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Representations of the Nordic Seas overflows and their large scale climate impact in coupled models

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ABSTRACT

The sensitivity of large scale ocean circulation and climate to overflow representation is studied using coupled climate models, motivated by the differences between two models differing only in their ocean components: CM2G (which uses an isopycnal–coordinate ocean model) and CM2M (which uses a *z*-coordinate ocean model). Analysis of the control simulations of the two models shows that the Atlantic Meridional Overturning Circulation (AMOC) and the North Atlantic climate have some differences, which may be related to the representation of overflow processes. Firstly, in CM2G, as in the real world, overflows have two branches flowing out of the Nordic Seas, to the east and west of Iceland, respectively, while only the western branch is present in CM2M. This difference in overflow location results in different horizontal circulation in the North Atlantic. Secondly, the diapycnal mixing in the overflow downstream region is much larger in CM2M than in CM2G, which affects the entrainment and product water properties. Two sensitivity experiments are conducted in CM2G to isolate the effect of these two model differences: in the first experiment, the outlet of the eastern branch of the overflow is blocked, and the North Atlantic horizontal circulation is modified due to the absence of the eastern branch of the overflow, although the AMOC has little change; in the second experiment, the diapycnal mixing downstream of the overflow is enhanced, resulting in changes in the structure and magnitude of the AMOC.

1. Introduction

The Nordic Seas, which include the Greenland Sea, Norwegian Sea and Iceland Sea, are located at the northern end of the Atlantic Ocean. The Nordic Seas basin is one of the few regions where the formation of the densest water occurs. It is relatively isolated from the rest of the Atlantic by the Greenland–Iceland–Scotland (GIS) ridge with connections through the Denmark Strait (DS) and Iceland–Scotland channels (IS). The dense water formed in the Nordic Seas flows out through these channels in the form of overflows, i.e. density-driven currents flowing down the continental slope. The Nordic Seas overflows are important components of the Atlantic Meridional Overturning Circulation (AMOC), acting as a major source water of the North Atlantic Deep Water (NADW), which is the lower branch of the AMOC upper cell (Kuhlbrodt et al., 2007). The time-averaged transport of the overflows at the ridge is about 6 Sv (e.g. Macrander et al., 2005; Mauritzen et al., 2005; Olsen et al., 2008) and is partitioned approximately evenly between the DS and IS overflows. As the overflows flow downhill from the ridge, they entrain ambient water and the transport of the total product water is doubled (Dickson and Brown, 1994), making the overflow product water transport 2/3 of the AMOC transport magnitude (18 Sv, Talley et al., 2003). Thus the overflows and their variability are important to the AMOC and the North Atlantic climate.

Due to the lack of long term observations, hindcast studies of the connection between the overflows and the AMOC need to apply either data assimilation or ocean models forced by atmospheric fields. Köhl and Stammer (2008) found that in the German ECCO reanalysis data set AMOC variability during 1952–2001 has a high correlation with DS overflow, which is in turn correlated to the North Atlantic Oscillation. On the other hand, observational and modeling studies by Olsen et al. (2008) showed that during 1948–2005 although AMOC was weakened, overflow transports remained stable, and the change of AMOC was caused by variations south of the GIS ridge. In coupled climate model studies, different models often give different results. For example, Hawkins and Sutton (2007) found that the multidecadal variability of the AMOC was dominated by the changes in the Nordic Seas convection and overflows. By contrast, Jungclaus et al. (2005) and Danabasoglu

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et al. (2012) argued that the AMOC variability was mostly explained by convection in the Labrador Sea rather than the Nordic Seas overflows, and Medhaug et al. (2012) reported that AMOC variability only has an indirect linkage with the overflows.

Although models disagree on the role that overflows play on the AMOC variation and variability, modeling studies suggest that the overflow magnitude influences the structure and strength of AMOC as well as North Atlantic climate. For example, Zhang et al. (2011) studied the transient response of AMOC to overflows using GFDL's high resolution model CM2.5. They found that in response to a stronger overflow, AMOC was significantly strengthened, although the changes tended to diminish after 15 years. Also the subpolar gyre was contracted and the North Atlantic climate was subsequently modified. This modification is caused by the vortex stretching of the upper-layer circulation by the increased transport of the Deep Western Boundary Current (DWBC), which is set by the overflows and their entrainment (Zhang and Vallis, 2007).

Overflows and downstream entrainment are poorly represented in most climate models mainly due to their coarse resolution. For coarse resolution *z*-coordinate models, spurious numerical mixing during the descent of overflow often results in too light overflow product water. Winton et al. (1998) used idealized models and theoretical analysis to show that for a *z*-coordinate model, the required resolution for the appropriate representation of the overflow with a slope of 0.01 is 30–50 m in the vertical and 3–5 km in the horizontal, with horizontal resolution being a more severe constraint. This is far beyond the resolution of current climate models, which have horizonal grid spacing of about 100 km and vertical resolution of 100–200 m at the depth of 2000 m. Thus either explicit parameterization of the overflows (e.g. Legg et al., 2009; Danabasoglu et al., 2010; Yeager and Danabasoglu, 2012) or excessive sill depth is often used in *z*-coordinate models to produce dense overflow water. Nonetheless, the product water may still be too light to fill the deep ocean due to the excessive spurious mixing during the descent. The upper cell of AMOC is then too shallow compared with observations (Gnanadesikan et al., 2006; Danabasoglu et al., 2012; Delworth et al., 2012; Danabasoglu et al., 2014). For isopycnal–coordinate models, although parameterizations of the diapycnal mixing during the downstream entrainment are still required, they are not subject to the problem of spurious numerical mixing. Therefore overflow product water is usually better preserved downstream (Legg et al., 2006), resulting in a more realistic structure of the AMOC (Roberts et al., 1996).

In addition to the problem of spurious mixing, 1° climate models include bottom topography that usually does not depict channels with realistic widths and depths, a problem in both *z*-coordinate and isopycnal models. This problem is often particularly severe for the complex topography of IS. Topography is commonly deepened as a tuning measure to improve the overflow product water density and AMOC structure. The minimum width of the channel is also limited by the models' horizontal resolution. Chang et al. (2009) studied the influence of horizontal resolution on the relative magnitudes and pathways of the DS and IS overflows, and realistic overflow transports and pathways were only found at their finest resolution (1/12°). Not only does the misrepresentation of the overflow pathways affect the horizonal distribution of the dense waters, it also leads to errors in the pattern of the surface gyre circulation which influences regional climate representation in the model. For example, Roberts and Wood (1997) and Beismann and Barnier (2004) used regional models to show that the North Atlantic climate is sensitive to the magnitude of the IS overflow.

In previous work using different models, there is no consensus on whether or how the overflows influence variability of the AMOC. At the same time, it has long been known that climate models represent overflows poorly, and the representations have great influence on the structure and magnitude of the AMOC, and potentially on the connection between the overflows and AMOC variability. Thus, our study is intended to answer the following questions: How sensitive is the AMOC and North Atlantic climate to the overflows? What processes related to the overflows, including the locations of the transport and magnitude of the mixing are responsible for the sensitivity? We use coupled climate models as tools to study how representation of these overflows processes influence AMOC and the climate. More specifically, we apply two identical climate models differing only in their ocean components: one uses an isopycnal–coordinate model (CM2G) and the other a *z*-coordinate model (CM2M) to examine how overflow representation can affect the mean state as well as the variability of the AMOC and the North Atlantic climate. In Danabasoglu et al. (2014), sensitivity of AMOC to overflow density is studied using various ocean-ice only models forced by CORE forcing. Here, we use coupled models instead, aiming to focus on overflow's impact on both ocean circulation and climate. By analyzing the models' control simulations and two perturbation experiments (CM2G_NOIS and CM2G_ADDIFF, which are described in Section 3), we find that two processes are the main contributors to model differences: the inclusion of the IS overflow can change the horizontal circulation, which impacts the regional climate; the excessive diapycnal mixing in the downstream region of the overflows can result in errors in the vertical structure of the AMOC.

The paper is laid out as follows: in Section 2 we first describe the model specifications, then show the overflow and AMOC related climatology in the two models and specify the major differences between them; then we conduct two perturbation experiments in the isopycnal–coordinate model with differences in overflow representation and show the results in Section 3. Further discussion of comparison with observational studies and concluding remarks are presented in Section 4.

2. Control simulations in CM2G and CM2M

2.1. Model description

We employ two GFDL coupled physical climate models, CM2G and CM2M for our study. They are similar to GFDL's ESM2 models contributed to the CMIP5 model intercomparison (Dunne et al., 2012), but exclude the interactive biogeochemistry and carbon cycle. CM2G and CM2M share the same atmosphere (AM2), sea ice (SIS) and land model (LM3), which are identical to those used in ESM2 models. Compared to the previous GFDL coupled climate model CM2.1, the atmospheric and sea ice models are very similar (see Delworth et al., 2006; Dunne et al., 2012 for detailed description of the models), while the land model (LM3) is a newer version (Dunne et al., 2012). Both CM2G and CM2M use radiative forcing at the year 1990 level.

CM2M and CM2G differ only in their ocean component: CM2M uses the Modular Ocean Model (MOM, Griffies, 2009) with geopotential levels for the vertical coordinate and a B-grid for the horizontal discretization, while CM2G uses the Generalized Ocean Layer Dynamics model (GOLD, Hallberg and Adcroft, 2009), a C-grid isopycnal vertical-coordinate model. Both models have a 1° Mercator horizontal resolution (with finer resolution up to 1/3° at the equator). In CM2M, as in ESM2M, MOM4p1 is used, whereas MOM4 is used in CM2.1. MOM4p1 has 50 geopotential levels in the vertical direction, with intensified resolution near the surface. GOLD has 63 σ_2 layers in the vertical direction, with two mixed layers and two buffer layers being the first four layers. In this study both models have a simulation length of centuries (700 years for CM2M and 1000 years for CM2G) after initialization, which allows