$P$ precipitation
$R$ river runoff
$S$ salinity
$Sv$ Sverdrups
$T$ temperature
$W$ watts
$\delta$ salinity anomaly from eddies
$\phi$ latitude
$\lambda$ longitude
$\rho$ density
$\varsigma$ vorticity
$\tau$ wind stress
$\Omega$ Earth's rate of angular rotation

## See also

**Sphenisciformes. Tides.**

## Further Reading


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# INTRUSIONS

**D. L. Hebert**, University of Rhode Island, Rhode Island, USA



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## Introduction

In most frontal regions, where waters of different salinities and temperatures meet laterally, an interleaving of the different waters is observed. These features are commonly referred to as intrusions. Sometimes a single layer of water from one region is advected into the other region, such as the Mediterranean salt tongue in the North Atlantic, by either a mean flow or eddy motion. Multiple layers of the two different water masses are also seen quite often. The driving mechanism for these multiple intrusions is related to horizontal gradients in salinity and temperature and the small-scale (e.g., smaller than the thickness of the intrusions) mixing occurring between the interleaving layers. In this article, only intrusions produced by this latter process are discussed. Both observational and theoretical studies are presented.

Frontal regions are locations where waters of different temperature and salinity meet and interact. They are usually characterized by relatively large horizontal gradients in these two properties. Fronts have been found in the coastal ocean, at the shelf-break and at the boundaries of major currents, such as the Gulf Stream and Antarctic Circumpolar Current. An example of a front (**Figure 1**) is shown by the azimuthally averaged salinity structure of a Mediterranean eddy. A Mediterranean eddy (Meddy) is a coherent eddy of Mediterranean Sea water found in the eastern North Atlantic Ocean. The front with its larger horizontal gradients in salinity is located at a depth range of 700–1300 m and with a radius of 15–30 km. The temperature field has a similar structure to the salinity structure shown in **Figure 1**. With the horizontal change in salinity, it would be expected that there would be a horizontal change in the density of the sea water. However, the effect of the horizontal change of temperature on the density nearly completely compensates the density change due to the salinity change across the front. Thus, the density surfaces are nearly horizontal. However, there is a slight upward (downward) tilt of density surfaces in the lower (upper) half of the Meddy. The resulting pressure gradient balances the geostrophic flow of the eddy. Along-front geostrophic flows are found at most fronts.

A closer look at the structure of temperature and salinity in the frontal region shows an interleaving of water with the characteristics of the temperature and salinity on the two sides of the front. The temperature and salinity of the water in these interleaving layers show evidence that mixing of the two water types has also occurred. **Figure 2** shows a section of closely spaced (e.g., 1–2 km) vertical profiles of salinity starting from the center of the Meddy (**Figure 1**) and moving towards the outside edge. In

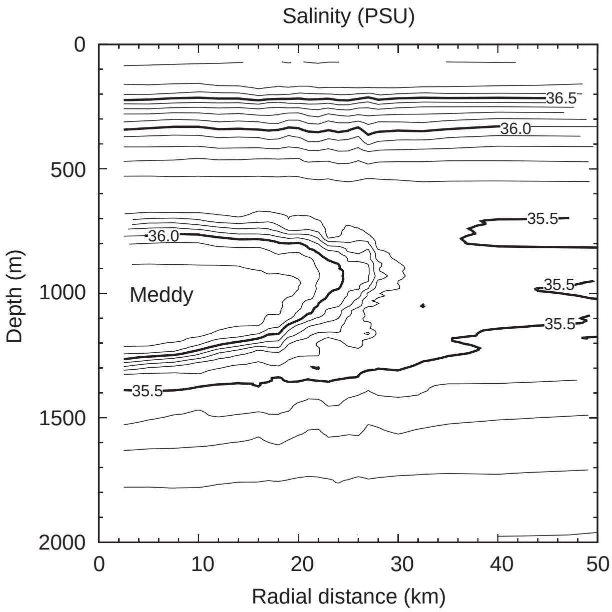


**Figure 1** Azimuthally averaged cross-section of the salinity of a Mediterranean eddy (Meddy) embedded in eastern North Atlantic water. This survey, the second one of this Meddy, was made in June 1985, PSU, practical salinity units.

each profile, there are wiggles in the salinity field, typically of 1–2 km vertical scale, which represents the water moving horizontally from the center of the Meddy to the edge or vice versa. These wiggles are referred to as intrusions. Intrusions like these are found in most frontal regions such as those associated with the Gulf Stream and Antarctic Circumpolar Current.

The observed interleaving of temperature and salinity is thought to develop as an instability of the thermohaline front. These fluctuations lead to regions of enhanced double-diffusive mixing. Two types of double-diffusive mixing can occur: salt-fingering under the warm, salty layers and diffusive-convection under layers that are relatively cold and fresh (**Figure 3**). Both forms of double-diffusive mixing generate a downward density flux, that is, a release of potential energy. The convergence or divergence of this density flux makes the intrusion either heavier or lighter, respectively. These density changes produce pressure gradients which drive the interleaving motions across the front. If the density flux of salt-fingering exceeds that of diffusive-convection, waters in the warm, salty layers become less dense and, therefore, rise as they cross the front. The cold, salty layers become more dense and sink as they cross the front. It is believed that this case applies for the intrusions found for the lower half of the Meddy. If diffusive-convection dominates (which is believed to be the case for the intrusions occurring in the upper half of the Meddy), water in the cold, fresh layers should rise across the front and the warm, salty layers sink.

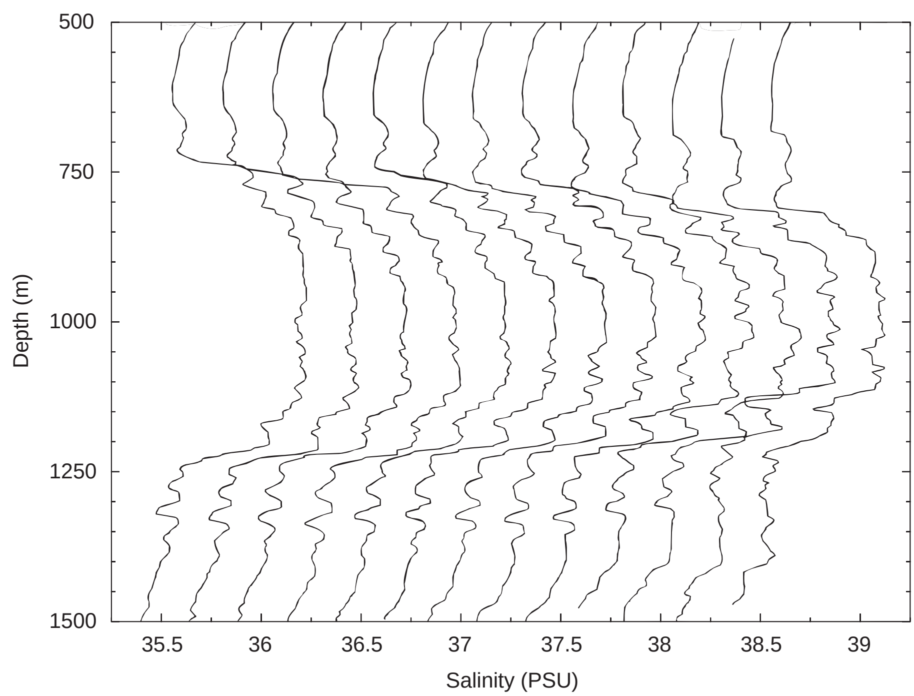


**Figure 2** A set of closely spaced vertical profiles of salinity taken from the center of the Meddy towards its edge during June 1985. Profiles have been offset by 0.25 PSU (practical salinity units).

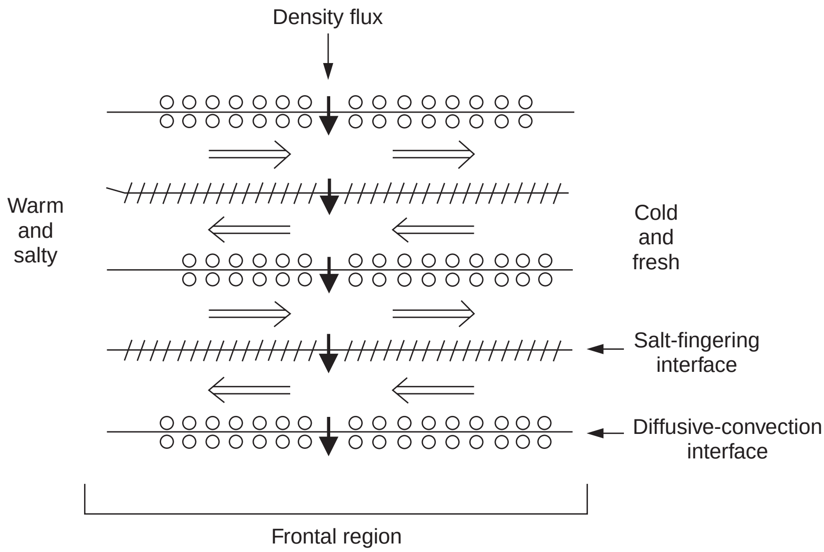


**Figure 3** A schematic of the interleaving layers representing the intrusions. The open arrows indicate the cross-frontal motion driven by the depth-varying density flux (solid arrows). In this diagram, salt-fingering is the dominant form of double-diffusion; thus, the warm, salty water rises as it crosses the front.

## Observational Studies

There have been many observations of intrusions in vertical profiles of salinity and temperature taken in frontal regions. Other than demonstrating the presence of intrusions and indicating their vertical scale, it is difficult to make any other conclusions about the dynamics of the intrusions. Closely spaced profiles (e.g., **Figure 2**) show that the horizontal structure of intrusions is complex. Although it is possible to track an intrusion across several kilometers (and several profiles), the structure of the individual intrusion changes significantly. In addition, some intrusions appear to start and end abruptly. One of the problems of interpreting this type of data is that the frontal region usually has a horizontal velocity field associated with it. Although the water in the intrusions is moving across the front, it is also being advected along the front by the geostrophic current of the front. Therefore, some of the observed cross-frontal variability could be due to differential advection of the intrusions along the front. Most of the observations of intrusions have been single surveys of the front; the evolution and the dynamics of the intrusions could not be determined. Even if multiple surveys are undertaken, temporal changes in the intrusions cannot be separated from possible along-frontal variations of the intrusions.

However, there has been one study where some of the dynamics of the intrusions could be investigated. This was an experiment to determine the evolution of a Mediterranean eddy. The front (**Figure 1**) between these two water masses can be thought of as a circular front. Thus, the problem of differential along-front advection of the intrusions is removed since the front loops back on itself. It would be expected that the individual cross-frontal transects could be typical for all radial sections and that along-frontal variations are small. Thus, the cross-frontal transects could be used to determine the intrusion dynamics. This Meddy was surveyed four times over a two-year period as it decayed.

The vertical structure of the intrusions evolves as the cross-frontal temperature and salinity gradients change (**Figure 4**). For the first year of the study, the Meddy had a core region unaffected by intrusive mixing. During this time, the intrusions appeared to have a similar wiggly vertical structure at all locations for both surveys with vertical scale of about 20 m. The wiggles are rather smooth (i.e., sinusoidal) and have approximately the same vertical scale. By the time of the third survey, the intrusions just reached the center of the Meddy. We can imagine that there was a constant cross-frontal gradient (driving the intrusions) for the first year of observation and that the intrusions had passed their initial (exponential) growth stage. By the time of the third survey, some of the intrusions appeared to have a step-like structure. A year later, the intrusions had a more pronounced step-like structure with a larger vertical scale, about 50 m (**Figure 4**). This structure is probably representative of decaying intrusions. Double-diffusive processes were still active vertically but the horizontal advection

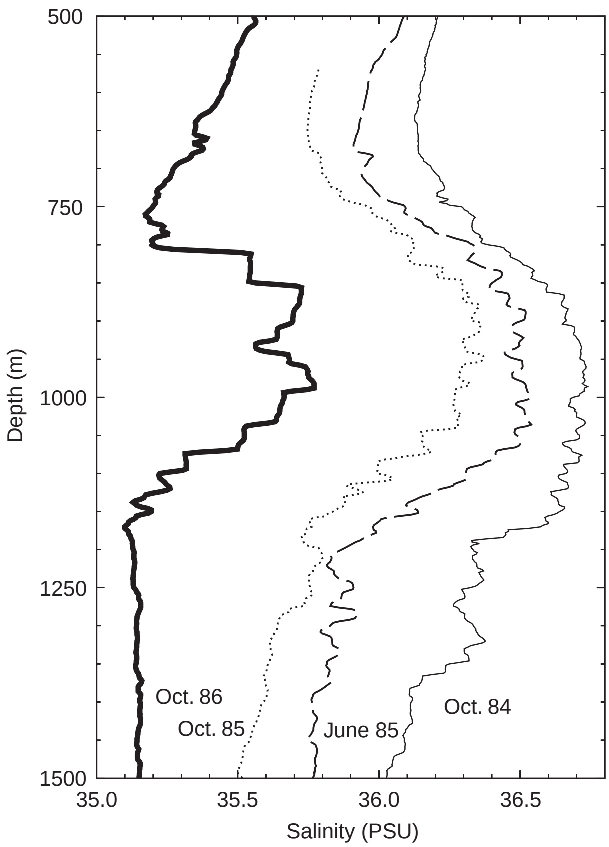


**Figure 4** Vertical profiles of salinity made through the intrusive region of the Meddy during four surveys: October 1984 (solid line), June 1985 (dashed line), October 1985 (dotted line) and October 1986 (bold line). The profiles have been offset by 0.2 PSU (practical salinity units) from each other.

mean gradients were less important; there was not a supply of new water unaffected by the mixing.

One major question that remains concerns the cross-frontal fluxes of heat and salt by the intrusions. In order to address this question, it is necessary to measure the very weak velocities in the intrusive layers or observe the large-scale changes in the properties of the frontal region. For the first year of study of the Meddy, it had a core region with very little horizontal variability (**Figure 1**). Using the rate at which the intrusions moved into this central core region, extremely small cross-frontal velocities, $u'$, on the order of $1\,\mathrm{mm\,s^{-1}}$ were found. Using the salinity anomalies associated with the intrusions, $S'$, and this order of magnitude estimate for the cross-frontal velocity, the average cross-frontal flux of salt, $F_S = -\langle u'S' \rangle$, was calculated. Parameterizing this flux in terms of horizontal diffusion,

$$F_S = K_H\left(\frac{1}{r}\frac{\partial S}{\partial r}\right) \qquad [1]$$

where $K_H$ is the horizontal eddy diffusivity and $\partial S/\partial r$ is the mean horizontal (radial) salinity gradient across the front; an eddy diffusivity coefficient of $0.4\,\mathrm{m^2\,s^{-1}}$ was found.

The dominant mechanism responsible for the decay and eventual demise of the Meddy was thermohaline interleaving, presumably driven by double-diffusive buoyancy fluxes. Over the 2-year observation period, intrusions at the edge of the Meddy core eroded the warm and salty central region from an initial diameter of 60 km until the core was no longer detectable. Using the rate at which the salinity and temperature of the Meddy at a specific radius changed, an eddy diffusivity could be estimated.

$$\frac{\partial S}{\partial t} = K_H\left(\frac{\partial^2 S}{\partial r^2} + \frac{1}{r}\frac{\partial S}{\partial r}\right) \qquad [2]$$

Likewise, by integrating eqn [2] from the center to a specified radius, changes in the salt and heat content of the Meddy can be used to estimate an eddy diffusivity. It was found that an eddy diffusivity of $1\text{–}5\,\mathrm{m^2\,s^{-1}}$ could be used to parameterize the cross-frontal fluxes of the intrusions.

To date, this Meddy study has been the only one where estimates of the fluxes by intrusions could be made. Estimates of the horizontal eddy diffusivity ranged from 0.5 to $5\,\mathrm{m^2\,s^{-1}}$. An attempt was made to understand the dynamics of the intrusions with these surveys but the temporal sampling (six months) was too infrequent to be of use in investigating the evolution of the intrusions.

## Theoretical Studies

The driving mechanism for the cross-frontal velocity of intrusions (i.e., the horizontal pressure gradients) is due to divergences in the vertical density fluxes, generally assumed to be due to double-diffusive mixing (**Figure 3**). Most of the theoretical studies to date have looked at the initial growth of the intrusions using linear stability analysis with parameterizations for the vertical flux by salt-fingers.

In these linear stability calculations, the background frontal structure is assumed to have linear gradients, both horizontally and vertically, of salinity and temperature. The horizontal gradients are chosen such that there is no horizontal gradient in density and thus, no along-front velocity. Vertical gradients are chosen such that the background structure is unstable to double-diffusion, usually salt-fingering. Double-diffusive mixing is parameterized as a constant eddy diffusivity for salt (or heat) and a constant ratio of the heat to salt flux. The perturbations are assumed to be small, so there are no inversions in temperature and salinity. The linear stability analysis predicts the vertical scale, cross-frontal and along-frontal slopes of the fastest-growing unstable mode given the salinity and temperature gradients. These properties have been compared to observations and have shown general agreement. For typical horizontal gradients of salinity and temperature found in frontal regions, the growth rate of the fastest mode has an e-folding timescale on the order of 10 days. Inclusion of a background velocity shear due to the sloping isopycnals across the front can produce faster-growing intrusions with an e-folding timescale on the order of several days.

Linear stability studies predict properties of the initial growth stage, in which fluxes grow exponentially, but say nothing about the finite amplitude 'steady' state properties. When the intrusions reach finite amplitude, the fluxes of heat and salt by the interleaving should reach a constant value. Since fronts in the ocean exist much longer than the time for the intrusions to grow, intrusions spend most of their lives in the finite-amplitude state. Therefore, the usefulness of extrapolating intrusion properties and fluxes from linear theory is questionable.

For growing intrusions to reach an equilibrium, a three-way balance between salt-finger, diffusive-convection and (cross-frontal) advective fluxes is necessary. The initial instability may set the vertical scale of the finite-amplitude intrusions, but the cross-frontal fluxes may depend critically on the form of the equilibrium that the growing intrusions eventually reach. A numerical model verified that small amplitude intrusions, predicted by linear stability analysis, evolved into large amplitude, equilibrium, intrusions. When the amplitude of the intrusion becomes large enough that temperature and salinity inversions occur, the growth of the intrusion slows and reaches an equilibrium state. This equilibrium state is characterized by interleaving layers with salt-fingering and diffusive-convection occurring at the interfaces separating statically unstable 'convecting' layers. As expected, the three-way flux balance is achieved. As well as obtaining a balance in the advection and mixing of the salinity and temperature, there must be a momentum (energy) balance. The double-diffusion mixing lowers the potential energy of the system. This potential energy is converted into kinetic energy within the convecting layers. In addition, the convecting layers allow a large flux of momentum from the salt-fingering interface to the double-diffusive interface. The friction between the interleaving layers balances the pressure gradient produced by the density flux divergence.

## Summary

The presence of intrusions in frontal regions has led oceanographers to believe that they must be important in the cross-frontal fluxes of heat and salt. However, at present, these fluxes are almost impossible to observe in the ocean. Thus, we must rely on theoretical and numerical studies to address this important question. In order to be useful, these studies must predict properties of intrusions which can be compared to observations. To date, comparisons have been limited to the vertical length scale of intrusions from single vertical profiles of temperature and salinity. Predictions of the slope of the intrusions (relative to density surfaces) in the cross-frontal and along-frontal directions have been compared to the few cross-frontal sections made. With improvements in navigation with global positioning satellites and the advent of undulating towed bodies, rapid three-dimensional high-resolution mapping of intrusions can be undertaken. Future work, both numerical and observational, will use the three-dimensional structure of intrusions to evaluate the two-dimensional studies done to date.

## See also

**Double-diffusive Convection. Meddies and Sub-surface Eddies. Shelf-sea and Slope Fronts. Upper Ocean Mean Horizontal Structure. Upper Ocean Mixing Processes. Water Types and Water Masses.**

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