11

Large-scale consequences

The global role of double-diffusion in the ocean and its impact on climate is perhaps the most contentious topic in the theory of double-diffusion. To say that opinions vary would be a huge understatement. The controversy is caused not so much by the incomplete understanding of double-diffusion, although certainly it does not help, but rather by the lack of firm criteria for what might be important and what is secondary for the general circulation of the ocean. In relative terms, oceanography is still a young science. As it goes through a period of teenage ambivalence, various problems go in and out of fashion and perceptions of what should be considered significant rapidly evolve. It certainly makes for an interesting and exciting period. But, if pressed for a definite opinion, many double-diffusers could respond in all honesty, "I am sure double-diffusion is important but I am not quite sure why."

The following discussion is an attempt to summarize a wide spectrum of arguments in favor of the tangible influence of double-diffusion on large-scale (i.e., comparable to the basin size in this context) patterns. Some of the rather extreme early views, ascribing double-diffusion an exclusive role in maintenance of the thermocline, are mentioned for reasons of historical interest. Overall though, this chapter is focused on more recent, more restrained and demonstrably more relevant arguments. We first examine the effects of fingering, which reflects both its higher incidence and the amount of attention it has received so far, and then proceed to discuss the potential large-scale impact of diffusive convection.

11.1 Effects of salt fingers

Density stratification and the Meridional Overturning Circulation

It all started as a fortunate misconception. The prevailing concern in physical oceanography during the sixties and seventies was the structure of the thermocline. The mainstream view on its dynamics at that time was expressed by the diffusive

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thermocline model (Robinson and Stommel, 1959; Munk, 1966) based on the assumed balance between vertical diffusion and the advection of density:

$$w\frac{\partial \rho}{\partial z} \sim K_V \frac{\partial^2 \rho}{\partial z^2}. \tag{11.1}$$

Analogous balances could be assumed for temperature, salinity or, for that matter, any other quasi-conservative quantity. The innocuous looking equation (11.1) held the promise of explaining ocean stratification using very basic and intuitive physical arguments. Furthermore, when supplemented by the geostrophic momentum balance, (11.1) made it possible to predict the strength of the Meridional Overturning Circulation (MOC) – one of the main components of the Earth's climate system.

The biggest unknown in the advective–diffusive balance (11.1) was, and still remains, K_V. If the molecular diffusivity is used, either $k_T \approx 1.4 \cdot 10^{-7}\,\mathrm{m^2\,s^{-1}}$ for temperature or $k_S \approx 1.5 \cdot 10^{-9}\,\mathrm{m^2\,s^{-1}}$ for salinity, then (11.1) can be satisfied only at vertical scales of 1 m and 1 cm respectively, which renders the whole model completely irrelevant for the thermocline problem. For the proponents of the diffusive theory, this inconsistency simply meant that the mixing coefficient K_V should be interpreted as the eddy-induced, rather than molecular, diffusivity. At this point, the fate of the diffusive theory hinged on the ability of ocean mixing to support the advective–diffusive balance – in short, on the average value of K_V. However, the task of evaluating the much-needed mixing coefficient on the basis of oceanographic observations proved to be a major challenge. Numerous obstacles, conceptual and technical, demanded no less than the birth of a new branch of oceanography, the small-scale ocean mixing program. Its ultimate mission was to test and hopefully verify the diffusive model of the thermocline and meridional overturning.

In the lower thermocline, vertical advection in mid-latitudes is expected to be generally upward ($w > 0$) in order to compensate for high-latitude sinking. The strength of upwelling can be estimated from the rates of deep water production ($w \sim 10^{-7}$ m s^{-1}). If (11.1) is valid, then K_V/w should be of the same order as the stratification scale (H). Inspection of vertical density profiles in the ocean suggests scales of $H \sim 10^3$ m and therefore the diffusivity required to maintain the advective–diffusive balance (Munk, 1966) is

$$K_V \sim wH \sim 10^{-4}\,\mathrm{m^2\,s^{-1}}. \tag{11.2}$$

The early large-scale numerical simulations lent some support to the diffusive model: In order to reproduce an MOC of realistic strength, the Atlantic-only models (e.g., Bryan, 1987) have to assume a vertical diffusivity that is commensurate with

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Munk's canonical value (11.2). The diffusive argument can be further bolstered by noting that if w and K_V are taken to be uniform, (11.1) leads to

$$\rho = C \exp\left(\frac{w}{K_V} z\right) + \rho_0. \tag{11.3}$$

For $K_V > 0$, as expected for predominantly turbulent mixing, (11.3) predicts a gradual reduction in stratification with increasing depth. It could be argued that, qualitatively, the actual density distribution is not inconsistent with the predicted exponential pattern.

Now enter double-diffusion. The double-diffusive flux of density is necessarily counter-gradient (i.e., downward) and therefore opposes turbulent mixing. Thus, the presence of double-diffusion reduces the net diffusivity of density (K_V) and thereby affects the stratification in the upwelling ($w > 0$) regions, as evident, for instance, from (11.3). For downwelling ($w < 0$) conditions, typical of the upper subtropical thermocline, the potential role of double-diffusion could be even more profound. In this case, it is possible to balance the downward density advection by negative diffusion, provided that finger-induced mixing dominates the turbulent transport. This scenario can be readily recognized as a double-diffusive counterpart of the classical diffusive thermocline theory. The possibility that double-diffusion plays a major role in maintenance of the thermocline was also supported by arguments based on the energetics of the general circulation (Stern, 1968, 1969; Schmitt and Evans, 1978). These early attempts, imaginative and internally consistent, suffered from only one major flaw. They were based on crude and indirect estimates of vertical mixing, the only kind available at that time.

The only cure for the uncertainty was an improvement in measurements. However, when the technical advancements of the mid eighties finally opened the stream of microstructure-based data, they brought rather disappointing news for the believers in the mixing-controlled ocean. As microscale measurements became more accurate and widespread, it became increasingly clear that mixing in the ocean interior, regardless of its origin, is generally too weak to support the vertical advective–diffusive balance. Thermocline diffusivity, inferred from microstructure and tracer dispersion measurements, is typically on the order of $K_V \sim 0.1 \cdot 10^{-4}\,\mathrm{m^2\,s^{-1}}$ (Ledwell e*t al.*, 1993; Toole *et al.*, 1994; St. Laurent and Schmitt, 1999), which falls significantly below Munk's canonical value (11.2). Fortunately, these findings did not curb the interest in small-scale mixing. By the nineties, microscale oceanography had expanded into an independent and vibrant field. Numerous new applications were found, including mixing of nutrients, carbon sequestration, dynamics of the bottom waters and naval functions. However, the original motivation of the mixing program as a support system for the thermocline theory had to be revised and early expectations downscaled.

On the theoretical level, recent years have witnessed a general retreat from the predominantly diffusive thermocline models to the adiabatic view, ascribing thermocline structure to the ventilation of water masses at the sea-surface. Diapycnal thermocline mixing was shown to be essential in isolated, dynamically distinct regions, such as the diffusive internal thermocline front (Samelson and Vallis, 1997; Vallis, 2000), but it plays a secondary role in much of the upper ocean. It was also argued that the MOC can be driven by adiabatic mechanisms (Toggweiler and Samuels, 1998; Marshall and Radko, 2003; Radko and Kamenkovich, 2011) associated with inter-hemispheric asymmetries in the ocean/landmass distribution. Webb and Suginohara (2001) estimate that only a third of the volume of deep waters originating in high-latitude North Atlantic regions is upwelled in the interior in response to diabatic mixing – the rest is brought to the surface in the Southern Ocean by Ekman suction.

In view of these findings, it is not too surprising that the geometry of the model ocean can constrain the global influence of double-diffusion. Let us first examine a few closed-basin models. Figure 11.1 shows a set of numerical simulations of the large-scale circulation in the Northern-Hemisphere basin (Gargett and Holloway, 1992). The upper panel presents the overturning streamfunction in a salt-finger experiment. This calculation was performed using uniform but unequal diffusivities of heat and salt ($r = K_S/K_T = 2$), which is a fairly reasonable, if somewhat crude, parameterization of finger-induced mixing. The outcome of this experiment is nothing short of astounding. The flow structure differs dramatically from the classical picture of an overturning cell, characterized by localized high-latitude sinking and broad upwelling. The central panel in Figure 11.1 shows the circulation pattern realized in the simulation with equal heat/salt diffusivities, which is meant to represent conventional turbulence. The magnitudes of the overturning in finger-driven and turbulence-driven experiments differ by an order of magnitude and even the sense of circulation is reversed. The reduction of r below unity (lower panel in Fig. 11.1) leads to more limited, but still clearly visible, modification of the turbulent flow pattern. The dramatic variation of the overturning patterns in Figure 11.1 is an indication of the sensitivity of large scales to the ratio $r = K_S/K_T$, which appears to be even more important than the magnitude of diffusion. In this regard, it should be kept in mind that, among various mixing mechanisms, salt fingering is unique in its ability to raise r above unity.

Qualitative changes in the variability and patterns of thermohaline circulation associated with the inclusion of salt fingers have been noted in many other modeling studies. Ruddick and Zhang (1989) examined box models of the ocean circulation driven by heating and evaporation at the sea-surface. They discovered, for instance, that self-sustained oscillations, common in the classical turbulent mixing models (Stommel, 1986; Welander, 1982) do not arise for finger-driven mixing. Gargett

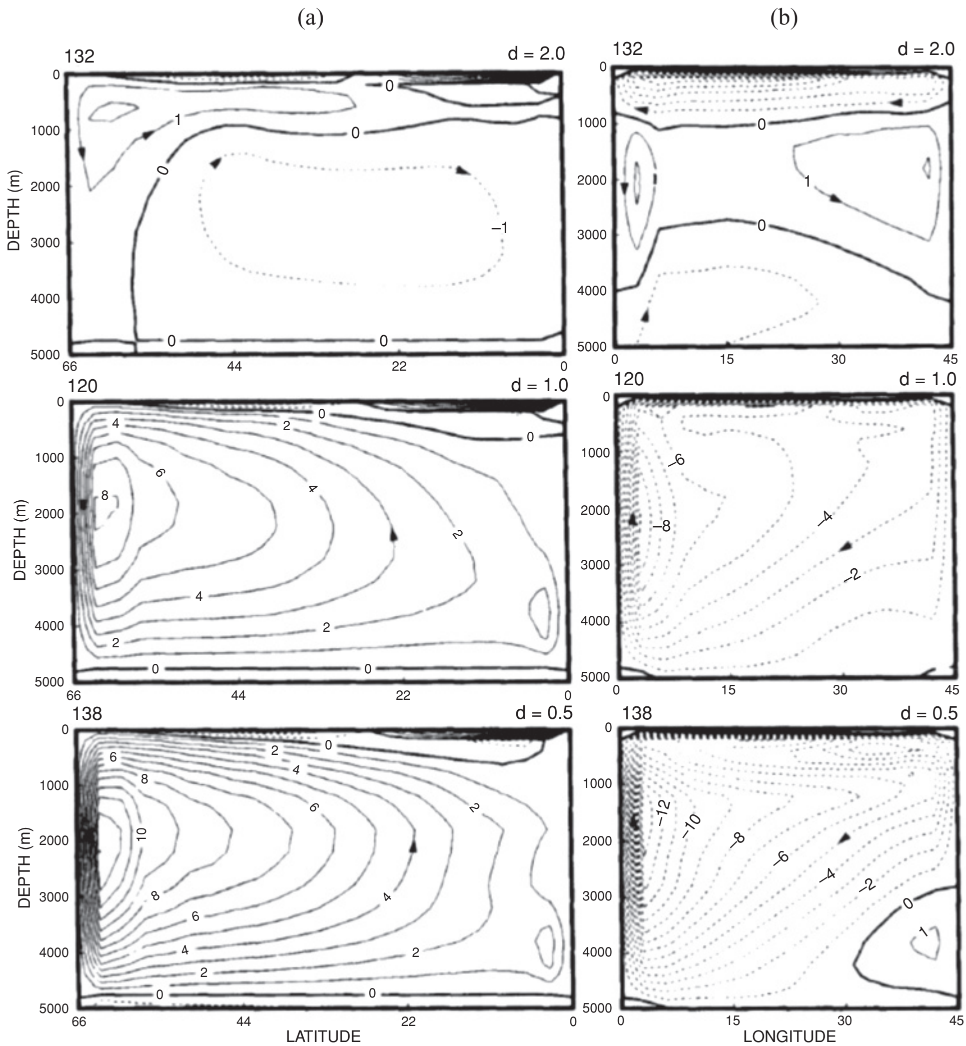

Figure 11.1 Meridional (a) and zonal (b) overturning streamfunctions for experiments with various values of $r = K_S/K_T$. Upper panels $r = 2$, middle panels $r = 1$, lower panels $r = 0.5$. From Gargett and Holloway (1992).

and Ferron (1996) examined multi-box models of thermohaline circulation and found that use of unequal diffusivities of heat and salt substantially modified both the equilibrium solutions and the transition points (in terms of forcing magnitude) between distinct states. An important step was made by Zhang *et al.* (1998), who incorporated a more realistic R_ρ-dependent double-diffusive parameterization into a numerical model. While in other respects the setup was similar to that of Gargett and Holloway (1992; Fig. 11.1), the more physical parameterization led to more

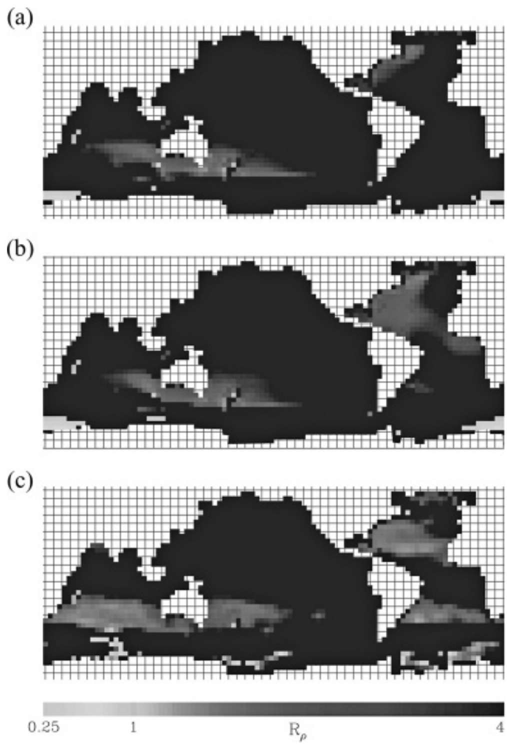

Figure 11.2 The pattern of density ratio at the 700 m depth in (a) the non-double-diffusive experiment, (b) double-diffusive experiment and (c) the annual-mean climatology. From Merryfield *et al*. (1999). See color plates section.

credible solutions. The effects of salt fingers were still pronounced, as reflected by a 22% reduction in the strength of the MOC. However, the flow structure was quite different from Gargett and Holloway's prediction: inclusion of salt fingers was not accompanied by the cardinal and implausible reorganization of the entire overturning circulation pattern.

In global models with realistic geometry and surface forcing, the effects of double-diffusion are even less prominent but still detectable (Merryfield *et al*., 1999; Glessmer *et al*., 2008). The inclusion of salt fingers brought modeled temperature and salinity closer to observations, increasing their values in the lower thermocline and in the deep ocean. Figure 11.2 shows the distribution of the density ratio at 700 m depth for the model runs (Merryfield *et al*., 1999) in which double-diffusion was excluded (a) and included (b). Somewhat counter-intuitively, taking double-diffusion into account created more favorable conditions for its occurrence (i.e., lower density ratio) particularly in the Atlantic. The

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distribution of R_ρ in the double-diffusive model (Fig. 11.2b) matched observations (Fig. 11.2c) much better than the non-double-diffusive pattern (Fig. 11.2a). However, the overall flow pattern was only slightly affected by double-diffusion and all major components of thermohaline circulation reduced by just a small percentage.

The cause of the dissimilar large-scale impact of double-diffusion in models with idealized (single-basin) and realistic geometry is likely to be related to the influence of the Antarctic Circumpolar Current (ACC) in the Southern Ocean. The absence of land barriers along its path results in distinct dynamical features that have no direct counterparts in the zonally blocked oceans regions (e.g., Marshall and Radko, 2003, 2006). The unique dynamics of the reentrant ACC engages powerful and fundamentally adiabatic mechanisms controlling the stratification and overturning. This inevitably reduces the relative impact of mixing, both turbulent and finger-driven. In the single-basin models (e.g., Bryan, 1987; Zhang *et al.*, 1998) diapycnal mixing is essential. It carries the full burden of supporting the MOC and therefore changes in the magnitude and type of mixing project directly onto large-scale patterns. It is possible to eliminate or even to reverse the sense of overturning circulation by simply modifying the mixing model. In realistic configurations, where alternative mechanisms exist, it is more appropriate to view the mixing-driven circulation as a correction – a substantial one but a correction nonetheless – to stronger adiabatically driven modes. This does not mean of course, that the diabatic interior processes can be discounted. Given the involvement of thermohaline circulation in issues of societal relevance, such as climate and ecosystem dynamics, its diffusively driven component should be better understood and better represented in models. However, in doing so, it is imperative to have a clear dynamical picture and realistic expectations for the interior mixing.

In view of apparent differences in model-based predictions of the impact of double-diffusion, a question could be raised whether much can be learnt from numerous idealized models (e.g., Gargett and Holloway, 1992) – models that focus on a selected subset of processes and ignore others in order to maintain physical transparency. I believe that the answer is yes and the reasons are three-fold. First of all, the general tendencies revealed and explained by the idealized models are invariably reflected in more realistic and comprehensive configurations (e.g., Merryfield *et al.*, 1999), albeit in a much reduced and harder-to-identify form. The second reason is related to the assessment of the relative roles of double-diffusion and turbulent mixing. These two types of microstructure affect large-scale patterns very differently and the dynamic dissimilarities can be interpreted more clearly when mixing effects are isolated. Finally, it should be realized that the integral measures and general circulation patterns tend to mask interesting regional effects. In areas where mixing is elevated and/or adiabatic advection is weak, flow can be governed by predominantly diffusive dynamics, brought to the fore by idealized mixing models.

Overall, the extant modeling studies suggest a detectable but moderate impact of salt fingers on the density stratification and global thermohaline circulation. This, however, does not preclude the possibility that double-diffusion could play a significant role in the context of global change (e.g., Oschlies *et al*., 2003). Unlike small-scale turbulence and mesoscale variability, which are controlled by density distribution, the intensity of double-diffusion depends very strongly on temperature and salinity patterns. Therefore, the response of double-diffusion to climatic change can be qualitatively different from that of other mixing processes. Salt fingers are likely to introduce new powerful feedback mechanisms into the ecosystem dynamics, which should be – but seldom are – taken into account in the projections of future climate. Another potentially significant caveat was noted by McDougall (1987). He argued that effects associated with the nonlinearity of the equation of state can amplify double-diffusive transformation of water masses by as much as a factor of four. McDougall's proposition warrants further analysis, validation and, possibly, reevaluation of the large-scale impact of salt fingers. On this intriguing and unorthodox suggestion we leave the thermohaline circulation problem and proceed to discuss more subtle implications of double-diffusive convection.

The T–S relation and the pattern of density ratio

Some of the oldest and most fundamental questions in classical ocean dynamics are related to the form of the T–S relation in the central thermocline. Two aspects should be emphasized: (i) its remarkable tightness and (ii) the presence of broad regions with uniform density ratio in areas susceptible to fingering. Figure 11.3 shows representative vertical profiles of the density ratio in the central waters of the North Atlantic and North Pacific. In the Atlantic, which is characterized by lower density ratios and therefore more active salt fingering, regions of uniform density ratio are more pronounced and vertically extended. Figure 11.3 also presents a histogram of the Atlantic density ratios, which exhibits a well-defined peak at $R_\rho \approx 2$ and a sharp reduction in probability at lower density ratios. These observations immediately raise a set of related dynamical questions. What mechanisms are responsible for aligning the T–S relation along the density ratio curve? Why is the density ratio effectively precluded from drifting significantly below $R_\rho \approx 2$ and what sets this very specific limit?

So far, the most promising attempts to address these questions have involved salt fingers (Schmitt, 1981, 1990). Since the intensity of double-diffusion rapidly increases with decreasing R_ρ, regions with anomalously low values of density ratio

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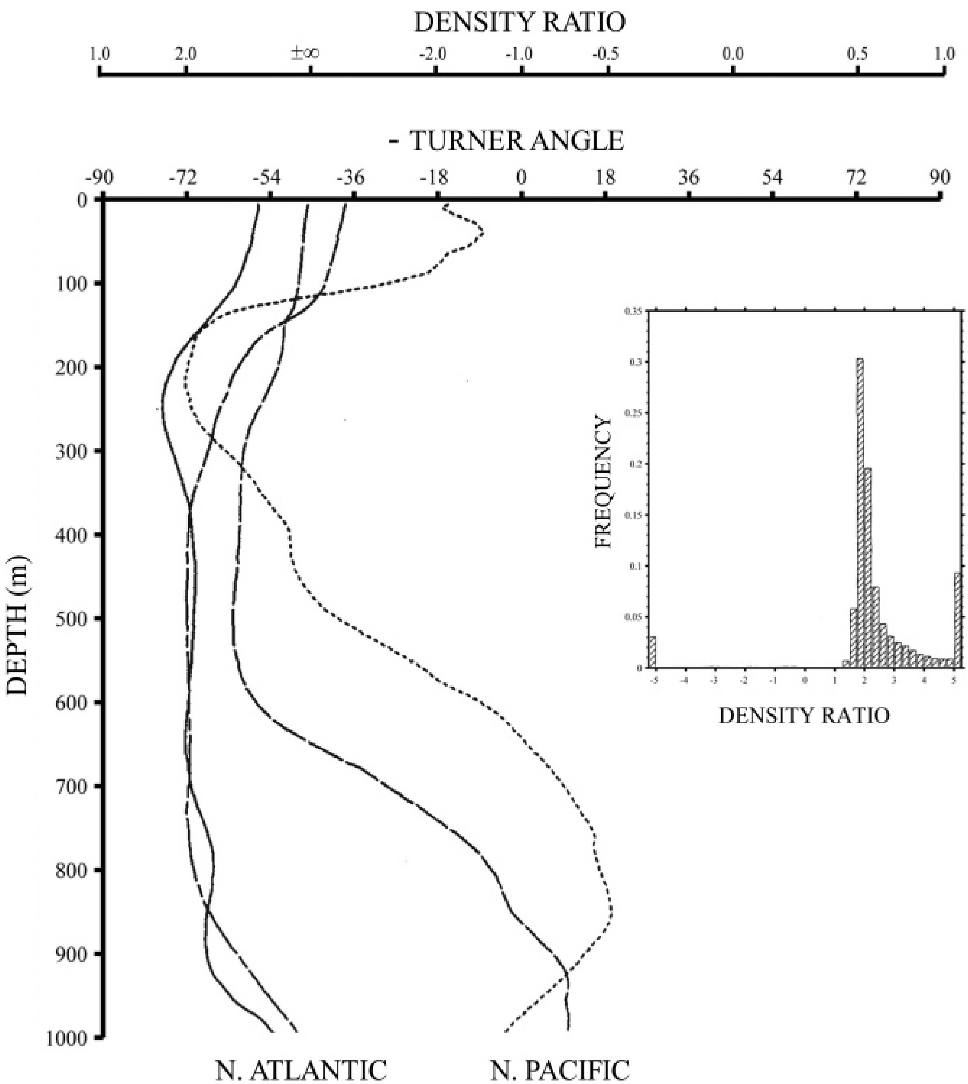

Figure 11.3 Density ratio computed over 100 m vertical intervals for four CTD stations in the eastern North Atlantic (solid), western North Atlantic (short-long dash), eastern North Pacific (short dash) and western North Pacific (dotted). The insert shows the histogram of occurrence of R_ρ in the Atlantic thermocline along 24° N. From Schmitt (1990).

inevitably become the sites of intense mixing. Fingers transport salinity faster than heat. As a result, they tend to reduce the salinity gradient more efficiently than the temperature gradient and thereby increase the density ratio $R_\rho = \frac{\alpha \bar{T}_z}{\beta \bar{S}_z}$. Thus, it could be argued that the density ratio is set by a balance between double-diffusive mixing acting to increase the density ratio and the large-scale forcing counteracting this tendency. It is generally accepted that salt fingers are most effective in modifying the large-scale *T–S* patterns for density ratios less than two. As discussed in Chapter 10, double-diffusive fluxes in the ocean reduce precipitously at $R_\rho > 2$, where fingers become weaker and more vulnerable to the adverse action of internal waves and intermittent turbulence. The nearly discontinuous on/off character of finger-induced mixing is essential; it implies that as soon as R_ρ reduces below the critical value of two, salt fingers get to work on increasing the density ratio, but they effectively disengage when $R_\rho > 2$. In order to produce the permanent low density ratio ($R_\rho < 2$) conditions, external forcing – which may be associated either with sea-surface heat/salinity fluxes or large-scale advection – needs to be strong enough to break the resistance of these tiny regulators. Of course, there are several locations in the world ocean where it does happen. In the Atlantic, the density ratio drops significantly below the critical value in the Mediterranean outflow region and in the Caribbean (C-SALT area), but these conditions are rather exceptional. Over most of the central thermocline, the salt-finger regulation of density ratio is highly effective.

To be completely fair, we should mention the possibility of non-double-diffusive regulation of the *T–S* relation. Stommel (1993) hypothesized that the density ratio could be constrained by the response of the upper mixed layer to atmospheric forcing. His temperature–salinity regulator model suggested the preferred horizontal mixed layer density ratio of two. In the ventilated regions of the thermocline, mixed layer properties are advected downward along the sloping isopycnals. This way, the surface density ratio can project onto its vertical distribution, which would explain the observed interior *T–S* pattern. What seriously undermines this argument – or, for that matter, any argument based on subsurface dynamics – is that the temperature and salinity patterns in the mixed layer are often characterized by density compensation on a wide range of scales (Rudnick and Ferrari, 1999). The projection of such patterns onto the vertical *T–S* profiles would produce a series of density-compensated segments with the density ratio close to unity. The absence of such features in most observations implies the existence of an internal mixing process acting to homogenize the density ratio.

It is interesting that it is possible to discriminate between the effects of turbulence and fingering on the *T–S* relation by exploring the nonlinearity of the equation of state (Schmitt, 1981). Since the expansion/contraction coefficients (α, β) in the ocean are non-uniform, curves of constant density ratio $R_\rho = \frac{\alpha T_z}{\beta S_z}$ in the *T–S* parameter space are distinct from the straight lines representing the constant gradient ratio $R_g = \frac{T_z}{S_z}$. Turbulence mixes temperature and salinity at equal rates, and therefore its effect on the *T–S* relation would be reflected in the tendency to homogenize the gradient ratio R_g. Salt fingers are different. The intensity of fingering is controlled by the density ratio and therefore they tend to align *T–S* values along the uniform R_ρ curves. An inspection of oceanographic data (Ingram, 1966; Schmitt, 1981) leaves no doubt with regard to the preferred pattern of the *T–S* relation. Observations (Fig. 11.4a) are obviously much better described by the uniform density ratio model. In fact, the standard error of the linear fit to the measured *T–S* values exceeds that of the $R_\rho = const$ model by an order of magnitude.

To illustrate the mechanics of density ratio regulation by salt fingers, Schmitt (1981) numerically integrated the one-dimensional (z) large-scale temperature and salinity equations (8.8) in time. The vertical fluxes were parameterized using the flux-gradient laws appropriate for salt fingers. Typical evolutionary patterns of this system are shown in Figures 11.4b,c. The experiment in Figure 11.4b was initiated by a uniformly low density ratio ($R_\rho = 1.1$), which evolved, within a few years, to the more typical value $R_\rho \approx 2$. The dotted line in Figure 11.4b represents the evolution of the density ratio pattern in a similar model for turbulent rather than finger-driven mixing, demonstrating just how ineffective turbulence is in terms of removing the density ratio anomalies. The experiment in Figure 11.4c was initiated by the variable density ratio, which in time developed extended quasi-uniform regions. Once again, the anomalously low values of R_ρ drifted towards the pervasive value of two.

The obvious limitation of Schmitt's (1981) model is related to the questionable ability of any one-dimensional system to reflect the dynamics of oceanic circulation. However, it was later shown that the key ideas of the model are sufficiently general. Using a fully three-dimensional framework, Schmitt (1990) went on to demonstrate that the $R_\rho = const$ character of the central waters can be plausibly attributed to double-diffusion but is inconsistent with either turbulent diapycnal or isopycnal mixing.

Another compelling argument in support of the double-diffusive control of the *T–S* relation is based on its tightness. The ocean is full of mesoscale eddies that actively stir the adjacent water masses predominantly along isopycnal surfaces. It is intuitively clear that the variation in eddy-transfer rates at different isopycnals is bound to produce strong vertical *T–S* variability, unless this tendency is balanced by some active internal mixing process. While such density-compensated variability has been detected in observations (Shcherbina *et al.*, 2009; Ferrari and Polzin, 2005), it is surprisingly limited in most of the ocean, particularly at large vertical scales (Fig. 11.3) exceeding that of thermohaline intrusions ($\sim$10 m). The density-compensated variability is most conveniently represented by "spiciness" – the quantity orthogonal to density in terms of its thermal and haline components – see (7.25). While mesoscale eddies and surface forcing are the obvious sources of spiciness, double-diffusion might be its major consumer (Schmitt, 1999). This expectation is consistent with the generic bias of large-scale non-double-diffusive numerical models towards unrealistic growth of spiciness (McWilliams, 1998).

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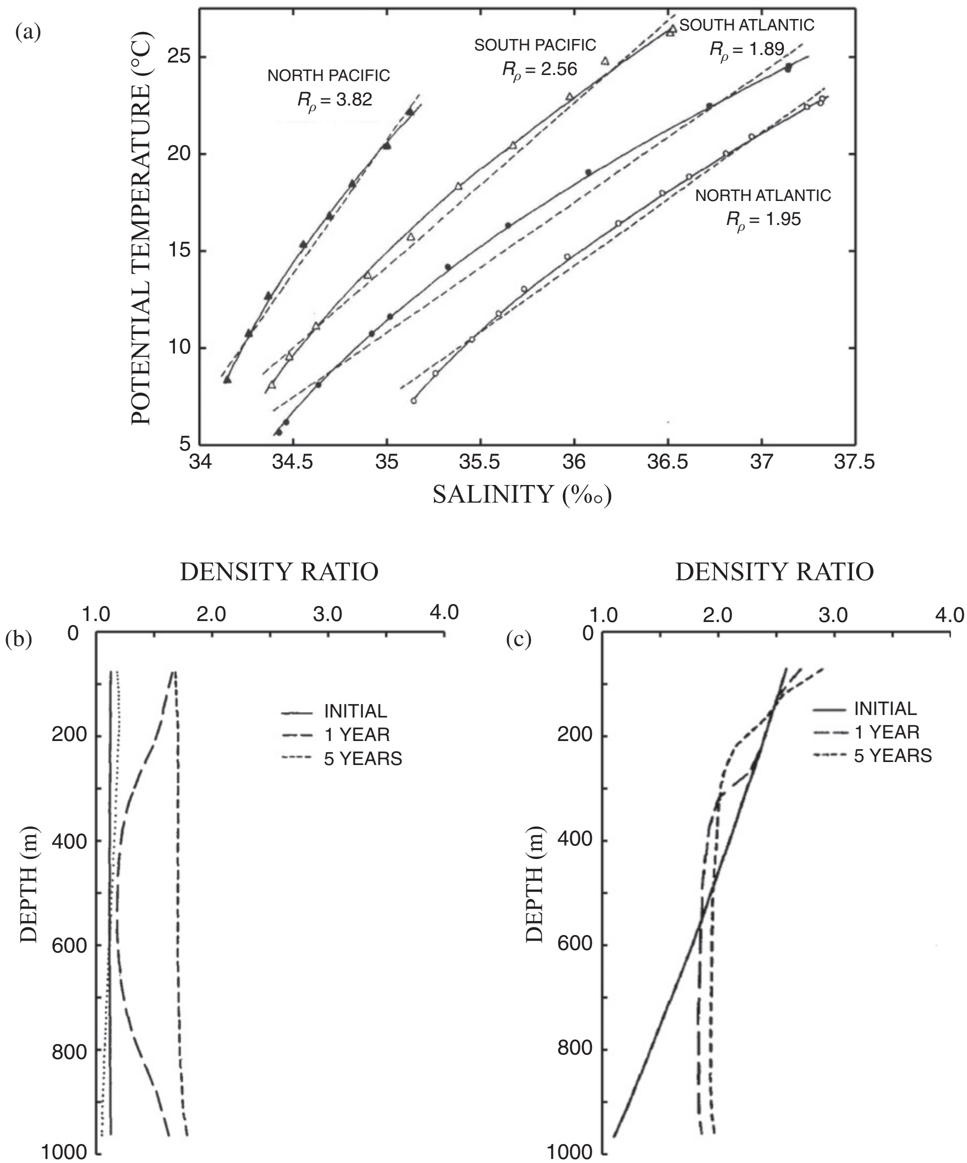

Figure 11.4 (a) Potential temperature versus salinity plot for four hydrographic stations in the Atlantic and Pacific. The linear fit (dashed) and a curve of constant density ratio (solid) are shown for each station. (b) Solution of the one-dimensional model. The density ratio pattern is shown initially (solid curve), after one year (long dash) and after five years (short dash). The profile after five years of turbulent mixing is indicated by a dotted curve. (c) The same as in (b) but for the non-uniform initial distribution of the density ratio. From Schmitt (1981).

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What makes double-diffusion particularly effective in reducing ocean spiciness is its ability to dynamically discriminate between the thermal and haline components of density. Unlike turbulence, double-diffusion can actively respond, by varying its intensity, to the perturbations in T and S that are not accompanied by changes in density. There are at least two distinct double-diffusive mechanisms for removing spiciness. The first mechanism has already been alluded to. The direct effect of the preferential vertical transport of salinity by fingers is to remove the density ratio anomalies, which heavily constrains the excursions of the T–S curve and thereby suppresses the growth of density-compensated perturbations. The second mechanism involves thermohaline interleaving (Chapter 7). Intrusions are driven by – and act to diffuse – the isopycnal gradients of temperature and salinity. Active interleaving ceases only when the along-isopycnal variability is effectively removed, which tightens the T–S relation in the central waters, turning the spicy ocean into a mild one.

The view of double-diffusion as a global regulator of the T–S distribution was recently reinforced by Johnson and Kearney (2009), who suggested that oceanic signatures of climate change can be attenuated by salt fingers. Their proposition is very intuitive. Generally finger-favorable conditions of the mid-latitude thermoclines in all oceans are maintained by the surface patterns of evaporation and precipitation. In the subtropics, evaporation exceeds precipitation, which tends to increase surface salinity. The evaporation/precipitation balance is reversed in subpolar regions, where surface salinity is relatively low. Thus, water is relatively fresh and cold at denser isopycnals that outcrop in subpolar regions; at lighter and therefore shallower isopycnals, it is warm and salty. One of the likely consequences of global warming is the intensification of the Earth's hydrological cycle. A warmer atmosphere can transport more moisture meridionally, which leads to even saltier subtropical and fresher subpolar surface waters. As a result, the salinity stratification increases, making the ocean even more susceptible to salt fingers. However, the intensification of finger-driven mixing can accelerate the transfer of temperature and salinity anomalies downward into the deep ocean, partially compensating the direct effects of changing atmospheric forcing. This way, the imprint of global warming in the thermocline can be reduced. Johnson and Kearney warn of the potential dangers of ignoring the salt-finger attenuation: climate studies that focus on the variability of the upper ocean and that do not take double-diffusion into account could significantly underestimate the ocean change brought about by global warming.

The hypothesis of attenuation has been supported by the analysis of data from the repeated trans-Indian Ocean surveys along 32° S from 1987 to 2009. The Indian Ocean becomes progressively more susceptible to fingering from west to east. Johnson and Kearney (2009) argued that this pattern is responsible for qualitative differences in the evolution of the *T–S* anomalies in the eastern, central and western sectors of the basin. In the western sector, the density ratio systematically decreased and anomalies spread into deeper regions of the thermocline, which can be viewed as the natural response of the ocean that is only slightly affected by double-diffusion. In the central segment – the region characterized by moderate fingering – the downward spread of anomalies was still noticeable but the density ratio values did not change significantly. Finally, in the east, where fingering is always most intense, the *T–S* distribution remained largely invariant in time. These evolutionary patterns were interpreted as a manifestation of spatially non-uniform (more effective from west to east) moderation of changes in the water-mass properties by double-diffusion. The observed temperature and salinity tendencies were consistent with the prediction based on the vertical convergence of parameterized salt-finger fluxes, lending further credence to the idea of the finger-induced attenuation of the climate signal.

Regional effects

While the global impact of double-diffusion is difficult to evaluate and extant estimates are much debated, no serious doubts have been expressed with regard to the ability of salt fingers to profoundly influence regional climate and dynamics. The intensity of double-diffusive mixing is spatially inhomogeneous, with thermohaline staircases being the obvious mixing hot spots. A case in point is the Caribbean staircase. A fairly detailed description of this staircase and its transport characteristics resulted from major field programs, including C-SALT and the Salt Finger Tracer Release Experiment (SFTRE). The diffusivities of heat and salt in this area ($K_T \approx 0.45 \cdot 10^{-4}\,\mathrm{m^2\,s^{-1}}$ and $K_S \approx 0.9 \cdot 10^{-4}\,\mathrm{m^2\,s^{-1}}$) approach Munk's canonical value (11.2), which implies that mixing is sufficiently intense to effectively control the local flow patterns. One of the critical dynamical consequences of the elevated mixing rates in the C-SALT area is the injection of salinity into the Antarctic Intermediate Water, which preconditions waters for later sinking in the high-latitude Atlantic, thus affecting thermohaline circulation.

In contrast to the mixing environment of C-SALT, smooth-gradient regions are characterized by very low diffusivities ($\sim 10^{-5}\,\mathrm{m^2\,s^{-1}}$ or less). This disparity puts the C-SALT staircase into a league of its own in terms of its ability to affect water-mass transformation in the North Atlantic thermocline. An instructive illustration of the mixing intensity of the C-SALT staircase is based on the comparison of the staircase-driven and turbulent mixing (Ray Schmitt, private communication). The net salt flux in the C-SALT staircase can be estimated as a product of the salt diffusivity, C-SALT area and the vertical salinity gradient, resulting in

$$F_{\text{C-SALT}} \sim (0.9 \cdot 10^{-4}\,\text{m}^2\,\text{s}^{-1}) \times (1.3 \cdot 10^{12}\,\text{m}^2) \times (3 \cdot 10^{-3}\,\text{psu}\,\text{m}^{-1})$$
$$\sim 3.5 \cdot 10^{6}\,\text{psu}\,\text{m}^3\,\text{s}^{-1}. \tag{11.4}$$

A similar estimate can be made for the turbulent (wave-induced) mixing over the whole area of the North Atlantic subtropical gyre:

$$F_{\text{turb}} \sim (0.05 \cdot 10^{-4}\,\text{m}^2\,\text{s}^{-1}) \times (20 \cdot 10^{12}\,\text{m}^2) \times (1.5 \cdot 10^{-3}\,\text{psu}\,\text{m}^{-1})$$
$$\sim 1.5 \cdot 10^{6}\,\text{psu}\,\text{m}^3\,\text{s}^{-1}. \tag{11.5}$$

The comparison of (11.4) and (11.5) is astonishing. The salt flux over a relatively small C-SALT region, less than a tenth of the North Atlantic subtropics, significantly exceeds the net turbulent transport over the whole gyre. What the C-SALT staircase lacks in area, it more than makes up for in mixing intensity. The turbulent diffusivity inferred from mixing parameterizations of the wave field in the thermocline ($\sim 0.05 \cdot 10^{-4}\,\text{m}^2\,\text{s}^{-1}$) is simply incommensurate with the staircase diffusivity suggested by tracer release measurements ($\sim 0.9 \cdot 10^{-4}\,\text{m}^2\,\text{s}^{-1}$). Note also that most of the subtropical North Atlantic thermocline is susceptible to both double-diffusion and turbulence; in regions lacking staircases their mixing contributions are comparable. But even if we generously ignore the finger-driven transport everywhere outside of the C-SALT staircase, double-diffusion still beats turbulence hands down in terms of water-mass transformation.

Another example of the profound impact of double-diffusion on regional dynamics is given by the Tyrrhenian staircase in the western Mediterranean (Chapter 7). Its extraordinarily large steps (up to 500 m) and low values of the density ratio ($R_\rho \sim 1.2$) create favorable conditions for some of the most vigorous finger-driven mixing in the world ocean. The vertical transport of heat and salt by the Tyrrhenian staircase is recognized as the dominant mechanism for the exchange of properties between the Lewantine Intermediate Water and the Mediterranean Deep Water (Zodiatis and Gasparini, 1996). Because of its interactive character and ability to adjust to evolving environmental conditions, the Tyrrhenian staircase could prove to play a major role in controlling the Mediterranean climate. As the upper Mediterranean waters become warmer and saltier, the staircase responds by systematically increasing the layer heights and *T–S* variation across the interfaces. The increase in step size is accompanied by a corresponding intensification of mixing, which, in turn, acts to moderate climatic changes in the stratification of the Tyrrhenian Sea.

While permanent staircases are the most obvious candidates for the substantial modification of water masses, regional changes caused by double-diffusion have also been detected in smooth-gradient regions. Double-diffusion is a major mixing

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process between the intruding layers of subpolar and subtropical waters. Talley and Yun (2001) examined water-mass transformation in the Mixed Water Region of the North Pacific, where the Oyashio waters mix with more saline Kuroshio waters east of Japan. They showed that double-diffusion (mostly salt fingering) significantly affects the Oyashio water-mass properties and increases the density of the salinity minimum at the top of the North Pacific Intermediate Water. A rare example of an analysis of the role of fingering in the dynamics of deep/bottom water masses was presented by McDougall and Whitehead (1984). In this study, salt fingering was invoked to explain the variation in the Antarctic Bottom Water properties in the Atlantic.

Several interesting case studies of finger-induced large-scale effects focus on the so-called mode waters. The term mode water describes water masses with exceptionally uniform properties, usually formed during wintertime convection in regions of strong heat loss from the ocean to the atmosphere. The role of double-diffusion in the dynamics of South Pacific Eastern Subtropical Mode Water was explored in detail by Johnson (2006). Johnson's analysis was based on the observed evolution of large positive isopycnal T–S anomalies produced by unusually strong air–sea heat fluxes in austral winter 2004. The warm and salty water was then advected along the isopycnal surfaces. Within six months after injection, the magnitude of the perturbation was halved on the isopycnals at which it was introduced, but increased at higher densities. Johnson suggested that the observed evolution of the upper-ocean structure can be largely attributed to finger-driven mixing, which intensified when the T–S anomalies spread into the main thermocline. The model based on the parameterization of finger-driven mixing successfully reproduced the spatial and evolutionary patterns of both temperature and salinity, whereas a turbulence-based parameterization led to inconsistent predictions. Similarly, double-diffusion was shown to cause the rapid downstream modification of certain types of mode waters in the North Pacific (Saito *et al*., 2011; Toyama and Suga, 2012). Salt fingers have also been implicated in the downstream variability of the Atlantic mode waters, transferring the excess salt, and to a lesser extent temperature, to deep layers (e.g., Gordon, 1981; Tsuchiya, 1986).

Biogeochemical applications

A different and often overlooked application of double-diffusion comes from a somewhat unexpected source – biological oceanography. Biologists first set their sights on salt fingers after a controversial attempt by Lewis *et al*. (1986) to use microstructure measurements to estimate the rate of supply of nutrients to the euphotic zone in the eastern subtropical North Atlantic. The inferred nitrate fluxes were about six times too small to balance the biological uptake of nitrate measured

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by incubation techniques and were also much lower than the estimates based on observed changes in upper-ocean oxygen over annual scales.

The apparent inconsistency between the microstructure-based estimates and the standard biogeochemical techniques demanded urgent resolution. By that time, the problem of evaluating the nitrate flux had already transcended the conventional boundaries of chemical and biological oceanography and entered into the discussion of climate change. The nitrate budget of the upper ocean affects photosynthetic incorporation of carbon dioxide and constrains the export of organic carbon from the ocean surface layer, which is the primary oceanic sink for atmospheric carbon dioxide. Thus, the uncertainty in the nitrate transport affects our ability to model carbon dioxide concentrations in the atmosphere and ultimately hinders climate prediction efforts.

A plausible resolution of the nitrate flux conundrum was proposed by Hamilton *et al*. (1989). These authors noted that the observations of Lewis *et al*. (1986) were taken in an ocean region susceptible to active salt fingering. In estimating the vertical flux from microstructure measurements of viscous dissipation, Lewis *et al*. used the pure-turbulence model and made no attempt to account for fingers. However, as we discussed in Section 10.4, the relationships between fluxes and kinetic energy dissipation are very different for finger-dominated and turbulence-dominated environments; use of an inappropriate diagnostic model inevitably leads to major errors.

In order to constrain the range of fluxes potentially supported by the dissipation measurements, Hamilton and collaborators examined the opposite limit of pure finger-driven mixing. They assumed that the eddy diffusivity of nitrate is equal to salt diffusivity and predicted a nitrate flux that was six times as large as previously inferred, for the same data, using the turbulence model. The finger-based calculation was in much better agreement with the incubation and geochemical estimates. The success of the finger model, combined with the failure of the turbulent one, suggested that the origin of microstructure analyzed by Lewis *et al*. was indeed double-diffusive. This proposition is quite sensible, given that the density ratio at the location of their measurements was consistently less than two. Admittedly, the finger model can only predict the upper limit for the vertical transport of properties. A more precise estimate of fluxes from viscous dissipation data requires a-priori knowledge of the microstructure composition. Nevertheless, the results reported by Hamilton *et al*. were highly significant. For the first time, the biogeochemical community realized the importance of discriminating between the two major mixing processes and the potential of double-diffusion to dramatically elevate biological productivity in the upper ocean.

Hamilton's ideas instigated a series of inquiries, data-based and modeling, into the contributions of salt fingers and turbulence to the vertical transport of nutrients

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into the euphotic zone. Dietze *et al*. (2004) analyzed hydrographic measurements taken along the meridional section at 30° W in the subtropical North Atlantic. Turbulent diffusivities were deduced from the finescale shear data according to the mixing parameterizations of the internal wave field (Gregg, 1989). For salt fingers, Dietze *et al*. used the density ratio based model of Zhang *et al*. (1998). The results unequivocally demonstrated the critical role of finger-induced mixing for ecosystem dynamics. Transport of nitrates into the nutrient-consuming layer by salt fingering was more than five times higher than transport due to wave-induced turbulence and substantially exceeded the combined effects of horizontal diffusion, eddy pumping and advection (vertical and horizontal).

Modeling studies have also been highly effective in illustrating the biogeochemical consequences of fingering. One of the perceived weaknesses of data-based analyses is related to their regional emphasis. Since most such studies focus on a specific location or a hydrographic section, the possibility exists that the inferences they provide are not representative of general oceanic conditions. In this regard, modeling can nicely complement and reinforce the observational message by providing net, basin-integrated estimates of nutrient fluxes and quantifying their spatial variability. An example is given by Oschlies *et al*. (2003), who used a coupled circulation–ecosystem model to quantify the contribution of finger-induced mixing to nutrient fluxes in the North Atlantic. The domain-averaged contribution of salt fingers was necessarily less than in the selected particularly finger-favorable locations (e.g., Dietze *et al*., 2004) but still essential. Taking finger-induced mixing into account approximately doubled the flux of nitrates in the eastern part of the oligotrophic subtropical gyre. It was shown that the nutrient supply by fingering is at least comparable to the contribution from mesoscale eddies which, so far, have received considerably more attention (McGillicuddy *et al*., 1998).

An even more definitive analysis of the double-diffusive influence on biogeochemical cycles was performed by Glessmer *et al*. (2008). Using a global ocean model, these authors argued that, despite the relatively modest impact of double-diffusion on upper-ocean temperatures and salinities, its effects on marine biology and biogeochemistry are dramatic and widespread. Taking salt fingers into account increased nutrient supply to the upper ocean, resulting in the enhancement of primary production by up to 100% over broad areas of the subtropical gyres. Higher biological productivity, in turn, led to substantial changes in the carbon dioxide and oxygen uptake of the ocean. To test the sensitivity of their simulations to the assumed parameterizations, Glessmer *et al*. considered two different double-diffusive flux laws (Zhang *et al*., 1998; Large *et al*., 1994). The differences in simulated nutrient supply between the two versions of the model turned out to be smaller than the differences caused by inclusion of salt fingers, which to some extent validated qualitative inferences from the model.

Although the inclusion of double-diffusive mixing clearly improved the correspondence with biogeochemical data for the upper ocean, particularly when used in conjunction with the Zhang *et al*. (1998) parameterization, Glessmer's model still underestimated the nitrate concentration in the subtropics and tropics. The residual error could be, at least partially, attributable to the uncertainties in the double-diffusive parameterizations. The key complication here – and the common thread running through all biogeochemical studies involving double-diffusion – is that even the smallest changes in mixing can have a substantial impact on the organic composition of the upper ocean. Such sensitivity reflects a highly nonlinear response of biology to the variation in nutrient supply, motivating future efforts to better understand and better parameterize double-diffusion.

Salt fountains in the ocean

To complement the discussion of biogeochemical applications, it is worth touching upon one more issue – an issue that most readers would probably classify now as entertaining rather than hard-core scientific or even serious, but things could change. Given the benefits of double-diffusion for ocean biota and our dependence on fisheries, the question arises whether the principles of double-diffusion could be exploited to artificially increase ocean productivity. It is becoming increasingly clear that fish supply is unlikely to keep up with growing demand without an intervention of some sort. However, if we give the ocean a helping hand by installing artificial double-diffusive systems, ameliorating the low productivity zones of the world ocean, then the problem could be alleviated. This proposition appears to be the stuff of sci-fi novels, but is it that unfeasible?

Inspired by the landmark discovery of "an oceanic curiosity: the perpetual salt fountain" (Stommel *et al*., 1956), a group of Japanese researchers (Maruyama *et al*., 2004) performed a curious experiment of their own. In August of 2002, they deployed a 300-meter long free-floating pipe (Fig. 11.5) in the main thermocline (60–360 m depth range) west of the Mariana Islands in the tropical Pacific, a region characterized by finger-favorable stratification. The purpose of the experiment was to explore the potential of salt fountains for fish-farming (something that Stommel *et al*. described as an "improbable application"). The salt fountain can draw up deep nutrient-rich water without an external energy source and thereby fertilize the euphotic zone with minimal investment of resources. Unlike salt fingers, which are disorganized and vulnerable to adverse ambient forcing (Chapter 10), the flow in the pipe is unidirectional and unimpeded by oceanic shears and turbulence. Therefore, the salt fountain mechanism is expected to be much more effective than fingering in transporting nutrients into the near-surface layer. An associated proposal has been made for the cultivation of ocean deserts by an array of salt fountains (Fig. 11.5a).

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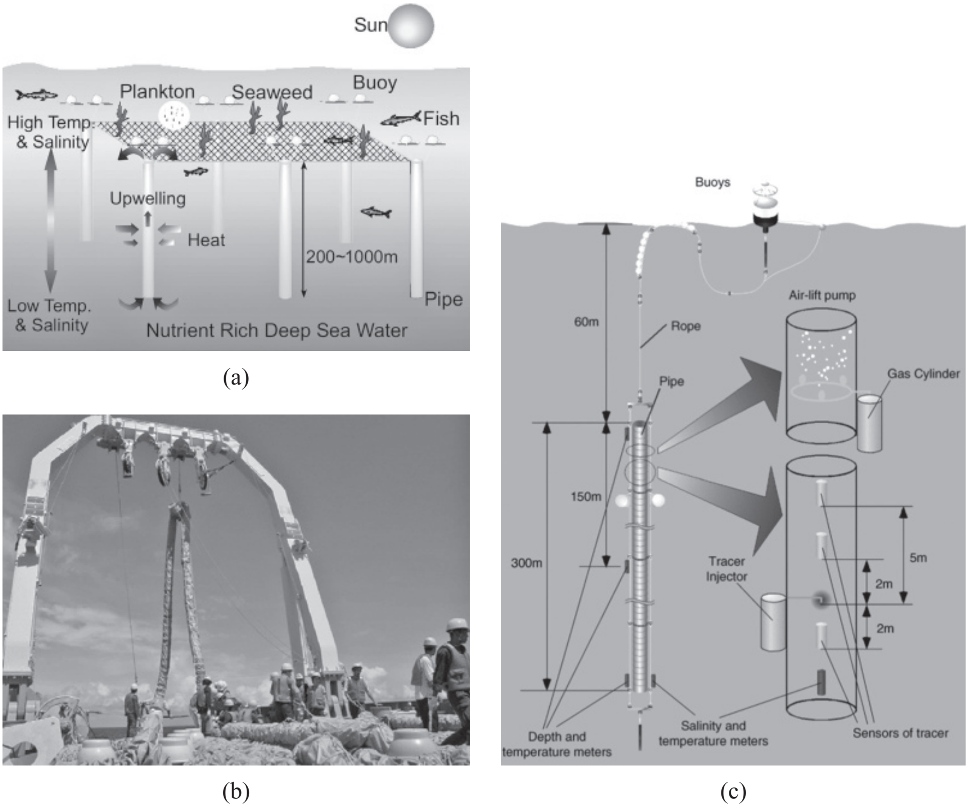

Figure 11.5. (a) Schematic of the proposed salt-fountain ocean farm (Laputa project). From Maruyama *et al.* (2004). (b) Deployment of the salt fountain. (c) Diagram of the experimental apparatus. From Tsubaki *et al.* (2007).

In a neat reference to a floating island in Jonathan Swift's *Gulliver's Travels*, the proposed undertaking was named the Laputa Project and the Mariana experiment was the first step in determining its feasibility.

Of course, neither the idea nor even the execution attempt is completely original. In 1971, Luis Howard and Henry Stommel performed a similar experiment in the Caribbean, but the outcome was deemed ambiguous because of the uncertain origin of the flow through the pipe. However, the 2002 Mariana experiment was a clear success. Throughout the duration of deployment, the system operated in accord with expectations based on salt-fountain physics and with the corresponding numerical predictions. Following the initial trial, similar salt-fountain experiments have been performed several times (Tsubaki *et al.*, 2007; Maruyama *et al.*, 2011), consistently generating artificial upwelling. Transport characteristics of the salt fountain were quite impressive, with upwelling velocities of up to 593 m/day, corresponding to a pumping rate of 43 m^3/day. To put these numbers in perspective, let us recall that diapycnal velocities in the ocean ($w \sim 10^{-7} - 10^{-6}\,\mathrm{m\,s^{-1}}$) are four to five orders of magnitudes less. Thus, the volume transport by a single pipe is equivalent to the natural upwelling over an area of ~500–5000 m^2. The signal of artificial upwelling was clearly visible in satellite ocean-color images taken during the Philippines Sea experiment (Maruyama *et al*., 2011), indicating an increased surface chlorophyll distribution in the vicinity of the pipe.

At this point it is perhaps premature to speculate about the prospects of implementing salt-fountain farms on the industrial level. Before embarking on such a project, all its aspects – physical, environmental and even social – have to be considered to ensure that the benefits of artificial upwelling for the ocean ecosystem outweigh any potential adverse consequences. A host of technological challenges will need to be addressed. Nevertheless, the initial success is noteworthy. At the very least, it offers the long-awaited proof of concept for Stommel's curious idea, the idea that ultimately changed our understanding of ocean mixing.

11.2 Effects of diffusive convection

The extensive evidence accumulated during half-a-century of double-diffusive research, only a fraction of which is presented here, leaves little doubt that salt fingering is fully capable of influencing the large-scale dynamics. But what about its little sister, diffusive convection? In terms of both mixing intensity and the net volume of ocean regions affected, diffusive convection lags significantly behind salt fingers. Until recently, diffusive convection has been rarely invoked in discussions of global circulation patterns and the ocean climate. However, two factors could make a difference. First, diffusive convection is most common in high-latitude regions, in dangerous proximity to the formation sites of deep and bottom waters of the world ocean. Low preexisting density stratification in such locations tends to amplify water-mass transformation effects and even a modest amount of diffusively driven mixing can have a substantial impact on thermohaline circulation, the ocean's great conveyor belt. The second argument, particularly relevant for the diffusive layer in the Arctic, emphasizes the large contribution of diffusive convection relative to other mixing mechanisms. In the pristine regions of the central Arctic, wave energy is much less – by as much as a factor of fifty (Levine, 1990) – than typically observed in mid-latitude oceans. The anomalously low wave activity can support very limited levels of turbulent mixing ($K_V \sim 10^{-6}\ \mathrm{m^2\ s^{-1}}$). This by default makes diffusive convection the dominant interior mixing process, potentially governing key water-mass balances in the Arctic.

One of the first attempts to quantify the role of diffusive convection in high-latitude water-mass transformation was made by McDougall (1983), who argued that diffusive convection controls the formation rate of Greenland Sea bottom water and thereby influences global thermohaline circulation. A simple model was developed based on a balance between (i) vertical T–S fluxes driven by diffusive convection and (ii) the horizontal advection of the Atlantic water towards the center of the Greenland Gyre. McDougall's model was remarkably consistent with the observed formation rates of bottom water and its properties. The role of diffusive convection was also shown to be far more significant than the role of cabbeling – another mixing process known to affect high-latitude water-mass transformation, arising from variation in the thermal expansion coefficient. Given the involvement of Greenland bottom water in the maintenance of thermohaline circulation, McDougall's suggestion places diffusive convection right at the heart of the abyssal mechanics of the world ocean.

One of the most rapidly growing environmental concerns is related to the systematic reduction of the Arctic summer-time sea-ice coverage. The sea-ice cover in the Arctic Ocean has experienced dramatic changes in both extent and volume and these trends have notably accelerated in recent years. Observations reveal a decrease of 40% in the volume of sea ice in the Arctic Ocean over the past three decades, which corresponds to an average melt rate of 1% per year (Deser and Teng, 2008). The Arctic sea-ice decline is undoubtedly controlled by a combination of several processes, including solar input at the surface and albedo feedback effects – see the schematic in Figure 11.6. Recently, however, a suggestion has been made (Turner, 2010) that the ice melt could also be influenced by heat transport through the diffusive layer separating the cold and fresh waters of Pacific origin and the cold halocline region from warmer and saltier Atlantic waters.

The Atlantic water contains enough heat to melt all the ice in the Arctic, but the question is how this heat can reach the surface of the ocean. The most direct route is of course straight up, from the warm Atlantic layer through the diffusive staircases and eventually into the ice (Fig. 11.6). In this scenario, the rate of upward heat transport is controlled by the diffusive staircase, which plays the role of the transport bottleneck in the dynamics of the Arctic halocline. However, it is not immediately clear (i) whether this mechanism is physically viable and (ii) even if heat does penetrate the halocline and reach the surface, that the fluxes are large enough to significantly affect the melting rates. The exact dynamics of the heat transfer across the cold halocline region where the vertical temperature gradient changes sign is uncertain, but it likely involves a combination of lateral and vertical mixing processes. To address the first concern, Turner and Veronis (2000, 2004) performed a series of laboratory experiments designed to represent the Arctic configuration. These experiments demonstrated that extra heating at depth (the laboratory analogue of the Atlantic layer) leads to faster melting of floating ice.

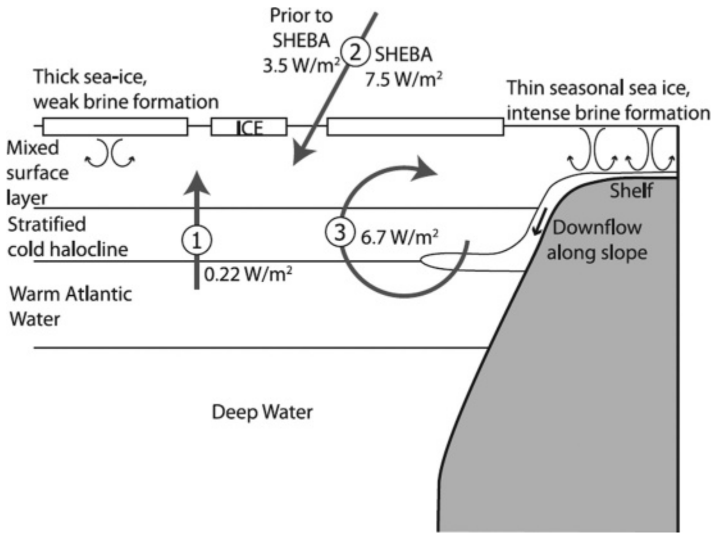

Figure 11.6 Mechanisms that can contribute to the melting of ice in the Arctic Ocean include: (1) upward double-diffusive transport from the warm layer of Atlantic water, (2) heat flux from the atmosphere and (3) downflows on the slope. From Turner (2010).

If we assume that the Arctic dynamics are adequately captured by the laboratory models, then it becomes rather straightforward to estimate the impact of diffusive convection on the ice content. Using the laboratory calibrated four-thirds flux law, Turner (2010) arrived at the vertical staircase-driven heat flux of $F_H = 7.1 \cdot 10^6\,\mathrm{J\,m^{-2}\,yr^{-1}}$. This flux is sufficient to melt 1% of sea ice in one year, which is of the same order as the observed melt rates (Deser and Teng, 2008). For the purpose of this discussion it is also important to keep in mind that the heat flux through the present-day staircase has increased by a factor of three to four within the past three decades, most likely in response to the advance of anomalously warm Atlantic water (e.g., Timmermans *et al.*, 2008). Thus, the dynamics suggested by the double-diffusive model are generally consistent with the sea-ice trend and the predicted melt rates come tantalizingly close to the observed values. Unless the agreement is coincidental, a significant fraction of the reduction in sea-ice coverage can be attributed to the increase in double-diffusive transport. Note also that Turner's argument is based on the laboratory-calibrated heat fluxes. Our ongoing research suggests that, in application to Arctic staircases, these estimates may require upward revision by as much as a factor of two to three, in which case the impact of diffusive convection could be even more substantial than Turner (2010) originally visualized.

The waters surrounding Antarctica are also generally susceptible to diffusive convection. One such region is the Weddell Sea, which has been studied most extensively as the main source of the Antarctic Bottom Water. It is interesting to consider the dynamics of this region with an eye to double-diffusion, but let us first review some basic background. Most of the Weddell Deep Water either forms at the continental shelves or is produced by intermittent open-ocean convection. A particularly energetic convective event resulted in the appearance of the so-called Weddell Polynya – a large area of ice-free water that formed in the eastern Weddell near the Maud Rise seamount and persisted through the winters of 1974–6. The spectacular spatial extent and duration of the Weddell Polynya indicated that the deep-ocean convection occurred on a massive scale. The associated deep-water formation rates greatly exceeded the shelf-derived production (Gordon, 1982). Major convective events of such scale produce a detectable impact on the lower limb of the thermohaline circulation and profoundly influence the regional climate. The extraordinary large amount of heat transferred from the ocean to the atmosphere during the Weddell Polynya years resulted in substantial cooling of the Antarctic Bottom Water and it took decades for the Weddell stratification to fully recover. While events of such scale have not occurred since 1976, more localized single-winter ice-free openings are common.

Despite the dramatic and climatically significant character of deep convection in the Weddell Sea, the specific conditions and mechanisms for its initiation are still uncertain. The winter stratification of the Weddell is much weaker than in the most of the world ocean. The marginally stable state is maintained by a subtle balance between (at least) two competing processes. The first one is the surface-layer densification driven by brine rejection during winter sea-ice growth, which tends to reduce the stratification. The destabilizing brine rejection is countered by the increasing upward heat flux from the warmer deep waters, which ultimately arrests the sea-ice growth, an effect often referred to as the "thermal barrier" mechanism. Thus, the precarious balance of the Weddell stratification is ultimately controlled by the processes involved in transporting heat through the main pycnocline. In order to predict the response of such a system – and to explain its resilience – to a wide a range of forcing conditions, it is essential to identify the dominant mixing agent. The list of usual suspects includes wave-induced turbulent mixing, cabbeling, double-diffusion and the mesoscale eddies impinging on Maud Rise. Their relative contributions still remain a subject of ongoing debate. However, a persistent stream of evidence (reviewed in Chapter 9) suggests that diffusive convection in the Weddell Sea is a significant, and possibly even the dominant, transport mechanism in the permanent pycnocline.

The possibility of predominantly diffusive control was reinforced by recent microstructure measurements made during the 2005 Maud Rise Nonlinear Equation of State Study expedition to the eastern Weddell Sea (Shaw *et al.*, 2013). One of the main objectives of this program was to quantify the variability and parameter

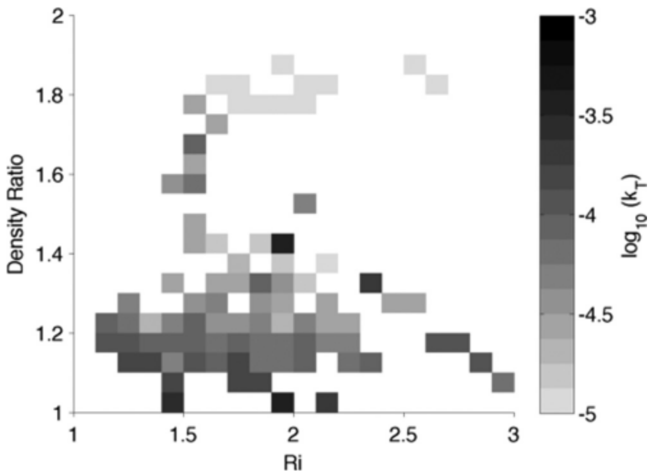

Figure 11.7 Thermal diffusivities in the Weddell pycnocline as a function of Richardson number and density ratio. Modified from Shaw *et al.* (2013).

dependence of thermal diffusivity (K_T) in the vicinity of Maud Rise. The most striking conclusion following from this analysis is the strong dependence of K_T on the finescale density ratio and the lack of statistically significant dependence on the strength of background shear, measured by the Richardson number (Fig. 11.7). Since turbulence is known to be sensitive to finescale shear, these results argue against the turbulent origin of mixing in the Weddell Sea. At the same time, typical diffusivity values and their rapidly decreasing dependence on density ratio are very much in line with the expectations for diffusive convection, as is the abundance of layers in the Weddell pycnocline.

Let us now consider the possible dynamic implications of diffusive mixing in the Weddell Sea. One of the distinguishing characteristics of diffusive convection is the counter-gradient (downward) transport of density. Recall also that this flux rapidly increases as the system drifts towards the marginally stable state ($R_\rho^* \to 1$). Combined, these properties produce a robust mechanism for the prevention of convective overturns. The wintertime brine rejection decreases R_ρ^*, intensifying double-diffusion, which in turn transports more density downward and thereby stabilizes the water column. This double-diffusion-specific negative feedback acts to strengthen the thermal barrier effect, making the Weddell stratification dynamically more resilient to external forcing. So why have we not observed convective overturns comparable to the Weddell Polynya for the last three-and-a-half decades? A definitive answer to this question clearly requires further research, observational and theoretical. However, the possibility of diffusive regulation

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appears very likely. Without double-diffusion, deep convection would be more common and energetic, making the Antarctic Bottom Water colder and more voluminous. This, in turn, could have a substantial impact on the global thermohaline circulation.

Diffusive convection has also been implicated in numerous regional processes. For instance, a numerical modeling study of sea-ice patterns in the West Antarctic Peninsula regions (Smith and Klinck, 2002) revealed strong sensitivity of wintertime ice thickness to double-diffusion. Doubling the parameterized diffusive flux reduced the ice thickness by a factor of two, tripling the flux-produced ice-free conditions in mid-winter, and removing double-diffusion increased the ice thickness by $\sim$50% towards less realistic values. On the other hand, replacing diffusive convection by the equivalent turbulent transport (of comparable intensity but with equal heat and salt diffusivities) produced surface conditions that are inconsistent with regional observations.

While high-latitude examples are common and, to some extent, expected, diffusive convection can also affect large-scale dynamics in more moderate conditions. For an illustration, consider the mixing environment of the Black Sea. Diffusive convection is supported in much of its interior, below the upper pycnocline, and constitutes the main vertical transport mode for heat and salt in the deep waters. However, the most prominent feature of the Black Sea stratification is its bottom convecting layer. With a thickness of 300–450 m and spreading across the whole basin, it is the largest known diffusive layer in the world's ocean. Here, convection is maintained by geothermal heat flux, which is balanced by the upward flux across the diffusive interface at the top. This structure profoundly affects the deep waters of the Black Sea by laterally homogenizing the water-mass properties inside the convective layer and thus setting a laterally uniform lower boundary condition for the interior stratification. The lateral homogenization of the bottom layer has also been implicated in the uniform distribution of bottom sediments across the basin (Ozsoy *et al.*, 1991; Murray *et al.*, 1991; Ozsoy and Besiktepe, 1995).

On this peculiar example we conclude the discussion of the potential large-scale implications of double-diffusive convection. The list of topics is not meant to be exhaustive. The choice of illustrative examples was governed by three factors: (i) interesting dynamics, (ii) representativeness and (iii) potentially serious impact on climate. However, even within these limits, one subject is notably missing – thermohaline interleaving. This exception is intentional and it does not imply that interleaving is unimportant. On the contrary, it is our belief that interleaving is one of the major mechanisms for lateral mixing, affecting a wide range of large-scale processes. The key difficulty in this regard is that, at present, the transfer characteristics of intrusions are poorly constrained. Quantitative estimates of their large-scale consequences are rare and speculative. Unfortunately, a meaningful discussion of this topic will have to await the development of acceptable models for intrusive mixing. The next chapter, however, attempts an even more ambitious undertaking – analysis of double-diffusion in environments that are far more mysterious and inaccessible than the ocean interior. Let us talk about stars, planets, liquid metals and magma chambers.