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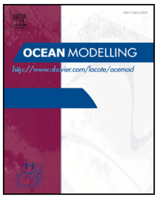

Characteristics of the Nordic Seas overflows in a set of Norwegian Earth System Model experiments

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ABSTRACT

Global ocean models with an isopycnic vertical coordinate are advantageous in representing overflows, as they do not suffer from topography-induced spurious numerical mixing commonly seen in geopotential coordinate models. In this paper, we present a quantitative diagnosis of the Nordic Seas overflows in four configurations of the Norwegian Earth System Model (NorESM) family that features an isopycnic ocean model. For intercomparison, two coupled ocean-sea ice and two fully coupled (atmosphere-land-ocean-sea ice) experiments are considered. Each pair consists of a (non-eddying) 1° and a (eddy-permitting) 1/4° horizontal resolution ocean model. In all experiments, overflow waters remain dense and descend to the deep basins, entraining ambient water en route. Results from the 1/4° pair show similar behavior in the overflows, whereas the 1° pair show distinct differences, including temperature/salinity properties, volume transport (Q), and large scale features such as the strength of the Atlantic Meridional Overturning Circulation (AMOC). The volume transport of the overflows and degree of entrainment are underestimated in the 1° experiments, whereas in the 1/4° experiments, there is a two-fold downstream increase in Q, which matches observations well. In contrast to the 1/4° experiments, the coarse 1° experiments do not capture the inclined isopycnals of the overflows or the western boundary current off the Flemish Cap. In all experiments, the pathway of the Iceland-Scotland Overflow Water is misrepresented: a major fraction of the overflow proceeds southward into the West European Basin, instead of turning westward into the Irminger Sea. This discrepancy is attributed to excessive production of Labrador Sea Water in the model. The mean state and variability of the Nordic Seas overflows have significant consequences on the response of the AMOC, hence their correct representations are of vital importance in global ocean and climate modelling.

1. Introduction

The exchange of waters between the North Atlantic and the Arctic Mediterranean occurs via the Greenland-Iceland-Scotland (GIS) Ridge (Fig. 1). Across this topographic barrier, warm/light North Atlantic Water (NAW) flows northward at the surface and cold/dense water from the Nordic Seas returns southward in the form of bottom-attached gravity currents, known as overflows (Hansen and Østerhus, 2000). The so-called Nordic Seas overflows descend down the slope, entrain and mix with the ambient water, and eventually double in volume transport (Dickson and Brown, 1994). The overflow waters, together with Labrador Sea Water (LSW) that is produced in the Labrador Sea, constitute North Atlantic Deep Water (NADW), which forms the lower branch of the upper cell of the Atlantic meridional overturning circulation (AMOC) (Kuhlbrodt et al., 2007). The AMOC transports heat poleward and contributes to the mild climate in northwestern Europe. The prominent role of AMOC in modulating North Atlantic and global climate has long been emphasised and is examined in a number of studies (Delworth et al., 1993; Rahmstorf, 2002; Hurrell et al., 2006). The Nordic Seas overflows are a major component of AMOC, and as such, a more complete understanding of their properties is an important target for both observationalists and modellers.

The Nordic Seas overflows consist of Denmark Strait Overflow Water (DSOW) that flows via the Denmark Strait, and Iceland-Scotland Overflow Water (ISOW) that flows via the Iceland-Faroe-Scotland Ridge. ISOW is mainly composed of the Faroe Bank Channel overflow, with minor contributions of water from the Iceland-Faroe Ridge and the Wyville Thomson Ridge. The Nordic

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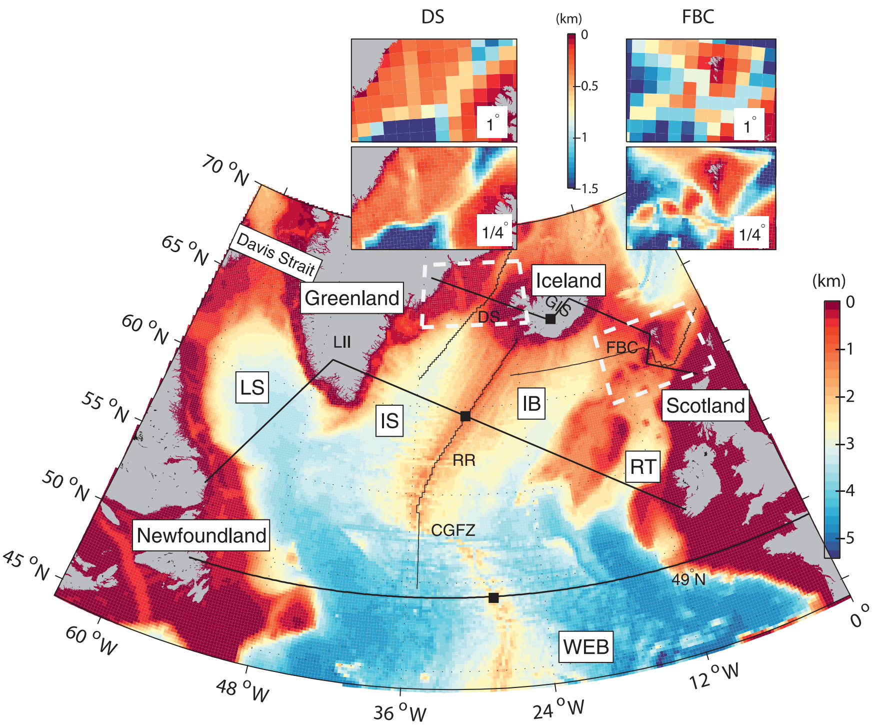

Fig. 1. Model bathymetry (1/4°) of the northern North Atlantic Ocean. The left two insets show the bathymetry at the Denmark Strait in the 1° (top) and 1/4° (bottom) models, and the right two insets show the same for the Faroe Bank Channel. The two white dashed boxes are the domains of the insets. The black lines denote the sections at which figures of vertical volume transport and/or cross-sectional view of temperature/salinity are shown later: the Greenland-Iceland-Scotland (GIS) Ridge section, the Labrador Sea-Irminger Sea-Iceland Basin (LII) section, the 49°N section, the Denmark Strait section, the Faroe Bank Channel section, and the Reykjanes Ridge + Charlie-Gibbs Fracture Zone (CGFZ) section. The black squares on the GIS, LII, and 49°N sections are the breaking points of the sections on the Mid-Atlantic Ridge and will be referred to in Fig. 10. The other topographic abbreviations in the figure are: DS - Denmark Strait; FBC - Faroe Bank Channel; IB - Iceland Basin; IS - Irminger Sea; LS - Labrador Sea; RR - Reykjanes Ridge; RT - Rockall Trough; West European Basin - West European Basin.

Seas overflows are driven by open ocean convection primarily in the Greenland Sea, the descent of dense water from the Arctic shelves, and the transformation of the recirculated NAW that occurs within a cyclonic boundary current at the periphery of the Nordic Seas (Rudels et al., 1999; Hansen and Østerhus, 2000; Eldevik et al., 2009). The volume transport of the DSOW is approximately 2.9 Sv [1 Sv $\equiv 10^6$ m^3 s^{-1}] at the sill of the Denmark Strait (Dickson and Brown, 1994). The DSOW descends down from the sill and flows along the western Irminger Sea, tight against the continental slope (see Fig. 1 for the geographic locations). The overflow waters then turn westward into the Labrador Sea at Cape Farewell (Dickson and Brown, 1994).

The pathway of ISOW is more complicated. Overflow waters passing through the Faroe Bank Channel (~ 1.9 Sv; Hansen and Østerhus, 2007) descend and flow along the Iceland-Faroe slope, where they are joined by waters spilling in over the Iceland-Faroe Ridge. They then proceed south-westward into the Iceland Basin, flowing as a boundary current along the eastern flank of the Reykjanes Ridge. Unlike DSOW, ISOW continues to evolve along multiple pathways. Acoustically tracked RAFOS floats (Bower et al., 2002) reveal the westward passage of ISOW across the Reykjanes Ridge via several topographic gaps. High-resolution eddy-resolving simulations by Xu et al. (2010) show a volume transport of 1.2 Sv across these gaps. Saunders (1994) used year-long current meter measurements from south of the Reykjanes Ridge at the Charlie-Gibbs Fracture Zone (CGFZ) to calculate a mean transport of 2.4 ± 0.5 Sv, indicating that this is the major pathway of the ISOW downstream of Iceland. Saunders (1994) showed that ISOW flow is mostly directed westward at CGFZ, with the deepest layers fluctuating east-westward (see also Shor et al., 1980). After turning westward across the Reykjanes Ridge and the CGFZ, ISOW enters the Irminger Sea and swings back northward along the western flank of the Reykjanes Ridge into the northern Irminger Sea, where it joins and rides above the DSOW. The portion of ISOW that does not turn into the Irminger Sea flows instead into the West European Basin. Signatures of ISOW in the West European Basin have been identified from hydrography and CFC-11 observations (Fleischmann et al., 2001; LeBel et al., 2008). Fleischmann et al. (2001) estimated the transport to be 1.6 ± 0.3 Sv, although this could be as much as 2.4-3.5 Sv if the density range is relaxed. Xu et al. (2010) estimated in their model a volume transport of 1 Sv to the West European Basin.

Understanding of the processes and dynamics related to the Nordic Seas overflows has been advanced in recent years by numerous studies using both field observations (Macrander et al., 2007; Fer et al., 2010; Darelius et al., 2013; Jochumsen et al., 2015) and regional high-resolution process modelling (Guo et al., 2014; Magaldi et al., 2011), which provides a valuable benchmark for evaluating the performance of overflow representations in climate models. Overflows are characterized by their small scales - a few kilometres in the horizontal and a few tens of meters in the vertical, and this represents a serious challenge for basin or global scale models (Winton et al., 1998; Legg et al., 2009). It is known that models using different vertical coordinates (geopotential, isopycnic, or terrain-following) have varying levels of success in correctly capturing overflow characteristics (Griffies et al., 2000; Legg et al., 2006).

In geopotential coordinate ocean models (a common choice in the state-of-the-art climate models) the coarse horizontal resolution of approximately 100 km renders the topography into staircases, over which the overflows tend to exhibit excessive convective mixing, resulting in too light and too shallow penetration of deep waters (Roberts et al., 1996; Winton et al., 1998). Although such excessive mixing can be mitigated by applying the partial