

Review: tc-2021-174, “The influence of snow on sea ice as assessed from simulations of CESM2”, by Marika Holland et al.

1. GENERAL COMMENTS

This work is of considerable importance. It addresses a major gap in our understanding of Earth’s polar sea-ice environments and their likely trajectory in a warming climate – namely (change and variability in) the role of snow accumulation. At the same time, it provides new insight into the climatic importance of snow on sea ice, and identifies and highlights a number of important feedbacks in the system. Another important factor is that the paper directly compares results from both the Arctic and Antarctic, and highlights different hemispheric responses of sea ice in the two hemispheres as a result of differing simulations in snow accumulation in both Pre-Industrial and 2xCO₂ climate scenarios. This underlines the critical importance of accurately representing snow accumulation in Earth system models, and lays the groundwork for important future work towards more accurate representation of the cryosphere and cryospheric processes in such models.

The article is generally well written, and lays out its scientific rationale, discussion and conclusions in a clear, concise and well-structured fashion. There are relatively few grammatical and punctuation errors, but a number of ambiguous statements and uses of modeling jargon that may challenge the general reader (see SPECIFIC COMMENTS below) - but these can be easily fixed. Re the figures, these are largely informative and well presented, but I’m afraid that I’m colour blind so struggled with some of them – notably Figures 4, 6 and 7. The paper is also well referenced, with an appropriate number and quality of references.

I have a number of questions/issues regarding the methods used and the results and their interpretation – that I feel need addressing before the paper can be published. First up, it’s not clear how important snow properties (apart from thickness) – such as density, thermal conductivity and albedo - are treated/parameterised in the model, if at all. Other issues relate to the treatment of wind-blown snow removal/redistribution, and the conversion of snow to snow ice – the Methods section needs more information on the how snow is treated/parameterised in the model. Also, current observations of the thickness distributions of Antarctic sea ice and its snow cover are inadequate to validate model results such as those shown here e.g., in Figure 1d-e. A further question relates to the use of 70-90 deg as the geographical domain for both the northern and southern hemispheres i.e., in Figure 7. I can understand this for the Arctic, but not for the Antarctic – where 70-90 deg S mainly covers the Antarctic ice sheet and only partially covers the Antarctic sea-ice zone. There’s also an apparent discrepancy between the contributions of frazil ice to the mass balance in the model output (low) versus that which is typically observed (high). These and other questions/issues are outlined in SPECIFIC COMMENTS below.

Moreover, the Conclusions section would benefit from discussion of possible caveats and limitations in this study, and also future work that could or needs to be carried out in both observation and modeling. This could again highlight key gaps in our understanding of snow in the sea ice systems, the seasonal, regional and hemispheric dependence of the relationships, and the need for more large-scale observations of snow thickness and properties as well as accurate precipitation rates (see Webster et al., 2018). It should also address the snowfall v accumulation discrepancy factor (due to wind-blown snow redistribution/loss).

Given the importance of this work, the substantial large-scale conclusions reached and the fact that it represents substantial progress beyond current scientific understanding, may I recommend publication pending the authors addressing both the minor and more major comments/issues. In all cases, I hope that my comments/suggestions help.

2. SPECIFIC COMMENTS

- 2.1 The Introduction puts the study and its importance nicely into context, including previous work in the field. Possibly one thing lacking is equal coverage in the Introduction of snow on Arctic and Antarctic sea ice, and important properties and attributes therein from the perspective of this study. Notably, the 3 paragraphs from lines 40 to 69 almost exclusively focus on the Arctic. Please provide more information on what is known – and what is not known – about Antarctic snow on sea ice, and how it is relevant to this study.
- 2.2 Line 21 – what are these competing processes and feedbacks?
- 2.3 Line 34 – the assumption here is that sea ice thickens by thermodynamic growth alone, whereas dynamics are also important – this needs stating/clarifying here.
- 2.4 Line 36 – high snow albedo also reduces solar heating of the underlying ocean.
- 2.5 Line 48 – needs Andreas and Ackley reference.
- 2.6 I didn't fully understand Lines 53-57.
- 2.7 Regarding treatment of snow on Antarctic sea ice and the effects of snow on sea ice simulations - may I also suggest referring to: Wu et al. 1999 (Wu, X., W.F. Budd, V.I. Lytle, and R.A. Massom. 1999. The effect of snow on Antarctic sea ice simulations in a coupled atmosphere-sea ice model. *Climate Dynamics*, 15, 127-143).
- 2.8 Line 80 - State that SHEBA is an Arctic campaign.
- 2.9 Lines 87-88 – as stated, another important part of this question is how snow affects the retreat and duration of sea ice coverage, and whether there is regional and hemispheric dependence.
- 2.10 While the emphasis and focus is on snow accumulation/thickness, it is not clear from the Methods Section how snow properties (apart from thickness) are treated/parameterised in the model – if at all. These properties include snow density, related thermal conductivity, and grain size as it affects albedo/light transmission etc. What values are used for the different snow parameters (including albedo)? Also – how is snow converted into snow ice? Please include more information in the Methods section on how the snow is treated, and the possible caveats/limitations.
- 2.11 By the same token, it is not clear whether Antarctic snow is parameterised differently to Arctic snow in the model. What are the differences between the physical, optical and thermal properties of snow on Arctic versus Antarctic sea ice, and do they make a difference to (the modelling of) sea ice mass balance and areal coverage? – and if so, how?
- 2.12 Also, it's not clear how the model treats or accounts for any discrepancy between snowfall and snow accumulation, given horizontal redistribution of the snow by winds. Sorry if I'm missing something here, but I'm just wondering whether wind speed is taken into account in the model re the different climate state scenarios, and whether increasing (change in) wind speed can also be tested as an additional factor affecting snow accumulation. This point is stimulated by the tendency of snowfall over Antarctic sea ice to typically occur under stormy, windy conditions – with wind-blown horizontal redistribution being a major process determining the snow thickness distribution and also snow loss into leads. In other words, snowfall does not equal snow accumulation. This factor is acknowledged in lines 75-77 of the Introduction – but it's again not clear how or whether this “discrepancy factor” is accounted for here and, if not, whether this is an issue.

- 2.13 Also - while snowfall may increase in a warmer climate scenario, will this be compensated by increased wind-blown "loss" (including sublimation) in terms of snow accumulation on sea ice?
- 2.14 These additional snow factors/properties – on top of snow accumulation alone – may potentially be important in terms of their effects on sea-ice mass balance. My suggestion would be to state this in the Introduction (as possible caveats), then revisit in the Conclusions i.e., state there that the results presented here are based on accumulation only, and that more work is required (if this is the case). This would make a more convincing case for focussing on snow accumulation and thickness alone here. Maybe future work would/could involve sensitivity studies to account for what is currently known about Arctic and Antarctic snow physical and optical properties on sea ice.
- 2.15 Regarding these comments, may I suggest that the Methods section focus more on snow, how it is modelled here, and why that approach is taken. By the same token, the paper would benefit from providing more details on the nuts and bolts of the sea ice, atmosphere and ocean components of the model, and how hemispheric differences are catered for – in a Supplementary Section. While relatively concise, the current description provided in Lines 107-114 could be expanded upon in a Supplementary Section, to also remove jargon and aid/enhance the reader's understanding. It could also highlight current strengths and weaknesses of the model; this information is currently lacking.
- 2.16 Lines 108-114 – not clear to a non-modelling person – jargon.
- 2.17 Line 121 – what environmental conditions? Needs more detail.
- 2.18 Lines 126-128 – I read this a number of times but still didn't fully understand.
- 2.19 Line 130 – what atmospheric feedbacks? Give details here.
- 2.20 Lines 144-147 – these statements need backing up with references.
- 2.21 Lines 148-149 – it could be argued that current knowledge of large-scale sea ice thickness and its variability and change in space and time is very poor indeed and inadequate (see IPCC SROCC report etc.).
- 2.22 Line 154-155 – needs backing up with a reference.
- 2.23 Lines 158-161, Figure caption – make it clear here whether these are observed or modelled.
- 2.24 In the Results, one thing that struck me about Fig 2b – the SH mass budget control run – is the relatively low contribution of frazil ice (compared to congelation ice), as discussed in Lines 182-192. This is different to what is typically observed around Antarctica, with a relatively high proportion of frazil due to the highly-dynamic and turbulent conditions there. See for example: <http://aspect.antarctica.gov.au/home/about-sea-ice/ice-formation> (based on Worby et al., 1998): "Analysis of 173 cores taken on six voyages into the East Antarctic pack between 1991 and 1995 revealed that on average the pack was comprised of 39% columnar ice, 47% frazil ice and 13% snow ice, with other ice types making up the remaining 1%. These figures indicate the importance of the dynamic processes within the pack, which favour the growth of frazil ice. Snow ice is also seen to make a significant contribution to the total ice mass of the region." See also Lange and Eicken 1991 - (Lange, M., & Eicken, H. (1991). Textural characteristics of sea ice and the major mechanisms of ice growth in the Weddell Sea. *Annals of Glaciology*, 15, 210-215. doi:10.3189/1991AoG15-1-210-215). I'm not quite sure what to suggest here, given the discrepancy between this general understanding of the composition of Antarctic sea ice and the model results vis a vis the contribution of frazil ice.
- 2.25 Line 202 – I didn't understand this sentence.
- 2.26 Line 231 – what exactly are these different factors? Also, this is rather ambiguous, as different factors control ice edge location in different regions – at least around Antarctica.

- 2.27 Line 234 – what is meant by “reduced annual cycle”?
- 2.28 Lines 294-296 – these findings are similar to those of Wu et al. 1999 (Wu, X., W.F. Budd, V.I. Lytle, and R.A. Massom. 1999. The effect of snow on Antarctic sea ice simulations in a coupled atmosphere-sea ice model. *Climate Dynamics*, 15, 127-143).
- 2.29 Line 306 – why is lateral melt low across all Antarctic simulations? Lateral melt is thought to be a major factor in the annual meltback of Antarctic sea ice (numerous papers by Gordon etc.). Once again, it should probably be stated that ice formation/advance and retreat/meltback are driven by not only thermodynamics but also ice dynamics.
- 2.30 Lines 308-309 – how realistic is this assertion that most Antarctic ice forms in coastal regions? Other studies have shown that formation within the pack and at the ice edge are also very important, depending on region.
- 2.31 Line 376 – does rainfall occur over the entire sea-ice zones, and is this rainfall area also seasonally dependent? Also, does rainfall remove an existing snow cover, or change its albedo?
- 2.32 Lines 415-421 – May I also suggest including discussion of the new results in the light of the Wu et al. (1999) paper in paragraph 1 of the Conclusions i.e., comparing findings of that study with this one. This also relates to Lines 440-447.
- 2.33 Line 425 – doesn’t this also depend on ice concentration? i.e., a lower concentration or area of sea ice coverage enhancing air temperatures.
- 2.34 Lines 435-438 – I didn’t quite follow this argument of higher growth rates under thicker perennial ice. Does not congelation ice growth decrease with increasing ice thickness? Also, what about rapid frazil ice formation in more turbulent conditions of the marginal ice zone? Moreover, the conceptual model proposed is again only based on consideration of thermodynamics. How does the model account for dynamic thickening by deformation?
- 2.35 Line 466 – suggest changing to: “...is a “friend” to sea ice rather than a “foe” (see Sturm and Massom, 2017)....” NB This reference is also incomplete in the Reference List, missing the chapter title.
- 2.36 Page 22 – May I suggest that the Conclusions section ends with discussion of possible caveats and limitations in this study, and also future work that could or needs to be carried out in both observation and modelling. This could reiterate key gaps in our understanding of snow in the sea ice systems, the seasonal, regional and hemispheric dependence of the relationships, and the need for more large-scale observations of snow thickness and properties as well as accurate precipitation rates (see Webster et al., 2018). It should also address the snowfall v accumulation discrepancy factor (due to wind-blown snow redistribution/loss).
- 2.37 Page 11 – probably better to add full figure captions to Figures 5 and 6.
- 2.38 General question - What impact does (changing) snow accumulation have on the timing of sea ice advance and retreat, and the resultant duration of annual coverage in both polar regions?

3. TECHNICAL CORRECTIONS

- 3.1 Consistency – use either snow depth or snow thickness throughout.
- 3.2 Line 19 – grammar
- 3.3 Line 24 – reference needed.
- 3.4 Lines 258-259 – grammatical error.