

## ***Interactive comment on “Formulation of an ocean model for global climate simulations” by S. M. Griffies et al.***

**S. M. Griffies et al.**

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We thank the reviewer for the many useful comments. They have been incorporated into the revised draft, and we detail here how we have done so.

- **p176, lines 15-20:** We agree that in many cases the development of realistic topography, especially with older models, can be influenced by numerical instability considerations. We have added the following paragraph to raise this issue and to highlight the improved situation relative to older models.

Before leaving the discussion of model topography, we note that in many global models from previous generations, additional numerical considerations prominently weighed in the development of a suitable topography. For example, in the commonly used rigid lid models [Bryan(1969)], steep topography could initiate a numerical instability described by [Killworth(1987)], thus prompting modellers to artificially smooth ocean bathymetry. The computational cost of computing is-

land boundary conditions (the *island integrals* arising in the rigid lid method) also prompted modellers to sink most islands in the World Ocean. Additional concerns arose from large dispersion errors contributing to unphysical tracer extrema next to rough topography, with these extrema especially prominent with second order centered advection schemes [Griffies et al.(2000)]. Fortunately, these concerns are absent in the present model. Namely, the use of a free surface algorithm (Section 3.1) removes the rigid lid topographic instabilities and costly island integrals. The use of partial step topography (Figure 4), and higher order dissipative tracer advection (Section 2.7) both reduce the presence of spurious tracer extrema.

- **p177, lines 19-23:** Based on comments from Reviewer 1, in particular reference to the work of [Tang and Roberts(2005)], we have refined this discussion, pointing to the new possibility that our implementation of *only* the diffusive portion of the [Beckmann and Döscher(1997)] scheme may have been a contributor to the lack of sensitivity seen in our model. We therefore feel this discussion should maintain its present length in order to fully document our experiences in this critical area of ocean climate modelling.
- **p179, lines 20-25:** As noted in reference to comments from Reviewers 1 and 2, we have enhanced the discussion of tracer advection to now include more comments on the diffusive nature of the chosen advection scheme. We do feel, however, that a complete discussion of the shape preserving aspects of the scheme must rely on the various references provided in the text.
- **p183, lines 17-22:** We agree. We note that the editor also made this comment. Very few ocean climate models have thus far included double diffusive processes, so it is important that details be clearly exposed. We have thus added the following discussion, taken from another draft of the manuscript perhaps seen by the reviewer.

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Interior mixing in the ocean model is enhanced by double diffusion due to salt fingering and diffusive convection. These processes occur in regions where the vertical temperature and salinity gradients have the same sign, and so contribute oppositely to the vertical density gradient<sup>1</sup> (for discussions of these processes, see [Schmitt(1994)], [Laurent and Schmitt(1999)], [Toole and McDougall(2001)], and [Kantha and Clayson(2000)]). We follow the recommendation of [Large et al.(1994)] for the parameterization of diffusive convection (see their equation (32)), yet take the alternative parameterization of double diffusion<sup>2</sup> given by  $\kappa_{\theta} = \kappa^{\text{other}} + 0.7 \kappa_{dd}$

$$\kappa_s = \kappa^{\text{other}} + \kappa_{dd}$$

$\kappa_{dd} = \kappa_{dd}^0 \left[ 1 - \frac{R_{\rho}-1}{R_{\rho}^0-1} \right]^3$ , where  $\kappa^{\text{other}}$  is a diffusivity arising from mixing processes other than double diffusion,  $\kappa_{dd}^0 = 10^{-4} \text{ m}^2 \text{ s}^{-1}$ , and  $R_{\rho}^0 = 1.9$ . This formulation is applied so long as  $1 < R_{\rho} < R_{\rho}^0$ . A similar parameterization was used by [Danabasoglu et al.(2005)] in the recently developed Community Climate System Model, but with  $R_{\rho}^0 = 2.55$ . They reported a minor sensitivity of mixed layer depths to the inclusion of double diffusion (deepening of mixed layers by less than a metre). Limitations in time and resources prevented us from performing careful sensitivity tests in the GFDL model.

- **p195, lines 6-10:** We agree with the reviewer that some may argue for there not to be a relation between the neutral diffusivity and skew diffusivity. However, there are others, such as [Dukowicz and Smith(1997)], who argue theoretically for the coefficients to be the same. We also note that taking the values to be the

<sup>1</sup>Double diffusion occurs when warm and salty water overlies cold and fresh water (e.g., subtropical and tropical thermoclines). That is, where  $\alpha_{\theta,z} > 0$ ,  $\beta_{s,z} > 0$ ,  $1 < R_{\rho} < R_{\rho}^0$ , and  $R_{\rho}^0$  roughly equal to 2. Here,  $\alpha = -\partial_{\theta} \ln \rho$  is the thermal expansion coefficient,  $\beta = \partial_s \ln \rho$  is the saline contraction coefficient, and  $R_{\rho} = \alpha_{\theta,z} / \beta_{s,z}$  is the density ratio. Diffusive convection occurs primarily in Arctic and adjacent regions with cold and fresh water over warm and salty water. That is, where  $\alpha_{\theta,z} < 0$ ,  $\beta_{s,z} < 0$  and  $1 < R_{\rho} < 1$ .

<sup>2</sup>Recommended to us by Bill Large, 2004, personal communication.

same has been the common choice in the literature. We thus think it important to raise this issue in the present discussion. It is not clear from a fundamental perspective what to do, and we hope that by highlighting this issue, research may ensue to clarify the issue.

Physical arguments for taking the coefficients to be the same concern the following. Ocean mesoscale eddies slump isopycnals as they reduce potential energy of the flow, thus connecting the skew-diffusivity to the strength of mesoscale eddies. In addition, these same eddies act to mix tracer concentration *within* density classes, and this process is parameterized by neutral diffusion. Hence, it is argued that the strength of neutral diffusion is a function of the strength of the same mesoscale eddies acting to slump the isopycnals. If the strength of the diffusive component of the mesoscale eddies dominates the diffusive mixing arising from sub-mesoscale processes (e.g., breaking gravity waves), then the neutral diffusivity can be taken roughly the same as the skew-diffusivity.

- **p195, lines 22-25:** Tapering in the model occurs for two reasons: (1) if the neutral slope  $S$  is greater than  $1/500$ , (2) if the depth of a grid point is shallower than  $SR$ , with  $R$  an approximation to the first baroclinic Rossby radius. The second tapering method was detailed in Appendix B of [Large et al.(1997)]. We hope our discussion, albeit brief, is sufficient in combination with the more detailed discussion in [Large et al.(1997)].
- **p196, lines 19-25:** We are preparing a follow-up study [Gnanadesikan et al.(2005)] to further clarify the issue of maximum slope parameter. In particular, we argue more fully in the new manuscript that  $1/500$  is better than  $1/100$  for our climate model simulations. Nonetheless, prompted by comments from the editor, we have enhanced the discussion in this section to now read as follows.

Our choice of  $1/500$  for the “maximum slope” parameter  $S_{max}$  is smaller than

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the more commonly used  $1/100$  [Cox(1987)], and much less than the  $3/10$  used by [Danabasoglu et al.(2005)]. Our reasoning for choosing this value is as follows. Namely, the diffusivity times the maximum slope represents a maximum volume flux associated with the [Gent and McWilliams(1990)] parameterization. This product determines an upper limit on what parameterized eddies can do in countering wind-driven Ekman fluxes. Given that Ekman volume fluxes are of order  $1\text{m}^2\text{s}^{-1}$ , we chose not to let the parameterized fluxes greatly exceed this value. The maximum skew diffusivity used in OM3 experiments is  $600\text{m}^2\text{s}^{-1}$ , which motivated taking a maximum slope on the order of  $1/500$  rather than the larger  $1/100$ .

The specific choice for the maximum slope is important especially in regions such as the Southern Ocean, where the simulation is sensitive to neutral physics details. We illustrate this sensitivity by considering the mixed layer depth. Figures 13a and 13b show mixed layer depth differences between a run with  $S_{max}=1/100$  and another with  $S_{max}=1/500$ . The smaller  $S_{max}$  simulation generally results in decreased mixed layer depth, particularly in the Southern Hemisphere mode water formation regions and in the Labrador Sea. This behaviour illustrates how details in the neutral physics parameterization interact with the mixed layer, and thus can have a nontrivial impact on the potential vorticity structure of the mode and intermediate waters. Further discussion of this topic is given in [Gnanadesikan et al.(2005)].

- **p198, lines 21-25:** Reducing neutral physics to horizontal diffusion near the upper boundary is physically motivated by the work of [Treguier et al.(1997)]. Near the solid wall boundaries, we believe the enhanced levels of physical mixing warrant some increased diapycnal mixing in these regions. The use of horizontal diffusion at the box just next to the solid walls aims to respect this physical process. But it certainly does so in an *ad hoc* manner, with potentially too much diapycnal mixing introduced. We are not proud of this part of the parameteriza-

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tion, and will aim to remove this element in future studies.

- **182, line 26:** *equatorial* has been replaced with *equatorward*. We believe the use of *equatorial* is correct on p183, line 1.
- *jettisoned* has been replaced by *eliminated*, and *guts* has been replaced by *inner workings*.
- We prefer the symbol  $\nabla_z$  to denote horizontal gradient on constant z-surfaces. This usage is consistent with the commonly used  $\nabla_\rho$  to denote lateral gradient on constant  $\rho$ -surfaces, and more generally  $\nabla_s$  for lateral gradient on constant  $s$ -surfaces.

## References

- [Beckmann and Döscher(1997)] Beckmann, A. and Döscher, R.: A method for improved representation of dense water spreading over topography in geopotential-coordinate models, *Journal of Physical Oceanography*, 27, 581–591, 1997.
- [Bryan(1969)] Bryan, K.: A numerical method for the study of the circulation of the world ocean, *Journal of Computational Physics*, 4, 347–376, 1969.
- [Cox(1987)] Cox, M. D.: Isopycnal diffusion in a  $z$ -coordinate ocean model, *Ocean Modelling*, 74, 1–5, 1987.
- [Danabasoglu et al.(2005)] Danabasoglu, G., Large, W., Tribbia, J., Gent, P., Briegleb, B., and McWilliams, J. C.: Diurnal ocean-atmosphere coupling, *Journal of Climate*, submitted, 2005.
- [Dukowicz and Smith(1997)] Dukowicz, J. K. and Smith, R. D.: Stochastic theory of compressible turbulent fluid transport., *Physics of Fluids*, 9, 3523–3529, 1997.

- [Gent and McWilliams(1990)] Gent, P. R. and McWilliams, J. C.: Isopycnal mixing in ocean circulation models., *Journal of Physical Oceanography*, 20, 150–155, 1990.
- [Gnanadesikan et al.(2005)] Gnanadesikan, A., Griffies, S., and Samuels, B.: How the representation of eddy-driven advection affects climate in a coupled model, *Ocean Modelling*, in prep, 2005.
- [Griffies et al.(2000)] Griffies, S. M., Pacanowski, R. C., and Hallberg, R. W.: Spurious diapycnal mixing associated with advection in a  $z$ -coordinate ocean model, *Monthly Weather Review*, 128, 538–564, 2000.
- [Kantha and Clayson(2000)] Kantha, L. H. and Clayson, C. A.: *Small Scale Processes in Geophysical Fluid Flows*, Academic Press, New York, USA, 883 pp, 2000.
- [Killworth(1987)] Killworth, P. D.: Topographic instabilities in level model OGCM's, *Ocean Modelling*, 75, 9–12, 1987.
- [Large et al.(1994)] Large, W. G., McWilliams, J. C., and Doney, S. C.: Oceanic vertical mixing: A review and a model with a nonlocal boundary layer parameterization, *Reviews of Geophysics*, 32, 363–403, 1994.
- [Large et al.(1997)] Large, W. G., Danabasoglu, G., Doney, S. C., and McWilliams, J. C.: Sensitivity to surface forcing and boundary layer mixing in a global ocean model: annual-mean climatology, *Journal of Physical Oceanography*, 27, 2418–2447, 1997.
- [Laurent and Schmitt(1999)] Laurent, L. C. S. and Schmitt, R.: The contribution of salt fingers to vertical mixing in the North Atlantic tracer release experiment, *Journal of Physical Oceanography*, 29, 1404–1424, 1999.
- [Schmitt(1994)] Schmitt, R. W.: Double diffusion in oceanography, *Annual Review of Fluid Mechanics*, 26, 255–285, 1994.

[Tang and Roberts(2005)] Tang, Y. and Roberts, M.: The impact of a bottom boundary layer scheme on the North Atlantic Ocean in a global coupled climate model, *Journal of Physical Oceanography*, 35, 202–217, 2005.

[Toole and McDougall(2001)] Toole, J. M. and McDougall, T. J.: Mixing and stirring in the ocean interior, in *Ocean Circulation and Climate: Observing and Modelling the Global Ocean*, edited by G. Siedler, J. Gould, and J. Church, pp. 337–356, Academic Press, 2001.

[Treguier et al.(1997)] Treguier, A. M., Held, I. M., and Larichev, V. D.: On the parameterization of quasi-geostrophic eddies in primitive equation ocean models, *Journal of Physical Oceanography*, 27, 567–580, 1997.

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