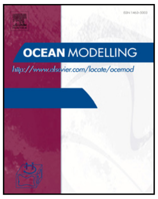
Ocean Modelling 113 (2017) 50–65

Contents lists available at ScienceDirect

Ocean Modelling

journal homepage: www.elsevier.com/locate/ocemod



Vertical resolution of baroclinic modes in global ocean models

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ARTICLE INFO

Article history:
Received 3 November 2016
Revised 3 February 2017
Accepted 19 March 2017
Available online 22 March 2017

Keywords:
Vertical resolution
Baroclinic modal structure
High-resolution global ocean model

ABSTRACT

Improvements in the horizontal resolution of global ocean models, motivated by the horizontal resolution requirements for specific flow features, has advanced modelling capabilities into the dynamical regime dominated by mesoscale variability. In contrast, the choice of the vertical grid remains a subjective choice, and it is not clear that efforts to improve vertical resolution adequately support their horizontal counterparts. Indeed, considering that the bulk of the vertical ocean dynamics (including convection) are parameterized, it is not immediately obvious what the vertical grid is supposed to resolve. Here, we propose that the primary purpose of the vertical grid in a hydrostatic ocean model is to resolve the vertical structure of horizontal flows, rather than to resolve vertical motion. With this principle we construct vertical grids based on their abilities to represent baroclinic modal structures commensurate with the theoretical capabilities of a given horizontal grid. This approach is designed to ensure that the vertical grids of global ocean models complement (and, importantly, to not undermine) the resolution capabilities of the horizontal grid. We find that for *z*-coordinate global ocean models, at least 50 well-positioned vertical levels are required to resolve the first baroclinic mode, with an additional 25 levels per subsequent mode. High-resolution ocean-sea ice simulations are used to illustrate some of the dynamical enhancements gained by improving the vertical resolution of a 1/10° global ocean model. These enhancements include substantial increases in the sea surface height variance (∼30% increase south of 40°S), the barotropic and baroclinic eddy kinetic energies (up to 200% increase on and surrounding the Antarctic continental shelf and slopes), and the overturning streamfunction in potential density space (near-tripling of the Antarctic Bottom Water cell at 65°S).

1. Introduction

Ocean modelling is an exercise in subjective compromise. Model development involves the continual reconfiguration of the three-way balance between those processes deemed essential to resolve, those processes deemed acceptable to parameterize (along with the methods to do so), and finite computational resources. Each model configuration is specifically selected for the intended purpose of the ocean model and the dynamics of interest, and the model output must be interpreted judiciously. Models offer valuable insights into numerous and specific aspects of the ocean's circulation and role in Earth's climate, although the compromises of model design mean that no single model can be a complete description of Earth's ocean.

Evidence of these compromises is perhaps nowhere more apparent than in the selection of spatial resolution (Griffies et al., 2000). The benefits of resolving the smallest length-scales are obvious: the inclusion of all fluid processes with a complete and mature energy cascade permits the exact closure of the energy budget (e.g., Gayen et al., 2013). On the other hand, the computational expense of resolving the smallest length-scales is prohibitive; the computational resources required for direct numerical simulation studies of laboratory scale circulations (O(1) m^3 domain) are comparable with those of modern coupled climate models. Therefore, in order to obtain a useful, manageable ocean model, a line must be drawn as to a minimum dynamically-active length-scale and a model configuration selected. The art of ocean modelling is knowing where to draw this line.

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http://dx.doi.org/10.1016/j.ocemod.2017.03.012
1463-5003/

For the horizontal dimensions, the ubiquity of mesoscale eddies and their profound contributions to the ocean's kinetic energy (e.g., Ducet et al., 2000; Wunsch, 2007; McWilliams, 2008) and general circulation (e.g., Hallberg and Gnanadesikan, 2006; Chassignet and Marshall, 2007; Waterman et al., 2011) provide a natural principal objective for model horizontal grid spacing, and thus, resolution requirements. The rotating and stratified nature of the ocean means that the dominant spatial scales of mesoscale eddies is largely reflected by the first baroclinic Rossby radius of deformation, L_1. Resolving the ocean processes and variability at the L_1-scale extends the dynamical functionality of the model into a regime suitable for short-term forecasting and many operational applications, as well as mesoscale eddy-mean-flow interactions and the associated inverse cascade of energy. Thus, L_1 serves as a convenient target length-scale for the refinement of horizontal resolution, motivating efforts to ensure the horizontal grid spacing is some predetermined fraction of L_1 (e.g., Griffies and Treguier, 2013; Hallberg, 2013).

For the vertical resolution, no equivalent quantifiable principal objective exists. Studies examining the effects of altering vertical resolution demonstrate the fundamental influence it has on ocean circulation (e.g., Adamec, 1988; Weaver and Sarachik, 1990; Barnier et al., 1991), although these efforts are far less mature than their horizontal resolution counterparts. Additionally, there is no obvious indication that a given vertical grid is sufficient for representing the dynamics resolved by the horizontal grid. In other words, there is presently no way to determine whether dynamics that are resolved horizontally can be resolved vertically, meaning the efforts to refine the horizontal resolution up to and beyond the L_1-scale are potentially being undermined by an inadequate vertical grid. Methodologies to ensure consistent vertical and horizontal resolution capabilities exist for atmospheric models (e.g., Lindzen and Fox-Rabinovitz, 1989; Roeckner et al., 2006), however such an approach for ocean models is yet to be formulated. Developing this methodology is the primary motivation for this paper. We aim to ascertain the vertical resolution requirements for ocean models that are based on the theoretical capabilities of the horizontal grid, and to use these requirements to guide the construction of a vertical grid that is at least as good as the horizontal grid.

In order to establish resolution requirements we must first consider the processes that we are attempting to resolve. Vertical velocities throughout the ocean interior ($w \approx$ O(10^{-5}) m s^{-1}) are typically 4–5 orders of magnitude smaller than their horizontal counterparts ($u, v \approx$ O(1) m s^{-1}); this is in part due to constraints imposed by Earth's rotation, the ocean stratification and the ocean's geometrical aspect ratio (Mahadevan, 2006; Thomas et al., 2007). Based on these typical background vertical velocities, maintaining a stable Courant number (C)[1] for horizontal grid spacings aimed at resolving L_1 (Δx, $\Delta y \sim$ O(10) km) calls for a vertical grid with typical spacing no less than Δz of O(10) m. Arguably more dynamically important than the background geostrophic motion are specific, localized vertical flows, such as the rapid diurnal restratification of the surface mixed layer (e.g., Brainerd and Gregg, 1993; Bernie et al., 2005) or the convective sinking of dense overflows, exhibiting velocities reaching upwards of O(10^{-3}) m s^{-1} (e.g., Legg, 2012; Phillips and Bindoff, 2014). A vertical grid that is designed to be numerically stable for the background motions will not be adequate for these vitally important but highly-localized processes (often too localized to be resolved by the horizontal grid).

At present, the standard design of a vertical grid is one where the vertical grid spacing is a function of depth, with fine spacing of O(1–10) m at the ocean surface and coarser spacing of O(100) m below the pycnocline, reflecting the current understanding of the different ocean processes at these depths (e.g., Treguier et al., 1996). Despite this effort to acknowledge the different dynamical regimes, neither the fine surface resolution nor coarse abyssal resolution are adequate for resolving the dominant vertical dynamics at either of these levels, requiring that these processes still be parameterized through enhanced vertical eddy viscosities and diffusivities, convective adjustment, and numerous surface- and bottom-intensified schemes. Indeed, this issue led Griffies and Treguier (2013) to hypothesise: "*Physical parameterizations, more so than vertical coordinates, determine the physical integrity of a global ocean climate simulation.*" That is, the bulk of the oceanic vertical motions are parameterized. Bearing this in mind, we should now have a better sense for *the primary purpose of the ocean vertical grid*: it is not to necessarily resolve the vertical motions, but rather to *resolve the vertical structure of the horizontal motions*. Therefore, the objective for constructing a vertical grid is a function of the vertical complexity of the horizontal velocities. Characterizing this vertical complexity is fundamental to choosing the vertical grid.

Horizontal velocities can be expressed as a superposition of mutually orthogonal vertical eigenmodes. The vertical structure of the horizontal velocities will be at least as complicated as these eigenmodes. For the ocean, the shape of these eigenmodes form the basis functions of the baroclinic modes, and depends on the water depth and stratification, allowing them to be estimated from observations and global hydrography (e.g., Wunsch, 1997; Smith, 2007). The characteristic horizontal length-scale of the m-th baroclinic mode is reflected by the mode-m deformation radius, L_m. These deformation radii are largest for L_1 and decrease for higher baroclinic modes, meaning a given horizontal grid can only support the fundamental modal dynamics of a finite number of baroclinic modes. It follows that the vertical grid should be designed to resolve the baroclinic modal structure of the highest mode supported by the horizontal grid. For example, based on Hallberg (2013), an ocean model with ~1/4° horizontal resolution should have a vertical grid designed to resolve the vertical structure of at least the first baroclinic mode. Equivalent calculations for horizontal resolution requirements of higher baroclinic modes calls for the vertical grids of ~1/10° ocean models to be designed to resolve the vertical structure of the second baroclinic mode.

Following Chelton et al. (1998) and Ferrari et al. (2010), the baroclinic modal structure can be approximated with the Wentzel–Kramers–Brillouin method (WKB; detailed in Section 2). It is important to note that the presence of bottom topography, the free-surface, and non-uniform stratification violates the conditions for the strict validity of the WKB approximation (Hallberg and Rhines, 1996; Chelton et al., 1998), meaning the actual ocean horizontal velocity field is likely to be more complicated than the WKB method suggests. Also, topographic slopes and mean flows affect the baroclinic modal structure and are taken into account by the WKB method (e.g. Tailleux, 2003; Hunt et al., 2012). Nevertheless, the WKB approximation provides an indication of the lower limit of the complexity of the vertical structure of the horizontal flows, from which minimum requirements for the vertical resolution can be formulated. This approach has the advantage that the vertical grid can be tailored to the theoretical resolution capabilities of the horizontal grid; that is, if the horizontal grid is designed to resolve dynamics at the mode-m baroclinic deformation radius, this methodology ensures the vertical grid can do the same. Additionally, this methodology provides an objective means to quantify the ability of a given vertical grid to resolve baroclinic mode-m and directly compare this with other vertical grids.

The goals for this paper are twofold. Firstly, we introduce a methodology for objectively constructing (Section 2) and comparing (Section 3) vertical grids that is based on hydrography and

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[1] Courant number $C = u\Delta t/\Delta x$, $v\Delta t/\Delta y$, and $w\Delta t/\Delta z$, where Δx, Δy and Δz are the longitudinal, latitudinal and vertical grid spacings, respectively, and $\Delta t \approx 1800$ s is the model timestep typical of L_1-scale global models.