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A multi-column vertical mixing scheme to parameterize the heterogeneity of oceanic conditions under sea ice

Antoine Barthélemy[a,*], Thierry Fichefet[a], Hugues Goosse[a], Gurvan Madec[b,c]

[a] Georges Lemaître Centre for Earth and Climate Research (TECLIM), Earth and Life Institute, Université catholique de Louvain, Louvain-la-Neuve, Belgium
[b] LOCEAN-IPSL, Sorbonne Universités, (UPMC Paris 6), CNRS/IRD/MNHN, Paris, France
[c] National Oceanography Centre, Southampton, United Kingdom

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ABSTRACT

The heterogeneity of ocean surface conditions associated with a spatially variable sea ice cover needs to be represented in models in order to represent adequately mixed layer processes and the upper ocean density structure. This study assesses the sensitivity of the ocean-sea ice model NEMO-LIM to a subgrid-scale representation of ice-ocean interactions. The sea ice component includes an ice thickness distribution, which provides heterogeneous surface buoyancy fluxes and stresses. A multi-column ocean scheme is developed to take them explicitly into account, by computing convection and turbulent vertical mixing separately in the open water/lead fraction of grid cells and below each ice thickness category. For the first time in a three-dimensional simulation, the distinct temperature and salinity profiles of the ocean columns are allowed to be maintained over several time steps. It is shown that the model response is highly sensitive to the homogenization time scale between the columns. If the latter are laterally mixed with time scales shorter than 10 h, subgrid-scale effects exist but the mean state is practically unaffected. For longer mixing time scales, in both hemispheres, the main impacts are reductions in under-ice mean mixed layer depths and in the summer melt of sea ice, following decreased oceanic heat flux at the ice base. Large changes in the open water temperature in summer suggest that the scheme could trigger important feedback processes in coupled simulations.

1. Introduction

The sea ice covering the surface of polar oceans is an extremely heterogeneous medium. Within a restricted region, areas of open water, thin newly-formed ice, level ice a few meters thick or pressure ridges several meters thick may be found (Thorndike et al., 1975). Because the insulating properties of ice strongly depend on its thickness, the atmosphere-ice-ocean interactions are highly spatially variable as well. The ice growth rate, which is associated with brine rejection in the underlying ocean, decreases rapidly with thickness, especially for thin ice (Maykut, 1982). Furthermore, warming of the oceanic mixed layer in summer results mostly from the absorption of solar radiation in ice-free areas (Maykut and McPhee, 1995). The effects of sea ice on the sea surface temperature and salinity, hence on upper ocean stratification and mixing, are therefore variable at small horizontal scales. The mixed layer dynamics, on the other hand, is of crucial importance for the evolution of the sea ice cover. Indeed, it determines the ice bottom boundary conditions, most importantly influencing the ice energy balance through modulations of the oceanic heat flux at the ice base.

Modeling studies have shown that representing the heterogeneous nature of ocean surface boundary conditions under sea ice might be necessary to achieve an adequate simulation of the upper ocean physics in polar regions (Losch et al., 2006). Convective mixing related to intense brine rejections following ice formation is for instance likely to prevail only in open water or thin ice areas, which may represent a small fraction of grid cells in large-scale models. Brine rejection parameterizations have been developed to mimic such processes (e.g., Nguyen et al., 2009), but their effect is to suppress convection instead of making it localized (Barthélemy et al., 2015). They are consequently not able to account for the entrainment of water from the upper pycnocline, which could constitute a significant component of the mixed layer heat budget (e.g.,

* Corresponding author. Georges Lemaître Centre for Earth and Climate Research, place Louis Pasteur 3, box L4.03.08, 1348 Louvain-la-Neuve, Belgium.

E-mail addresses: antoine.barthelemy@uclouvain.be (A. Barthélemy), thierry.fichefet@uclouvain.be (T. Fichefet), hugues.goosse@uclouvain.be (H. Goosse), gm@locean-ipsl.upmc.fr (G. Madec).

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Polyakov et al., 2013; Close and Goosse, 2013). In the Arctic, a part of the solar heat that is absorbed in summer is indeed stored in a near-surface temperature maximum below the mixed layer (e.g., Jackson et al., 2012; Timmermans, 2015). In addition, although they are largely insulated from the surface layer by the strong halocline stratification (e.g., Toole et al., 2010; Shaw and Stanton, 2014), warm waters of Atlantic and Pacific origins are present at depth in the Arctic Ocean. Because of the much weaker stratification, entrainment of heat from below the mixed layer by localized convective mixing might be even more important in the Southern Ocean (e.g., Gordon and Huber, 1984; Martinson, 1990; Wong and Riser, 2011).

In most advanced sea ice models nowadays, an ice thickness distribution is used to represent the subgrid-scale variability of ice thickness, which has long proven crucial to simulate accurately the ice cover evolution (e.g., Hibler, 1980). Heterogeneous ocean surface boundary conditions are therefore available in such models. For example, in the coupled ocean-sea ice model NEMO-LIM (see the next section for description), all surface variables behave very differently in the open water fraction of grid cells compared to the ice-covered one (Barthélemy et al., 2016). This includes freshwater, salt, solar heat and non-solar heat fluxes and the surface stress. Salt and freshwater fluxes, as well as the solar heat flux reaching the under-ice interface in the Arctic, further show a strong dependency on ice thickness. However, the coupling with a single ocean grid cell underneath requires the subgrid contributions from the various fractions of the surface to be aggregated (Fig. 1). The information about their heterogeneity is hence not utilized and potentially important subgrid-scale ocean physics is not resolved. Such merging of subgrid-scale fluxes amounts to assuming an instantaneous lateral mixing between the different parts of the ocean model columns. Although horizontal homogenization definitely occurs, it is most likely not instantaneous in all situations. For instance, measurements performed during the SHEBA campaign (Surface Heat Budget of the Arctic Ocean) have shown that, following a period of calm winds, the surface of a lead had warmed to around 1 °C above the freezing point and freshened to become close to 15 PSU (Holland, 2003).

Previous studies have investigated the implications of explicit subgrid-scale vertical mixing schemes on ocean and sea ice simulations. By performing the mixed layer calculations separately in six columns corresponding to five ice thickness categories and to open water, Holland (2003) reproduced in a one-dimensional ocean and sea ice model the above-mentioned warming and freshening of summertime leads observed during SHEBA. In this study, the ice-covered columns were laterally mixed every time step, while the mixing with the open water column occurred every six hours. A large sensitivity to this homogenization time scale was underlined. Jin et al. (2015) implemented a two-column vertical mixing scheme in an ocean-sea ice configuration of the Community Earth System Model (CESM). The total salt flux resulting from ice growth was applied solely in one of the two columns, and lateral mixing between them occurred at the end of each time step. They noted strong effects on the simulated mixed layer depths only when the salt column was reduced to a size much smaller than the actual lead fraction. In the different context of heterogeneous ocean convection related to unresolved eddies, Ilıcak et al. (2014) also developed a two-column scheme with a homogenization at each time step. In contrast to the previous examples, changes in the depth of convective mixing between the columns were not caused by heterogeneous surface fluxes, but rather by different initial stratifications in each of them. Strong assumptions were needed to set the relative size of the two columns as well as the imposed spread in density profiles.

Our main objective in this study is to assess the impacts of a representation of subgrid-scale ice-ocean interactions on the NEMO-LIM model results. For that purpose, an improved multi-column ocean mixing scheme has been developed for NEMO-LIM, based on and generalizing the studies described above. The basic principle is to divide each ocean grid cell in several columns, whose areas are imposed by the ice thickness distribution and the open water fraction provided by the sea ice model. Those columns are forced at the surface by available subgrid fluxes and vertical physics computations are done separately in each of them (Fig. 1). The major novelty lies in the possibility to maintain different columns properties over several time steps. It is the first time that this option is enabled in three-dimensional simulations. The sensitivity to the columns' homogenization time

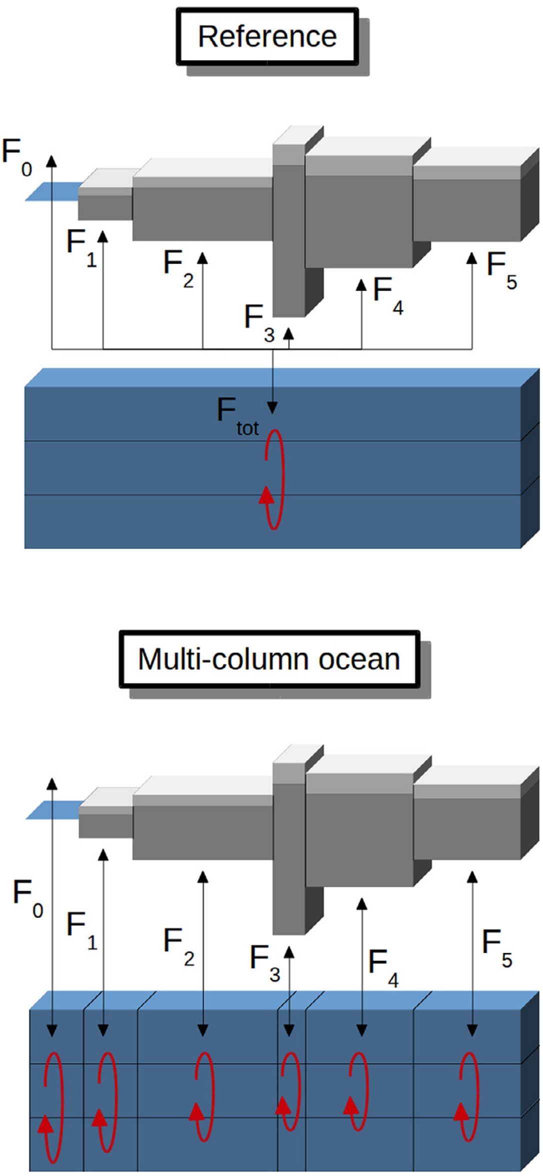

Fig. 1. Schematic illustration of the main principles of a multi-column ocean scheme. In the reference case, the subgrid fluxes and stress (F_n) from the sea ice model are aggregated before being transmitted to the single ocean grid cell underneath, and the ocean vertical physics computation (represented by a red arrow) is unique. In the multi-column case, the water column is divided into several sub-columns, corresponding to the open water fraction and to the categories of the ice thickness distribution. The specific fluxes and stress are applied at the surface of the sub-columns and the oceanic vertical physics is computed separately in each of them. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)