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Ocean models need to parameterise the detrainment from bottom water plumes

Trevor J. McDougall[1], Ryan M. Holmes[2], Kathryn L. Gunn[3]

[1]School of Mathematics and Statistics, University of New South Wales, Sydney, New South Wales, Australia
[2]Bureau of Meteorology, Sydney, New South Wales, Australia
[3]University of Southampton, Southampton, United Kingdom

Correspondence to: Trevor J. McDougall (Trevor.McDougall@unsw.edu.au)

Abstract. Because diapycnal advection in the ocean is a consequence of diapycnal mixing, there is a tendency to think that knowledge of the mixing intensity throughout the abyss would determine the ocean's density stratification. This is not the case. We show that in the abyssal ocean (deeper than ~3000m) the magnitude of the stratification depends not only on the strength of diapycnal mixing but also on the rate of detrainment from the dense Antarctic Bottom Water plumes. Ocean models have never attempted to represent such detrainment physics so that the magnitude of the stratification in the deepest half of ocean models, if run to equilibrium, would not be the result of a correct physical balance. We show that the detrainment process causes the vertical stratification in the abyss to be approximately 2.75 as large as it would be in the absence of this detrainment process. This means that we cannot rely on how the abyss in ocean models reacts to changes in forcing, such as global warming. Also, the detrainment process causes the density of sinking plumes to increase downstream, and this has not been observed in ocean models to date. We conclude that detrainment from dense plumes is an important physical process that needs to be incorporated into ocean models.

1 Introduction

The magnitude of the abyssal density stratification enters estimates of thermosteric sea level rise, the rate of the overturning circulation, and the meridional heat transport, but the causes of the magnitude of the abyssal stratification remain unresolved.

Recently, McDougall et al (2025) showed that the bulk abyssal stratification depends on the rate of detrainment from the sinking plumes of Antarctic Bottom Water (AABW), and not only on the vertical distribution of diapycnal mixing. That demonstration relied on an integral taken with respect to a normalised buoyancy coordinate, and so was encumbered by the fact that this coordinate is itself defined using buoyancy. Here, we present an improved and more convincing derivation, arriving at an expression that involves only quantities which can be specified independently of the stratification. The centrality of the detrainment process for determining the magnitude of the abyssal stratification then follows directly. We conclude that we must strive to have ocean models represent detrainment from dense bottom-water plumes.

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2 Two ways of integrating the Walin buoyancy balance

The uppermost buoyancy surface of the abyss is taken to be the 28.11 kg m^{-3} Neutral Density surface (Jackett and McDougall, 1997), a density surface that does not outcrop to the sea surface except as Antarctic Bottom Water. The abyssal ocean that lies below this surface is isolated from direct contact with the atmosphere and can only be modified by mixing and by the AABW plumes that enter the region.

As in McDougall et al. (2025), three quantities are imposed at, or on, the upper buoyancy surface B^u: (i) the volume flow rate of Antarctic Bottom Water (AABW) at the top of the abyss, $\mathcal{E}^u_{\text{AABW}}$, (ii) the volume-flux-weighted average buoyancy of these AABW plumes at the top of the abyss, A^u, and (iii) the area-integrated diffusive buoyancy flux on buoyancy surfaces $F(B)$ as a function of buoyancy, B.

In a steady state, the net upwelling transport across buoyancy surfaces, $\mathcal{E}_{\text{net}}(B)$, caused by diapycnal mixing is equal to the transport of AABW, $\mathcal{E}_{\text{AABW}}(B)$, in the plumes sinking adjacent to the buoyancy surfaces (see Fig. 1).

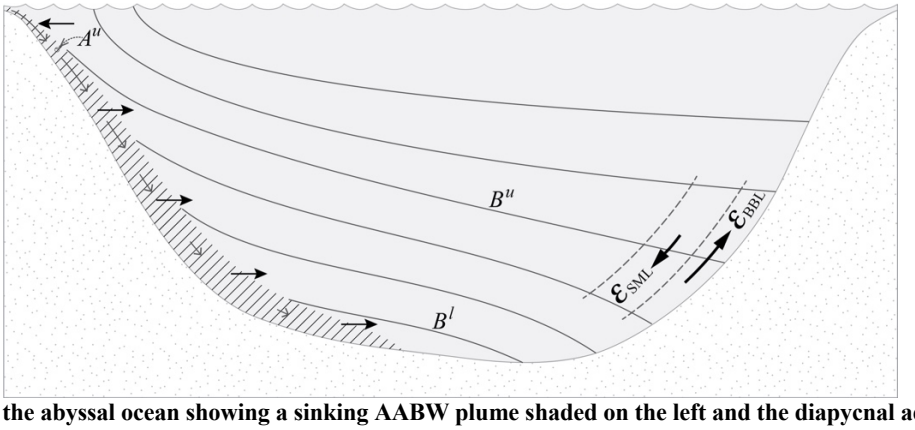


Figure 1: A sketch of the abyssal ocean showing a sinking AABW plume shaded on the left and the diapycnal advection in the Stratified Mixing Layers of the ocean interior, $\mathcal{E}_{\text{SML}}$, and in the Bottom Boundary Layers, $\mathcal{E}_{\text{BBL}}$, at the sloping boundaries around the ocean's periphery. The net diapycnal transport across an entire buoyancy surface is $\mathcal{E}_{\text{net}}(B) = \mathcal{E}_{\text{SML}}(B) + \mathcal{E}_{\text{BBL}}(B)$.

The Walin (1982) buoyancy balance,

$$\mathcal{E}_{\text{net}} = \frac{\mathrm{d}F}{\mathrm{d}B} \tag{1}$$

states that the net upwelling diapycnal volume transport $\mathcal{E}_{\text{net}}$ across a buoyancy surface is the rate of change of F with buoyancy B, where F is the magnitude of the area-integrated diffusive buoyancy flux on the buoyancy surface.

We introduce the non-dimensional volume transport variable $q = \mathcal{E}_{\text{net}}/\mathcal{E}^u_{\text{net}}$, and the non-dimensional diffusive flux variable $f = F/F^u$ where the superscript u means the uppermost buoyancy surface of the abyss (at ~3000m deep) and the superscript l will mean the densest, deepest (*lowest*), buoyancy surface in the abyss. In terms of our imposed quantities on the uppermost buoyancy surface, the natural buoyancy scale is $F^u/\mathcal{E}^u_{\text{net}}$ so the dimensionless buoyancy is defined as $b = B/[F^u/\mathcal{E}^u_{\text{net}}]$, and in terms of the dimensionless variables the Walin (1982) buoyancy balance is

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$$q = \mathrm{d}f/\mathrm{d}b. \tag{2}$$

McDougall et al. (2025) integrated Eq. (2) from the lowest part of the abyss (where $f = 0$ because the area of the buoyancy surface tends to zero there) to the uppermost buoyancy surface (where $f \equiv 1$), obtaining

$$[b^u - b^l] \;=\; 1/\int_0^1 q(\phi')\,\mathrm{d}\phi', \tag{3}$$

where $\phi \equiv [b - b^l]/[b^u - b^l]$ is the normalized buoyancy scale of the abyssal stratification, varying from zero to 1 over the abyssal ocean. Note that not only is $[b^u - b^l]$ unspecified a priori in an ocean model, but also the vertical shape of the stratification, $b(z)$ (and hence of $\phi(z)$), is also not specified. Therefore, while Eq. (3) has been used in section 6b of McDougall et al. (2025) to strongly imply the necessity to understand the detrainment from AABW plumes as a prerequisite to modelling $[b^u - b^l]$, the explanation was rather convoluted due to the ϕ-dependence within the integral in Eq. (3).

The present article integrates the Walin (1982) buoyancy balance in a different manner, so arriving at a succinct explanation of why ocean models must either parameterize or somehow impose the detrainment from AABW plumes in order to be able to correctly model the magnitude of the abyssal bulk stratification $[b^u - b^l]$. The traditional way of using the Walin (1982) buoyancy balance is to treat the stratification as known, to impose the diffusive buoyancy flux and then to use the buoyancy equation to solve for the diapycnal advection. By contrast, in this article we take both the diffusive buoyancy flux and the diapycnal advection as imposed and use the Walin buoyancy equation to solve for the stratification.

This second way of integrating the Walin buoyancy balance begins by first dividing Eq. (1) by $\mathcal{E}_{\mathrm{net}}(B)$ and then integrating to find (noting that $F^l = 0$)

$$[B^u - B^l] \;=\; \int_0^{F^u} \frac{\mathrm{d}F}{\mathcal{E}_{\mathrm{net}}}, \tag{4}$$

or, in dimensionless form,

$$[b^u - b^l] \;=\; \int_0^1 \frac{\mathrm{d}f}{q}. \tag{5}$$

Fig. 2 shows $1/q$ versus f for the seven cases of $q(\phi)$ used in Figs 4, 5 and 6 of McDougall et al. (2025). For each of the seven cases, the area under the $1/q$ versus f curve is equal to the bulk abyssal stratification $[b^u - b^l]$ of that example [see Eq. (5)]. This figure is a very direct way of illustrating that the bulk abyssal stratification, $[b^u - b^l]$, depends not only on how f varies with height in the abyss, but also on the corresponding variation of $1/q$. Sections 3 and 6b of McDougall et al (2025) use Eq. (3) to show, with some approximations, that $[b^u - b^l]$ cannot be deduced from $f(z)$ alone, but Eq. (5) and Fig. 2 make this point much more convincingly; clearly, both $f(z)$ and $q(z)$ are needed to predict $[b^u - b^l]$. The key feature of the approach of McDougall et al. (2025) that caused their convoluted interpretation was the dependence of the integral in Eq. (3) on the stratification which is part of the solution to the Walin (1982) upwelling and diffusion balance. In Fig. 2 both f and $1/q$ can be regarded not only as functions of each other but also as being functions of a third independent variable such as buoyancy, or the mean height z of a buoyancy surface.

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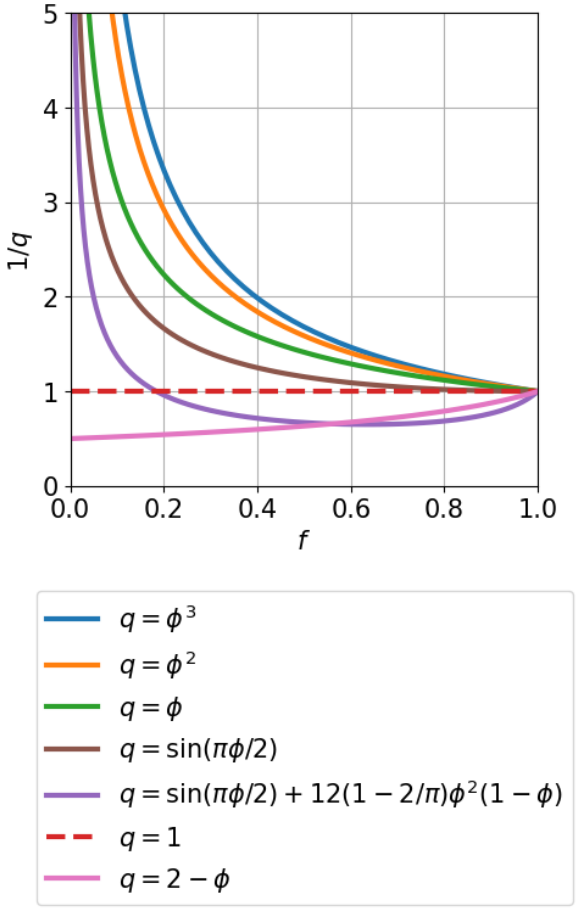


Figure 2: Seven examples of the vertical variations of the non-dimensional area-integrated diffusive buoyancy flux f and the reciprocal of the non-dimensional transport of Antarctic Bottom Water q. The non-dimensional buoyancy in the abyss is labelled ϕ, varying from 0 in the densest abyssal location to 1 at the uppermost buoyancy surface of the abyss. The non-dimensional bulk buoyancy stratification in the abyss, $[b^u - b^l]$, is the area under the curves of this figure, $\int_0^1 \mathrm{d}f/q$.

3 Implications for ocean models

Imagine imposing F as a function of space in an ocean model. Only when one also knows how $1/\mathcal{E}_{\mathrm{AABW}}$ varies in space (actually, as a function of F) will the ocean model be able to simulate the bulk abyssal stratification; see Eq. (4) or (5). Fig. 2 makes it clear that to realistically simulate the abyssal stratification, the sub-grid-scale physics of detrainment from the sinking AABW plumes (Baines, 2001) needs to be accurately simulated or parameterized in ocean models so that $\mathcal{E}_{\mathrm{AABW}}$ is correctly modelled at all heights. This detrainment from dense sinking plumes has never been incorporated into an ocean model. The transport of dense AABW, q, is not a consequence of f, because while these quantities obey $q = \mathrm{d}f/\mathrm{d}b$, the vertical stratification b is an outcome of the physics, not an input. The physics of detrainment (and entrainment) from dense AABW plumes (Baines, 2001) is quite separate physics to

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that of diapycnal mixing in the ocean interior. Once both $f(z)$ and $q(z)$ are imposed, the vertical stratification $b(z)$ follows from the Walin (1982) buoyancy balance to be

$$b(z) = b^u - \int_z^{z^u} \frac{f_z}{q} \mathrm{d}z', \tag{6}$$

or in terms of dimensional quantities,

$$B(z) = B^u - \int_z^{z^u} \frac{F_z}{\mathcal{E}_{\mathrm{net}}} \mathrm{d}z'. \tag{7}$$

Consider the evolution of the abyssal stratification towards a steady state. We impose the volume flow rate of AABW at the top of the abyss, $\mathcal{E}^u_{\mathrm{AABW}}$, the volume-flux-weighted average buoyancy of this AABW plume fluid, A^u, and the area-integrated diffusive buoyancy flux as a function of space, $F(z)$, noting that this buoyancy flux is itself due the product of the model's diapycnal diffusivity and the evolving stratification which is not strictly fixed. The abyssal stratification $B(z)$ and the net upwelling across buoyancy surfaces $\mathcal{E}_{\mathrm{net}}(B)$ then evolve towards a steady state in which $\mathcal{E}_{\mathrm{AABW}}(B) = \mathcal{E}_{\mathrm{net}}(B)$, $B^u = A^u + F^u/\mathcal{E}^u_{\mathrm{net}}$ (Hogg et al., 1982) and $B^l = B^u - \int_0^{F^u} \mathrm{d}F/\mathcal{E}_{\mathrm{net}}$. The point of this article is that this end state depends not only on $F(z)$ but also on the entrainment into, and detrainment from, the dense AABW plumes.

While the key result of this article, Eqs. (4) and (5) as illustrated in Fig. 2 may seem counter-intuitive, it is consistent with the following qualitative thought experiments. Imagine that the descending AABW plumes neither entrain nor detrain any fluid as they sink to the deepest parts of the abyss, then $q = 1$ at all depths in the abyss and the area on the right-hand side of Eq. (5) is 1, so that $[b^u - b^l]$ is equal to 1, that is, $[B^u - B^l]$ is equal to $(B^u - A^u)$ as expected in this situation. If the descending AABW plumes entrain a lot of seawater from the abyss as they sink, then q becomes large and $1/q$ small, so the area of the integral in Eq. (5) is small and $[b^u - b^l]$ is small. Conversely, when the descending AABW plume loses fluid by detrainment, q becomes small and $1/q$ large so that the integral on the right-hand side of Eq. (5) becomes large and $[b^u - b^l]$ is significantly larger than 1. The uppermost four curves in Fig. 2 describe these detrainment cases; these cases are the ones that are relevant to the abyssal ocean because they have the transport of AABW decreasing towards the densest part of the abyss.

Present ocean models do not explicitly parameterize the detrainment loss of AABW plume fluid into the ocean interior. Rather it seems likely that the decreasing volume transport of AABW that is found in ocean models as these plumes sink in the abyss (Ferrari et al., 2016) is achieved by excessive numerically caused diapycnal and particularly horizontal mixing which would likely decrease the density of the AABW plume fluid. This is the opposite of what should occur as these AABW plumes sink through the abyssal ocean, since the detrainment of plume fluid into the environment actually increases the density of the remaining AABW plume fluid. Hence it is very likely that present ocean models do a poor job of replicating the detrainment from the dense AABW plumes and cannot be relied upon to respond realistically to changes brought about by global heating.

Is it realistic to imagine being able to model a steady-state abyss? If this is a realistic ambition of the ocean modelling community, then the physics of detrainment from dense AABW plumes in the abyss must be understood, parameterized, and incorporated into ocean models.

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4 Hints from the observed abyssal stratification

The discussion so far has been directed at understanding and modelling the physics of what causes the magnitude of the abyssal stratification in an ocean modelling context. For example, when the abyss in an ocean model has reached a steady state, why isn't the abyssal stratification one tenth or ten times the observed stratification. Here we consider what else can be deduced if we allow ourselves to use the observed stratification in today's ocean.

The deployment of mooring arrays in say ten locations to measure the transport and density of AABW is perhaps too daunting to tackle at present. Nevertheless, we do have the combined observational and theoretical diagnostic study of de Lavergne et al (2017), a paper that uses the observed hydrography in the abyss, as well as the observed topography and a spatially imposed (bottom-intensified) theoretically derived mixing parametrization that gives a three-dimensional field of mixing intensity. That is, de Lavergne (2017) found $F(z)$ from a theoretical model of diapycnal mixing, together with the observed ocean stratification, $B(z)$, to calculate (from the Walin buoyancy balance) the net diapycnal advection in the ocean interior, $\mathcal{E}_{\text{net}}(B)$, as shown in Fig. 5 of de Lavergne et al (2017), from which it appears that $q(\phi)$ can be represented approximately as a power law between $\phi^{1.5}$ and ϕ^2 in the range of Neutral Density greater than 28.11kg m^{-3}. It follows that $f(\phi)$ would be between $\phi^{2.5}$ and ϕ^3 and $[b^u - b^l]$ would be (from Eq. (3) or (5) above) between 2.5 and 3 (say ~2.75). This means that the detrainment process has amplified the vertical stratification in the abyss to be larger than what if would have been without detrainment (namely $F^u/\mathcal{E}^u_{\text{net}}$) by a factor of ~2.75. We conclude that detrainment from AABW plumes is an important process, and we should be unhappy that ocean models do not currently include this process.

5 Conclusions

A new vertical integral of the area-integrated buoyancy equation shows that the detrainment from the sinking AABW plumes needs to be specified in order to deduce the bulk vertical buoyancy contrast in the abyss, $[B^u - B^l]$. This point was made, but rather awkwardly, by McDougall et al. (2025) based on an integral of the Walin (1982) buoyancy balance (Eq. (3)), but in this article a different integral of the Walin (1982) buoyancy balance is performed (Eqs. (4) or (5)) from which the above statement arises directly and unambiguously.

Existing ocean models do not directly resolve, impose or parameterize the detrainment out of AABW plumes. This detrainment process has to date only been studied in the ground-breaking theoretical/laboratory papers of Baines (2001, 2005). This detrainment causes the density of AABW plumes to increase as they sink; a feature that has not yet been observed in ocean model simulations.

The combined observational and theoretical approach of de Lavergne et al. (2017) has shown that the transport of AABW varies strongly with buoyancy, and we have deduced that the bulk abyssal stratification in the abyss is larger than what if would have been without detrainment ($F^u/\mathcal{E}^u_{\text{net}}$) by a factor of ~2.75. This shows that detrainment from AABW plumes is an important process in the abyss and ocean models need to include this detrainment process if the abyssal stratification is to be correctly simulated.

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Code and data availability

This paper has produced no data.

Author contributions

TMcD conceived the new way of integrating the buoyancy budget, Eq. (4), which greatly simplifies the process required to justify the main conclusion of this paper. Note that this paper is an extension of the previous McDougall et al. (2025) paper that is authored by the same three authors. TMcD wrote the first draft of the present paper and RH produced Figure 2 while all three authors worked on several subsequent drafts to refine the message and its presentation.

Competing interests

The authors do not have any competing interests.

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