

DOUBLE-DIFFUSION AND THE FINE STRUCTURES IN THE SEA

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ABSTRACT

Recent data on the variation of temperature and salinity with depth have shown that these parameters do not vary smoothly with depth but have a steppy profile. The effects of different rates of diffusion of heat and salt known as "double-diffusion" is one of the factors that contributes towards these steps in temperature and salinity profiles. Various laboratory results reported in the literature, on double-diffusion have been discussed and conditions responsible for the formation and merging of layers in diffusive system as well as in the finger system have been indicated. Horizontal gradients can also produce double-diffusion and it has been suggested that care should be taken while extending the results of laboratory studies to oceanic environment.

1. FINE AND MICROSTRUCTURES

Continuous records of temperature and salinity with depth from different regions of the ocean have shown that fine structures is an ubiquitous phenomenon. These are characterized by homogeneous layers separated by sharp interfaces. Fine structures is the name generally given for the fluctuations of scales 1 to 100 m. The fluctuations of much smaller scales are known as microstructures (Gregg, 1975). Vertical wave number spectra show a minimum between these two scales, demarcating the two. Fine structures of 1 to 10 m scales have a horizontal extent of about a few kilometres. Microstructures which are more transient are much less coherent in the horizontal.

There are several mechanisms which can cause the formation of fine structures. Interleaving of watermasses is one of them. When two watermasses of different properties come in contact, they intrude into each other at different levels and the structures of temperature and salinity thus formed will be density compensating. Internal waves can also distort a smooth variation by straining it and thus generate fine structures. In the presence of numerous internal wave or modes, the distorted profile can be very complicated. Billow turbulence is produced by the passage of internal waves along a sharp boundary in between two layers. At the interface, waves roll up and overturn producing billow turbulence. Woods and Wily (1972) have attributed the microstructures observed in the seasonal thermocline in the Mediterranean to billow turbulence.

Gross overturning of internal waves, turbulence and double-diffusion are also the possible factors for the formation of these structures. In this communication the double-diffusive convection and its effects are described in detail.

2. DOUBLE-DIFFUSION

The convection arising from different diffusion rates of heat and salt is known as 'double-diffusion'. The effect of different diffusivities was brought out by Stommel, Arons and Blanchard (1956) who put forward the idea of 'salt fountain'. To understand this phenomenon, consider a tube (superconductive to heat) which is lowered into the ocean where both temperature and salinity decrease with depth and where the water column is statically stable. If the water is pumped up through this tube, the rising water would quickly attain the temperature of the surroundings while its salinity would change very little. Hence the density of rising water would be less than that of the surrounding water. The water will go on rising even after the pumps are stopped and thus a perpetual fountain will be maintained.

Many laboratory studies on double-diffusion have been conducted by various investigators. Impetus to such studies came from numerous observations of layers in the sea for which double-diffusive convection was believed to be a causative factor. Even though many experiments were conducted on heat-salt systems, it was found difficult to maintain large gradients and steady conditions with these solutes due to the side wall effects. Hence, in many laboratory studies other solute pairs (e.g. sugar and salt) were made use of. Salt and sugar can produce double-diffusion even though their molecular diffusivities are closer compared to those of heat and salt (salt $\propto 1.5 \times 10^{-5}$ cm²/sec and sugar $\propto 0.5 \times 10^{-5}$ cm²/sec); the solute of higher diffusivity is substituted for heat. However, to avoid ambiguity, T and S are used to indicate faster and slower diffusing components respectively.

The resulting effects caused by the difference in diffusivities can manifest in two ways depending on the gradients of properties. Turner (1973) has summarised the various theories and the related experiments.

2.1 DIFFUSIVE SYSTEMS

Consider cold, fresh water overlying warm, saline water. The lower layer is denser and hence the system is statically stable. The coefficients of molecular diffusion of heat and salt are about 1.5×10^{-3} cm²/sec and 1.5×10^{-5} cm²/sec respectively. Heat, thus diffuses 100 times faster than the salt. Therefore, the density of the lower layer at the interface increases and that of the upper layer decreases causing sinking and rising of the respective layers. The interface, however, is not destroyed (Fig. 1). It is the unstable buoyancy flux which escapes through the interface that drives the convection. This is one of the double-diffusive processes and is known as 'diffusive system'.

By heating a stable salinity gradient from below, a 'diffusive system' can be set up. In this case salinity is the stabilizing agent while the heat destabilizes the system. Turner (1965) studied heat-salt 'diffusive system' and compared the measured heat flux with that for solid plane (in between the two solutes). The ratio, measured heat flux/solid plane flux, is a function of the density ratio R_ρ , where $R_\rho = \beta \Delta S / \alpha \Delta T$, (ΔS and ΔT are the changes in salinity and temperature at the interface and β and α are the corresponding coefficients of expansion). For $R_\rho < 2$ the measured heat flux is considerably greater than that for the solid plane. This can be due to the breaking of the waves at the interface which increases the surface area. Another argument is

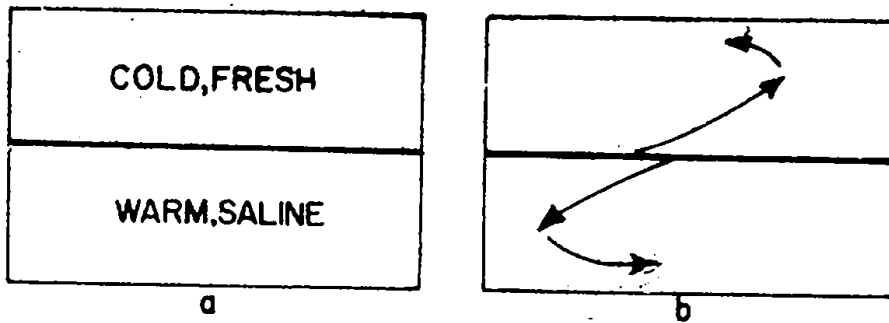


Fig. 1. Diffusive system (a) Initial condition (b) Convection on either side of the interface.

that in a limiting case, the interface acts as a free surface with reduced constraints on the horizontal motion. Again, for increasing R_ρ , the heat flux diminishes. Huppert (1971) has given an empirical relationship for the observed range of R_ρ .

The heat and salt fluxes, if converted into corresponding density fluxes, their ratio $\beta F_S / \alpha F_T$ again becomes a function of the density ratio R_ρ (here F_S and F_T stand for salt and heat fluxes respectively). When $R_\rho > 2$, $\beta F_S / \alpha F_T$ remains constant and is equal to 0.15. However, as R_ρ reaches towards unity, the density flux ratio also becomes unity suggesting that heat and salt are transported similarly. The region of R_ρ where the density flux ratio is constant is called a constant regime and the other portion is called a variable regime. Within the variable regime, the flux is a contribution of double-diffusion and turbulent entrainment and hence it leads to a considerable increase in flux as compared to the solid plane flux in the neighbourhood of $R_\rho \rightarrow 1$ (Linden 1974).

Turner (1968) has verified the theoretical hypotheses in a heat salt 'diffusive system'. When a stable salinity gradient is heated from below, a convecting layer grows from below, which at a certain stage stops growing further. A second layer, then, starts growing. Many layers can be set up in this manner. The initial gradient and the heating rate determine the depth of the convective layer. The stability of double-diffusive layers was investigated by Huppert (1971). Considering a diffusive system in which a layer is sandwiched between the two semi-infinite layers, it is found that when the system is in constant regime ($R_\rho > 2$), the middle layer can be in a stable equilibrium. However, in the variable regime of R_ρ the middle layer merges with one of the semi-infinite layers. Diffusive layers merge in two different ways. Firstly, by the vertical migration of the interface which moves in the direction of the shallower layer. Secondly, the layers merge by the destruction of the interface.

Conditions existing in nature, *i.e.*, with inherent gradients in properties, were studied by Linden (1976). Experiments were conducted in a diffusive system using sugar and salt. Here the gradients are defined by the ratio $G_\rho = -N_T^2 / N_S^2$ where N_T and N_S are the buoyancy frequencies due to T and S respectively. In this way the effect of the external energy (an imposed flux) and the internal energy (unstable T gradient) can be studied. While an increase in the external energy increases the layer depth, an increase in internal energy decreases the layer depth. Thus, the two energies have opposing effects on the layer depth. In the limiting condition ($G_\rho \rightarrow 1$) all the layers formed will be of similar thickness.

2.2 FINGER SYSTEM

Salt fingers are also the result of double-diffusive convection. This phenomenon occurs in the condition opposite to that of the diffusive system i, e , when warm saline water overlies the denser, cold, fresh water. Because of the faster diffusion of heat, the equilibrium is disturbed by an increase in the density of the upper layer close to the interface and a decrease in the density in the lower layer. As a result, alternate intrusions develop which finally grow into long fingers to either directions (Fig. 2).

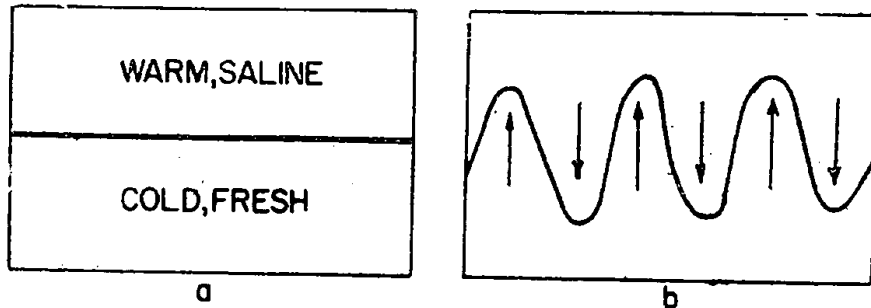


Fig. 2. Salt fingers (a) Initial condition, (b) Fingers which grow to either directions.

In laboratory experiments these fingers were observed to be about 1 mm thick. In a sugar-heat case, Linden (1973) observed finger length of 2.3 mm and vertical speed within the fingers of 0.05 cm/sec. Green and Kirk (1971) found that the descending rates of fingers in a heat-salt case are about 0.1 to 10 cm/min. These increased with increasing salinity difference between the layers. The lumpy nature of the fingers indicates that motion within the fingers is not uniform. Fingers observed in the ocean were 24 cm long and 6 mm in diameter.

Fingers at a sharp interface were studied by Turner (1967) in a heat-salt experiment in which the buoyancy flux was driven by the salinity which was the destabilising agent. The flux/density ratio ($\alpha F_T / \beta F_S$) had a constant value of 0.56 for $2 < R_\rho < 10$, which corresponded to a constant regime. Here R_ρ is the density ratio given by $\alpha \Delta T / \beta \Delta S$. However, a variable regime for $R_\rho < 2$, as in the case of a diffusive system, is possible in the case of fingers too. Stern (1969) has found that fingers can be set up only if the salt flux is less than a critical value.

Experiments with different solutes were conducted by Huppert and Manins (1973) in order to find out the limiting conditions for the fingering to occur. Salt fingers do not form when density ratio, R_ρ is greater than $\tau \sqrt{\tau}$, where $\tau = k_T / k_S$ which is the ratio of the molecular diffusivities. The limiting value for the oceans being 700, fingering is possible if salinity difference exceeds $2 \times 10^{-4} \text{‰}$ per $^\circ\text{C}$ temperature difference. Again, at the limiting condition, the potential energy released by one component is used by the other.

Salt fingers can cause the formation of layers. When a uniform S-flux is applied at the top and when the T gradient between the layers is high, the fingers are long. The fingers are smaller vertically, when the T gradient is small. A further reduction

in the T gradient produces a second layer below the first. For every T gradient, there is a critical value of ΔS above which a convecting layer gets formed. Before the formation of the second layer, the first layer reaches an equilibrium thickness. The fingers bring in flux from above and if the convective flux in the layer is greater than this the layer grows into the finger regions. It has been suggested that in a sugar-salt 'diffusive system' the layers merge when R_ρ lies between 1.10 and 1.06. Due to the similarity of the systems, in the finger case also, the layers should merge below a critical value of R_ρ . Linden (1978) observed that at the interfaces which are not sharp but are gradient-regions between the homogeneous layers the fingers break down. This leads to the formation of two interfaces containing fingers and three layers.

In a sugar-salt experiment, Stern and Turner (1969) observed inversion of properties in the layers. This is due to the intermittent convection driven by buoyant particles which accumulate first and then move in the layers. Interface between the layers, in a slow decay, passes through many quasi-steady states. The convection in the layers, for which fingers are a cause, breaks the fingers down. Thus, the fingers are self limiting in vertical direction. Nevertheless, the fingers are very efficient in the transport of heat and salt vertically.

Spectral studies will be of immense help to determine whether the observations made in the sea are in the region of salt-fingers. Huppert and Linden (1976) studied theoretically and found that the velocity spectrum of fingers will have a sharp peak at a frequency $\omega = \sqrt{2} kv$ where k is the wave number of fingers and v is the velocity of the sensor. Results of the laboratory experiments are in agreement with the theory.

Spectra of conductivity fluctuations along an interface containing salt fingers in the Mediterranean outflow was studied by Magnell (1976) using a towed sensor. The fluctuations had a dominant wave length of 4.16 cm and the spectra was flatter as compared to those postulated by Huppert and Linden (1976). Schmitt (1979) pointed out that this difference is because the fingers may have different sizes.

Maximum buoyancy flux occurs when the fingers are in a stable equilibrium (Stern, 1976). In the transition region between the fingers and the convective layer, the fingers merge together.

3. HORIZONTAL GRADIENTS

Chen and Turner (1974) studied in a series of experiments the effects of horizontal gradients and local disturbances. Horizontal variation in the properties can set up vertical gradients and vertical motions. If T and S are supplied from two sides of a tank, double diffusion as well as layers with closed circulation are produced with strong shears at the interface. Horizontal differences in the properties on an inclined surface can cause a reversal in properties to produce fingers in an originally diffusive arrangement. Mechanical disturbances introduced at the beginning of fingering, produce horizontal wave motion at the interfaces which, however, overturns to produce fingers. After the formation of fingers, the disturbances cannot cause any change. Thus the fingers which feed energy into the waves at the beginning, act to suppress the waves at later stages.

Double-diffusive convection in an inclined slot was studied by Chen and Sandford (1977). Experiments were conducted for different angles of inclination and for different values of $\lambda = \alpha \frac{\partial T}{\partial Z} / \beta \frac{\partial S}{\partial Z}$ where $\partial T / \partial Z$ and $\partial S / \partial Z$ stand for temperature gradient and salinity gradient respectively. For a given value of λ , instabilities occur earlier for larger angles of inclination.

Intrusions of different solutions into stable gradients were also studied (Turner, 1978). The intruding solution creates layers at different depths and produces double diffusive convection. Also, the intruding layers are inclined to the horizontal, the reason for which is the excess buoyancy flux. A reverse flow opposite to the direction of intrusion indicates the interleaving process. Such a process will be prominent near oceanic fronts.

Even though many theories were developed and experiments were conducted on 'diffusive system', they are applicable to salt fingers also, with the necessary modifications. This is due to the similarities between the systems.

4. OBSERVATIONS AND EXTRAPOLATIONS

As can be seen from the previous sections, double-diffusion, under favourable conditions, can cause layerings. Structures that are the result of double-diffusive convection are reported from regions where temperature and salinity contribute in opposing sense towards density. Increasing temperature steps in the lake Vanda (Hoare, 1966) and the layers in the Arctic Ocean (Neal, Nayshaba and Denner, 1969) can be due to 'diffusive system'. Observations on the layers from the North Atlantic under the Mediterranean waters are many (Tait and Howe, 1968, 1971; Howe and Tait, 1970; Zenk 1970; Pingree, 1971 and several others). These can be due to salt fingering. Recently, Varma and Rao (1978) have observed layerings in the northern Arabian Sea (Fig. 3) and have pointed out the possibility of finger like convection contributing to the layerings. Vertical mixing in microscale for which double-diffusion is an important agent, plays a vital role in the mixing of water masses (Joyce, 1977).

Although indirect evidence for double diffusion from the oceans are many, the direct evidence came only when the pictures of salt fingers were obtained using SCIMP (self-contained imaging micro profiler) from the Mediterranean out-flow (Williams, 1974).

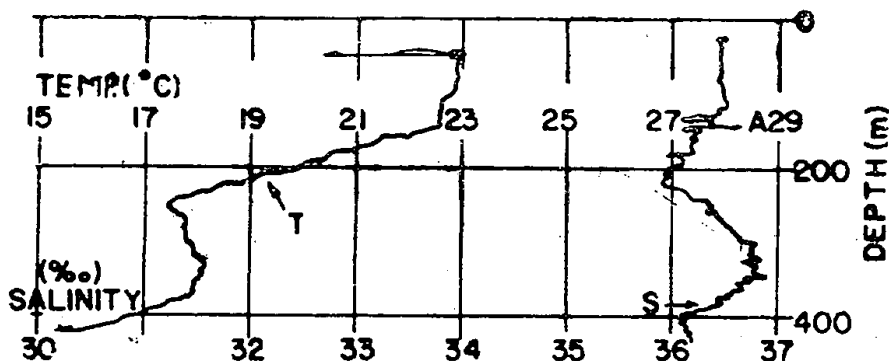


Fig. 3. Temperature and salinity fine structures observed in the northern Arabian Sea.

Attempts to extrapolate the results of laboratory experiments are also many. Linden (1973) obtained 40 m thickness of a layer which was in accordance with the observations in the sea and an interface thickness of 20 cm which was far less than that observed in the sea. Reasonable values of diffusion coefficient and interface thickness were obtained when the results were applied to layers of the Mediterranean influence in North Atlantic (Stern and Turner, 1969). However, the layer thickness was less than the observed values. Increasing layer thickness with depth in the Tyhranean Sea can be explained according to the theory given by Linden (1976). Under the assumption of steady state, the equation for maximum buoyancy flux was applied to the thermohaline staircase, to obtain the possible values of vertical diffusivities, $K_s = 5.7 \text{ cm}^2/\text{sec}$ and $K_T = 0.73 \text{ cm}^2/\text{sec}$ (Lambert and Sturges, 1977). Laboratory results were applied to a steady state model of lake Vanda and satisfactory suits were obtained (Huppert and Turner, 1972).

It is suggested that care should be exercised while extending the experimental results to natural situations, for in oceanic conditions advection plays an important role which is neglected in controlled laboratory experiments. Many experiments have been conducted with solutes other than heat and salt and hence their results may not be directly applicable to the observations from the sea.

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REFERENCES

- Chen, C.F. and R.D. Sandford, 1977. Stability of time dependent double diffusive convection in an inclined slot. *Journal of Fluid Mechanics*, **83**: 83-95.
- Green, T. and R.G. Kirk, 1971. Descent rates of salt fingers. *Nature*, **232**: 123-124.
- Gregg, M.C., 1975. Oceanic fine and microstructure. *Reviews of Geophysics and Spacephysics*, **13**: 586-591.
- Hoare, R.A., 1966. Problems of heat transfer in lake Vanda, a density stratified Antarctic lake. *Nature*, **210**: 787-789.
- Howe, M.R., and R.I., Tait, 1970. Further observations on the thermohaline stratification in deep ocean. *Deep Sea Research*, **17**: 963-972.
- Huppert, H.E., 1971. On the stability of a series of double diffusive layers. *Deep Sea Research*, **18**: 1005-1021.
- Huppert, H.E., and P.F. Linden, 1976. The spectral signature of salt fingers. *Deep Sea Research*, **23**: 909-914.
- Huppert, H.E. and P.C. Manins, 1973. Limiting conditions of salt fingering at an interface. *Deep Sea Research*, **20**: 315-323.
- Huppert, H.E. and J.S. Turner, 1972. Double diffusive convection and its implications for temperature and salinity structure of the ocean and Lake Vanda. *Journal of Physical Oceanography*, **2**: 456-461.
- Joyce, T., 1977. A note on the lateral mixing of water masses. *Journal of Physical Oceanography*, **7**: 626-629.

- Laubert, R.B. and W. Sturges, 1977. A thermohaline staircase and vertical mixing in the thermocline. *Deep Sea Research*, **24**: 211-222.
- Linden, P.F., 1973. On the structure of salt fingers. *Deep Sea Research*, **20** : 325-340.
- Linden, P.F., 1974. A note on the transport across a diffusive interface. *Deep Sea Research*, **21**: 283-287.
- Linden, P.F., 1976. The formation and destruction of fine structures by double diffusive processes. *Deep Sea Research*, **23** : 895-908.
- Linden, P.F., 1978. The formation of banded salt finger structure. *Journal of Geophysical Research*, **83**: 2902-2912
- Magnell, B., 1976. Salt fingers observed in the Mediterranean outflow region (34°N, 11°W) using a towed sensor. *Journal of Physical Oceanography*, **6**: 511-523.
- Neal, V.T., S. Neshyba and W. Denner, 1969. Thermal stratification in the Arctic Ocean. *Science*, **166** : 373-374.
- Pingree, R.D., 1971. Analysis of temperature salinity small scale structure in the region of Mediterranean influence, in the N. E. Atlantic. *Deep Sea Research*, **18** : 485-491.
- Schmitt, R.W., 1979. The growth rate of supercritical salt fingers. *Deep Sea Research*, **26** : 23-40.
- Stern, M.E. 1969. Collective instability of salt fingers. *Journal of Fluid Mechanics*, **35** : 209-218.
- Stern, M.E., 1976. Maximum buoyancy flux across a salt finger interface. *Journal of Marine Research*, **34** : 95-110.
- Stern, M.E., and J.S. Turner, 1969. Salt fingers and convective layers. *Deep Sea Research*, **16** : 497-511.
- Stommel, H., A.B. Arons, and D. Blanchard, 1956. An oceanographical curiosity : a perpetual salt fountain. *Deep Sea Research*, **3** : 152-153.
- Tait, R.I. and M.R. Howe, 1968. Some observations of thermohaline stratification in deep ocean. *Deep Sea Research*, **15**: 275-280
- Tait, R. I. and M.R. Howe, 1971. Thermohaline staircase. *Nature*, **231**: 178-179.
- Turner, J. S., 1965. The coupled turbulent transport across a sharp density interface. *International Journal of Heat and Mass Transfer*, **8**: 759-767.
- Turner, J.S., 1967. Salt fingers across a density interface. *Deep Sea Research*, **14**: 599-611.
- Turner, J.S., 1968. The behaviour of a stable salinity gradient heated from below. *Journal of Fluid Mechanics*, **33**: 183-200.
- Turner, J.S., 1973. *Buoyancy effects in fluids*, Cambridge University Press, 370 pp
- Turner, J.S., 1978. Double diffusive intrusions into a density gradient. *Journal of Geophysical Research*, **83**: 2887-2901.
- Turner, J.S. and C.F. Chen, 1974. Two dimensional effects in double-diffusive convection. *Journal of Fluid Mechanics*, **63** : 577-592.
- Varma, K.K. and L. V.G. Rao, 1978. Observations of fine structure in the northern Arabian Sea. *Indian Journal of Marine Sciences*, **7** : 79-83.
- Williams, A.J., 1974. Salt fingers observed in the Mediterranean outflow. *Science*, **185** : 941-943.
- Woods, J.D. and R.L. Wiley, 1972. Billow turbulence and ocean microstructure. *Deep Sea Research*, **19** : 87-121.
- Zenk, W., 1970. On the temperature and salinity structure of Mediterranean water in N. E. Atlantic. *Deep Sea Research*, **17** : 627-632.