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Mixed layer depth calculation in deep convection regions in ocean numerical models

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ABSTRACT

Mixed Layer Depths (MLDs) diagnosed by conventional numerical models are generally based on a density difference with the surface (*e.g.*, 0.01 $kg.m^{-3}$). However, the temperature-salinity compensation and the lack of vertical resolution contribute to over-estimated MLD, especially in regions of deep convection. In the present work, we examined the diagnostic MLD, associated with the deep convection of the Labrador Sea Water (LSW), calculated with a simple density difference criterion. The over-estimated MLD led us to develop a new tool, based on an observational approach, to recalculate MLD from model output. We used an eddy-permitting, 1/12° regional configuration of the Nucleus for European Modelling of the Ocean (NEMO) to test and discuss our newly defined MLD. We compared our new MLD with that from observations, and we showed a major improvement with our new algorithm. To show the new MLD is not dependent on a single model and its horizontal resolution, we extended our analysis to include 1/4° eddy-permitting simulations, and simulations using the Modular Ocean Model (MOM) model.

1. Introduction

The surface Mixed Layer (ML) is a very active part of the ocean, with the unique feature of ocean-atmosphere interactions. Due to various intensities of wind forcing, this upper layer is characterised by strong turbulent mixing (D'Asaro et al., 2014), wind-driven activities (Grant and Belcher, 2011), freshwater fluxes (Dong et al., 2015), and heat flux loss, homogenising temperature and salinity properties (Clarke and Gascard, 1983). Defining the Mixed Layer Depth (MLD) is important because of its implication in numerous active research areas, including ocean circulation (Marshall and Schott, 1999; Haine et al., 2008), carbon dioxide absorption (Sallee et al., 2012), or phytoplankton blooms (Henson et al., 2009; Brody and Lozier, 2015).

By definition, MLD is characterised by homogenous temperature and salinity through the water column. This simple definition, however, does not reflect the complexity of the processes involved in the homogenization mechanism, such as the mechanical stirring driven by wind stress, or the convective instabilities. This could explain why there is no common criterion in the literature, to determine the MLD. For example, Kara et al. (2003) define the MLD as a boundary delimiting the extent of the turbulent mixed layer. On the other hand, Castro-Morales and Kaiser (2012) use dissolved oxygen concentrations to determine MLD in the Bellingshausen Sea, and suggest this new approach for gas exchange studies. In addition to this complexity, the MLD picture is of a very large spatial and temporal variability (Kara et al., 2003; de Boyer Montégut et al., 2004). While very shallow during summer months (10–50 m), the MLD can reach up to 2000 m in regions where deep convection occurs and major buoyancy loss prevails (*e.g.*, Labrador Sea, Mediterranean Sea, Weddell Sea). The seasonal and interannual variability of the MLD has been intensively studied as it is closely related to physical (Nishikawa and Kubokawa, 2012), chemical (Sallee et al., 2012) and biological processes (Brody and Lozier, 2015).

The Mediterranean Sea has been the focus of numerous studies, as being one region where deep convection occurs in the Northern Hemisphere (Schott et al., 1994; D'Ortenzio et al., 2005; Herrmann et al., 2010). In the Mediterranean Sea, observational studies showed that the MLD in the Gulf of Lion exceeded 1500 m depth on a regular basis, with two maxima in 1987 (2200 m) and in 2005 (2500 m) (Mertens and Schott, 1998; Testor and Gascard, 2006; Schröder et al., 2006; Herrmann et al., 2010). The Greenland Sea is also a place for deep and intermediate convection. Though winter convection was thought to cease after 1970, tracer measurements showed otherwise (Rhein, 1991; 1996). Recently, a convective chimney of 10 km diameter was observed near the Greenland Fracture Zone in winter 2001, exceeding 2400 m (Wadhams et al., 2002). In contrast to a regular deep convection event, the authors showed that the core of the chimney was

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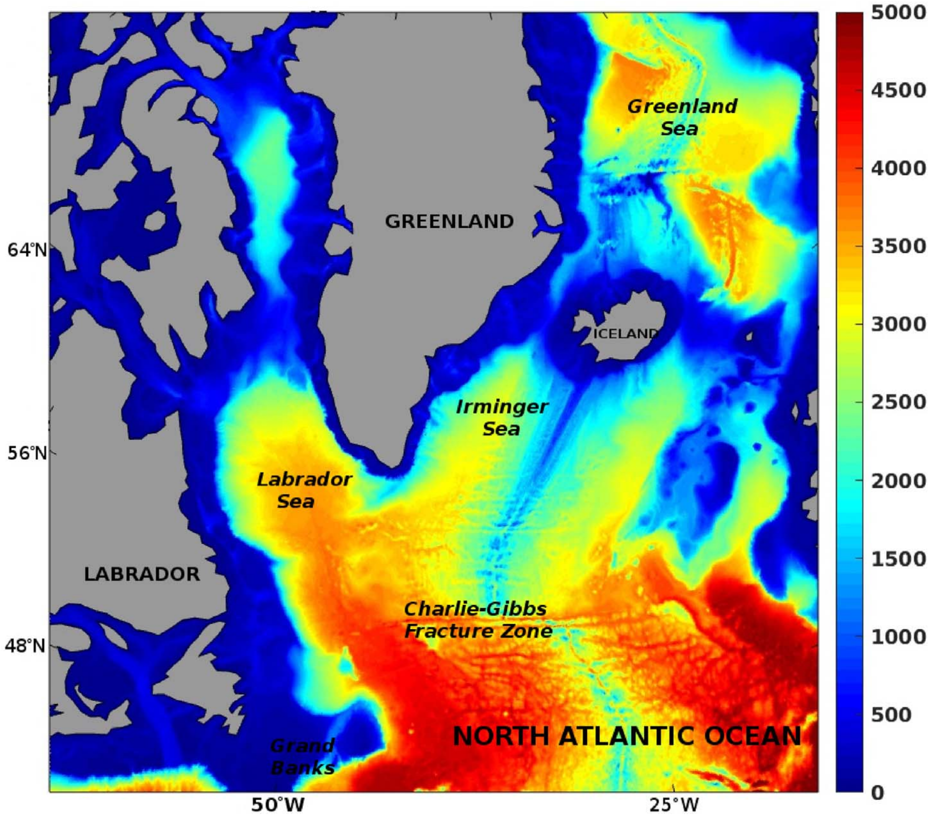

Fig. 1. Map focusing on a part of the sub-polar gyre in the North Atlantic, showing the Labrador, Irminger and Greenland Seas. The color represents the depth in meter.

less dense than the surrounding water. Recent publications pointed out other regions such as the Irminger Sea (Pickart et al., 2003a; de Jong et al., 2012; Piron et al., 2016; Paquin et al., 2016) and the Weddell Sea (Gordon et al., 2007; de Lavergne et al., 2014) as additional locations for deep convection. Gordon et al. (2007) showed that the deep-reaching ocean convection in the Weddell Polynya in mid-1970s resulted from a prolonged period of negative Southern Annular Mode (SAM). As the negative SAM phase reduced the precipitation over the Weddell surface water, the winter cooling of the salty surface preconditionned the convection in this area.

The Labrador Sea (*c.f.* Fig. 1) remains the most observed region regarding deep convection in the North Atlantic Ocean (Kieke and Yashayaev, 2015). Estimating the resulting Labrador Sea Water (LSW) is crucial as it impacts the ventilation of intermediate waters, and consequently the lower limb of the Atlantic Meridional Overturning Circulation (AMOC) (Pickart et al., 2003b). The linkage between LSW and the strength of the AMOC is still under debate (Lozier, 2012). Observations show that deep water convection in the LS has intensified in the last few years (Yashayaev and Loder, 2017), and that the decreasing strength of the AMOC is arguable (Parker and Ollier, 2016). The Overturning in the Subpolar North Atlantic Program (OSNAP) works to quantify the subpolar AMOC and its variability, as well as its connectivity to the deep boundary current system (Lozier et al., 2016). By defining a better MLD, especially during convective events, better estimations of the impact of the LSW on the AMOC could be achieved.

LSW formation has a long monitoring history (Kieke and Yashayaev, 2015). After consecutive severe winters, by the end of 1994, the resulting LSW was the coldest, the densest and the most voluminous water mass since 1960, extending to 2400 m (Lazier et al., 2002; Yashayaev et al., 2003). In 2000s, the MLD recorded in the Labrador Sea ranged from 700 m to 1600 m (Yashayaev and Loder, 2009). In winter 2007/2008, a deep convection event occured producing a dense LSW with a MLD reaching 1600 m (Våge et al., 2009; Yashayaev and Loder, 2009). Several MLD climatologies were recently published on global (de Boyer Montégut et al., 2004; Kara et al., 2003) and regional scales (*e.g.*, Mediterranean Sea (D'Ortenzio et al., 2005; Houpert et al., 2015), Southern Ocean (Dong et al., 2008)). Kara et al. (2003) used a density-based criterion with fixed temperature difference and variable salinity to provide monthly climatological fields of MLD for the global ocean. The authors constructed MLD fields on temperature and salinity data from World Ocean Atlas 1994. Other observational studies compiled in situ data, such as Argo data, to define their MLD (Holte and Talley, 2009; Chen and Yu, 2015).

In ocean modelling, diagnostic MLD is usually calculated from model outputs, using property difference methods based on the density difference (*e.g.*, 0.01 kg.m^{-3}) with the surface (Da Costa et al., 2005; Thomas et al., 2015). Although this approach works well on a global scale, it shows discrepancies when it comes to deep convection. Temperature-salinity compensation often yields a uniform potential density profile for a region below the actual ML, resulting in much deeper MLD estimates than is actually the case (Rudnick and Ferrari, 1999; Ferrari and Paparella, 2003). This may lead to misinterpreting the model output and its error, as well as misunderstanding the results and possible model improvement. For example, if the diagnostic MLD is taken at a deeper depth (usually over 2500 m in LS), the assessment of the model outputs could lead to an over-estimated volume of new LSW. Due to its linkage to the AMOC, an over-estimated and unusually dense LSW production could deceive in its impact on the North Atlantic circulation (Rattan et al., 2010). Spreading along the deepest isopycnals (Clarke and Gascard, 1983), one could think that the only pathway to cross the North Atlantic Ridge would be the Charlie-Gibbs Fracture Zone (CGFZ). The Labrador Current would be much deeper and more offshore following the local bathymetry. As the LSW is contributing to the lower limb of the AMOC, we might expect a greater northward transport of lighter water masses. Although diagnostic MLD does not interfere with the dynamics of the model itself, a better estimation of the MLD could contribute to a better dynamical understanding of the model output.

In this present work, we study the calculation of the MLD in deep convection regions in geopotential coordinate numerical models. The