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Comparison of entrainment in overflows simulated by z-coordinate, isopycnal and non-hydrostatic models ☆

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Abstract

A series of idealised numerical simulations of dense water flowing down a broad uniform slope are presented, employing both a *z*-coordinate model (the MIT general circulation model) and an isopycnal coordinate model (the Hallberg Isopycnal Model). Calculations are carried out at several different horizontal and vertical resolutions, and for a range of physical parameters. A subset of calculations are carried out at very high resolution using the non-hydrostatic variant of the MITgcm. In all calculations dense water descends the slope while entraining and mixing with ambient fluid. The dependence of entrainment, mixing and down-slope descent on resolution and vertical coordinate are assessed. At very coarse resolutions the *z*-coordinate model generates excessive spurious mixing, and dense water has difficulty descending the slope. However, at intermediate resolutions the mixing in the *z*-coordinate model is less than found in the high-resolution non-hydrostatic simulations, and dense water descends further down the slope.

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Isopycnal calculations show less resolution dependence, although entrainment and mixing are both reduced slightly at coarser resolution. At intermediate resolutions the z-coordinate and isopycnal models produce similar levels of mixing and entrainment. These results provide a benchmark against which future developments in overflow entrainment parameterizations in both z-coordinate and isopycnal models may be compared.

Keywords: Overflows; Entrainment; Vertical coordinate; Model resolution; Mixing parameterization

1. Introduction

Dense water formed through cooling or evaporation in marginal seas (e.g. the Greenland–Iceland–Norwegian sea, the Mediterranean, the Red sea) or on coastal shelves (e.g. the Arctic and Antarctic shelves) enters the general ocean circulation by flowing over topographic features, such as straits and sills (e.g. the Denmark Straits, Faroe Bank Channel, Gibraltar Straits, Bab-el-Mandab) and down the continental slope. These density driven currents flowing down topography are known as overflows. As the water descends it entrains ambient fluid, which mixes with the dense water, modifying the tracer properties and increasing the volume of the dense water mass (Price and Baringer, 1994). The overflow waters, modified by entrainment, include North Atlantic Deep Water (Dickson and Brown, 1994), Mediterranean Overflow Water (Price et al., 1993), and Antarctic Bottom Water (Gordon et al., 1998), and ultimately fill much of the abyssal ocean. Accurate representation of overflows and the entrainment they produce is therefore vital for correctly representing these deep water masses in ocean general circulation models.

It is now well known that different model formulations have different levels of success in representing overflows (Griffies et al., 2000). Of particular importance is the model's vertical discretization (Willebrand et al., 2001). Terrain-following coordinate models (e.g. the Princeton Ocean Model, http://www.aos.princeton.edu/WWWPUBLIC/htdocs.pom/, the Rutgers Ocean Modeling System (Haidvogel et al., 2000)) have the ability to concentrate resolution near the bottom boundaries, and hence can resolve overflow processes well, provided the vertical resolution is sufficiently fine. However, when topography is steep they have problems with pressure-gradient errors (Haney, 1991), although these are reduced but not eliminated by recent improved numerical schemes (Ezer et al., 2002; Shchepetkin and McWilliams, 2003). Isopycnal coordinate models (e.g. HIM (Hallberg and Rhines, 1996), MI-COM, http://oceanmodeling.rsmas.miami.edu/micom/) have no difficulties accurately representing topography, and are able to concentrate resolution in regions of large density gradients (often found at the interface between overflow waters and ambient fluid). In addition the diapycnal mixing and entrainment associated with the overflow can be explicitly parameterized (Hallberg, 2000; Papadakis et al., 2003). While isopycnal models and related hybrid coordinate models (e.g. HYCOM, http://oceanmodeling.rsmas.miami.edu/hycom/; Poseidon, http://www.scs.gmu.edu/climate/poseidon/) are increasingly being employed for climate studies, the majority of the established climate models (e.g. CCSM, http://www.ccsm.ucar.edu/; MOM, http://www.gfdl.noaa.gov/fms/pubrel/j/mom4/doc/mom4_manual.html) use height as their vertical coordinate. Height or z-coordinate models have particular difficulties in