Oceanic Double-diffusion: Introduction

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Abstract

Double-diffusion, the mixing of fluids with two constituents of different molecular diffusivities, was originally discovered in the mid-1800's, forgotten, then rediscovered as an "oceanographic curiosity" a century later. Many oceanographers suspect that double-diffusion has major effects on oceanic water masses and circulation, but direct measurement of the effects has proven difficult. In 1996, a Working Group was formed under the auspices of the Scientific Committee on Ocean Research (SCOR WG108), with the goal to: **Identify progress and barriers to quantifying oceanic double-diffusive fluxes, and make recommendations for further progress**. This document gives a brief history of double-diffusion, a review of evidence of its potential effects in the ocean, and gives an overview of the review articles contained in this volume, written by the Working Group members with the above aim in mind.

1. Introduction

In 1996 Y. Chashechkin proposed and received approval for formation of Scientific Committee on Ocean Research (SCOR) Working Group 108, with the topic "Double-diffusion in the ocean". Working group members undertook as a central objective to: **Identify progress and barriers to quantifying oceanic double-diffusive fluxes, and make recommendations for further progress**. The review articles in this volume represent efforts to examine specific areas of activity in double-diffusion, in light of this mandate. For those unfamiliar with the field, this introductory article will briefly describe the history of oceanographic double-diffusion (Section 2), explain how double-diffusive processes differ from “ordinary” turbulence (Section 3), review various reasons why fluxes associated with the small-scale processes of double-diffusion might be expected to be important to larger-scale oceanography, and detail existing circumstantial evidence for (and against) this importance (Section 4). Throughout this summary, we point out more complete discussions to be found in the following papers. Recommendations for future directed activity in specific areas of double diffusive research may be found in the relevant individual papers.

2. History

In Sydney, Australia in the 19th century, W.S. Jevons (1857) performed the first known laboratory experiments on heat-sugar fingers. He described long, narrow convection cells that formed when warm, sugary water was introduced over cool, fresh water and correctly attributed the phenomenon to a difference in the diffusivities for heat and sugar. He suggested the instability might be responsible for the streamers sometimes observed in cirrus clouds, although they are now thought to arise from a difference in turbulent diffusivity of mass and momentum (McIntyre, 1970). Although Jevons' work motivated

Rayleigh (1883) to first derive the expression for the frequency of internal waves in a stratified fluid, the fundamental notion that convective fluid motions can arise as a result of different molecular diffusivities was forgotten for nearly 100 years (Schmitt, 1995)!

The rediscovery of double-diffusion is described by Schmitt (1995) and in compressed form by Henry Stommel in his autobiography (Stommel, 1984). While trying to design a method of monitoring deep-sea pressure off Bermuda using submarine liquid-filled tubes to carry the pressure signal, Arnold Arons suggested that a pipe with heat-conducting walls would allow a self-sustaining flow to occur (Stommel, Arons & Blanchard, 1956), the "perpetual salt fountain". Stommel (1984) illustrates (figure 1) the sequence of interactions among himself, Melvin Stern, Arnold Arons, Alan Faller, and Willem Malkus. Within a few years came a simple laboratory demonstration of the fountain, recognition of the possibility of some form of convection, including the setup for lateral interleaving, a simple laboratory experiment finding tall thin salt-fingers, and an analytic salt-finger solution (Stern, 1960). As noted by Schmitt (1995), both Arons and Faller credit Stern (1960) as having rediscovered salt-fingers.

Soon afterwards, Turner (1965, 1967) brought his understanding of turbulence, entrainment, and dimensional reasoning to the field of oceanography. He performed laboratory experiments inferring the fluxes of heat and salt across thin diffusive and salt-finger interfaces , and used dimensional reasoning to collapse the observations, establishing the so-called "4/3" flux laws. This may represent the single most important step towards quantifying double-diffusive fluxes to date, although its general applicability in oceanic situations is becoming increasingly questioned.

The development and use of the continuously profiling salinity-temperature-depth (STD) recorder brought the rapid realization that salinity and temperature profiles were not smooth between the point observations afforded by bottles. Instead, profiles often exhibited a huge variety of finestructure, including salinity-compensated temperature inversions (Roden, 1964;Stommel & Fedorov, 1967) and systems of interfaces or steps separated by apparently well-mixed, convecting layers (Tait & Howe, 1968) -- the so-called "thermohaline staircase". These observations coincided with laboratory work showing how a staircase can be formed from smooth gradients by double-diffusive fluxes, both diffusive (Turner, 1968) and fingering (Stern & Turner, 1969). Stern (1967) used instability theory to show how salt-finger fluxes can drive lateral interleaving to produce salinity-compensated temperature inversions, and demonstrated that turbulent mixing with equal diffusivities for heat and salt cannot create such inversions.

By 1969 the picture appeared to be complete: smooth oceanic gradients can be broken down into steps and layers by double-diffusion. The fluxes can be carried across the steps by double-diffusive processes, and then across the layers by convection. These fluxes were estimated by the 4/3 flux laws to be vastly greater than they would be in smooth gradients. Double-diffusion moved in the eyes of (some) oceanographers from being an "oceanographic curiosity" to a potentially major player that could drive significant diapycnal mixing. The diapycnal double-diffusive fluxes could drive lateral interleaving motions, and hence lateral fluxes of salt and heat. This early work, and much more, is described in a clear and physical manner in Turner (1973); it is highly recommended reading.

Most of the world ocean has strong double-diffusive potential somewhere in the water column. The pycnoclines of the world's subtropical gyres (Central Waters) are strongly finger stratified (Ingham, 1966), apparently driven by net evaporation at the surface. Most of the upper Arctic is diffusively stratified because ice formation, brine rejection, then melting creates a cold fresh layer above the warm and saline Atlantic-origin layer. Furthermore, virtually all fronts dividing water masses have numerous lateral intrusions, which have strongly double-diffusive gradients on their upper and lower boundaries. The key question is, so what? What *are* the double-diffusive fluxes of heat, salt, density, and momentum? and what are the consequences of those fluxes?

While observational verification of the existence of oceanic salt-fingers was not long in coming (Williams, 1974; Magnell, 1976), efforts to measure *in-situ* double-diffusive fluxes and observationally test the flux laws have had mixed success. Notable triumphs include Padman and Dillon’s (1987) confirmation that the flux due to molecular diffusion across the steps of an Arctic thermohaline staircase was consistent with the 4/3 flux laws, and Kelley's (1984) dimensional arguments leading to and observationally confirming a predictive relationship for layer thicknesses in double-diffusively stratified staircases. The combined effect of those results is a predictive flux/gradient law for diffusive stratification. Similar efforts to test and quantify the salt-finger case have yielded much more puzzling results. The Carribean Sheets and Layers Transects (C-SALT, Schmitt, Perkins, Boyd & Stalcup, 1987: Schmitt, 1988) found that the salt-finger interfaces in the thermohaline staircase off Barbados were thicker than extrapolations from laboratory observations suggested, and that the fluxes were smaller than the 4/3 flux laws predicted (see the discussion in Schmitt, 1994). Efforts to derive predictive laws for layer thickness in salt-finger staircases were inconclusive (Kelley, 1984). Many salt-fingering regions in the ocean, including most of the salt-fingering portions of intrusions, exhibit irregular finestructure rather than well-defined steps. Salt-finger fluxes are effectively not quantified, and we cannot say exactly why not.

Schmitt (1994) describes efforts to understand the variety of often conflicting oceanic evidence regarding salt-fingers, and makes the case that we still need to quantify and understand their oceanic role. Diffusive sense convection seems to be better understood, but major questions still remain. Intrusions, which involve both finger and diffusive fluxes, are similarly not quantitatively understood.

3. How does diapycnal mixing associated with double-diffusion differ from “ordinary” turbulence?

In terms of diapycnal fluxes, double-diffusion is dramatically unlike “ordinary” turbulence, hence must be considered, and incorporated in models, separately. To illustrate the fundamental difference, consider a mean state favourable to salt-fingering, in which salty water lies above fresher water, but net stratification remains gravitationally stable because the temperature gradient is "warm on top" (Fig.2a). The key to the salt-fingering instability is the fact that on molecular scales heat diffuses much more rapidly than salt . A downward moving parcel of warm saline water (see Fig.2b) cools off via molecular diffusion of heat while exchanging very little salt; the blob thus becomes more dense, providing a downward buoyancy force that reinforces the initial downwards motion of the blob. Similarly, an upward-moving blob gains heat from the surroundings, becomes lighter, and continues to rise. The net effect is a vertical exchange of water containing salt, hence a down-gradient (downwards) salt flux. The heat flux, while also down-gradient, is much smaller since most of the heat diffuses out sideways to adjacent blobs. The combination of these heat and salt fluxes yields a density flux that is also downwards, so that the initially less dense top layer of water actually becomes even less dense over time, while the lower layer becomes more dense, with the required energy being released from the unstable potential energy associated with the initial salt field

A glance at Figure 2(c and d) shows that similar conclusions result from the small-scale processes involved in the diffusive layering instability. The upwards molecular diffusion of heat across the relatively high-gradient interface exceeds (in density terms) the diffusive salt flux, resulting in a downwards density flux that drives convection in the well-mixed layers. The symbiotic relationship between molecular diffusion and convection supports enhanced vertical fluxes in a staircase, with the interfacial flux carried by molecular diffusion, and convection carrying the flux from one interface to the next. Thus double-diffusive fluxes of T and S produce an *up-gradient* density flux rather than the down-gradient density flux characteristic of "ordinary" turbulence. Expressed in terms of the eddy diffusivities normally used in models, double-diffusive diapycnal diffusivities for T and S are positive (though unequal), but that for density would be negative Indeed, the flux convergences associated with the negative density diffusivity are one possible mechanism for creating staircases from smooth gradients (see Question 2 in Kelley, 2001). The fact that double-diffusive convection utilizes the potential energy of either the T or S component allows it to work slowly and steadily as opposed to more energetic but intermittent mechanically-driven turbulent mixing. In this sense, double-diffusive mixing may be the "tortoise" in comparson with the "hare" of mechanically-driven turbulence. It may achieve a great deal in the end, but be more difficult to detect.

Another difference between oceanic turbulent and double-diffusive processes is more subtle. "Ordinary" turbulence in the ocean interior is presently believed to be characterized by a constant diapycnal diffusivity, irrespective of mean water column properties (Polzin, Toole & Schmitt. 1995). If so, the turbulent diffusivity determined from observations in today's ocean will continue to be applicable in future oceans. In contrast, double diffusive fluxes are strong functions of mean ocean properties as expressed in the ratio $R_\rho = \alpha T_z / \beta S_z$ of the relative contributions of T and S to the density gradient. Thus unlike turbulent fluxes, fluxes associated with double-diffusive processes may be expected to change as mean ocean properties evolve under changing atmospheric forcing .

4. Possible importance to larger scales

It has been suggested that double-diffusive fluxes produce significant effects on various large-scale features of the ocean, and it is the potential of such effects that has driven much of the active research in the field. Here we briefly describe potential impacts on water mass properties, and on results of both steady-state and time-dependent ocean models.

(a) Effects on water mass properties

Ingham (1966) first noticed that T/S relationships of the vast Central Waters of the upper subtropical gyres are well described by curves of constant R_ρ. Subsequently, Schmitt (1981) argued that this "R_ρ = constant" character could only arise through the strong dependence of salt-fingering fluxes on R_ρ, leading to flux convergences which, coupled to the fact that salt is transported at a greater rate than heat, act to remove any deviations from constant R_ρ. If true, the action of double diffusive processes serves to remove density-compensating T and S anomalies that are imposed on water parcels at the ocean surface, before their subduction and incorporation into the upper subtropical pycnocline (Rudnick & Ferrari, 1999).

(b) Effects on steady-state ocean circulations

Double-diffusive fluxes are important to ocean models for the same reasons that “ordinary” turbulent fluxes are important. The effects of these sub-grid processes must be parameterized in both regional (mesoscale) and global numerical models, since computer resources are insufficient to resolve the microscales at which both energy and scalar variance are removed from the system by irreversible molecular processes, yet must incorporate the consequences of such processes. In numerical ocean models, parameterization usually takes the form of constant “eddy” diffusivities which multiply the appropriate (vertical/diapycnal or horizontal/isopycnal [1]) resolved gradients of velocity or scalar to provide quantitative measures of momentum and scalar fluxes due to unresolved scales. All small scales, whatever their origin, would be insignificant if models proved relatively insensitive to the values used for such eddy diffusivities. Initial results from coarse-resolution models suggested the opposite, however.

An early sensitivity study (Bryan, 1987) of a coarse-resolution basin-scale model indicated that crucial metrics, such as the strength of the meridional overturning and associated meridional heat flux, were extremely sensitive to the value used for K_v , the vertical eddy diffusivity for density (and to a lesser degree to K_h , the horizontal eddy diffusivity for density). Modelling a basin scaled to the size of the North Atlantic, Bryan showed that varying K_d from $1x10^{-5}$ m^2s^{-1} to $5x10^{-4}$ m^2s^{-1} resulted in a roughly 4-fold increase in the magnitude of the meridional mass transport, while the climatically important meridional heat flux increased by almost an order of magnitude. This reported sensitivity to K_v led to the first exploration of potential effects of *different* diffusivities for T and S on the steady-state of basin-scale models. Duplicating Bryan's model domain and forcing, but carrying T and S as separate fields with different diffusivities, Gargett & Holloway (1992) defined a diffusivity ratio $d \equiv K_S/K_T$, and carried out exploratory model runs with constant values of $d = 0.5$ and $d = 2$. These results showed major sensitivity of the magnitude (and even the direction) of meridional overturning, as well as mean steady-state distributions of T and S, to this relatively minor (given observational uncertainities) variation from the usual assumption of $d = 1$.

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[1] It is generally accepted that diffusive processes in the ocean result in transports which are much larger within a local isopycnal plane than normal to it. Ocean models may variously incorporate this belief via eddy diffusivities which differ, usually by orders of magnitude, between vertical and horizontal (ie in level surfaces) or, more commonly, between diapycnal and isopycnal. In this account, we will normally use the latter terms, unless the work referenced was originally framed in the former.

While these initial results have often been used to motivate further effort on double diffusive processes, the situation has become less clear. In the same paper, Gargett & Holloway (1992) also reported cases incorporating more complicated prescriptions for double diffusivities (in which d = 2 wherever model gradients favoured salt-fingering, $d \leq 1$ elsewhere) which resulted in smaller changes in meridional overturning and heat flux, although still large changes in water mass structure and deep-ocean stability. In subsequent work, Zhang, Schmitt and Huang, (1998) ran a basin-scale model using more complicated parameterizations of K_T and K_S as functions of R_p , and found qualitatively similar but even smaller effects on meridional overturning and heat flux. Unfortunately it is not clear whether this results from the differences in diffusivity parameterizations or from the implementation by Zhang et al. (1998) of diapycnal/isopycnal mixing rather than the vertical/horizontal scheme chosen by Gargett & Holloway (1992) to allow direct comparison with Bryan (1987). Most recently, Merryfield, Holloway & Gargett (1999) added similar R_-dependent parameterizations of diapycnal mixing by double-diffusive processes to a coarse-resolution global-domain ocean model. In this multi-basin domain, where there are multiple sources and sinks of subsurface water masses, and Antarctic circumpolar regions offer an alternate pathway for bottom and deep waters to return to the surface, the steady-state circulation proves insensitive to implementation of double-diffusive mixing. The changes in water mass properties and in water column stability (R_ρ) associated with the addition of double-diffusion are much smaller in magnitude than those that result from implementation of seasonal rather than annual-mean surface forcing, as seen in Figure 3.

The potential importance of double diffusive processes, along with other small-scale processes, to the large-scale ocean circulation has diminished somewhat in recent years, in step with decline in the belief that the main pycnocline of the major subtropical gyres is necessarily diffusively balanced. In the absence of observationally-based estimates of K_d, much early thinking about pycnocline maintenance became fixated on a model in which dense waters forming at high latitudes were returned to the surface by upwelling through the main pycnocline. Balancing an upwards advective flux set by deepwater formation rates by a downwards turbulent diffusive flux requires $K_d \sim 10^{-4}\ m^2s^{-3}$ (this value, Munk's (1966) famed "abyssal recipe", was originally derived for the Central Pacific between 1 and 4 km, but has become a standard metric). However over the past decade, much effort has refined observational estimates of K_d in the main pycnocline. Results from microstructure profiling (Polzin, Toole & Schmitt, 1995) appear consistent with conclusions that K_d is constant over ocean depths that span the main pycnocline, but only of order $10^{-5}\ m^2s^{-3}$, much smaller than Munk's metric. Meanwhile, careful analysis of results from a purposeful tracer release experiment (Ledwell, Watson & Law, 1993) in the North Atlantic upper subtropical pycnocline led St. Laurent & Schmitt (1998) to conclude that T and S (tracer) diffusivities differ significantly, and do so in the sense expected for this salt-fingering unstable region. However the smallness of all the recent estimates for pycnocline K_d (or for K_T and K_S , when determined separately), coupled with the ability of present numerical models to produce convincing results when run with these small values, leads to a conclusion that diapycnal diffusion, of whatever origin, may be a second-order process in establishing the depth of the main pycnocline. Indeed, a recent article by Gnanadesikan (1999) presents scaling arguments which illuminate the potential for the formation of dense deep waters in the North Atlantic to be balanced at least partially through Southern Ocean processes, rather than solely by upwelling through the pycnocline.

While the actual balance between Southern Ocean and diapycnal processes in establishing the main pycnocline is still unclear, it certainly appears that the original numerical studies may have overestimated potential effects of double-diffusion through use of a single equator-to-pole basin which forces the sinking flux of mass to return to the surface through the main pycnocline, ie forces a diffusively balanced pycnocline. Given alternate thermocline models available and much smaller effects of double diffusive implementation observed in global-domain rather than basin-scale numerical models, can we now conclude that double-diffusion is not, after all, of first order importance to larger scales? Or is it merely that the vertical resolution of global-domain models, which necessarily greatly smooths vertical property gradients hence may substantially underestimate diagnosed fluxes, is still too coarse for such models to provide a reliable answer to this question? The jury is still out.

Recent observations of enhanced diapycnal diffusivities over rough topography in the South Atlantic (Polzin, Toole, Ledwell & Schmitt, 1997) suggest that diapycnal processes may yet be of major importance to water mass properties, circulation patterns, and heat storage in the *deep* ocean, with consequent influence on the climate system over decadal to millenial time scales. From a global inverse calculation, Ganachaud & Wunsch (2000) derive volume-averaged values of $K_d \sim O(3\text{-}9\times10^{-4}\ m^2s^{-1})$ for depths greater than 2000m, suggesting that sub-pycnocline waters may indeed obey Munk's "recipe" on a global scale (although this conclusion contradicts Webb & Suginohara (2001), who argue that the deep ocean too mixes primarily at near-surface outcrops within the Southern Ocean). However if turbulent diffusivities are indeed enhanced in the deep ocean, the *relative* importance of double diffusive processes will be smaller, given that deep values of R_ρ are not significantly smaller (hence double diffusive fluxes are not significantly larger) than those in the upper ocean. Instead, a major influence of double diffusive processes on the thermohaline circulation, hence ocean heat content and the climate system, may arise through a dominant role in setting the rate of deep convection in the Greenland Sea, as proposed by Carmack and Aagaard (1973) and McDougall (1983).

(c) Effects on time-dependent ocean circulation

It presently seems possible that double-diffusion within the ocean interior may have more significant effects in models of the time-dependent thermohaline circulation than in the steady-state models considered in the previous section. Our understanding of time variability of the thermohaline circulation is rooted in Stommel's (1961) analysis of a simple 2-box model in which one box was cooled and freshened, as are subpolar surface oceans, while the other was heated and salinized, like subtropical surface oceans, and the resulting density difference drove an advective exchange circulation. Stommel showed that if the thermal forcing time scale was shorter than the haline time scale, this simple model had two stable solutions, one with polar sinking and strong "normal" exchange flow from polar to subtropical boxes, the other with subtropical sinking, and weak reversed exchange flow. Subsequent embellishments of this model (e.g. Marotzke, Welander & Willebrand, 1988; Thual & McWilliams, 1992) all exhibit the existence of similar so-called multiple equilibrium states. In addition, a generation of coarse-resolution general circulation models (e.g. Bryan, 1986; Rahmsdorf & Willebrand 1995) have documented large-scale reorganizations of thermohaline circulation which can occur abruptly as surface hydrologic (freshwater/evaporative) forcing passes through some threshold relative to surface heat fluxes. Using both a scaling analysis and results from single-basin numerical model runs, Zhang, Schmitt & Huang (1999) have suggested that this behaviour, interpreted as "jumps" of the system between multiple steady-states, should also depend strongly upon the magnitude of K_d , hence also presumably to differences between K_T and K_S (note however that extension of this conclusion to the real ocean is again suspect, since the importance of K_d is essentially assumed in the diffusive balance used for the scale analysis, and is forced to be true in the numerical model by the restriction to a single equator-to-pole basin).

The only existing study of the possible effects of double-diffusion on time-dependent model behaviour is that of Gargett & Ferron (1996), who used a four-box model of the thermohaline circulation to examine how differential vertical fluxes of T and S, parameterized by fixed values of the diffusivity ratio d in the range $0.5 < d < 2$, might affect the stable states and time-dependent behaviours of the "standard" ($d = 1$) case.

When forced by constant surface fluxes, the double-diffusive model exhibits additional steady-state modes, in which convection is totally absent from the system, as well as a periodic oscillatory mode within a small range of forcings. When forced by mixed boundary conditions, in which a fixed T-flux is replaced by relaxation of T towards a fixed (atmospheric) temperature, model runs with $d \neq 1$ exhibited extended ranges of multiple equilibria, a different mode transition near present-day values of freshwater forcing, and the possibility of quasi-periodic oscillatory states, the latter reminiscent of self-sustained oscillations of the thermohaline circulation observed in the numerical simulations of Weaver & Sarachik (1991). Although similar box models have long been used as simple tools for investigating behaviour of the thermohaline circulation, applicability of the Gargett & Ferron (1996) results to the real ocean is certainly an open question, particularly because their “two-gyre” model again contains the underlying assumption that the pycnocline is diffusively-balanced. Assessment of the true importance of double-diffusion on time-dependent behaviour awaits future work with models of global scale.

(d) Effects on isopycnal mixing

Lateral intrusions are now known to be driven by double-diffusion (Stern, 1967; Ruddick, 1992). The ultimate energy source involves the lateral T-S differences in water masses, and the potential energy release associated with vertical double-diffusive fluxes. Thermohaline interleaving thus represents a self-driven form of lateral mixing, requiring no external kinetic energy input. It appears to compete with eddy stirring (Joyce, Zenk, and Toole 1978), and certainly will have (when we figure it out) a different dependence on mesoscale variables than, for example, baroclinic instability. Interleaving is known to cause a broad range of eddy diffusivities, ranging from a few to several thousand $m^2\ s^{-1}$. This lateral mixing can cause water mass changes and, through cabbelling effects, subsidence and convergence at fronts (Garrett & Horne,1978). Although a great deal of progress has been made towards understanding the basic mechanisms, the dominant slopes and wavelengths of intrusions, and the effects of baroclinicity and shear, there are currently no tested parameterizations that can predict the properties ands fluxes of the finite-amplitude intrusions that are observed at ocean fronts. The quantitative role of intrusions, particularly relative to other mixing mechanisms, may be poorly known, but as Schmitt (1994) sums it up:

"Double-diffusively driven intrusions could turn out to be a primary horizontal mixing mechanism of the ocean. ... Though large-scale baroclinic instability is an active "stirring" mechanism, serving to increase mesoscale lateral gradients, it does not actually cause mixing (the destruction of gradients). Intrusions provide a key link in conveying heat and salt variance from the mesoscale to the microscale."

As numerical models of ocean circulation achieve higher resolution and become more able to incorporate more realistic (ie small and possibly unequal for heat and salt) diapycnal and lateral diffusivities, they will "grow their own" lateral intrusions. It is important to either resolve these and parameterize the vertical double-diffusive fluxes correctly, or to suppress them and simulate both their mesoscale and microscale effects parametrically. We are currently unable to do either.

5. Conclusion

Uncertainty about the magnitude of double-diffusive fluxes leads to associated uncertainty in the magnitudes of both K_d and K_i , coefficients that may yet be key to the accuracy of our numerical models of the present ocean and, particularly, to its evolution under global climate change. The existence and magnitude of double-diffusive fluxes depends upon “mean” gradients of ocean properties, and these gradients which will assuredly evolve under changing atmospheric forcing. Without accurate physically-based flux predictions, we are unable to predict associated changes in double-diffusive fluxes, compounding uncertainties for ocean models being used in the effort to predict the future state of the global atmosphere/ocean system. The papers which follow are reviews of the present state of our quantitative knowledge of double diffusive processes. Such knowledge has been obtained by the variety of theoretical, laboratory, numerical and observational studies summarized within the individual papers. As seen in the Table of Contents, reviews of various aspects of salt-fingering studies (Schmitt; Kunze; Yoshida & Nagashima) are followed by those of the layering instability (Kelley, Fernando, Gargett, Tanny & Özsoy; Yoshida & Nagashima), and then by those treating the larger-scale intrusions that result from the presence of lateral mean gradients (Ruddick & Richards; Ruddick & Kerr, Ruddick). A final article (Gargett) treats the topic of *differential* diffusion, ie possible differences between turbulent diffusivities for T and S when they are mixed by "ordinary" turbulence. This is not double-diffusion, since it may occur in situations where both mean property gradients are stabilizing. However it is included in this review because the underlying cause of differential diffusion, the difference in molecular diffusivities of the two scalars, is the same, as are the challenges posed to the problem of small-scale parameterization in large-scale models.

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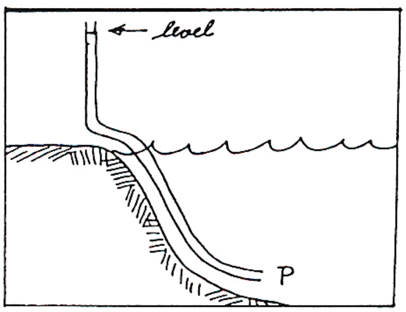
Figure captions:Figure 1: (from Stommel 1984. Reproduced with the permission of the American Meteorological Society) a) The initial discovery of the salt fountain, b) The discovery of salt-fingers by Stern.

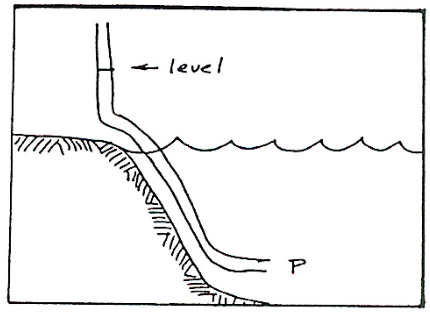
Exciting Ten Minutes at the Blackboard

These two cartoons are supposed to reconstruct the creative process as it occurred at Woods Hole on the third floor on two separate occasions. In both cases several people were involved. They were talking over an unrelated problem when suddenly a good idea came up, and something very thrilling happened.

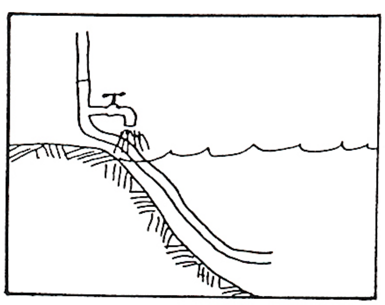
The Salt Fountain



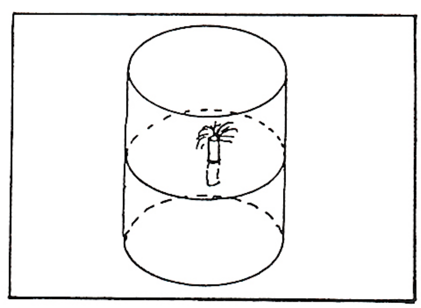
Arnold Arons and Henry Stommel are trying to sketch some kind of hydraulic method using submarine tubes to measure the pressure at some deep ocean point P when the end of the tube is placed at the other end on shore. They recognize that if they fill the tube with fresh water it will quickly equilibrate in temperature with the ocean and on the shore end will stand quite high above sea level.



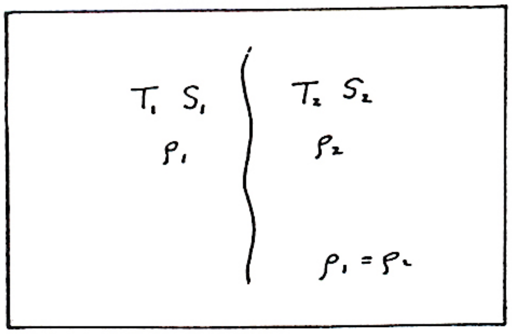
Henry says that fresh water is dear on Bermuda so why not use the ocean water at the deep end by sucking it into the tube. It is fresher and will still stand above sea-level. They calculate it at about one meter.



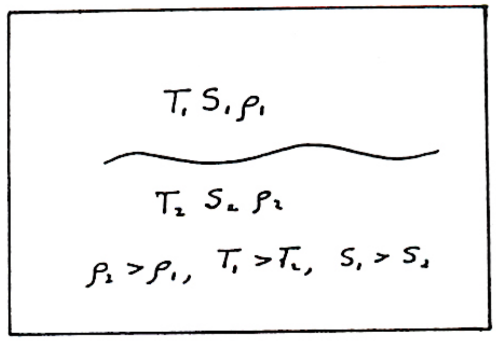
Arnold sketches a faucet in the tube at about a half meter above sea-level because he sees that it can run forever.



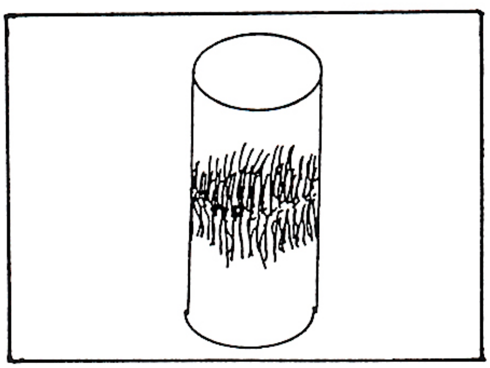
They both run downstairs to Duncan Blanchard's lab where they build a little working salt fountain in a battery jar.



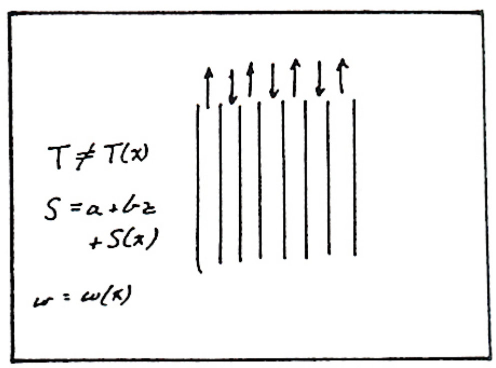
Melvin Stern and Henry Stommel are standing at the blackboard trying to formulate a convection problem in which two fluids of the same density but different temperatures and salinities are initially at rest and separated by a vertical interface. They know that the thermometric conductivity is greater than the salt diffusivity, but can't settle on an analytical model.



Suddenly they remember the equivalent Rayleigh convection problem with the gradients vertical instead of horizontal. Melvin begins the algebra; Henry worries that the cells will be too big and visualises some sort of small granular structure.



Running to Allan Faller they do an experiment in the sink and to their surprise find long thin fingers.



Willem Malkus across the hall hears the ruckus, walks in and quickly works out the steady state finite amplitude salt finger solution with maximum velocity. They check out the numbers and it seems to work!

Figure 2: (a) Background stratification (WS/CF) during a "rundown" salt-fingering experiment. The net fluxes, shown schematically as arrows, are proportional to the difference between the initial (dashed) and final (solid) profiles. (b) diagram of tank containing salt-finger interface between well-mixed layers (c Magnified view of salt-fingers showing the mechanism of the instability. (d) Background stratification (CF/WS) for a diffusive sense convection experiment, with a diffusive interface and well-mixed layers above and below.(e) diagram of tank showing convecting layers and diffusive interface.

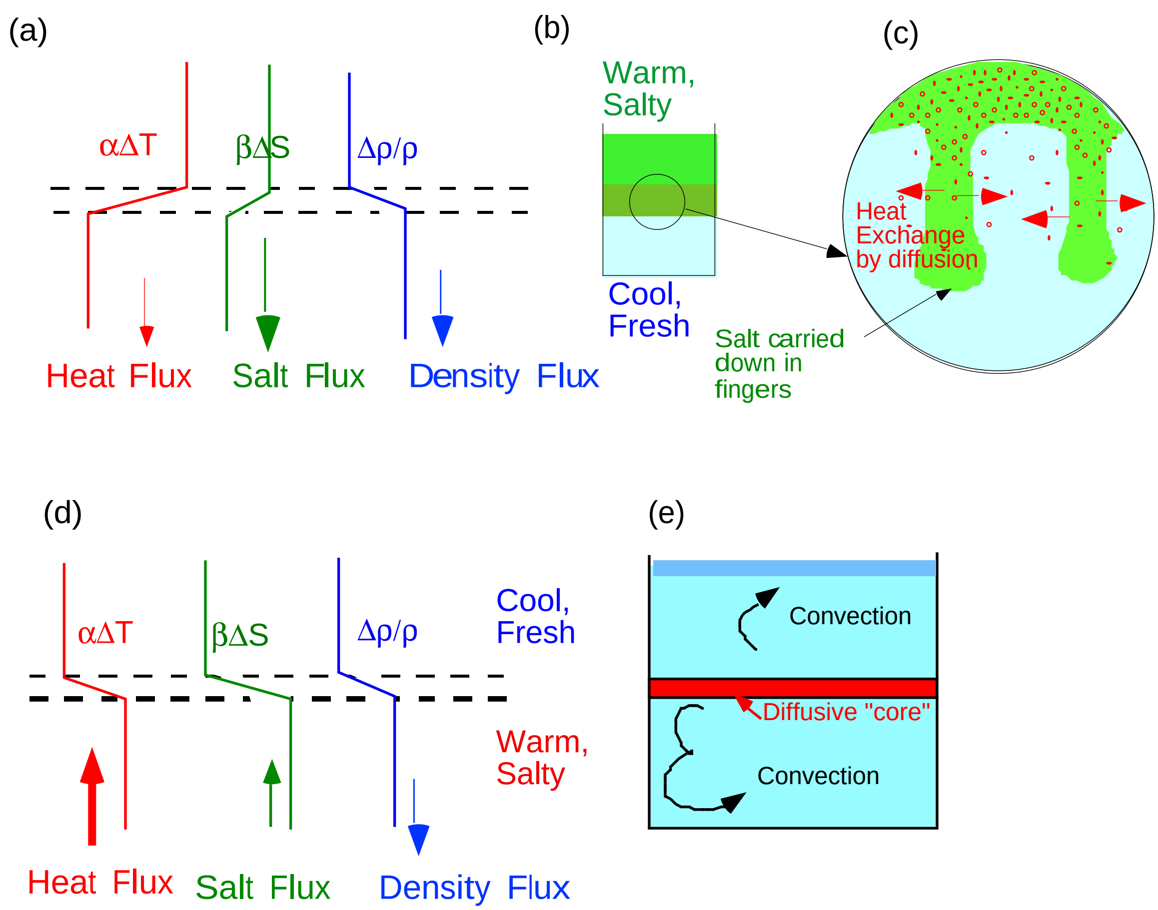


Figure 3: Water properties from a coarse resolution global ocean model (Merryfield et al.1999) run under annual mean surface forcing (I: upper panels, (a)-(c)), compared with seasonal surface forcing (II: lower panels, (d)-(f)). In each panel, results from model runs with (heavy lines) and without (light lines) parameterized double-diffusion are compared with climatological values (dotted lines) determined from the Levitus (1982) data set. The distribution of ocean volume found in different stability (R_) classes (left panels) and profiles of volume-averaged temperature (middle panels) and salinity (right panels) all exhibit larger changes due to different surface forcing than to the presence or absence of parameterized double-diffusion.