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Modifications of mode water properties by sub-mesoscales in a bio-physical model of the Northeast Atlantic

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ABSTRACT

Northeast Atlantic mode waters (NEAMW) are formed by subduction in a region which is a strong sink of atmospheric CO_2. The mechanisms underlying this sink were thoroughly examined in the frame of the POMME experiment, which covered the 2001 seasonal cycle with particular focus on meso to sub-mesoscales. The biological and physical data collected during POMME were used to initialize, constrain and evaluate a regional, 4.5 km-resolution, bio-physical model simulation of the 2001 seasonal cycle in the region of NEAMW formation. We used this model to examine the contribution of sub-mesoscales on the annual budget of carbon export below the mixed-layer and on NEAMW biogeochemical characteristics. This is done by comparing a high-resolution (*eddy*) simulation at 4.5 km resolution with a high-diffusivity (*non-eddy*) simulation where the only change is a stronger eddy diffusivity. We found that the model mixed-layer depth is more stratified and closer to reality in the *eddy* simulation. This result confirms with observational data the proposed mechanism of restratification of the upper ocean driven by sub-mesoscales. We found that the phytoplankton bloom and the subduction of NEAMW display strong contrasts at the sub-mesoscale. Nevertheless, the mean intensity of the bloom and of the subsequent biological pump are only marginally modified by sub-mesoscales (less than 5%), while the intensity of the physical pump (subduction of carbon) is moderately reduced (−10%) in the *non-eddy* experiment. Moreover, the biogeochemical and thermodynamical characteristics of NEAMW are substantially affected, with, in particular, a wider range of densities and biogeochemical characteristics biased toward winter conditions in the *eddy* simulation. These differences ensued essentially from lateral induction across sub-mesoscale filaments, which is found to contribute to subduction before seasonal stratification, i.e. before the effective subduction period.

1. Introduction

Northeast Atlantic mode waters (NEAMW) are a light variety of sub-polar mode waters, centered on the potential density 1027.0 kg/m^3. They are formed by subduction in the midlatitude Northeast Atlantic (McCartney and Talley, 1982; Reverdin et al., 2005, 2009). According to the traditional standpoint, NEAMW subduct north of 42 °N where the maximum winter mixed-layer depth is often larger than 200 m (Marshall et al., 1993; Paillet and Arhan, 1996). The seasonal retreat of the mixed layer between winter and spring leaves a thick layer of weakly stratified water, the NEAMW. This large volume of water is then advected southward by the southern branch of the North Atlantic current, and crosses a strong gradient of winter mixed-layer depth near 42 °N (Fig. 1, de Boyer Montegut et al., 2004). After crossing this gradient, it remains below the seasonal mixed-layer, and is slowly advected at sub-surface across part of the North Atlantic, before been re-entrained after a few years in the surface layer in obduction regions (Marshall et al., 1993). NEAMW acquire their physical (temperature, salinity) and biogeochemical (nutrient concentrations) characteristics in the region where they are formed and at the time when they escape the surface mixed-layer. They are then transported across the subtropical gyre. Mode water characteristics are important because they constitute the sub-surface nutrient reservoir and eventually condition downstream productivity (Sarmiento et al., 2004; Palter et al., 2005; Williams et al., 2006; Reverdin et al., 2009).

The POMME program conducted in 2001 was aimed to investigate the process of NEAMW formation and their biogeochemical properties (Memery et al., 2005). An important outcome of POMME was the evidence that frontogenesis at sub-mesoscale fronts played a role in NEAMW subduction (Paci et al., 2005; Reverdin et al., 2005; Giordani et al., 2005). These sub-mesoscale fronts were

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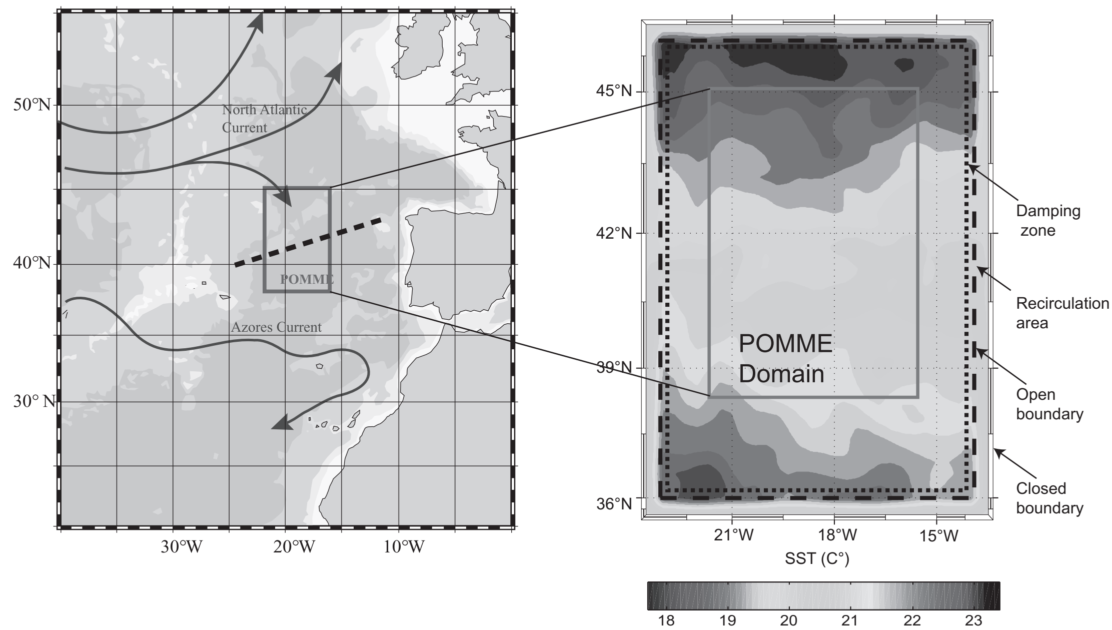

Fig. 1. Location of the POMME domain. The left panel displays the topography (grey shading), with a schematic representation of the main currents (black arrows) and of the strongest gradient in winter mixed-layer depth (dashed line). The right panel shows the initial sea surface temperature field in the model (27 Sept., 2000), issued from the MERCATOR MERA-11 reanalysis, with the coldest temperatures in the north of the domain and the warmest in the south. The damping zone of the model is comprised between the doted line and the open boundary (dashed line). The recirculation area is comprised between the open boundary and a closed boundary.

essentially formed by the deformation field associated with the numerous mesoscale eddies found in the area during the experiment. They had a length of $\mathcal{O}(100\ \text{km})$, a width of $\mathcal{O}(10\ \text{km})$ and persisted over $\mathcal{O}(10\ \text{days})$.

The importance of sub-mesoscale frontogenesis on subduction was originally established for energetic, eddy-rich regions (Follows and Marshall, 1994; Spall, 1995; Williams et al., 1995; Marshall, 1997; Hazeleger and Drijfhout, 2000; Thomas and Joyce, 2010). In the POMME area, the average southward circulation is $\mathcal{O}(1\ \text{cm s}^{-1})$ whereas the eddy structures have velocities of $\mathcal{O}(10\ \text{cm s}^{-1})$ according to satellite altimetry: this characterizes the area as rather quiescent (Ducet et al., 2000). Certainly, in quiescent regions, the contribution of eddy subduction is less than in more energetic regions. Nervertheless, previous model studies (Valdivieso da Costa et al., 2005; Gebbie, 2007), including one devoted to POMME (Paci et al., 2007), suggest that it cannot be neglected in the total subduction budget.

From a biogeochemical perspective, the region of NEAMW formation is the scene of a medium-range spring phytoplankton bloom (Levy et al., 2005b) and is also recognized as a strong sink region for atmospheric CO_2 (Takahashi et al., 1995; Rios et al., 1995). This strong CO_2 sink is due both to the biological pump associated with the spring bloom and to the physical pump associated with NEAMW subduction (Karleskind et al., 2011).

The biogeochemical characteristics of NEAMW thus result from a tight coupling between the timing and duration of subduction versus the timing and duration of the spring bloom. If subduction occurs well after the spring bloom, then nutrients are consumed by photosynthesis before the water mass leaves the surface, resulting in the formation of nutrient-poor mode waters (Kremeur et al., 2009). On the other hand, if subduction occurs well before the bloom, mode waters subduct with nutrient-rich, winter characteristics.

This study aims to investigate the role played by sub-mesoscale fronts in the subduction of NEAMW, with particular focus on the physical and biogeochemical characteristics of NEAMW. Specifically, we address the following questions: (1) How do sub-mesoscale fronts impact NEAMW subduction and how are subduction intensity and timing modified when physical processes occurring at sub-mesoscales fronts are accounted for? (2) How do these sub-mesoscale physical processes affect the phytoplankton bloom intensity and timing in the Northeast Atlantic? (3) What are the consequences of (1) and (2) in terms of the physical and biogeochemical characteristics of NEAMW?

These questions are addressed in the frame of the POMME experiment, during which four oceanic cruises surveyed an area of 7° by 5° centered on 42 °N during the complete seasonal cycle in 2001 (Fig. 1, Memery et al., 2005). The large amount of data collected during POMME enabled the construction of a high-resolution bio-physical model for the area, constrained with the observations (Levy et al., 2005a; Paci et al., 2005, 2007; Resplandy et al., 2009, Karleskind et al., 2011). In Karleskind et al. (2011), this model was used to provide large scale, integrated annual budgets of carbon, nitrogen and oxygen over the POMME region.

In this study, the experiment of Karleskind et al. (2011) is revisited with a focus on the role of sub-mesoscale fronts. For that purpose, the results are compared with those of a "coarse-resolution like" simulation where mesoscale eddies are dissipated, precluding the formation of sub-mesoscale fronts. In the next section, the model experiments are presented. Then the model results are presented in three sections. The first presents the basic characteristics and differences between the two model solutions, the second presents more focused diagnostics on NEAMW subduction, and the third examines the impact in terms of carbon fluxes. Finally, the last section discusses the model results.

2. Context and method

2.1. Model configuration

Our analysis are based on the results of a regional, bio-physical model of the POMME area, integrated over the duration of the POMME experiment during which meteorological and in situ data