Ocean Science Discussions, 2, S127–S135, 2005
www.ocean-science.net/osd/2/S127/
European Geosciences Union

Ocean Science Discussions

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

S. M. Griffies et al.

Received and published: 2 August 2005

- 2.3.2 Time stepping

  We fully agree with the reviewer in that this section has problems. We made the mistake of trying to be too brief. The result is a somewhat confusing presentation. In particular, we failed to articulate the central reason motivating our investigation of alternative time stepping schemes, which is to employ a scheme allowing for precise tracer conservation. Additionally, our language was sloppy in places (e.g., *stability* and *leap frog*).

  Our use of the word *new* to sometimes refer to the modified time stepping method used in OM3.1 is misleading. It is indeed new for MOM, but it is not new to a broader community. As noted in the manuscript, the time stepping schemes used in the Hallberg Isopycnal Model [Hallberg(1997)] and the MITgcm [Marshall et al.(1997), Campin et al.(2004)] share many of the features of the time staggered scheme used in OM3.1. And as noted by

the reviewer, these issues are not new to the literature, as they have been treated by [Mesinger and Arakawa(1976)], [Haltiner and Williams(1980)], and [Durran(1999)]. We have therefore corrected this usage of the term *new*.

Relatedly, we have added [Mesinger and Arakawa(1976)] to the citations in the manuscript. This is a seminal reference and it describes many issues that we consider in our manuscript. We have also given many references to the lucid textbook by [Durran(1999)]. This is our primary reference for the time stepping methods described in the manuscript.

As a result of the comments from the reviewer, we have rewritten this section and believe it addresses the reviewer's concerns as well as clarifies many issues. We now respond in detail to the reviewer comments.

1. Use of the term *leap frog*

   We agree that it is a mis-representation of the various time stepping methods to say that a model is a *leap frog model*. As emphasized by the reviewer, different portions of the primitive equations require different treatment. We have therefore refined our usage of the term *leap frog* to refer just to the use of a central second order time differencing for the time tendency. We have also reviewed the time stepping methods required for different terms in the tracer and velocity equations. This treatment allow us to better highlight motivation for using certain methods in the OM3.0 and OM3.1 simulations. In particular, we have corrected the discussion of implicit vertical mixing to reflect its use for allowing the inclusion of fast vertical mixing processes in the model.

2. Time label on equation (8)

   This equation is not wrong *if* one chooses, as we do, to use an upwind biased tracer advection scheme such as the Sweby scheme. Nonetheless, we have modified the time step labels for this term to reflect the more general

OSD

2, S127–S135, 2005

possibility that it is evaluated at the τ, $\tau - 1$, or both time steps. The τ time step is needed for central differences, both time steps are used for Quicker, and $\tau - 1$ is needed for Sweby.

3. Where is Sect 19?

   The reference to Sect 19 is spurious. Our best guess is that is was introduced during the translation by the technical editors of our submitted document into the web document. The correct reference is to Section A.2 in the appendix.

4. Stability

   We have endeavoured to correct the usage of *stability* in the revisions. For example, instead of saying the time staggered scheme is *twice as stable* as the standard scheme, we now say its time step can be doubled.

5. Coriolis force

   We have new better highlighted the treatment of the Coriolis force both in the main time stepping section, and in the appendix. We were led to the *trapezoidal* or *semi-implicit* treatment of the Coriolis force for *both* the OM3.0 and OM3.1 models. The reason relates to an incompletely understood inertial-like instability encountered in the Arctic related to ocean and sea ice coupling. When using the standard leap frog for the Coriolis force in OM3.0, the model exhibited instabilities (e.g., blow ups) that were readily eliminated by switching to the trapezoidal method. We now emphasize that switching to a forward time step for the velocity tendency *necessitates* a trapezoidal or fully implicit treatment of the Coriolis force. This requirement represents a limitation for many model uses. For our purposes, however, the choice to use trapezoidal was made for other reasons and so it presented no added restriction.

6. A restriction to upwind biased advection

OSD

2, S127–S135, 2005

We now raise the issue of advection more visibly in the revisions. In particular, the motivation for using the upwind biased Sweby scheme has nothing to do with the switch to a forward time stepping scheme. Instead, it has to do with our desire to reduce spurious extrema, and to reduce the levels of spurious convection arising from dispersion errors in the central differenced advection scheme. These points are clarified in the revised manuscript.

Thus, the use of a forward difference for the time tendency, just as for Coriolis force, did not introduce new restrictions to our methods used for the climate model. The forward difference does, however, present new restrictions to other users who may feel that alternative methods are suitable for their purposes.

7. Time stepping supported in MOM4

   As an aside, we note that the latest version of MOM4 maintains the ability to employ *both* the standard time stepping scheme and the staggered scheme. It is because of the restrictions noted above that we decided to allow the user community to make the decision themselves regarding their choice. However, many new model develpment efforts are moving away from the leap frog for the time tendency. In particular, layered modellers *must* employ monotone advection schemes for advecting layer thickness, and such schemes are generally upwind biased. It is therefore natural for them to use forward time differences rather than leap frog.

8. We are not using first order upwind

   As noted above and highlighted in the revised manuscript, we chose to use the upwind biased Sweby scheme for reasons unrelated to our switch to a forward time differencing of the tendency. We use this scheme in both OM3.0 and OM3.1. Our discussion in the manuscript presents the potentials of there being enhanced diffusion associated with the advection scheme. Notably, however, the scheme is third order, not first order. Furthermore, as

OSD

2, S127–S135, 2005

noted in the manuscript, in regions away from river mouths, test runs with the climate model revealed very little distinction between simulations using the third order Quicker scheme and the third order Sweby scheme.

9. A comment regarding leap frog accuracy

   The leap frog scheme is a second order accurate discretization of the time tendency. It furthermore has favorable properties for wave propagation [Mesinger and Arakawa(1976)]. Unfortunately, no ocean model with the leap frog employs it without an *ad hoc* method to suppress the time splitting mode. As described in Section 2.3.5 of [Durran(1999)], these methods degrade the second order leap frog to first order.

10. Did we use extra viscosity or diffusivity?

    We did not add extra viscosity in OM3.1 as a result of changing the time stepping scheme. In contrast, as discussed in Section 3.4, the middle and high latitude horizontal viscosity in OM3.1 is five times smaller than OM3.0. Changes in the neutral diffusivity were made, but for reasons unrelated to the time stepping scheme. These changes are described in Section 3.3.

11. Implicit time stepping

    We agree that the discussion about implicit time stepping for vertical physics is mis-leading, and it is not central to our points in the manuscript. This discussion has therefore been eliminated in the revised draft.

12. Coriolis force again

    As noted above, we have clarified the treatment of the Coriolis force, both for the standard time stepping used in OM3.0 and the alternative in OM3.1.

13. Predictor-corrector dissipative aspects

    We agree that the statements regarding the predictor-corrector dissipation properties are not justified. To address this problem, we have included a short discussion in the appendix which exposes these properties. This material greatly supports the discussion in the main text.

OSD

2, S127–S135, 2005

14. Comments on time stepping schemes: unnecessary

    We agree, this section is unnecessary. It has been eliminated from the revised manuscript.

References

[Bentsen et al.(1999)] Bentsen, M., Evensen, G., Drange, H., and Jenkins, A.: Coordinate Transformation on a Sphere Using Conformal Mapping, Monthly Weather Review, 1267, 2733–2740, 1999.

[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.

[Bryan and Cox(1972)] Bryan, K. and Cox, M. D.: An approximate equation of state for numerical models of the ocean circulation, Journal of Physical Oceanography, 4, 510–514, 1972.

[Campin et al.(2004)] Campin, J.-M., Adcroft, A., Hill, C., and Marshall, J.: Conservation of properties in a free-surface model, Ocean Modelling, 6, 221–244, 2004.

[Coward et al.(1994)] Coward, A., Killworth, P., and Blundell, J.: Tests of a two-grid world ocean model, Journal of Geophysical Research, 99, 22 725–22 735, 1994.

[Deleersnijder et al.(1993)] Deleersnijder, E., Van Ypersele, J.-P., and Campin, J.-M.: An orthogonal curvilinear coordinate system for a world ocean model, Ocean Modelling, 100, 7–10, 1993.

[Durran(1999)] Durran, D. R.: Numerical Methods for Wave Equations in Geophysical Fluid Dynamics, Springer Verlag, Berlin, 470 pp, 1999.

OSD

2, S127–S135, 2005

[Eby and Holloway(1994)] Eby, M. and Holloway, G.: Grid transformation for incorporating the Arctic in a global ocean model, Climate Dynamics, 10, 241–247, 1994.

[Gnanadesikan et al.(2005)] Gnanadesikan, A., Dixon, K. W., Griffies, S. M., Balaji, V., Beesley, J. A., Cooke, W. F., Delworth, T. L., Gerdes, R., Harrison, M. J., Held, I. M., Hurlin, W. J., Lee, H.-C., Liang, Z., Nong, G., Pacanowski, R. C., Rosati, A., Russell, J., Samuels, B. L., Song, S. M., Spelman, M. J., Stouffer, R. J., Sweeney, C. O., Vecchi, G., Winton, M., Wittenberg, A. T., Zeng, F., and Zhang, R.: GFDL's CM2 Global Coupled Climate Models-Part 2: The Baseline Ocean Simulation, Journal of Climate, submitted, 2005.

[Griffies(2004)] Griffies, S. M.: Fundamentals of ocean climate models, Princeton University Press, Princeton, USA, 496 pages, 2004.

[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.

[Hallberg(1997)] Hallberg, R. W.: Stable split time stepping schemes for large-scale ocean modeling, Journal of Computational Physics, 135, 54–65, 1997.

[Haltiner and Williams(1980)] Haltiner, G. T. and Williams, R. T.: Numerical Prediction and Dynamic Meteorology, John Wiley and Sons, New York, USA, 1980.

[Latif et al.(1998)] Latif, M., Anderson, D., Barnett, T., Cane, M., Kleeman, R., Leetmaa, A., O'Brien, J., Rosati, A., and Schneider, E.: A review of the predictability and prediction of ENSO, Journal of Geophysical Research, 103, 14 375–14 393, 1998.

[Madec and Imbard(1996)] Madec, G. and Imbard, M.: A global ocean mesh to overcome the North Pole singularity, CD, 12, 381–388, 1996.

[Marshall et al.(1997)] Marshall, J., Hill, C., Perelman, L., and Adcroft, A.: Hydrostatic, quasi-hydrostatic, and nonhydrostatic ocean modeling, Journal of Geophysical Research, 102, 5733–5752, 1997.

[Marsland et al.(2003)] Marsland, S., Haak, H., Jungclaus, J., Latif, M., and Röske, F.: The Max-Planck-Institute global ocean/sea ice model with orthogonal curvilinear coordinates, Ocean Modelling, 5, 91–127, 2003.

[McDougall et al.(2003)] McDougall, T. J., Jackett, D. R., Wright, D. G., and Feistel, R.: Accurate and computationally efficient algorithms for potential temperature and density of seawater., Journal of Atmospheric and Oceanic Technology, 20, 730–741, 2003.

[Meehl et al.(2001)] Meehl, G., Gent, P. R., Arblaster, J., Otto-Bliesner, B., Brady, E., and Craig, A.: Factors that affect the amplitude of El Niño in global coupled climate models, Climate Dynamics, 17, 515–526, 2001.

[Mesinger and Arakawa(1976)] Mesinger, F. and Arakawa, A.: Numerical Methods used in Atmospheric Models, in GARP Publication Series, vol. 1, p. 66 pages, 1976.

[Murray(1996)] Murray, R. J.: Explicit generation of orthogonal grids for ocean models, Journal of Computational Physics, 126, 251–273, 1996.

[Murray and Reason(2002)] Murray, R. J. and Reason, C. J. C.: A curvilinear version of the Bryan-Cox ocean model, Journal of Computational Physics, 171, 1–46, 2002.

[Roberts et al.(2005)] Roberts, J., Heil, P., Murray, R., Holloway, D., and Bindoff, N.: Pole relocation for an orthogonal grid: an analytic method, Ocean Modelling, accepted, 2005.

[Russell et al.(2005)] Russell, J., Stouffer, R., and Dixon, K.: Intercomparison of the Southern Ocean Circulations in the IPCC Coupled Model Control Simulations, Journal of Climate, submitted, 2005.

[Schneider et al.(2003)] Schneider, E., DeWitt, D., Rosati, A., Kirtman, B., Link, J., and Tribbia, J.: Retrospective ENSO forecasts: sensitivity to atmospheric model and ocean resolution, Monthly Weather Review, 131, 3038–3060, 2003.

[Smith et al.(1995)] Smith, R. D., Kortas, S., and Meltz, B.: Curvilinear coordinates for global ocean models, Los Alamos preprint, LA-UR-95-1146, 1995.

[Wittenberg et al.(2005)] Wittenberg, A., Rosati, A., Lau, G., and Ploshay, J.: Tropical simulations with the recent GFDL coupled climate model, Journal of Climate, submitted, 2005.

Interactive comment on Ocean Science Discussions, 2, 165, 2005.