Overflow parameterisations in climate models

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1. Introduction

Flows across shallow sills and through straits control the distribution of the water masses in the deep ocean. Yet, the credibility of present climate models is limited by their ability to represent processes that occur on scales smaller than the model grid scale (currently typically 100 km) such as overflows (Legg et al., 2009). A proper representation of overflows in numerical models must adhere to two principles: 1) minimization (or understanding) of numerically induced dianeutral mixing (also called “spurious” mixing), and 2) a decent parameterisation of unresolved processes. The practical implementation of parameterisations is directly linked to the vertical coordinate choice (Griffies et al., 2000a). Numerically induced dianeutral mixing arises in fixed-coordinate (level or terrain-following) models because of advective truncation errors and horizontal/isosigma diffusion tensors. Isopycnal models by definition have no spurious diapyncal mixing and small dianeutral mixing as long as isopycnals do not deviate far from neutral surfaces. The challenge for fixed coordinate models is to reduce the numerically-induced mixing to levels that are below observations (Griffies et al., 2000b; Marchesiello et al., 2009).

In the case of overflows, Ilicak et al. (2012) state that in order to reduce spurious dianeutral mixing, the grid Reynolds number should be small enough to suppress the grid noise and resolve the flow. This is consistent with Legg et al. (2008), who argued that the bottom frictional boundary layers should be resolved to avoid spurious entrainment. However, the small scale nature of overflow processes with horizontal and vertical length scales (order 1 km and 10 m, respectively) requires finer horizontal and vertical resolutions than what is commonly used in climate models (100 km and 50-200 m, respectively). In level coordinate models with such a coarse resolution, the flows over staircase topography tend to have excessive convective entrainment, resulting in deep waters that are too light and that remain too shallow (Roberts et al., 1996; Winton et al., 1998). Several approaches have been proposed that attempt to reduce this bias with mixed results (Treguier et al., 2012): artificial modification of the model’s bottom topography, bottom boundary layer parameterisations, and streamtube models. Implementation of these approaches turned out to be quite sensitive to small changes in the topography and models grids. The most successful implementation to date in a climate model is the parameterisation used by the NSF-DOE Community Earth System Model (CESM), which is based on the Marginal Sea Boundary Condition (MSBC) of Price and Yang (1998). When Nordic Sea overflows are parameterised, Danabasoglu et al. (2010) report a significant improvement in the penetration depth of the North Atlantic Deep Water (NADW), reducing the chronic, shallow penetration depth bias in level coordinate models. They also show bias reductions in the deep temperature and salinity distributions in the North Atlantic with parameterised overflows.

Even at high horizontal and vertical resolutions, reduction of the spurious dilution of dense waters in level coordinate models is only achieved when high viscosity is used to render the simulated flow more laminar (Ilicak et al., 2012). Terrain-following coordinate models at fine resolution do not exhibit as much spurious mixing as the level coordinate models (Legg et al., 2006; Ilicak et al., 2012), but at the present the use of this vertical coordinate for climate modelling purposes is very limited (see Griffies et al. (2000a) and Marchesiello et al. (2009) for a discussion). It is, however, ideal for the representation of bottom boundary layers (important for the large scale ocean circulation primarily as sinks of momentum and for mixing) since it can enforce very high resolution near the bottom and incorporate high-order turbulence closure schemes (Hallberg, 2000; Legg et al., 2006). The fact that, in contrast to level (and to some extent terrain-following) coordinate ocean models, an isopycnal coordinate model inherently has too little mixing, meaning that there is a need for parameterisations of entrainment due to shear-driven mixing in this class of models. To date, most entrainment

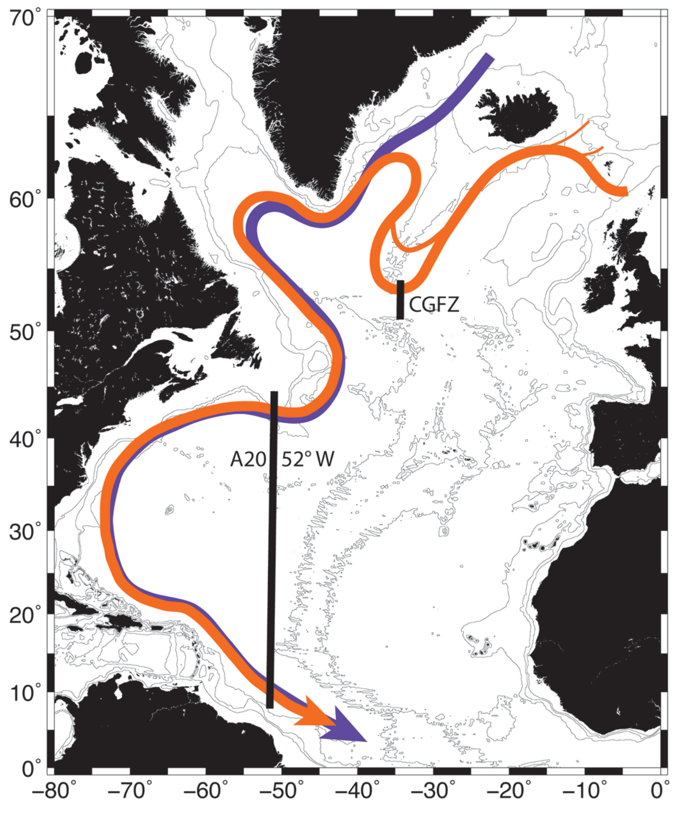

Figure 1: A schematic flow pattern of the Denmark Strait overflow water (purple) and the Iceland-Scotland overflow water (orange) in the deep western boundary current of the North Atlantic Ocean. The black vertical lines denote two meridional sections along which observed and modelled salinity/tracer distribution are shown (Figure 2).

parameterisations are based on either a critical Froude number as in the work of Price and Baringer (1994) (e.g., Hallberg, 2000; Xu et al., 2006; Jackson et al., 2008), or a subcritical Froude number (e.g., Cenedese and Adduce, 2010), or second-order turbulent closures (e.g., Ilicak et al., 2009).

2. Modelling overflows in the North Atlantic

Dense water formed in the Nordic Seas and the Arctic Ocean enters the deep North Atlantic via two overflow systems over the Greenland-Scotland Ridge (Figure 1). To the west, the Denmark Strait overflow water (Jochumsen et al., 2012) flows through the Denmark Strait and continues down the continental slope of the western subpolar North Atlantic (e.g., Schott et al., 2004). To the east, the Iceland-Scotland overflow water takes a more complex pathway, involving flows over the Iceland-Faroe Ridge and out through the Faroe Bank Channel. The Iceland-Scotland overflow water then continues to flow southwestward along the northwestern slope of the Iceland Basin (Saunders, 1996) and westward through the Charlie-Gibbs fracture zone (CGFZ) (Saunders, 1994). The Iceland-Scotland overflow water through the CGFZ subsequently turns northward into the Irminger Sea. Some Iceland-Scotland overflow water also enters the Irminger Sea by flowing westward across the Reykjanes Ridge north of CGFZ (Xu et al., 2010). In the Irminger Sea, the Iceland-Scotland overflow water joins and overrides the Denmark Strait overflow water on its way south toward the equator (Saunders, 2001). The Denmark Strait overflow water and Iceland-Scotland overflow water are two important components of the NADW, which also includes Labrador Sea

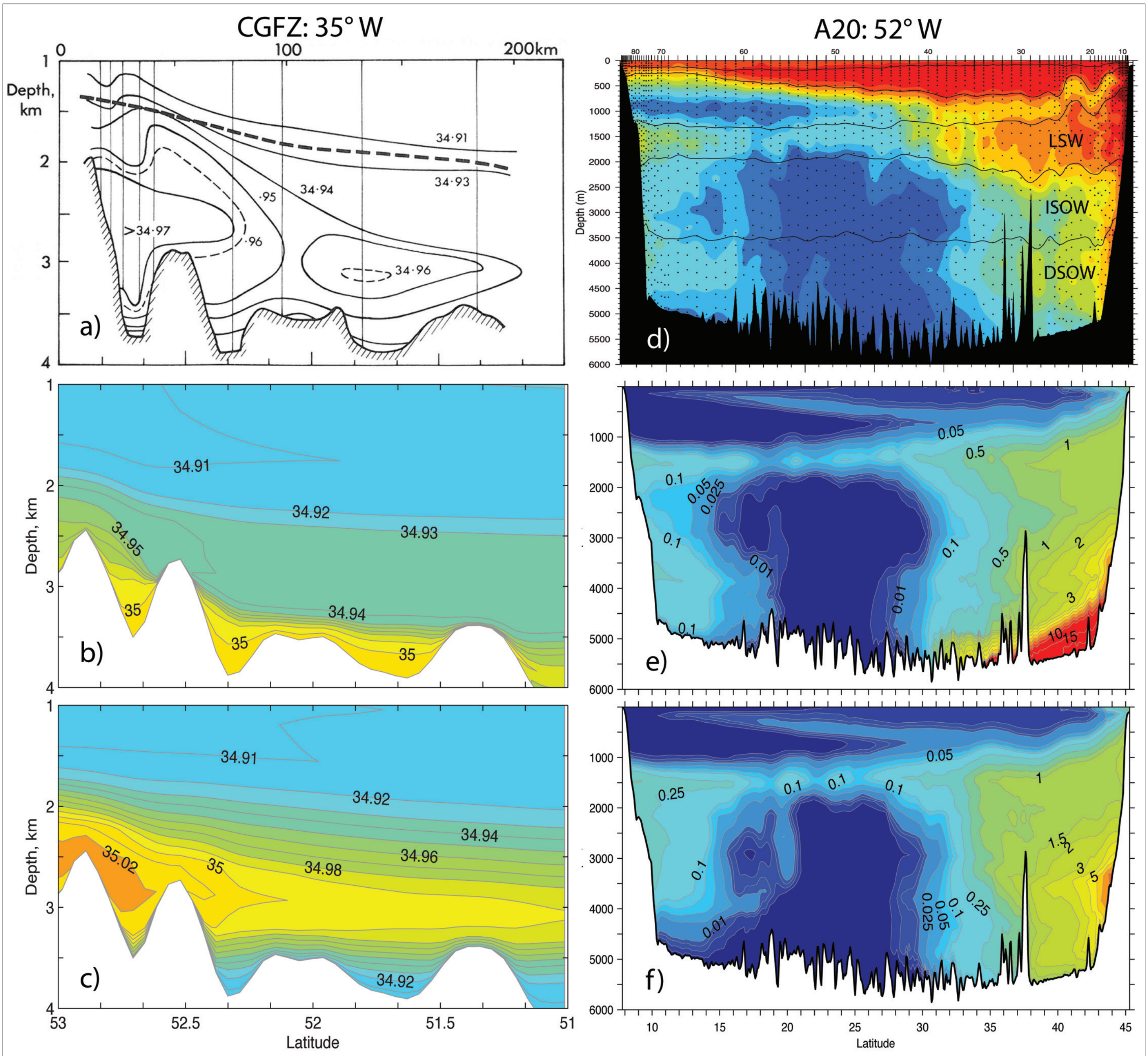

Figure 2: (a-c) Salinity distribution along a meridional section across the Charlie-Gibbs Fracture Zone at 35ºW, and (d-f) tracer distribution along the WOCE section at 52ºW in the western North Atlantic. (a) and (d) are observed salinity from Saunders (1994) and CFC concentration from Hall et al. (2004), respectively. (b) and (e) are modelled salinity and passive tracer concentration (x100) in the HYCOM simulations using KPP; (c) and (f) are the same as (b) and (e), but with the Xu et al. (2006) entrainment mixing parameterisation.

Water (LSW) and modified Antarctic Bottom Water (AABW). Knowledge of the detailed circulation pathways and volume transports of these overflow water masses is therefore fundamental for a general description of the Atlantic meridional overturning circulation. Moreover, the overflow waters can influence decadal (and longer time scale) climate variability, primarily through their impacts on the Labrador Sea stratification (Yeager and Danabasoglu, 2012).

Here we discuss an example of how one can represent these overflows in eddy-rich or "eddying" numerical simulations, meaning that they are eddy-resolving over most of the domain and include an energetic mesoscale eddy field. The grid spacing in these simulations also allows for a reasonable representation of the topography of the overflows. Using the HYbrid Coordinate Ocean Model (HYCOM, Bleck, 2002; Chassignet et al., 2003) configured for the North Atlantic with 1/12° resolution, Xu et al. (2010) showed that while the model overflow water from the Greenland-Scotland Ridge to Irminger Sea was in reasonable agreement with the observed volume transports as well as temperature and salinity characteristics, the modelled Iceland-Scotland overflow water through the CGFZ exhibited a salinity maximum near the bottom, whereas in observations the salinity maximum is located above the bottom at 2500-3000 m (Saunders, 1994; see Figure 2a). The default vertical coordinate configuration of HYCOM is isopycnic in the open stratified ocean, but it makes a dynamically and geometrically smooth transition to terrain-following coordinates in shallow coastal regions and to fixed pressure-level (mass conserving) coordinates in the surface mixed layer and/or unstratified open seas. In doing so, the model takes advantage of the different coordinate types in optimally simulating coastal and open-ocean circulation features (Chassignet et al., 2006). In HYCOM, the default shear-driven mixing parameterisation is that of the K-profile parameterisation (KPP, Large et al., 1994), which results in insufficient diapycnal mixing for overflow entrainment process (Xu et al., 2006) (Figure 2b,e). Since this parameterisation was developed to represent upper-ocean physics primarily, it is not surprising that it does not work in a different regime where the length scales and velocity shears driving the turbulence are different (Jackson et al., 2008).

The impacts of shear-driven mixing parameterisations on the Iceland-Scotland overflow water and Denmark Strait overflow water in the North Atlantic are evaluated in twin experiments, one with the default KPP and the other with the entrainment parameterisation of Xu et al. (2006). Both simulations have a horizontal resolution of 1/12° and 64 layers in the vertical. They are forced with climatological atmospheric forcing from the European Center for Medium range Weather Forecasting (ECMWF) reanalysis ERA40 for 20 years. Figure 2a,b,c compare the observed and modelled salinity distributions along a meridional section near 35°W across the CGFZ (Figure 1). The observations (Saunders, 1994) are based on a conductivity-temperature-depth (CTD) survey in 1988 while the model results are time average over the last 5 years. The observed high-salinity Iceland-Scotland overflow water, defined as salinity greater than 34.94, occupies a depth range from 1500–3500m (Figure 2a) which is well represented in the simulation with entrainment mixing parameterisation (Figure 2c), but not in the simulation with KPP (Figure 2b) where the highest salinity is found at bottom as in Xu et al. (2010). The Iceland-Scotland overflow water has a high salinity signature due to entrainment of the warm and salty upper North Atlantic Water as it flows into the Iceland Basin. It can be easily distinguished from the relatively low salinity of the Denmark Strait overflow water within the Irminger and Labrador Seas, but further south in the subtropical western North Atlantic the Denmark Strait overflow water overrides the modified AABW, which also has low salinity. In order to identify the model Denmark Strait overflow water without ambiguity, a passive tracer is injected in the numerical models north of the Denmark Strait sill. In Figure 2d,e,f, the distribution of the passive tracer is compared to observed chlorofluorocarbons (CFCs) (e.g., Hall et al., 2004) along a meridional section in the western North Atlantic near 52°W (Figure 1). This section (WOCE A20) has been surveyed several times and the basic structure has not changed. The high concentration of CFC near 3500-4000 m is the Denmark Strait overflow water core. As for the salinity fields, the HYCOM simulation with entrainment mixing parameterisation exhibits a tracer distribution that agrees with the observed CFCs, whereas the simulation with KPP show highest tracer concentration near the bottom. Note the discrepancy between models and observations in the upper layers is due to the fact that the model tracer was directly injected into the Denmark Strait overflow water below 400 m at the Denmark Strait sill whereas the CFCs enters the ocean through winter time convection. Figure 2 highlights the importance of the shear-driven mixing parameterisation in representing the structure of water mass distributions in the deep ocean. It is important to note that the density difference between the Denmark Strait overflow water and AABW is subtle (less than 0.02 kg m^{-3} in σ_2 in the subtropical North Atlantic), making it challenging to accurately model.

3. Discussion

The above results demonstrate that it is possible to parameterise the water mass transformations associated with overflows. The shear-driven mixing parameterisation of Xu et al. (2006) worked well for this specific configuration and class of model, but it is unclear how it would hold for coarser or finer horizontal resolutions – any shear mixing parameterisation needs to take into account changes in the magnitude of the vertical shear induced by any increase/decrease in the horizontal grid spacing (most of the time also associated with a change in numerical viscosity). However, shear-driven mixing is not the only physical process that controls the transport of dense water through overflows and its mixing with the ambient water. Hydraulic control, interactions with narrow canyons, mesoscale eddies, tides, and bottom friction also play a role (Legg et al., 2008). Bottom boundary layers are not resolved in current climate models and are seldom parameterised (Killworth, 2003). Legg et al. (2006) showed how important it is to properly capture the homogenization of tracers induced by the mixing driven by frictionally driven shear.

The ability of isopycnic coordinate models to have a decent representation of overflows is one of the reasons behind the development of a new generation of generalised vertical coordinate ocean models: Model for Prediction Across Scales (MPAS; Ringler et al., 2013) and MOM6 (http://www.gfdl.noaa.gov/ocean-model). Furthermore, the horizontal and vertical grid resolutions in the next generation of high-resolution climate simulations will still be coarser than what is needed to resolve the overflow physics. One approach that could be used to circumvent many of the issues raised in this article would be to apply very high-resolution nested grids in overflow regions (Fox and Maskell, 1996). Despite its potential, this approach has not yet been implemented in climate models, primarily because of technical challenges associated with three-dimensional two-way grid interactions and computing cost. Recent developments behind two-way grid interaction software (AGRIF and OASIS) and new computer architectures (GPUs, MICs) may provide an impetus for the inclusion of high resolution nested grids in the near future. MPAS with its multi-resolution approach is also well suited to test this approach.

Acknowledgements

E. Chassignet and X. Xu acknowledge support from the Office of Naval Research grant N00014-09-1-0587. Grants of computer time were provided by the Department of Defense (DoD) High Performance Computing Modernization Program. NCAR is sponsored by the National Science Foundation (NSF).

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