

Inclusion of the Bottom Boundary Layer in Ocean Models

Peter D. Killworth

Southampton Oceanography Centre, Southampton, England

Abstract. The effects of the turbulent bottom boundary layer of the ocean are examined from various process, physical, and climatic perspectives. We discuss how parameterisations might be employed for climate models, which cannot resolve such layers, and discuss the extant parameterisations and their implications.

Introduction: should we care about Bottom Boundary Layers?

At the base of the atmosphere lies a turbulent layer, thickness of order 1000 m. The layer is occasionally stable, but more usually convective in nature due to heating sources at its base. Above the ocean, it connects with a layer of a similar nature at the ocean surface, of depth a few tens of meters. Again, this layer is turbulent and can be both stable or convective. At the bottom of the ocean lies a third such layer, which we shall be concerned with here: the Bottom Boundary Layer (BBL). This layer, like the others, is turbulent, but – apart from possible surface-driven convective events in high latitudes and superheated vents – is stable at all times. While the layer is observed to entrain, detrain, and generally mix with its environment like any other turbulent region, it possesses no well-defined energy budget, so that modelling work on BBLs has been, until recently, limited.

Armi and Millard (1976, and earlier references) were among the first to draw attention to BBLs, and demonstrated that the behaviour of BBLs appeared to vary depending on the type of bottom, and of bottom topography, underlying the layer. The layer was clearly dynamically active, with Froude numbers $u/\sqrt{g'h}$ of order unity, where u is a typical velocity, g' a reduced gravity and h the depth of the layer. *Armi and Millard* (1976) discussed how the scaling of the layer thickness might depend on u_*/f and u_*/N , where u_* is a typical friction velocity, f the Coriolis parameter and N the local buoyancy frequency (the latter dependency giving rise to the Froude numbers of order unity).

Later work (e.g., the HEBBLE experiment, *Nowell et al.*, 1982) showed temporal variability, which is also evident in recent near-equatorial data (*Lozovatsky et al.*, unpublished), so that the deep ocean is far from the passive abyss originally postulated by early workers. That events happening within the BBL interact

with the ocean interior is clear from the striking data of *Polzin et al.* (1997), showing regions of increased mixing, probably internal tides, stretching several km above areas of rough ocean bottom.

Recent work has tended to concentrate on regions of overflows, and not generically on BBLs. In such areas the BBL is clearly important. It controls the position and magnitude of the Gibraltar Strait outflow (*Baringer and Price*, 1997) and the Denmark Strait overflow (*Girton et al.*, 2001). How the BBL is modelled – if it is modelled at all – in climate models has a strong effect on the water mass characteristics and overturning stream function in such models (*Dengg et al.*, 1999).

The BBL is thus one of the many unresolved features in extant climate models, which when modelled appears to play an important role in ocean dynamics. This paper briefly discusses the processes occurring in BBLs and then examines how models currently treat BBLs and what may happen in the near future.

Is a parameterisation needed everywhere?

The answer must be yes. Attempts to include parameterisations in certain areas (cf. *Nakano and Sugino*, 2002, who were forced to do so because their parameterisation failed over larger areas) cannot be useful for climate change scenarios at the very least. In addition, it seems clear that a parameterisation must work *everywhere*, including dynamically active regions such as downflows, deep western boundary currents, as well as passive regions with little mean or eddy flow.

What do most models do about BBLs?

The short answer to this question is this: nothing whatever. Many modellers believe that the addition of a BBL module to their code is time-consuming. This is certainly untrue for the simpler parameterisations dis-

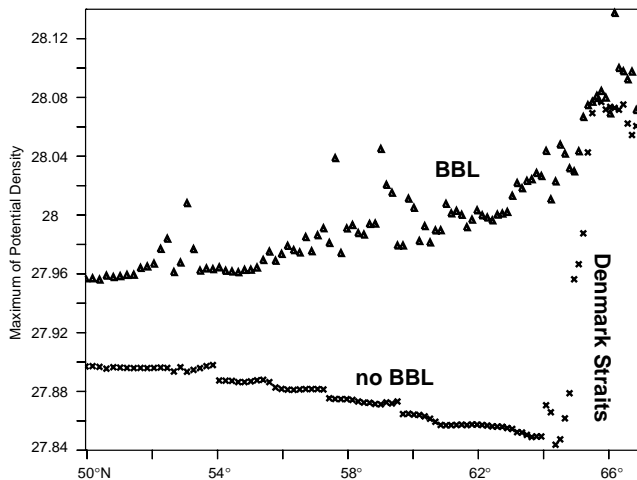


Figure 1. Zonal maximum of N. Atlantic bottom potential density as a function of latitude south of the Denmark Straits with a BBL formulation (triangles) and without (crosses), from *Dengg et al.* (1999).

cussed below, and even the more complex codes are speeding up as they migrate from pure research codes to ones of more general availability.

This neglect of BBLs has serious consequences. Modellers are already aware that inadequate overflow dynamics – particularly at the Denmark Strait – causes gross changes to overturning circulation and water mass structure (cf. *Roberts and Wood, 1997*). Erroneous sill throughflow (itself beyond the remit of this paper) is then followed by the now familiar dilution of the lowest part of the overflow water during the descent of this water mass into the main N. Atlantic. The dilution occurs because the dense water immediately mixes vertically due to convection as it passes over each step in the topography, inducing a cascade mixing effect leading to severe dilution within a few grid boxes of the overflow region. *Dengg et al.* (1999) give an excellent quantitative example of the effect (Fig. 1).

Clearly the inclusion of a BBL cannot entirely remove the erroneous mixing. Some will continue in the interior of the fluid, above any BBL representation. However, at worst a BBL will *reduce* the strength of the mixing.

In addition to simple neglect of BBLs, most extant models further penalise the local physics by applying no slip lateral boundary conditions. In a z -coordinate model, when slopes are represented as brick stacks, this causes downflows to be slowed by lateral friction.

Though climate models neglect BBLs, process models which handle the fall of individual turbulent outflow plumes (but not BBLs per se) have been in use

for decades: *Smith (1975)*, *Killworth (1977)*, and many others up to *Price and Baringer (1994)*, with extensions to two-dimensional plumes by *Jungclauss and Backhaus (1994)*. None of these models are embedded within a larger gyre-scale model, largely due to the difficulty of parameterising detrainment effects (all the process models entrain only).

Processes within BBLs

A difficulty of parameterising any set of physical processes is to find a happy medium between over-representation (producing a complex, costly but accurate scheme) and under-representation (which usually provides a scheme that functions well with tuning but is not globally generalisable). Observations and models of BBLs provide a lengthy list of potential candidates for included physics:

- Laboratory studies (*Lane-Serff and Baines, 2000*) suggest instabilities, mixing, and Ekman drainage
- Internal tides, entrainment, detrainment (e.g. *St. Laurent and Garrett, 2002*)
- Intrusions from internal wave reflections (e.g., *McPhee-Shaw and Kunze, 2002*)
- Internal wave generation from rough bottom, and wave drag (e.g., *MacCready and Pawlak, 2001*)
- Spindown (*MacCready and Rhines, 1993*), though the natural timescale $f/[N^2 \text{ slope}^2]$ may be too long for overflows such as Denmark Strait where there are strong downslope flows
- Dynamical differences between self-driven flows (downflows) and quiescent BBLs effectively driven from above
- Effects of rapid oscillations (*Mellor, 2002*) induced at the surface, in shallow waters
- Remote effects of BBLs, such as breaking internal waves far from BBL and as in atmospheric gravity wave drag parameterisations
- Possible “Reddy” effects (*Nof et al., 2002*) in which a double-front along-slope current cannot maintain its flux as the angle of slope weakens, causing the current to break up into eddies without there being a dynamical instability

Most of these processes are inherently downslope rather than abyssal, reflecting research interests in the past. It is not obvious that tailoring a BBL parameterisation based purely on downslope physics will yield good results everywhere.

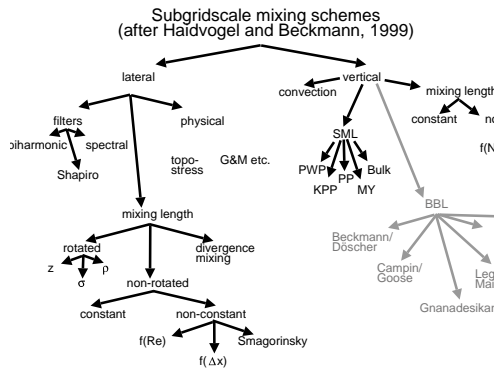


Figure 2. Haidvogel and Beckmann (1999) addended subgridscale parameterisation schematic.

In practice, few if any of the above effects are included in extant parameterisations to be discussed below, attention being concentrated mostly on the need to get dense waters downslope (at some angle to pure vertical) efficiently and, less frequently, on entrainment and detrainment.

Little attention has been given in the literature to the interaction between BBL parameterisations and parameterisations of other effects, e.g. eddies.

What parameterisations are available now for climate models?

All proposed schemes essentially treat the BBL as a problem in the vertical only, as so fit into Haidvogel and Beckmann’s (1999) scheme, suitably addended (Fig. 2).

(a) Beckmann and Döscher (1997)

The first authors to propose a simplified BBL scheme for *z*-coordinate models were Beckmann and Döscher (1997). Their scheme was designed to be simple (and accordingly has had the largest take-up rate of such schemes by other researchers). The scheme had several options which have in practice solidified to a single set. Their fundamental idea was to permit an additional diffusive flux along the bottom boundary of a model. The BBL occupies (essentially) the entire bottom grid box of the model, and whenever dense water occupies a bottom grid box connected laterally to another bottom box which is “below” it, and contains water which is less dense, an additional mixing occurs (i.e. when $\nabla \rho_{bottom} \cdot \nabla h < 0$, where *h* is the depth of the fluid).

In the usual version of the scheme, there is essentially no dynamics (i.e. pressure gradient changes), and water in the bottom box moves with the rest of fluid. There is an additional component due to advection. More complex versions include cutouts on the advective compo-

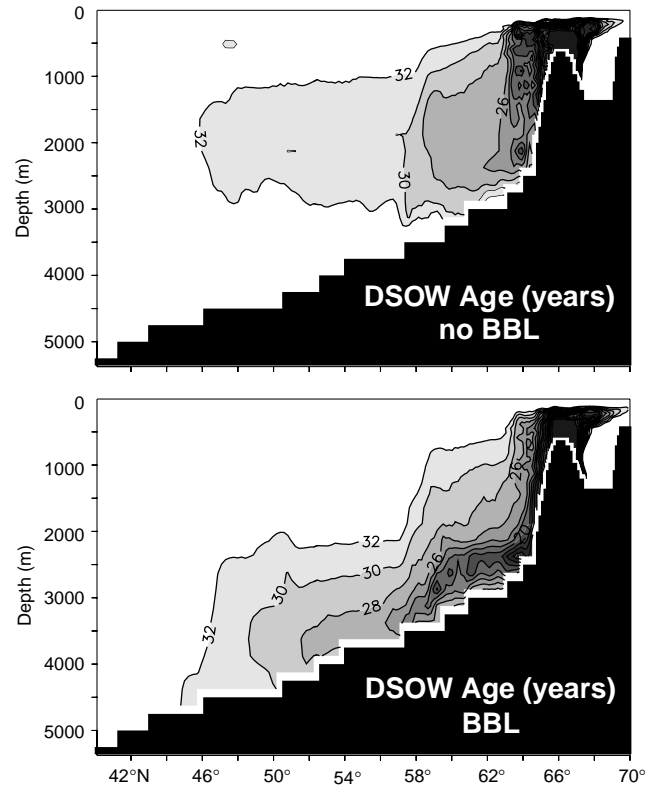


Figure 3. Meridional distributions of the zonal minimum of an artificial age tracer introduced at the Denmark Strait (r.h.s. of diagram), with a background age of 35 years (Dengg et al., 1999).

nent, limits on diffusion, etc. The scheme would play little if any role in a flat-bottomed region of the ocean.

In later tests (Döscher and Beckmann, 2000) the authors found a small but measurable effect on the barotropic circulation, as well as a larger NADW cell in the meridional circulation. Dengg et al. (1999) had similar findings for the meridional circulation, and inclusion of an age tracer added at the Denmark Strait showed a striking effect of the BBL scheme (Fig. 3.)

(b) Gnanadesikan (unpublished)

Gnanadesikan (unpublished) proposed a scheme that was the first to include nontrivial dynamics into the BBL. The work was never published, but a brief description of the scheme is to be found in the MOM3 manual¹. Gnanadesikan’s (unpublished) idea was to extend the Beckmann and Döscher (1997) concept so that the BBL essentially ‘hung’ off the bottom grid box of the model, with a finite but thin uniform thickness;

¹Pacanowski and Griffies, 2000: http://www.gfdl.gov/smg/MOM/web/guide_parent/guide_parent.html

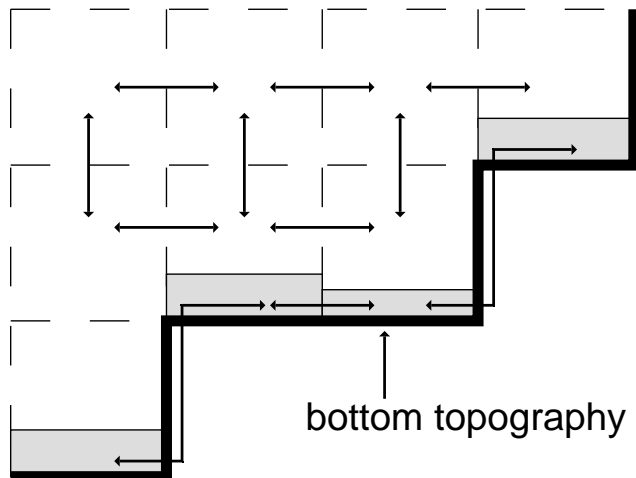


Figure 4. Schematic of the variable depth BBL scheme in a z -coordinate ocean model.

a pressure gradient was computed between the bottom cells, which could be partial depth; and a drag term was included to avoid flows being geostrophically tied to depth contours. A linear drag term was included, so that downflows could avoid being tied to bottom contours. An upwind scheme was used for tracers.

The formulation, in common with others discussed below, suffers from sigma-coordinate-like pressure gradient errors, despite extensive attempts to reduce these in his formulation.

(c) Killworth and Edwards (1999)

This was the first BBL scheme to permit ‘full’ dynamics and thermodynamics within a BBL of spatially and temporally varying thickness, and it exists within a parallelisable version of the MOM code. A schematic of the grid structure is given in Fig. 4. While interior gridboxes are connected only laterally, a spatially and temporally varying fraction of the bottom gridbox is taken up by the BBL, which is connected laterally as shown.

As noted above, it is not clear what dynamics are satisfied by a BBL. For a surface mixed layer, the approach historically has been to create some form of energy equation, simplify it, and use it as a diagnostic tool to predict the layer thickness h . This approach works because there are both sources and sinks of energy in the surface layer, so that both entrainment and detrainment are possible. In the BBL, there are only (apparently) *sources* of energy for mixing, and no sinks apart from dissipation.

The solution adopted was to assume the BBL tur-

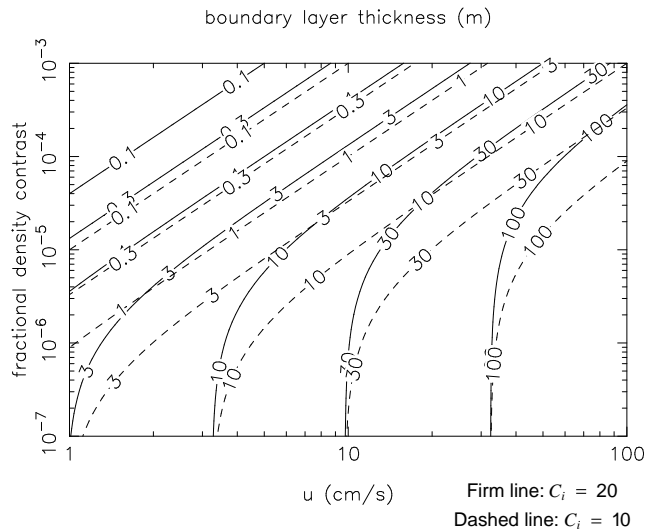


Figure 5. Equilibrium depth of the BBL predicted by the *Zilitinkevich and Mironov (1996)* scheme.

bulence is in equilibrium², and adapt a best-fit to a turbulent layer depth from *Zilitinkevich and Mironov (1996)*:

$$\left(\frac{h}{C_n u_* / f}\right)^2 + \frac{h}{C_i u_* / N} = 1 \quad (1)$$

where C_n , C_i are constants. C_n is well determined (using observations and LES runs) but C_i is not; *Zilitinkevich and Mironov (1996)* quote a range of 5 to 20, the latter being used in the scheme (but see later). Here $u_*^2 = C_D |\mathbf{u}_m|^2$, where \mathbf{u}_m is the mixed layer velocity in the BBL. The quadratic (1) shifts smoothly from the *Rossby and Montgomery (1935)* value $C_n u_* / f$ for weak stratification to *Deardorff's (1972)* value $C_i u_* / N$ for strong stratification or weak rotation. *Killworth and Edwards (1999)* used

$$\left(\frac{h}{C_n u_* / f}\right)^2 + \frac{h}{C_i^2 C_D |\mathbf{u}_m|^2 / g'} = 1 \quad (2)$$

(where g' is the reduced gravity between the BBL and the layer above, due to the density jump) though other formulae could be used. The fit for h at midlatitude, as a function of the BBL speed and density contrasts shown in Fig. 5. The solution is well-behaved but noticeably sensitive to the value chosen for C_i .

The method time-steps tracers and momentum, as well as thickness, as if there is no connection between the BBL and the interior, in both these regions. The equilibrium h_{ZM} is then computed from (2). If

²Exactly what time-scale is required for equilibrium to be reached is unclear.

$h_{ZM} > h_{computed}$, interior fluid is entrained into the BBL, conserving all tracers, and h is reset to h_{ZM} . If $h_{ZM} < h_{computed}$, BBL fluid is detrained into the interior, and h is again reset to h_{ZM} . This approach is somewhat crude but has the virtue of permitting both entrainment and detrainment within one set of physics.

Timestepping of momentum involves computation of horizontal pressure gradients, and suffers from the same sigma-coordinate difficulties as the *Gnanadesikan* (unpublished) scheme.

(d) Song and Chao (2000)

This approach started from the *Killworth and Edwards* (1999) model (and code) and sought to improve the representation of the pressure gradient using the Jacobian form of gradient derived by *Song and Wright* (1998). This had been proven to possess less sigma-coordinate errors than the form used by *Killworth and Edwards* (1999) (*Shepetchkin and McWilliams*, submitted to JGR, show that the errors remaining in *Song and Wright's* (1998) approach can again be reduced by higher-order methods, though it is not clear if these are applicable to the BBL case). Tests using the same test problem (inflow onto a slope) as *Killworth and Edwards* (1999) showed distinctly smoother solutions as well as better fits to SCRUM simulations, although there were no more global tests of good behaviour of the pressure gradient formulation. En route, *Song and Chao* (2000) embedded the BBL model into a partial cell representation of topography (also present in the MOM model which *Gnanadesikan* (unpublished) had used).

However, the code remains written for a lateral depth change of only one vertical grid point, which limitation needs to be overcome. It also inherits the *Killworth and Edwards* (1999) coding limitation of requiring the BBL thickness to be less than half the thickness of the lowest grid box (to avoid the new pressure gradient difficulties inherent in laterally varying vertical locations for tracer fields). It would be useful to adjust the coding to permit arbitrarily thick BBLs – although this has not yet been an issue under normal parameter values.

(e) Campin and Goose (1999)

Following the initial increase towards what might be termed pseudo-realistic BBL models, *Campin and Goose* (1999) deliberately turned to a much simpler formulation. They argued that climate models were likely to remain coarse resolution for the foreseeable future, and it was these models that gave the worst representation of downslope flows (partly due to resolution of sills and straits). They set out a formulation purely for downslope flows in poorly resolved areas (ignoring the BBL otherwise): if density at top of a step, or on a shelf,

is higher than that at the same level in a neighbouring deeper water cell, then an additional fluid transport in a closed cell is induced. (The entire bottom grid box is assumed to belong to the BBL.) The flux involved is proportional to the difference between densities at shelf level. This transport takes a proportion of the dense water out of its cell, laterally into the neighbouring cell, then vertically downwards until a level of denser water is located (or the bottom if one is not found). A return flux, conserving mass, is then induced upwards through the column back to the neighbouring cell, and then returned laterally to the original (dense) cell. An upwind advection is used, since the smoothing involved seems appropriate to the lack of topographic detail present in the models.

The formulation induces sinking in physically sensible locations and improves model reproduction of deep global density fields in a 3° model, but has no effect on the large errors present in more shallow density fields.

(f) Nakano and Sugimoto (2002)

These authors took *Gnanadesikan's* (unpublished) formulation and tested it globally, with some adaptations. First, a third-order accurate tracer advection was employed, much reducing numerical diffusion (a problem especially near overflows in BBL models). The authors found that background horizontal diffusion in the BBL caused warm waters on the shelf south of Iceland to be mixed with overflow waters lying one gridpoint to the west, since these points are neighbours in the BBL. (*Nurser et al.*, 2000, to be discussed later, found the same problem.) Any residual numerical noise in the BBL cells was assumed to be “suppressed vertically”, presumably through convection into the BBL.

Nakano and Sugimoto (2002) found that on a global basis the pressure gradient error in *Gnanadesikan's* (unpublished) scheme generated unphysical flows, and so they chose not to use the scheme in most of the world ocean. The area which included the BBL was limited to N of 49°N, and S of 54°S. While a good pragmatic solution, it is clear that this is not an ideal solution to the difficulties.

A 1° × 1° ocean model was then tested, using a high value of linear drag in the BBL, with a separate control run without a BBL formulation. (The authors showed that results including a *Gent and McWilliams*, 1990, eddy parameterisation yielded unphysical solutions unless the BBL was included; in general, the interactions between BBL and other parameterisations remains unexplored.) The presence of the BBL reduced the warming bias common in coarse resolution global models.

(g) Nurser et al. (2000)

In an attempt to alleviate the sigma-coordinate pressure gradient problem, Nurser et al. (2000) took the Killworth and Edwards (1999) scheme and made two changes. The first was to use an ‘upwind’ scheme for the pressure gradient, which tends to slow down light waters moving downslope (and is energetically consistent with upwind tracer differencing). Additional terms to handle compressibility (i.e., a complete equation of state) were also included. The new formulation was tested in a 1° global model (thus disproving Nakano and Sugimoto’s (2002) claim that the scheme was too expensive to use in a global model!).

The effects of the new scheme were dramatic. Hitherto, pressure gradient errors were mostly visible at the equator, where they cannot be concealed by small erroneous geostrophic flows around topography. In the case of the original Killworth and Edwards (1999) code, equatorial flow speeds increase monotonically with time, as do bottom temperatures, until unrealistic values are attained. The fields are also highly noisy. With the Nurser et al. (2000) pressure gradient, the flows are physically realistic and smooth.

However, many difficulties remain. As in Nakano and Sugimoto’s (2002) work, there is excessive quasi-horizontal diffusion between neighbouring BBL cells at widely differing depths, causing mixing in outflows of the kind that BBL codes were designed to alleviate. More accurate advection schemes are under investigation.

(h) Legutke and Maier-Reimer (2002)

These authors used a formulation for a coarse-resolution model which had similarities to both Beckmann and Döscher (1997) and Campin and Goose (1999). The exchange of properties was formulated as a diffusive rather than an advective process, with a strength inversely proportional to the number of possible pathways for the BBL to take. Again, an improvement in water mass structure was found, with the density of the deep and bottom waters increased in all three basins when the parameterisation was included. However, the BBL scheme did not have a strong impact on the general circulation and did not strengthen the N. Atlantic overturning (mainly since the strait exchanges were weakened by the reduction in pressure gradient caused by the scheme).

(i) Papadakis, Chassignet and Hallberg (2003)

The methods discussed so far have invariably treated the BBL as a unidimensional slab, rather in the spirit of atmospheric boundary layer models before adequate

resolution was available with the growth of modern computers. Another approach entirely would be to attempt to resolve not only the BBL but also to represent some of the turbulent diffusive processes within it. A sigma-coordinate model certainly permits resolution within the BBL, and schemes have been enunciated for this purpose (e.g. Song and Haidvogel, 1994); however, there are as ever pressure gradient issues. Papadakis et al. (2003) took a different approach, and sought to resolve the BBL within a model which possesses no pressure gradient difficulties, i.e. an isopycnal model due to Hallberg (2000). They employed a Richardson number dependent diapycnal mixing scheme with a vertical grid which was finely spaced in density, so that the turbulent downflow was well resolved. Outflow characteristics were in good agreement with field observations, including the existence of Meddy formation.

Nonetheless, the study leaves open the question of how poorly resolved outflows (e.g., the Denmark Strait in most isopycnal models) would be handled in practice.

How might we compare BBL parameterisations?

Researchers can choose to compare parameterisations in two ways: a comparison with data, and an intercomparison. Both approaches have merit. Data comparisons are difficult, since there are certainly insufficient data available in quiescent, relatively flat, areas. Indeed, the majority of data are only in downflow and overflow regions, so that any tuning of parameterisations based on data may be biased in favour of such areas.

DOMÉ (Dynamics of Mixing and Entrainment) is an unfunded international intercomparison exercise involving a large group of interested researchers³. DOMÉ is examining three levels of intercomparison: process studies, realistic local emulation, and global simulations.

(a) process studies

The studies have concentrated on an apparently simple problem: outflow from a reservoir onto a slope (cf. Fig. 6). This is an adapted version of the problem used by Killworth and Edwards (1999) and Song and Chao (2000). The ‘correct’ answer is here deemed to be a very fine resolution σ -coordinate run, as yet not carried out. The initial design configuration calls for a finite barotropic inflow (compensated by a gradual free-surface change in the flow above the slope). In practice, it has proven difficult to set up the non-zero inflow satisfactorily.

³cf. <http://www.rsmas.miami.edu/personal/tamay/DOME>

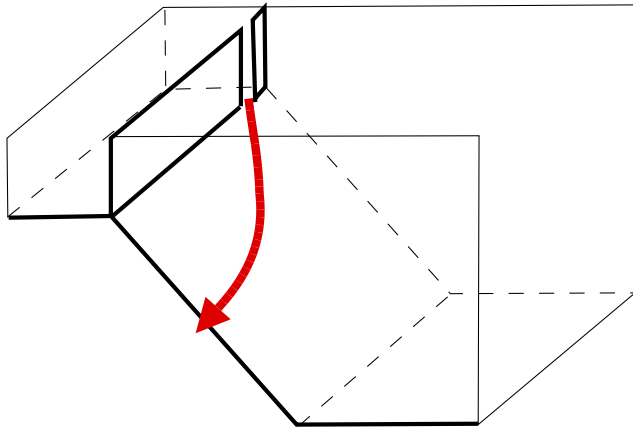


Figure 6. Schematic of the problem used in DOME intercomparisons.

(b) realistic local emulation

This has aimed at simulating, on the gyre scale or more locally, outflows such as Denmark Strait and Gibraltar. There is a variety of data available for testing purposes, raising the question of what is an optimal set of quantities for a comparison: e.g., velocity, tracers, or the path of the outflow. There is a good argument for looking at the path, since this is relatively easy to observe even from relatively coarsely spaced T-S data, and it also has implications about term balances.

An example of this, using streamtube concepts, is given by *Killworth* (2001) and *Girton and Sanford*, 2003, unpublished ms.⁴. Resolving the term balance along the flow of a streamtube removes the Coriolis force, leaving a frictional balance

$$g' |\nabla D| \theta = \frac{C_D u^2}{h}. \quad (3)$$

Here D is the fluid depth, C_D is a quadratic drag coefficient, h a measure of the thickness of the streamtube, and θ the angle the flow makes with the along-slope direction. *Girton and Sanford* (2003, unpublished ms) use this to estimate C_D from data (about 3×10^{-3}). However, combining this with *Zilitinkevich and Mironov* (1996) formula (2), and assuming the second term dominates, gives

$$\frac{u^2}{gh} = \frac{1}{C_i^2 C_D} \quad (4)$$

or a “fixed Froude number” for outflow, $O(1)$. Inserting this in (3) yields an expression for the rate of descent

of the plume

$$\frac{dz}{ds} = |\nabla D| \theta = C_D \frac{u^2}{gh} = \frac{1}{C_i^2}. \quad (5)$$

Here z is depth and s is an along-stream coordinate. *Killworth* (2001) found good agreement with *Baringer and Price* (1997) for the Mediterranean outflow, using the *Zilitinkevich and Mironov* (1996) value $C_i = 20$ (yielding a rate of descent = $1/400$).

Girton and Sanford (2003, unpublished ms), however, note that this value does not agree with rate-of-descent data for the Denmark Strait overflow, needing a descent rate of about 0.006. However, “simply” changing C_i from 20 to 13 (recall that *Zilitinkevich and Mironov*, 1996, were uncertain of its value between 5 and 20) gives a perfect fit to data. Are the data (and the parameterisations) capable of really distinguishing the difference between these values, given that a globally uniform value for a parameter would be far preferable?

The data may not yet be adequate for this purpose. Consider changing C_i to 13 in *Killworth’s* (2001) fit to the Gibraltar outflow (Fig. 7). The predicted depth changes are almost within the lower depth boundary observed by *Baringer and Price* (1997), so that an argument might be made that a uniform value of C_i gives a reasonable fit to data from both regions. Another line of argument would be that the Denmark Strait flow is sufficiently rapid that it has not reached turbulent equilibrium yet, but this is unsatisfactory since it negates the point of a parameterisation based on equilibrium statistics.

At all events, it is clear that researchers must avoid simply retuning parameterisations without improving the physics upon which they are based.

(c) global simulations

The examples given above comprise the sole global simulations to date. Global intercomparisons are clearly necessary to determine the role of the BBL in setting water mass properties. However, the *Dengg et al.* (1999) simulation shows the necessity to have a good model *ab initio*. For example, any BBL parameterisation will fail to give convincing Denmark Strait downflows if insufficiently dense water is formed north of the Denmark Strait. Thus adjusted surface flux fields are frequently employed in order to ensure an adequate supply of dense water in such locations.

Discussion: the future

This review is likely to remain up to date for only a short period, as other BBL improvements, and interactions with other aspects of model physics, are in-

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⁴cf. <http://ohm.api.washington.edu/~girton/working/paper/plume.pdf>

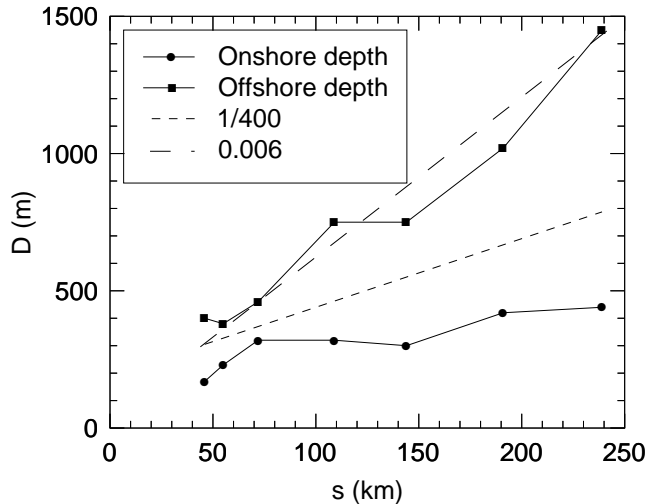


Figure 7. Fit of uniform Froude number model to the Gibraltar outflow. The lines with symbols are the onshore and offshore depth observed by *Baringer and Price* (1997). The short dashed line is *Killworth's* (2001) fit to the depth predicted by (5) with $C_i = 20$; the long dashed line uses $C_i = 13$, which gave a better fit for the Denmark Strait overflow.

cluded and tested. However, no BBL ‘slab’ parameterisation can hope to compete with a model that resolves the BBL properly, assuming adequate physics within the layer. Atmospheric modellers struggled with ‘slab’ BBLs until the resolution became available to resolve the layer. There is no substitute for resolution! It is hard to see how this can be achieved with a z -coordinate ocean model. Clearly an s -type coordinate, or arbitrary vertical co-ordinate would resolve the issue, at the cost of pressure gradient errors. A density coordinate, as argued above, together with a good turbulent mixing scheme, can produce excellent results locally, but without really fine density layers it is probably not a global solution. Thus no model yet appears ideal for resolving the BBL properly, so that a ‘slab’ approach may be necessary for the near future.

Parameterisations to date have been designed solely for overflow and downslope regions; we must be aware that such parameterisations may not work well in passive, quiescent regions. Most parameterisations adopted have been (predictably) those which are cheap and/or easy to include. It may well be that there is no need to appeal to a complicated and computationally expensive parameterisation when a cheap one will suffice, since the latter still contains a representation of most of the physical effects. Strict intercomparisons, using the best available model for embedding the possible parameterisations, will be necessary not only to decide between

competing methods, but also to determine the impact of the BBL on global models.

A useful test will be to examine whether a parameterisation gives good results for quantities which it was not designed to handle. For example, *Doney and Hecht* (2002) find only small improvements in their modelled CFC distributions due to the inclusion of a simple BBL, and felt that at present other effects were more important.

Thus BBL modelling is at an extremely sensitive time in its development, and the key question remains:

Could we as yet distinguish between a complicated and a simple parameterisation? Or are the differences subtle enough to be swamped by other effects, e.g. improvements to surface forcing data?

References

- Armi, L., and R. C. Millard, The bottom boundary layer of the deep ocean. *J. Geophys. Res.*, *81*, 4983-4990, 1976.
- Baringer, M. O., and J. F. Price, Mixing and spreading of the Mediterranean Outflow. *J. Phys. Oceanogr.*, *27*, 1654-1677, 1997.
- Beckmann, A., and R. Döscher, A method for improved representation of dense water spreading over topography in geopotential-coordinate models. *J. Phys. Oceanogr.*, *27*, 581-591, 1997.
- Campin, J. M., and H. Goosse, Parameterization of density-driven downsloping flow for a coarse-resolution ocean model in z -coordinate. *Tellus*, *51*, 412-430, 1999.
- Deardorff, J. W., Parameterization of the planetary boundary layer for use in general circulation models. *Mon. Wea. Rev.*, *100*, 93-106, 1972.
- Dengg, J., C. Böning, U. Ernst, R. Redler, and A. Beckmann, Effects of an improved model representation of overflow water on the subpolar North Atlantic. *International WOCE Newsletter*, no. 37, 1999.
- Doney, S., and M. W. Hecht, Antarctic bottom water formation and deep-water chlorofluorocarbon distributions in a global ocean climate model. *J. Phys. Oceanogr.*, *32*, 1642-1666, 2002.
- Döscher, R., and A. Beckmann, Effects of a bottom boundary layer parameterization in a coarse-resolution model of the North Atlantic Ocean. *J. Atm. Ocean. Tech.*, *17*, 698-707, 2000.
- Gent, P. R., and J. C. McWilliams, Isopycnal Mixing in Ocean Circulation Models. *J. Phys. Oceanogr.*, *20*, 150-155, 1990.
- Girton, J. B., T. B. Sanford, and R. H. Käse, Synoptic sections of the Denmark Strait Overflow. *Geophys. Res. Lett.*, *28*, 1619-1622, 2001.
- Haidvogel, D. B., and A. Beckmann, Numerical ocean

- circulation modeling, London: Imperial College Press, 318 pp, 1999.
- Hallberg, R., Time integration of diapycnal diffusive and Richardson number dependent mixing in isopycnal coordinate ocean models. *Mon. Wea. Rev.*, *128*, 1402-1419, 2000.
- Jungclaus, J. H., and J. O. Backhaus, Application of a transient reduced gravity plume model to the Denmark Strait overflow. *J. Geophys. Res.*, *99*, 12375-12396, 1994.
- Killworth, P. D., Mixing on the Weddell Sea continental slope. *Deep-Sea Res.*, *24*, 427-448, 1977.
- Killworth, P. D., On the rate of descent of outflows. *J. Geophys. Res.*, *106*, 22267-22275, 2001.
- Killworth, P. D., and N. R. Edwards, A turbulent bottom boundary layer code for use in numerical ocean models. *J. Phys. Oceanogr.*, *29*, 1221-1238, 1999.
- Lane-Serff, G. F., and P. G. Baines, Eddy formation by overflows in stratified water. *J. Phys. Oceanogr.*, *30*, 327-337, 2000.
- Legutke, S., and E. Maier-Reimer, The impact of a downslope water-transport parameterization in a global ocean general circulation model. *Clim. Dyn.*, *18*, 611-623, 2002.
- MacCready, P., and G. Pawlak, Stratified flow along a corrugated slope: separation drag and wave drag. *J. Phys. Oceanogr.*, *31*, 2824-2839, 2001.
- MacCready, P., and P. B. Rhines, Slippery bottom boundary layers on a slope. *J. Phys. Oceanogr.*, *23*, 5-22, 1993.
- McPhee-Shaw, E. E., and E. Kunze, Boundary layer intrusions from a sloping bottom: a mechanism for generating intermediate nepheloid layers. *J. Geophys. Res.*, *107*, 10.1029/2001JC000801, 2002.
- Mellor, G., Oscillatory bottom boundary layers. *J. Phys. Oceanogr.*, *32*, 3075-3088, 2002.
- Nakano, H., and N. Sugimotohara, Effects of bottom boundary layer parameterization on reproducing deep and bottom waters in a world ocean model. *J. Geophys. Res.*, *32*, 1209-1227, 2002.
- Nof, D., N. Paldor, and S. Van Gorder, The Reddy maker. *Deep-Sea Res.*, *49*, 1531-1549, 2002.
- Nowell, A. R. M., C. D. Hollister, and P. A. Jumars, High Energy Benthic Boundary layer Experiment: HEBBLE. *EOS*, *63*, 594-595, 1982.
- Nurser, A. J. G., P. D. Killworth, and S. G. Alderson, A new approach to the sigma-coordinate pressure gradient problem in a terrain-following bottom boundary layer model. *International WOCE Newsletter*, No. 39, 2000.
- Papadakis, M. P., E. P. Chassignet and R. W. Hallberg, Numerical simulations of the Mediterranean sea outflow: impact of the entrainment parameterization in an isopycnal coordinate ocean model. *Ocean Model.*, in press, 2003.
- Polzin, K. L., J. M. Toole, J. R. Ledwell, and R. W. Schmitt, Spatial variability of turbulent mixing in the abyssal ocean. *Science*, *276*, 93-96, 1997.
- Price, J. F., and M. O. Baringer, Outflows and deep water production by marginal seas. *Progr. Oceanogr.*, *33*, 161-200, 1994.
- Roberts, M. J., and R. A. Wood, Topography sensitivity studies with a Bryan-Cox type ocean model. *J. Phys. Oceanogr.*, *27*, 823-836, 1997.
- Rossby, C. G., and R. B. Montgomery, The layer of frictional influence in wind and ocean currents. *Pap. Phys. Oceanogr. Meteorol.*, *3*, 1-101, 1935.
- St. Laurent, L., and C. Garrett, The role of internal tides in mixing the deep ocean. *J. Phys. Oceanogr.*, *32*, 2882-2899, 2002.
- Smith, P. C., A streamtube model for bottom boundary currents in the ocean. *Deep-Sea Res.*, *22*, 853-873, 1975.
- Song, Y. T., and Y. Chao, An embedded bottom boundary layer formulation for z-coordinate ocean models. *J. Atm. Ocean. Tech.*, *17*, 546-560, 2000.
- Song, Y. T., and D. B. Haidvogel, A semi-implicit ocean circulation model using a generalized topography-following coordinate system. *J. Comput. Phys.*, *115*, 228-244, 1994.
- Song, Y. T., and D. Wright, A general pressure gradient formulation for ocean models. Part II: Energy, momentum, and bottom torque consistency. *Mon. Wea. Rev.*, *126*, 3231-3247, 1998.
- Zilitinkevich, S., and D. V. Mironov, A multi-limit formulation for the equilibrium depth of a stably stratified boundary layer. *Bound.-Lay. Meteorol.*, *81*, 325-351, 1996.

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