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Short communication

Benefits from representing snow properties and related processes in coupled ocean–sea ice models

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ABSTRACT

Several large-scale sea ice simulations are performed over the last three decades using a coupled ocean–sea ice model under the same experimental setup but partly modifying the representation of snow physics in the model. The inter-simulation spread analysis yields that the simulated multi-year ice is sensitive to such changes while the seasonal sea ice, is rather dominantly driven by the external oceanic and atmospheric forcings. In the context of a thinning Arctic sea ice cover, those findings suggest that including snow processes in large-scale sea ice models is beneficial, if not necessary, to predict the timing of the Arctic multi-year ice disappearance, whereas the operational forecasting of first-year ice extent using fully coupled models will likely require improvement to the oceanic and atmospheric components themselves.

1. Introduction

Snow on sea ice is a key component of the polar climate system. A review of the snow-related properties and processes of major relevance with respect to the sea ice energy and mass balances was established by Sturm and Massom (2009). Among them, the high albedo of snow as compared to the ocean or bare ice is probably the most important, drastically lessening the shortwave radiation input into the ice pack. Second, snow is a highly efficient insulator that reduces ice–atmosphere heat exchange, which smoothes temperature changes into snow and ice compared to the atmosphere and moderates the bottom ice growth rate. Snow directly contributes to the sea ice mass balance through snow ice formation, widespread in the Southern Ocean. The presence of snow generally delays the surface melting of the ice; however once snow starts melting, melt ponds start increasing in size, which lowers the albedo and enhances surface sea ice melting.

Snow has therefore long been expected to be an important component in sea ice models, with several studies supporting this idea (e.g., Eicken et al., 1995; Fichefet and Maqueda, 1999; Wu et al., 1999; Fichefet et al., 2000; Blazey, 2012; Blazey et al., 2013). Even so, its actual representation has so far been somewhat disregarded and kept relatively crude. Only recently, a new snow scheme was proposed in Lecomte (2014) and Lecomte et al. (2014) for use in large-scale sea ice models, including a melt pond formalism as well (Flocco and Feltham, 2007). The latter studies showed in particular an increased sensitivity of the Arctic multi-year ice (MYI) volume and of its summer melt pond cover to the effect of blowing snow on the late spring snow depth distributions on sea ice, in comparison with first-year ice (FYI). Extrapolating from those findings, the question of the distinct sensitivities of FYI and MYI to the physics of snow in present-day climate simulations may be asked in a broader way. This paper aims at addressing this issue in both the Arctic and the Antarctic, by analyzing the spread (simple statistical dispersion) between various simulations of a global ocean–sea ice model for which only snow parameterizations vary. The next two sections therefore give a brief overview of the models we use and the simulations we carried out, before results and their implications for future snow developments in sea ice models are discussed in the last two sections.

2. Model description

The coupled ocean–sea ice model we use here is NEMO-LIM (Nucleus for European Modeling of the Ocean – Louvain-la-Neuve Sea Ice Model), described in Madec (2008) for the ocean general circulation model OPA (Ocean PArallelisé, version 9) and Vancoppenolle et al. (2009) for the sea ice model LIM3 (LIM, version 3). LIM3 is a so-called multi-category, dynamic–thermodynamic sea

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ice model providing an explicit representation of the subgrid-scale ice thickness distribution. In order to complete this study, a physically based melt pond scheme and a new snow physics scheme were recently incorporated in the model. The melt pond formulation of Flocco and Feltham (2007) is utilized here. It retrieves the pond depth and fractional coverage of the sea ice based on the ice thickness distribution and the fresh water volume available to fill in the ponds. The snow representation includes a multi-layer snow thermodynamic scheme, accounting for the vertical heat transfer through snow layers with varying density and thermal conductivity and for the radiative transfer in the uppermost snow layers (following Beer's law and extinction coefficient from Järvinen and Lepparanta, 2011). The mass balance includes surface melt or sublimation based on the imbalance of the surface heat budget, internal melting and refreezing of fresh water into the snow (following Cheng et al., 2006), snow ice formation subsequent to flooding (as in Fichefet and Morales Maqueda, 1997) and a simple formulation of the effect of snow packing by winds on the snow density profile (Lecomte et al., 2013). The model also includes an intuitive parameterization of the snow redistribution by winds on the ice categories within a grid cell. This subgrid-scale redistribution process depends on the wind speed, snow density and the shape of the ice thickness distribution. It also accounts for snow losses in leads when winds blow snow away on top of an open sea ice pack. The comprehensive physical design of the snow scheme is described in Lecomte (2014) and Lecomte et al. (2014).

3. Simulations

In this section, we provide a succinct description of the main characteristics of each model run. Except for the last simulation described hereafter, the experimental setup and the atmospheric fields used to force the model are the same as in Lecomte (2014) and Lecomte et al. (2014). NCEP/NCAR daily reanalyses are used for 2 m air temperature and 10 m u- and v- wind components (Kalnay et al., 1996). Climatologies of Berliand and Strokina (1980) and Trenberth et al. (1989) are utilized for total cloudiness and relative humidity, respectively. Surface heat fluxes are computed following Goosse, 1997. For the snowfall specifically, we use the precipitation anomalies from DFS5.2 (DRAKKAR Forcing Set, version 5, Dussin and Barnier, 2013) added to the climatology of Serreze and Hurst (2000) in order to get a more realistic snowfall regional variability. DFS5 was obtained by applying the method of Brodeau et al. (2010) to the ERA-interim reanalysis product (Simmons et al., 2007; Dee et al., 2011).

The first simulation was performed enabling all snow and melt pond processes available in the model. This run is described and evaluated against observations in Lecomte (2014) and Lecomte et al. (2014). In short, the model demonstrates good skills in simulating the sea ice extent in both hemispheres (with respect to satellite observations), although the sea ice volume tends to be biased low in the Arctic. It also features realistic snow depth distributions and melt pond fractions in average over the Arctic Basin. In the second simulation, melt ponds were disabled, which resulted in a 40% (winter) to 50% (summer) higher mean Arctic sea ice volume as compared to the first one, due to the higher albedo and subsequent weaker sea ice surface melting in summer. Simulation 3 is the same as 2, except that the snow thermal conductivity was set equal to 0.31 W m^{-1} K^{-1}, a commonly used value in ocean–sea ice coupled models. This led to even higher sea ice volumes in both hemispheres as a result of increased winter ice growth rates (Lecomte et al., 2013). The melt pond scheme was kept active in the fourth simulation, but the albedo of deep melt ponds was lowered from 0.3 to 0.2. Owing to a slightly enhanced shortwave radiative forcing in this run, the mean Arctic sea ice volume decreased, but in small proportions. The reason for this is that ponds in the model are probably too shallow for the pond albedo to reach the deep-pond value. No major impact was observed on Antarctic sea ice, as melt ponds formation is very limited in the southern hemisphere. Run 5 was performed turning off the internal melting and refreezing of the fresh water into the snow. Again, the large-scale impacts on the simulated sea ice was not significant overall, because fresh water and cold snow are not necessarily present simultaneously, at least on FYI. The sixth simulation is also described in Lecomte (2014) and was achieved increasing the intensity of the blowing snow process in the model. Although the effect on the Arctic sea ice melt pond cover is small on average, it is clearly noticeable on MYI specifically, and influential enough to cause a ~10% loss in seasonal mean sea ice volume over the whole basin. The seventh and last simulation is identical to the first except that the snowfall forcing was changed back to a single climatology (Serreze and Hurst, 2000), mainly inducing changes in the geographical distribution of snow depths. For the sake of clarity, simulations are outlined in Table 1.

In the following, all simulations are analyzed over 1982–2011. The aim is not to proceed to the detailed analysis of each simulation, but rather to generally determine the extent to which changing the physical representation of snow in the model affects the main sea ice state variables, namely the total area and volume.

4. Results and discussion

In order to perform this analysis, the time series of the spatially integrated multi-year, first-year and total sea ice volumes in each hemisphere through 1982–2011 were first computed. The relative spread in ice volume between simulations, defined as the interquartile range (IQR) normalized by the median value over all simulations at a given date, was then retrieved for each ice type. The IQR/median statistics are used here instead of the standard deviation/mean usual ones because they are applied on a relatively small number of simulations and hence on data that do not particularly follow a Gaussian distribution. The trends of all time series and the average relative spread in ice volume between simulations over the period of analysis were finally computed and are reported in Table 2, together with the same statistics for sea ice area and snow volume in both hemispheres.

Firstly, the analysis indicates negative and positive trends in both the area and volume of the Arctic MYI and FYI, respectively, which is in agreement with the current status of Arctic sea ice studies (e.g., Maslanik et al., 2007; Kwok and Untersteiner, 2011), showing a progressive transition towards a seasonal Arctic sea ice cover. In the Antarctic however, those trends are both positive and corroborate the findings of Comiso and Nishio (2008) and Zhang (2014). Note that the signs of the trends in snow volume and ice volume are the same. This is to be expected since thicker ice, potentially older, is predisposed to a larger snow accumulation.

Second and most importantly, Table 2 exhibits systematically larger spreads for MYI than for FYI, except for Arctic sea ice area. The latter exception is discussed thereafter. The smaller spread on FYI can be explained by both the shorter lifetime of this type of ice and the competing processes it may undergo. Indeed, snow may accumulate on young ice only after it starts freezing, as opposed to the accumulation on older ice that survived the melt season. This natural limitation is critical in the Arctic where the maximum of snowfall occurs concurrently with the minimum in ice extent in September, which reduces the impact of changes in daily snowfall rates on the simulated Arctic FYI mass balance. In addition, an increase in snowfall rate triggers a series of competing processes that tend either to increase or decrease the ice thickness. First, in the cold season, more snow induces more thermal