, potential density, but transformed such that each value of potential density occurs at the average value of pressure found for the set of CTD stations (McDougall and Ruddick, 1982). This allows intrusions to be viewed at something like their true depth, and dramatically increases the lateral coherence of intrusive features, but of course the isopycnal surfaces in such a representation appear falsely to be horizontal. A useful enhancement to this would also be to show surfaces of constant pressure (which in the ocean are nearly horizontal) on the same plots as temperature versus stretched pressure, but this has not generally been done.

In a landmark series of papers, Joyce et al. (1978), and Toole, 1980, 1981a) described CTD observations of the Antarctic Circumpolar Current/Front system (Fig. 4), showing that quasi-isopycnal finescale layers are evident in sections of temperature, salinity and oxygen that are most intense within the frontal region (stations 26–28 in Fig. 4). These (particularly the oxygen) indicate variance production by lateral, cross-frontal interleaving motions. Some detailed towed CTD sections (Fig. 5) documented the strong lateral coherence of features on scales ranging from a few m to 100 m. These features can be clearly seen to rise in successive profiles, indicating the migration across isopycnals expected for intrusions driven by salt fingers discussed in Fig. 1. Joyce et al. (1978) also applied a theory by Joyce (1977) to estimate lateral heat and salt fluxes in terms of an assumed vertical eddy diffusivity, and found these fluxes to be significant (lateral diffusivities of order 0.2 m^2s^{-1}), and comparable with those driven by baroclinic eddy-shedding.

Fedorov (1976) showed a CTD section across a front in the North Atlantic, with intrusions that clearly crossed isopycnal surfaces, and discussed several other examples of thermohaline intrusions. Gregg and McKenzie (1979) and Gregg (1980) showed detailed three-dimensional mapping of a thermohaline intrusion, demonstrating that it crossed isopycnal surfaces in the cross-frontal direction. In a data set from the eastern subtropical Atlantic Fedorov (1980) followed the changes in T and S of intrusions over repeated CTD casts, interpreting them as purely temporal changes, and attributing them to double-diffusive flux

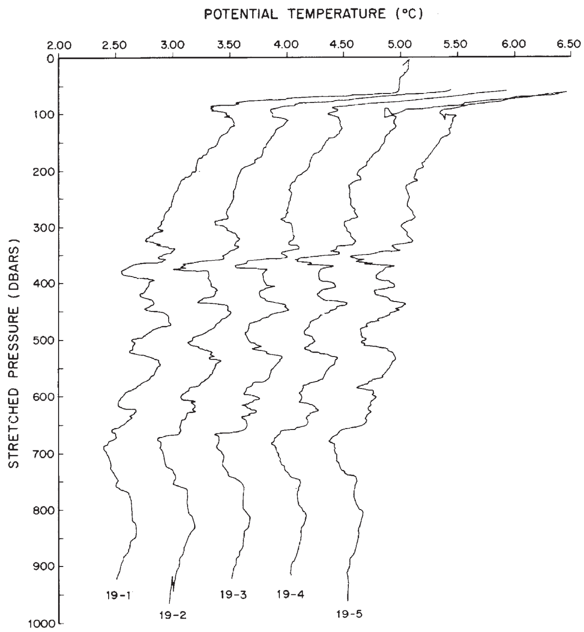

Fig. 5. Profiles of potential temperature versus stretched pressure (a variable designed to remove the effects of sloping isopycnals and internal wave displacements) for five lowerings of a tow-yo’d CTD section. Time separation between stations is about 20 minutes, corresponding to horizontal separations of O(1 km). Successive profiles are offset 0.5 °C. (Reproduced by permission of the American Geophysical Union, from Joyce et al., 1978).

convergences. The possible role of intrusion-scale or larger advection was not discussed. McDougall and Giles (1987) described vertical migration of intrusive features in the Tasman Sea.

Hallock (1985) performed a detailed CTD survey of the Iceland-Faeroe Island front, including some detailed tow-yo surveys. The upward migration of warm salty layers and the favorable correspondence of the observed intrusion scale (about 50 m) with the proposed scale of Ruddick and Turner (1979) supported a double-diffusive driving mechanism. Application of the Joyce (1977) model gave estimates of the poleward heat flux of 52 kW m^{-2} (lateral eddy diffusivity of 1200 m^2s^{-1}), of the same order as the eddy heat flux and larger than for the Antarctic circumpolar front.

Ruddick (1992) examined the cross-isopycnal migration of the Meddy Sharon intrusions, finding that the intrusions in the lower portion of the Meddy sloped upwards as they moved out from the warm, salty core, whereas those in the upper portion sloped downwards. The slopes he recorded were outside the range of angles for which the McIntyre (1970) mechanism can provide energy to the intrusive motions, but within the range of angles for which double-diffusive mixing can drive them. The observed wavelength was closer to the Toole-Georgi scale than that predicted by McIntyre (1970).

Warm salty intrusions slide laterally upwards, driven by their negative density anomaly, when finger fluxes dominate, and when diffusive fluxes dominate, they are anomalously dense and slide downwards. This is crucial to the conversion of potential energy inherent to the mean lateral T-S gradients (thermoclinicity), into layer-scale available potential energy, and then into kinetic energy of intrusive motions. Ruddick and Walsh (1995) examined the density perturbations in a subset of highly resolved CTD profiles from Meddy Sharon. They found the warm and salty layers tended to be anomalously dense in the upper part of the Meddy, and anomalously light in the lower part, consistent with the observed slopes and the hypothesized driving mechanism.

In analysing the slope of intrusions in a number of sections in the equatorial Pacific, Richards and Banks (2002) find that some sections have layers with slopes that are consistent with finger dominated interfaces. However, in the majority of sections there is no clear signal, with layers sloping in both senses across density surfaces.

3.3. Effects of rotation and baroclinic shear

In a theoretical analysis McDougall, 1985a) showed that in the absence of baroclinic shear, the primary effect of ambient rotation is to induce an along-front tilt to the intrusions that has the effect of balancing the Coriolis force resulting from cross-frontal velocities. The growth rates, vertical scale, and cross-front slope are not strongly affected. This observation, together with the finding by Joyce et al. (1978) that along front slopes are small, was used (implicitly in some cases) to justify a neglect of Coriolis effects in many of the studies described in the previous section. This may be reasonable in situations where vertical shear is zero and isopycnals are flat, but such situations are very rare in the field. Oceanic fronts commonly have vertical along-front shear and geostrophic cross-frontal isopycnal tilts. Both effects complicate the intrusion dynamics. The associated available potential energy associated with the tilted isopycnals is considerable, and can enhance intrusive growth (Kuzmina and Rodionov, 1992).

Kuzmina, Zhurbas and Sagdiev (1994) undertook an empirical characterization of interleaving intensity (defined as the intrusive temperature difference/thickness, divided by the along-layer temperature gradient) as a function of lateral thermoclinic and baroclinic forcing, using data from the subarctic frontal zone of the North Pacific. The primary dependence was on thermoclinicity, as expected for thermohaline intrusions. A secondary, non-monotonic dependence was found on baroclinicity (equivalent to the square of the smoothed inverse Richardson number), such that low and high baroclinicity appeared to enhance intrusions, whereas moderate baroclinicity (smoothed *Ri* about 50) inhibited them. Zhurbas, Kuzmina and Lozovatskiy (1988) analyzed intrusions in the vicinity of the Gulf Stream, and compared their intensity with the potential for baroclinic forcing. They concluded that baroclinic release of potential energy was a likely forcing mechanism. Kuzmina and Rodionov (1992) and May and Kelley (1997) have investigated the combined thermohaline/double-diffusive/McIntyre (1970) instability—double-diffusive intrusions in a baroclinic shear flow. May and Kelley (1997) concluded that release of baroclinic potential energy could enhance the growth rate of the Meddy intrusions by 35–90%. In contrast, vertical shear would reduce the growth rate by a similar amount (May and Kelley, 2002).

May (1999) applied linear theory with shear and rotation theory to two observational test cases. In the first test case, Meddy ‘Sharon’, May found the observed intrusion slopes in the lower, finger-stratified region to be consistent with driving by salt fingers, whereas in the diffusively stratified upper region, the intrusion slopes were consistent with diffusive-sense driving. In both cases, the along-front slope was significantly reduced as a result of the background vertical shear. The second test case (May and Kelley, 2001) involved frontal intrusions in the Arctic north of Svalbard (Perkin and Lewis, 1984). There the background stratification, averaged over scales larger than the intrusions, was stable to both double-diffusion and salt fingering (the temperature maximum was at 200 m, and the salinity maximum at 500 m; the water between these depths was warm/fresh over cool salty). They found that warm, salty intrusions were becoming more dense towards the cool, fresh side of the front (downward relative to isopycnals), consistent with salt finger dominance. However, the intrusions actually sloped upwards relative to the horizontal towards the cool side of the front, with a slope between that of isopycnals and the horizontal—the ‘wedge’ of baroclinic instability. This suggests that these Arctic intrusions were being driven by baroclinicity as well as double-diffusion. They applied the finite-amplitude model of McDougall, 1985b) to these intrusions and concluded that, in order to attain a steady-state advective-diffusive balance, the diffusive fluxes must become dominant.

3.4. Microstructure activity

In the Eastern North Pacific, Gregg (1975) found that thermal microstructure intensity (‘Chi–Theta’) was more intense in intrusions, particularly on the boundaries between warm and cold layers. Williams (1976) described observations of thermal microstructure from a free-drifting buoyancy-controlled float. Three lenses (or perhaps tongues) were found, each having greatly enhanced thermal microstructure near their upper and lower surfaces. In interpreting these observations, Williams (1976) noted that production of the lenses by lateral advection would lead to density ratio changes that would enhance double-diffusion, and that this could explain the observed correlation. While he did not appear to be aware of the double-diffusive driving mechanism identified by Stern, Williams (1976) was among the first to note the linkage between large-scale gradients, advection, double-diffusion, and microstructure intensity. Similarly, Gargett, 1976, 1978) described the use of local T/S relationships to separate regions with vertical double-diffusion, thermohaline staircases, and thermohaline intrusions in towed microstructure and fine-structure data. She found that the most intense temperature microstructure appears to be concentrated at the boundaries, both vertical and lateral, of intrusive features.

Alford and Pinkel (2000) analyzed observations of conductivity microstructure taken from R. V. *Flip* off the California coast, where Gregg (1975) found enhanced thermal dissipation associated with intrusions. The conductivity microprobe could resolve fluctuations as small as 8 cm, and yielded proxy estimates of thermal dissipation rate and Cox number. These quantities were found to be correlated with fine-scale (6.4-m) Richardson number, effective strain rate, and Turner angle (Ruddick, 1983), suggesting that both double-diffusion and shear-driven turbulence were active at the site. Batchelor spectral fitting techniques were used to estimate turbulent kinetic energy dissipation, which was found to correlate well with expectations from observations of overturning scales. Above and below intrusions, where double-diffusive stratification occurred, the dissipation was enhanced over that expected from observations of overturns.

Schmitt and Georgi (1982) observed intrusions in the North Atlantic current, and found some tendency for intrusions to have cross-isopycnal slopes consistent with finger-sense driving. They investigated the relationship between the intrusive fine-structure and optical microstructure using simultaneous CTD tow-yos and free-fall profiles from the optical shadowgraph instrument SCIMP. The SCIMP showed clear images of salt fingers at the lower boundaries of warm salty intrusions, confirming that double-diffusive processes are active in intrusive zones.

Larson and Gregg (1983) presented detailed profiles of velocity dissipation and shear in observations of thermohaline intrusions in the Bahamas, in a warm-core ring, and in the California Current. Both varied coherently with the intrusive structure, with high dissipation above and below the salinity maxima. The dissipation was generally less than the estimated buoyancy flux, indicating that shear production was relatively unimportant. The slope of the intrusions, O(10^{-3}), was weaker than found in other frontal situations, leading the authors to conclude that in this case, double-diffusion was not the main driving factor. A more detailed examination of the data (Larson, 1988) found the picture was more complicated with less equivocal conclusions.

Oakey (1988) analyzed the ‘mixing efficiency’ or the scaled ratio of thermal dissipation to kinetic energy dissipation, in the intrusive region of Meddy ‘Sharon’, and found an excess of thermal dissipation on the upper and lower boundaries of intrusions, where the local vertical gradients favored double-diffusion. This excess was inconsistent with turbulent mixing, and supported the contention that the diapycnal mixing between intrusions was dominated by double-diffusion, as it must be for the intrusions to grow. Armi et al. (1989) found that the most intense thermal microstructure was at the top, bottom, and within the intrusions of the Meddy, with a complete absence of microstructure in the non-double-diffusive Meddy core.

3.5. Intrusion fluxes

3.5.1. The Joyce (1977) model

Intrusions are important primarily because of the fact that they drive lateral mixing of heat and salt, and probably momentum, using the available ‘thermoclinic’ potential energy (Woods, Onken, and Fischer, 1986) of the lateral T/S water mass differences across fronts, released via double-diffusion. Joyce (1977) derived a model that gives the lateral flux of heat (and salt) assuming knowledge of the diapycnal eddy diffusivity generated by all (not just double-diffusion) mixing processes. This model has been widely used to estimate fluxes in a variety of observational settings.

Joyce (1977) recognized that the cross-frontal intrusive flux of heat is a result of advection of warm, salty intrusive layers across the front from the warm side, and conversely for the cool, fresh layers (see Fig. 1). The advective heat flux is linked to production of anomalously warm layers on the cool side of the front, and anomalously cool layers on the warm side. These anomalies must be erased by diapycnal mixing between the warm and cool layers. Joyce began with the equation for heat conservation and, using Reynolds averaging procedures to separate mesoscale, intrusive scale, and turbulent scale motions, derived a budget for intrusion-scale thermal anomaly variance. After scaling arguments, he showed that production of thermal anomalies by cross-frontal advection is, on average, balanced by the destruction of those anomalies by diapycnal mixing. The equation expressing this is:

$$\tilde{u}\tilde{T}\frac{\partial\overline{T}}{\partial X} = K_T\left(\frac{\partial\tilde{T}}{\partial Z}\right)^2 \tag{3}$$

where $\tilde{u}$ and $\tilde{T}$ are the intrusive-scale velocity and temperature, $\partial\overline{T}/\partial x$ is the horizontal cross- frontal temperature gradient, averaged over intrusion scales, and K_T is the vertical (diapycnal) eddy diffusivity for heat, defined as the ratio of the temperature flux to the intrusive scale vertical gradient. The tilde indicates intrusion-scale variables, and the overbar indicates averaging on scales larger than intrusions. The production-dissipation balance expressed in (3) is closely analogous to that developed by Osborn and Cox (1972) to infer diapycnal heat flux from microscale thermal dissipation.

To apply Joyce’s model, one typically uses CTD observations to map the intrusion field across a frontal zone, and then computes the average lateral temperature gradient $\partial\bar{T}/\partial X$, and the average vertical intrusion-scale temperature gradient variance, $\left(\frac{\partial\bar{T}}{\partial x}\right)^2$. After assuming a constant value for K_T (the canonical value of 10^{-4} m^{2}s^{-1} was used in almost all cases), the cross-frontal heat flux $\tilde{u}\tilde{T}$ can be solved for in (3). The same approach has often been used for salinity and even for density (c.f. Joyce et al., 1978). However, equal diffusivities were assumed for heat, salt and density by Joyce et al. (1978), and this failed to capture the key feature of vertical double-diffusive fluxes (the 'flux ratio'), leading to a distorted or possibly wrong view of the lateral flux of density.

Although the theory is valid for any eddy diffusivity, constant or variable, turbulent or double-diffusive, our lack of precise knowledge of the diapycnal eddy diffusivity causes serious problems. To begin with, we do not have precise knowledge of the vertical diffusivity. Polzin et al. (1997) cited studies based on advective heat budgets from semi-enclosed basins, ranging from 1–10 x 10^{-4} m^{2}s^{-1}, and noted that direct microstructure observations, and observations of deliberately-injected tracer spread, in the upper ocean interior yield about 0.1 x 10^{-4} m^{2}s^{-1}. These are predominantly from areas where double-diffusion plays a minor role. St. Laurent and Schmitt (1999) concluded that salt-fingering contributed significantly to the diapycnal fluxes in the North Atlantic Tracer Release Experiment, and estimated 0.08 and 0.13 x 10^{-4} m^{2}s^{-1} for heat and salt diffusivities, respectively, at an average density ratio of 1.6. Hence a range of two decades can be argued for, with the canonical value of 1 x 10^{-4} m^{2}s^{-1} falling in the geometric middle.

A second problem in the application of (3) is that the diffusivities are almost certainly a strong function of the intrusion-scale salinity and temperature gradients, primarily via the density ratio, and so will have strong depth variations on the scale of the intrusions. K_T will be larger where the vertical temperature gradient is larger and density ratio lower, and this co-variation will strongly affect the averaging in (3). (Notice that K_T is included in the average). It is difficult to assign an appropriate effective mean diffusivity, but it is likely to be larger than the actual mean.

A third unknown factor involves the interaction between double-diffusive mixing and shear-driven turbulence, which add in terms of salt and heat fluxes but have opposite buoyancy fluxes. Walsh and Ruddick (2000) discovered in numerical calculations that a major effect of turbulence is to alter the heat/salt flux ratio, and the consequence of this is to allow a finite-amplitude equilibration with a balance between lateral advection and vertical mixing consistent with the intrusive slope. It is also possible that enhanced frictional effects owing to shear-driven turbulence disrupt intrusive growth. Zhurbas and Oh (2000) performed linear instability analysis similar to that of Toole and Georgi (1981), allowing for an additional constant turbulent diffusivity, and found it to suppress the initial linear instability. This was noted to conflict with many instances of observations of intrusion from areas where the turbulent diffusivity is likely large enough to suppress intrusive growth. They offer three possible explanations for the discrepancy:

1. Uncertainty in the effective Prandtl number,
2. Enhanced effective finger diffusivity because of density ratio dependence (Walsh and Ruddick, 1995a,b, 2000).
3. Enhancement of intrusive growth by baroclinic energy release (Kuzmina and Rodionov (1992); May and Kelley (1997); Kuzmina and Zhurbas (2000).

Hebert, Oakey and Ruddick (1990) examined the evolution of the shape of a Meddy over the two years, using several nondimensional numbers. The Rossby number, based on either the central vorticity or the radius and velocity of the velocity maximum, did not change. The Burger number $(NH/fL)^2$ increased primarily owing to the decrease in L, while the ratio of total kinetic energy to available potential energy (another type of Burger number) decreased. The rates of salt and heat loss were equivalent to a horizontal diffusivity of O(5) m^{2}s^{-1}, consistent with 4 m^{2}s^{-1} estimated by using the Joyce (1977) model, and also consistent with the estimates of intrusive fluxes by Ruddick and Hebert (1988), which assumed an advection-diffusion heat balance to estimate $K_T = 1 \times 10^{-4}$ m^{2}s^{-1}, the value that was used in applying the Joyce (1977) model. This comparison is somewhat circular, since Ruddick and Hebert (1988) used the observed rate at which the Meddy radius decreased (1 mm s^{-1}) as the advective velocity, and this 'detrainment' velocity tightly constrained the salt budget. Nonetheless, from this comparison it appears that, provided the vertical diffusivity is reasonably well known (or can be estimated using microstructure or other observations) the Joyce (1977) model can be applied with some confidence. Taking the observed lateral temperature gradient of 4 °C over 15 km gives a temperature flux of 1.3 x 10^{-3} °C m s^{-1}.

The observed intrusion advance speed of 1 mm s^{-1} was noted by Ruddick and Hebert (1988) as consistent with the then-unpublished estimate of the intrusion advance speed estimated from laboratory experiments:

$$u = 0.005\mathrm{n}\, NH. \tag{4}$$

This relationship is more fully justified in a recent description and theoretical model of the laboratory experiments (Ruddick, Phillips and Turner, 1999). While it is possible to use this formula on field observations to estimate lateral fluxes, it is based on laboratory intrusions and a somewhat incomplete theory, and cannot yet be fully trusted. If confirmed in other situations, this could be used to derive predictive lateral flux laws, which will not be equivalent to Fickian diffusivity.

Nagasaka et al. (1999) presented CTD observations of thermohaline intrusions from the Oyashio Frontal Region, and compared the observed thicknesses with the formula of Ruddick and Turner (1979), along with laboratory observations by Ruddick and Turner (1979); Bormans (1992) and Nagasaka, Nagashima and Yoshida (1995), finding good agreement. Using Eq. (4) Nagasaka et al. (1999) estimated lateral diffusivity to be in the range 1–6 m^{2}s^{-1}, and found by assuming an advection-diffusion balance in the heat equation that the associated intrusion-scale vertical diffusivity was O(10^{-4} m^{2}s^{-1}), so that application of the Joyce (1977) model would yield similar results.

Table 1 summarizes the cross-frontal fluxes of heat estimated by the aforementioned authors using the Joyce (1977) model, as well as observations of temporal changes (Carmack et al.1997; Hebert et al., 1990) and use of the advective-diffusive balance in the salt or heat equation (Horne, 1978; Ruddick and Hebert, 1988). The heat fluxes cover a range of two orders of magnitude, while the lateral diffusivities range over three orders of magnitude, from 4–3000 m^{2}s^{-1}.

4. Questions for further study

The origins of intrusions are difficult to discern from observations because the observations are of finite-amplitude intrusions at fronts that have existed for a long time prior to the observations in some sort of balance between frontogenesis and intrusive frontolysis. All we can do is make inferences from comparing observed intrusion properties to theoretical expectations.

4.1. What sets the slope of oceanic intrusions?

Is the intrusion slope set by the initial linear instability and retained (unchanged) to finite amplitude, so that the fluxes and flux convergences adjust to achieve a steady state? This is the scenario assumed in the models of McDougall (1985a,1985b) and Walsh and Ruddick, 1998, 2000), and in consideration of baroclinic effects by May and Kelley (1997) and May (1999). In these cases, the observed slope supported linear theory. An alternative scenario is that the slope adjusts slowly in response to changing conditions. This was observed in the laboratory experiments of Ruddick, Phillips and Turner (1999) in a front sufficiently narrow that intrusions reached all the way across. In these experiments the cross-front change in height of the intrusions remained fixed, and the slope decreased as the front became wider.

4.2. Do intrusions reach a finite-amplitude steady state, as suggested by McDougall, 1985b) and Walsh and Ruddick, 1998, 2000), or do they go through a cycle of growth, evolution, instability and breakup, followed by regrowth?

Do slopes and wavelengths change during evolution, or just amplitudes? The fact that intrusion growth timescales (on the order of a day or so) are much shorter than the timescale for existence of oceanic fronts is often taken as support for the view that intrusions should rapidly evolve to a quasi-steady state. If intrusions go through complicated evolutionary cycles, what observations are needed to discover this?

4.3. What sets the scale of oceanic intrusions?

The models of Toole and Georgi (1981) and Niino (1986) are linear instability theories, which predict the initial scale of small-amplitude intrusions. The energy argument of Ruddick and Turner (1979) gives bounds for the vertical scale and is closer to a finite-amplitude prediction. Laboratory intrusions, and the numerically modelled intrusions of Walsh and Ruddick (1998) are often observed to merge, leading to scales larger than the initial instability. Are there limits to this merging, or is there a statistical balance between formation of new, small-scale intrusions and merging?

4.4. How do double-diffusive intrusions begin in a water column that is initially stable to double-diffusion?

Holyer (1983) showed how intrusions form in lateral T/S gradients under the influence of unequal molecular diffusivities, but these have extremely small scale and growth rate. For ‘conventional’ turbulent mixing, parameterized by equal eddy diffusivities for salt, heat and density, intrusive perturbations will decay because of the positive density diffusivity. (This was argued in the original paper by Stern, 1967). A finite-amplitude sheared lateral advection (such as an inertial oscillation) strong enough to produce T or S inversions and double-diffusive fluxes would then be required to create intrusions (Georgi, 1978).

Another possibility, noted by Hebert (1999); Merryfield (2002) and (implicitly by) Walsh and Ruddick, 1995a), is differential turbulent mixing of heat and salt, which can produce density perturbations that drive lateral motions. Gargett (1988, 2002, this issue) argues for differential mixing, and Merryfield, Holloway, and Gargett, 1998) find it in two-dimensional direct numerical simulations. Nash and Moum (2002) find observational support for differential mixing in microstructure observations of temperature and conductivity, with a ratio of haline to thermal turbulent diffusivities between 0.6 and 1.1. Merryfield (2002) discussing Arctic intrusions in a depth range where the overall stratification was not double-diffusive, argued that the vertical length scale was consistent with linear growth under differential turbulent diffusion.

Georgi (1978) examined the hypothesis that intrusions were produced by internal–inertial waves in the Antarctic Circumpolar Current/Front system. He found that vertical displacements by internal waves could not produce the observed fine structure. Near-inertial internal waves did produce an increase in lagged lateral coherence of the T-S fine-structure, and were hypothesized to play a significant role in production of intrusions. However, upon close inspection, Georgi concluded that they could produce neither the required total variance nor the expected spectral shape. Although inertial oscillations may initiate lateral intrusions, double-diffusive driving is required for their sustained growth. The fact that intrusions can be initiated by internal-inertial waves may explain how double-diffusive layering can begin in regions where the overall vertical gradient is stable in both T and S. In such regions, double-diffusion cannot occur, leaving turbulent mixing as the dominant contributor to vertical mixing. If the turbulent diffusivities of heat and salt are equal, as is widely assumed, then linear intrusion theories such as Stern (1967) predict zero intrusion growth rate until a finite-amplitude perturbation (such as an inertial wave) creates double-diffusive structures.

Woods, Onken and Fischer (1986) demonstrated an alternative mechanism to create an intrusive feature that appears to cross isopycnal surfaces: baroclinic instability at an ocean front, which advects water in a three-dimensional fashion on an isopycnal surface. However, this mechanism creates a single inversion, and does not appear able to create a regular series of inversions as commonly found at oceanic fronts. McIntyre (1970) discovered (theoretically) that differential diffusion of mass and angular momentum (i.e. a turbulent Prandtl number $\neq 1$) can destabilize a baroclinic shear flow, resulting in periodic intrusive layering, even in the absence of conventional double-diffusive effects. This instability was confirmed in laboratory experiments by Calman (1977). It is possible that this instability, which tends to have the fastest-growing mode on smaller scales than double-diffusive intrusions, might initiate intrusive motions, followed by coalescence of layers and development into larger, more thermohaline intrusions.

Another possibility, which may apply to the equatorial Pacific, is that the formation of the interleaving may be caused by inertial instability (Richards & Banks, 2002). In the presence of meridional gradients of salinity and temperature, the subsequent motion can produce overturns in each property and hence promote double-diffusive vertical fluxes.

4.5. How can we parameterize lateral intrusive fluxes?

The importance of intrusions to larger-scale ocean circulation is the lateral fluxes they cause. It is surprising that after decades of laboratory and observational study, so little is known about lateral intrusive fluxes and how to parameterize them. The model of Joyce (1977) gives an expression for lateral diffusivity of salt and for heat in terms of an assumed vertical diffusivity. Ruddick et al. (unpublished, manuscript in preparation) have devised a model that combines that of Osborn and Cox (1972), linking molecular and vertical turbulent heat diffusivity, and the Joyce (1977) model, linking vertical and lateral diffusivity (this connection was first recognized by Gargett, 1988). This combination allows lateral intrusive heat flux to be estimated using microstructure observations. The model has been tested using the Meddy observations, and the integrated thermal dissipation is found to be within 20% of the value expected from large-scale changes.

The cross-frontal fluxes of mass (density), and of momentum in a sheared front are also of interest, because of their direct dynamical effects. These fluxes are rarely estimated from observations because of difficulties in measuring the key quantities (the u and v velocity perturbations and their correlation, and/or the vertical eddy diffusivity).

4.6. If intrusions cause lateral density fluxes what are their consequences?

Intrusions that are dominated by salt fingering fluxes have a negative density anomaly in the warm salty layers, and positive in the cool fresh layers. These anomalies are correlated with the cross-frontal velocities, and so there must be an along-layer flux of density downwards from the cool side to the warm side of the front. If the diffusive flux dominates, there will similarly be an along-layer density flux downwards from the warm side. In both cases, the vertical component of this flux (times g/ρ) describes the conversion of potential to kinetic energy of intrusive motions. Joyce et al. (1978) used the Joyce (1977) model to estimate such fluxes, and McDougall, 1985b) discussed these fluxes in terms of his intrusion model. However, no one has discussed or estimated the consequences of lateral density fluxes for larger scales.

A number of questions remain unanswered for equatorial intrusions. What is the zonal structure of the layers? Does equatorial interleaving reach a quasi-steady state or does it go through a 'life-cycle'? How are the meridional fluxes related to the larger scale properties of the ocean? How is interleaving influenced by the presence of such things as tropical instability waves? Such questions need to be addressed before the full impact of equatorial interleaving can be determined.

5. Recommendations

5.1. Organization and analysis of existing observations

A first step in answering some of the questions above is the creation of an organized database of intrusion observations. This would contain pointers to the data as well as summary statistics such as vertical and lateral mesoscale gradients, intrusion scale, characteristics of the fine-scale intrusive profiles, such as the T-S intensity, the density ratio structure, and any other characteristics that can be defined clearly and accurately calculated, including intrusion slopes in physical and T/S space, and the mesoscale T, S, and density structure. Microstructure variables and results, as well as lateral flux estimates (and their basis) should also be catalogued. Such a database could be used to test some theories or search for clear quantitative patterns that might suggest improved models.

We need a reliable method of estimating and parameterizing lateral salt and heat fluxes using only hydrographic (CTD) observations. These observations would give the large-scale lateral and vertical gradients of salinity, temperature and density, the intrusion vertical scale and temperature/salinity amplitude, and possibly the lateral T/S gradient along intrusive features. Parameterizations for fluxes in terms of these quantities would allow the overall role of intrusive fluxes to be assessed, and would allow their effects to be incorporated into large-scale general circulation models. The database described above would provide a first test of any such methods.

5.2. Field experiments

A useful coordinated multi-investigator field experiment would include the following key elements:

1. An almost purely thermoclinic front. This would have small isopycnal slope and baroclinic shear, but easily measurable T/S variation across the front. Such a front would be much simpler to understand theoretically (as suggested originally by Garrett, 1982), would be stable to baroclinic/mixed/barotropic instabilities and eddy formation, and the lack of significant along-front velocity and shear would make tracking dye (see 3. below) feasible.
2. Tow-yo observations, using a CTD with excellent spatial and temporal response, and sensor matching, so that density observations on scales of 1 m or less should be feasible. Tow-yos would be taken in both across- and along-front directions.
3. Tracking of deliberately-injected fluorescent dye, using a fluorometer mounted on the CTD apparatus. This would show the temporal evolution of the dye, and show up the Lagrangian intrusion velocities, in both the across- and along-front directions. Assimilation of the dye evolution into the dye tracer equation, with advection and diffusion, would allow vertical diffusivity to be estimated. The along-front intrusion-scale velocity structure, which has never been observed before, would give valuable information about the vertical eddy diffusivity. Although a point release is known to be feasible, it is worth considering the feasibility of release in a vertical streak analogous to the streaks in the laboratory experiments of Ruddick, Phillips and Turner (1999). This may yield accurate estimates of the velocity shear, which are expected to be very small.
4. Observations of thermal, conductivity, and velocity microstructure.
5. Ideally, the frontal situation would be such that large-scale observations gave independent estimates of the fluxes; however, such situations are rare.

Such an experiment would allow the intrusion-scale T, S, density, and velocity fine-structure to be directly measured. Correlation between velocity and the other variables would give direct estimates of heat and salt fluxes. The vertical diffusivity inferred from the dye observations could be used to test the advection/diffusion relationship expected for heat and salt. Finally, the microstructure observations would give independent estimates of the diapycnal fluxes, and detailed analysis should give information about the double-diffusive nature of those fluxes. The total picture would then give detailed information about intrusion scales, slopes, intensities, velocities, fluxes and diffusivities. A first step would be to test these against the available linear theories. A second step would involve parameterization of the diapycnal diffusivities, and numerical modelling of the intrusions in an attempt to reproduce the details of the observations.

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