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Pathways of Nordic Overflows from climate model scale and eddy resolving simulations

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ABSTRACT

The overflows of cold, heavy waters from the Nordic Seas across the Greenland–Iceland–Scotland Ridges are simulated using the Hybrid Coordinate Model in a North Atlantic configuration. Results at three different horizontal model resolutions are compared to each other, to recent hydrographic sections and moored observations. Simulations in the finest grid employed, 1/12° resolution, show realistic overflow pathways, reasonable overflow and Deep Western Boundary Current mean velocities and transports, and overall reasonable North Atlantic three-dimensional temperature and salinity fields, namely the Atlantic Meridional Overturning Circulation (AMOC). In contrast, simulations at coarser grids of 1/3° and 1° resolution exhibit a range of significant problems owing to unresolved, dynamically vital features in the seafloor topography. This lack of resolution, for example of the Faroe Bank Channel, leads to unrealistic overflow pathways between Iceland and Scotland in the 1/3° and 1° cases. Accordingly, overflow mass transports are also unrealistic in this area. In the Denmark Strait Overflow the underlying topographical scales are larger, and pathways are reasonable even at coarse resolution. However, overflow speeds are too small in the 1/3° and 1° cases. Underestimated velocities in the 1° simulations are compensated by an overestimated sill cross-section, whereas it is too small in 1/3°. As such, the 1/3° and 1° simulations show both large under- and overestimations of volume transport at several locations. No significant improvement in modeled overflows takes place when the grid spacing is decreased from 1° to 1/3°. An experiment conducted with hand-tuned topography shows improved volume transports near the regions of modification, but somewhat increased errors in other parts of the deep circulation, indicating the complex response of the system to perturbations in bathymetry. These results demonstrate the importance of an accurate representation of the domain geometry, in particular the channels of the complex Iceland–Scotland ridge system, in order to reproduce the pathways of the deep AMOC.

1. Introduction

On a background of climate and climate change, the Atlantic Meridional Overturning Circulation (AMOC) represents a key physical process. The AMOC is thought to affect such important conditions as the comparatively warm climate of Northern Europe and to be sensitive to global warming, possibly even to the point of shut-down as an extreme case (Hansen et al., 2004; Quadfasel, 2005; Bryden et al., 2005; Broecker, 2003; Häkkinen and Rhines, 2004; Wunsch and Heimbach, 2006; Cunningham et al., 2007; Kanzow et al., 2007). Hence, there is great interest in the AMOC and in modeling it (Bentsen et al., 2004; Gregory et al., 2005; Lumpkin and Speer, 2007). The warm branch of the AMOC transports water between Iceland and Scotland northward at relatively shallow depths into the Nordic Seas, where it is cooled and transported to depth (Weaver et al., 1999; Blindheim and Francisco, 2004). The cold return branch has to cross over the Greenland–Iceland–Scotland ridge system (GIS). The flow then converts to overflows – gravity currents – on its southern side. These latter "Nordic Overflows" are the topic of this paper. It needs to be mentioned that deep water formation in the Labrador Sea is also part of the downward branch of the AMOC. Much of the cold water from the overflows and the Labrador Sea flows south on the western side of the North Atlantic as deep boundary currents (Fischer et al., 2004).

This study is conducted within the framework of the Climate Process Team on Gravity Current Entrainment (Legg et al., in press), a project aimed at improving the numerical simulation of gravity currents in global climate models. Within this context, we are asking the question of what the effect of the horizontal model resolution is on numerically simulated Nordic Overflows and other aspects of the North Atlantic circulation. This question is motivated

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by a current typical horizontal grid spacing in global climate models of 1° – which is comparable to, and sometimes far greater than the width of most overflows.

This is of course not the first investigation of the effect of horizontal resolution on overflow models. For example, Chang et al. (2008) found that the pattern and pathways of the Red Sea Overflow do not become realistic until the detail of the bottom topography is resolved. In that case the key topographic features are two channels that are 2–5 km wide. Among several studies to examine topographic influences on overflows and AMOC structure, Roberts and Wood (1997) performed sensitivity tests with a 1° model by artificially changing sill depths in the Denmark Strait as well as in the Iceland–Scotland ridges. The simulations across the entire domain from the Nordic Seas to the subpolar gyres proved to be highly sensitive to topographic variations. Similar results were obtained by Beismann and Barnier (2004) in an investigation of the strength of the AMOC as a function of topographic differences near the sills of the Nordic Overflows.

Herein, we are studying overflows, the AMOC and, more generally, wide aspects of the circulation in the subpolar and Nordic Seas as a function of horizontal model resolution. We are focusing on numerical simulations with a community ocean general circulation model, routine atmospheric forcing, routine initialization, and routine procedures for generating the model seafloor topography at various resolutions. There are other approaches to overflow modeling, such as the Marginal Sea Boundary Condition (MSBC). In this approach, the exchange between the marginal sea and the open ocean, descent and entrainment of the outflow on the continental slope are collapsed into what amounts to a side-wall boundary condition for an ocean general circulation model. This approach to modeling deep water formation by a marginal sea is appropriate from an oceanic perspective since the outflow water mass transformation takes place within one grid cell of a typical ocean climate model. The reader is referred to Price and Yang (1998) for details. In MSBC, the overflows are not explicitly simulated, and this type of parameterization is shown to be effective in coarse-resolution studies, in particular when the outflow from the marginal sea remains as a single branch before equilibrating in the open ocean, such as in the case of the Mediterranean outflow (Wu et al., 2007; Xu et al., 2007).

In light of the importance of overflows from Nordic Seas on the AMOC, and their complex structure, we pose the following questions:

- Can we obtain realistic Nordic Overflows and deep transport pathways using ocean general circulation models, in which the overflows are explicitly simulated?
- If so, at which model horizontal resolution is this achieved?

Experiments are conducted by gradually increasing horizontal resolutions. We start with 1° grid, which appears to be the typical ocean model resolution used in climate studies at the present time (e.g. Gnanadesikan et al., 2006). Then, we carry out simulations at 1/12° grid spacing, which resolves the most important topographic features, as well as many mesoscale turbulent eddies, jets and western boundary currents. A simulation at an intermediate, eddy-permitting resolution of 1/3° complements the other two. We are striving to trace the pathways of all components of the Nordic overflows and of the AMOC in the North Atlantic in good detail.

The paper is organized as follows. The principal properties of the Nordic Overflows are reviewed in Section 2. The model configuration, initialization, atmospheric forcing, bottom topography and model parameters are laid out in Section 3. The results of the simulations, including detailed comparisons with moored observations and hydrographic sections follow in Section 4. The paper concludes with summary and discussion.

2. Review of Observations on Nordic Overflows

The Greenland–Iceland–Scotland ridge system is a continuous, relatively shallow barrier which constrains the exchange of waters between the subpolar North Atlantic and Nordic Seas (Fig. 1). Sill depths at various locations range from 300 to 840 m. Iceland and the Faroe Islands divide the ridge into three gaps that are the main routes for the exchange between the water masses in the North Atlantic and Nordic Seas (Hansen and Østerhus, 2000). The fairly wide Denmark Strait (DS) is the westernmost gap with a sill depth of about 600 m. The rather dense Denmark Strait Overflow Water (DSOW) crosses the sill and continues southwestward and downward as illustrated in Fig. 1. Maximum speeds at the sill can exceed 0.5 m s^{-1} (Macrander et al., 2007). The corresponding DSOW mass transport is 2.7–2.9 Sv at the sill (Dickson and Brown, 1994; Hansen and Østerhus, 2000; Girton et al., 2001; Macrander et al., 2007). From the sill, the DSOW continues to flow through the Irminger Basin parallel to the east coast of Greenland southwestward and downward on a broad slope. Entrainment of ambient fluid along this path increases the overflow transport to $\sim$ 13.3 Sv at the southern tip of Greenland (Dickson and Brown, 1994). The DSOW then joins the deep water circulation in the Labrador Sea, where deep-convection processes increase the transport of this main return branch, the Deep Western Boundary Current (DWBC), to about 17 Sv near the Grand Banks (Fischer et al., 2004).

The middle gap in the GIS ridges is the Iceland-Faroe Ridge (IFR), which is broad and shallow with crest depths of 300–500 m. Since it was first probed more than a century ago by Knudsen (1898) a multitude of observations of the overflow across the IFR have been made (Tait, 1967; Steele, 1967; Meincke, 1974). However, because the IFR is broad and long and has highly-variable flow, the detail and overall magnitude of the overflows are still uncertain. The transport is estimated to be no more than 1 Sv. After crossing over the IFR, overflow waters flow mainly southwestward along the Iceland Basin (Fig. 1).

The easternmost gap on the GIS is the Faroe-Shetland Channel, which has a relatively deep sill about 1000 m deep. This channel is blocked at its southwestern end by the Wyville-Thomson Ridge (WTR) with a sill depth not deeper than 600 m. The Wyville-Thomson Ridge joins the Scottish shelf at its southern end and Faroe Bank at its northern end. The Faroe Bank is separated from the Faroe Plateau by the narrow and deep Faroe Bank Channel (FBC), which has a sill depth of 840 m. Because of its depth the FBC is the main outlet from the Faroe-Shetland Channel (FSC) and a major outlet from the Nordic Seas. Numerous observations in the FBC indicate maximum velocities up to $\sim$1 m s^{-1} (Mauritzen et al., 2005; Geyer et al., 2006). The reported volume transport from this channel is 1.5–2.1 Sv (Hansen and Østerhus, 2000; Lake and Lundberg, 2006; Geyer et al., 2006). After the overflow water passes through the FBC, a considerable part crosses the Island Basin and joins with the overflows that have crossed over the Iceland-Faroe Ridge (Steele, 1961; Swift, 1984; Saunders, 1996; van Aken, 1998; Hansen and Østerhus, 2000). Further on, the overflow water continues southwestward along the Iceland Basin and eventually reaches the Mid Atlantic Ridge. It flows southward along its eastern flank until parts of it escape into the Irminger Basin through the Charlie-Gibbs Fracture Zone (CGFZ; Saunders, 1994) and probably other gaps in the Mid Atlantic Ridge. The overflow water that crosses over the Wyville-Thomson Ridge continues flowing southward through the Rockall Channel along the eastern flank of the Rockall-Hatton Plateau (Ellett and Roberts, 1973; Sherwin and Turrell, 2005). Estimates of the overflow transport in this region are rather uncertain with a wide range of reported values between 0.1 and 2 Sv.