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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

Table 1
List of all performed simulations.

Simulation number	Simulation specificity
1.	Simulation with all new components enabled (snow and melt ponds), as in Lecomte (2014) and Lecomte et al. (2014)
2.	1. with melt ponds disabled
3.	2. with constant snow thermal conductivity equal to 0.31 W m^{-1} K^{-1}, as in Lecomte et al. (2013)
4.	1. with decreased deep pond albedo from 0.3 to 0.2
5.	1. with internal melting/refreezing of fresh water into snow disabled
6.	1. with increased erosion rates in blowing snow parameterization, as in Lecomte (2014) and Lecomte et al. (2014)
7.	1. with climatology of Serreze and Hurst (2000) only for snowfall forcing (no variability)

Table 2
Mean relative inter-simulation spreads and trends of the total sea ice volume, sea ice area and snow volume over 1982–2011, for both hemispheres. The mean relative inter-simulation spread of a variable is calculated as the ratio between its interquartile range (IQR) and its median value over all simulations (hence in %), averaged over the whole period of analysis. Trends are all significant at the 95%-confidence level.

	FYI		MYI	
	Mean spread %	Trend units[a] per decade	Mean spread %	Trend units[a] per decade
Arctic				
Sea ice volume [$\times 10^3$ km^3]	9.0	0.37	31	−3.3
Sea ice area [$\times 10^6$ km^2]	6.7	0.49	7.2	−0.97
Snow volume [$\times 10^3$ km^3]	21	0.049	81	−0.78
Antarctic				
Sea ice volume [$\times 10^3$ km^3]	14	−0.027	36	0.087
Sea ice area [$\times 10^6$ km^2]	10	0.064	27	0.12
Snow volume [$\times 10^3$ km^3]	23	−0.023	31	0.0060

[a] Corresponding units from the leftmost column.

insulation, a smaller oceanic heat loss to the atmosphere and, in turn, less basal ice growth. Second, if sufficient snowfall pushes the snow–ice interface below the sea level, snow ice starts to form, contributing to thicker ice. Finally, the summer melting of a thicker snow cover may ultimately lead to larger melt pond fractions on the sea ice and hence larger ice melt through the decrease in surface albedo. Thus, those competing processes moderate the impacts of an initial change in snow depth, due to altered snow physics or precipitation in the model, on the growth and melt of FYI. In contrast, MYI, which is thicker, enables both larger accumulation of snow throughout the year and larger water retention for melt pond formation in summer due to its uneven topography. A significantly thicker snow cover may persist through all or part of the summer, therefore protecting the ice surface from intense melting and impeding the development of melt ponds. On the other hand, the increased insulation effect of such a deeper snow pack combined with its total summer melting would result in both larger sea ice melting due to larger melt pond cover and reduced wintertime ice growth. The latter processes, subserving a progressive decrease in ice thickness, would then contribute to the replacement of MYI by FYI that would in turn accumulate less snow. In this sense, FYI is less sensitive than MYI to changes in snow physics or snowfall forcing in the model, since the snow-related processes and the snow–ice feedbacks that take place on FYI are limited by its seasonality. Besides, FYI has by definition no memory, whereas MYI may cumulate changes over the years. Hence, the larger sensitivity of MYI volume to changing physics in the model might even be a more general characteristic, with respect to FYI. As already mentioned, the Arctic sea ice area is the exception to the earlier finding that there is a systematic increase in spread from FYI to MYI. Here we find no statistically significant difference in the spread of Arctic ice area between the MYI and FYI (both close to 7%). The reason is twofold. First, snow processes in the model do not influence sea ice area directly. Second, contrarily to the Antarctic MYI that is relatively thin and may switch to a FYI regime more easily, a significant fraction of Arctic MYI is thick and resilient enough for not shifting regime and suffering from losses in coverage. Notwithstanding, this might be expected to change in a longer simulation where the MYI fraction in the Arctic would be further reduced.

An other interesting fact from Table 2 is that, although the relative spread between simulations is smaller for FYI than MYI in the Southern Ocean, it is still considerably larger than for Arctic FYI. Antarctic sea ice in simulations features only little surface melt, as compared to its Northern counterpart (Lecomte et al., 2013), and its mass balance is mainly governed by basal growth and melt, and snow ice formation. As explained earlier, those processes tend to compete against each other in terms of impact on the ice growth, but snow ice formation also mitigates any change in snow depth since it is a sink mechanism for snow. The snow and ice column being assumed in hydrostatic equilibrium in the process, a larger snow load on the sea ice induces larger snow ice production, all the while decreasing the snow depth, and conversely. As a consequence, alterations of the snow insulation effect by means of snow depth variations are mitigated likewise. The widespread occurrence of snow ice formation on Antarctic seasonal sea ice therefore gives the snow a greater influence through this process.

The inter-simulation spreads of Table 2 also exhibit a temporal evolution (not shown in the table) that is naturally explained by the aforementioned remarks. In the Arctic, the spread in FYI and MYI volume decreases toward the end of the simulations, accompanying the gradual replacement of MYI by FYI and suggesting a model sensitivity to the snow physics that is accordingly reduced. The Antarctic sea ice pack however, mainly seasonal, yields a weaker sensitivity to changes in snow parameterizations or accumulation in the model all along the period of analysis, which is consistent with the findings of, e.g., Massonnet et al. (2011) or Rae et al. (2014), showing a generally weaker sensitivity of the Antarctic sea ice to snow and sea ice physical parameters in large-scale models. This ultimately suggests that, in both hemispheres, the interannual variability of FYI is mainly driven by external forcing such as the heat fluxes from the ocean and the atmosphere, while both the variability and trend of the total Arctic MYI volume are responsive to both the forcing and the representation of snow in the model.

Last but not least, it is worth noting that the large sensitivities discussed here for MYI may overestimate the sensitivity of the real system. For instance, an increase (decrease) in albedo is generally associated with a decrease (increase) in the net surface energy balance. Consequently, ice growth is enhanced (weakened), but this is moderated by a reduced (increased) surface air temperature and hence lower (larger) sensible and latent heat losses. By running the model under forced-atmosphere configuration, the surface air temperatures are specified and the latter negative feedback is removed. The changes in ice volume in response to the same modifications made here to the snow physics in a coupled atmosphere–ice–ocean model may be expected to be different.

5. Conclusion

This brief study reports on the sensitivity of the ocean–sea ice coupled model NEMO-LIM to the representation of snow processes and properties. A series of simulations using different snow parameterizations or snowfall forcings is analyzed over the same period (1982–2011). Consistently with the current literature on the sea ice extent and volume trends over the last decades, model simulations show a decline in Arctic MYI and its progressive replacement by FYI. Likewise, the recently observed increase in Antarctic sea ice extent is qualitatively captured by model simulations. The analysis of the inter-simulation spread for MYI and FYI yields that the simulated MYI state and its snow cover are affected by the snow processes in larger proportions than FYI is. This finding had briefly been pointed out by Flato and Brown (1996) but had, to our knowledge, never been reported for large-scale sea ice models. Those conclusions therefore explain the reduced sensitivity of NEMO-LIM to snow physics in the Southern Ocean, as compared to the Arctic's, and the decreasing dispersion between model runs in the northern hemisphere as the sea ice cover shifts from MYI to FYI toward the end of the simulations. Furthermore, they have several implications in terms of future model developments. As the growth and decay of seasonal sea ice seems primarily driven by external forcing, due to its smaller thermodynamical inertia, the priority in the framework of the operational predictability of sea ice using fully coupled models (that, in particular, currently tend to fail in simulating the increase in Antarctic sea ice extent over the past decades; Arzel et al., 2006; Zunz et al., 2013) will likely be to get the oceanic and atmospheric mean states and variability well simulated. This task is complex and in turn prerequires well resolved subcomponents, such as atmospheric chemistry or meltwater inflow from ice sheets and glaciers. Including and improving snow processes in sea ice models will nonetheless be a necessary condition to predict the timing of MYI disappearance. In our model, MYI production proved to be most sensitive to the effect of the heat transfer through the snow layers on the ice bottom growth and to the melt pond scheme. However the other parameterizations, in particular blowing snow, are still insufficiently constrained by observations and might happen to be just as important as the latter processes in a fine-calibrated fully coupled model. Extensive observations of such mechanisms are thus crucially needed in order to address properly the problem of snow parameterization improvement in sea ice models. For instance, measuring the mass fluxes of transported snow on sea ice during a storm, as well as snow depth distributions before and after the event, may allow to constrain our parameterization and improve it so as to represent the widespread occurrence of partially bare ice, suggested by existing observations.

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