Hansen et al 2023 doi.org/10.5194/tc-2023-145

Reply to reviewer comments on

"The importance of cloud phase when assessing surface melting in an offline coupled firn model over Ross Ice shelf, West Antarctica"

by

Nicolaj Hansen, Andrew Orr, Xun Zou, Fredrik Boberg, Thomas J. Bracegirdle, Ella Gilbert, Peter L. Langen, Matthew A. Lazzara, Ruth Mottram, Tony Phillips, Ruth Price, Sebastian B. Simonsen, and Stuart Webster

Dear reviewers
On behalf of my co-authors and myself, I would like to thank you for your comments on our manuscript. You have made an extensive review of the manuscript, and we have followed your suggestions to our best efforts. We sincerely believe that your reviews have improved the manuscript.
In the following, we provide a point-by-point answer to all the issues raised by you. All issues will be followed by our suggestions for improvements to the manuscript highlighted in red.

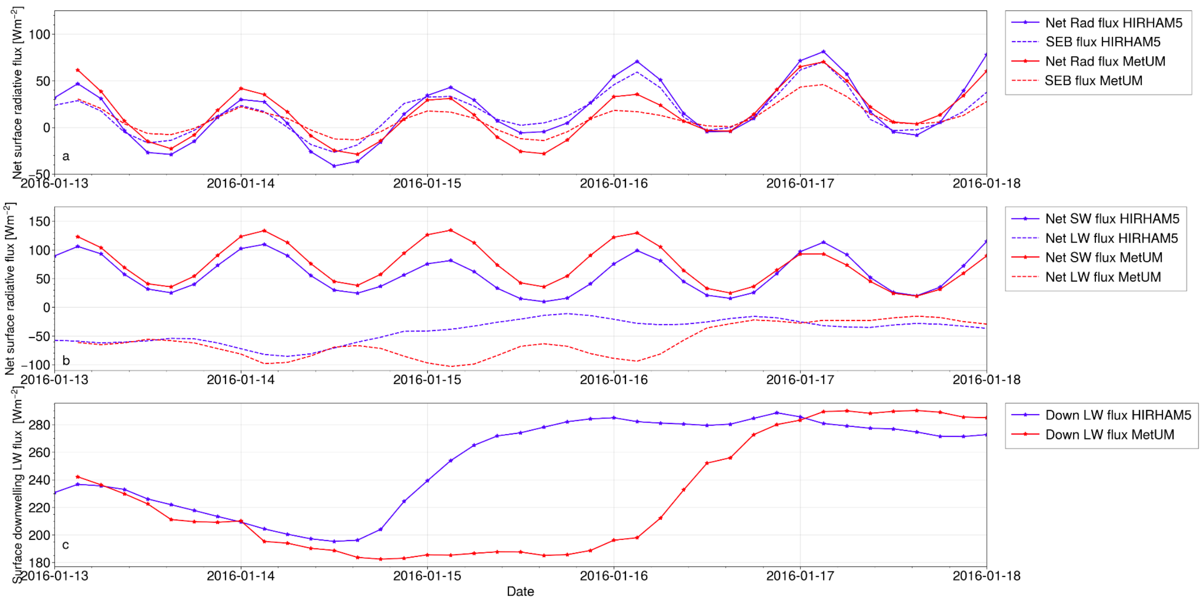
Best regards,
Nicolaj Hansen

Reviewer 1:

My concerns are the following:

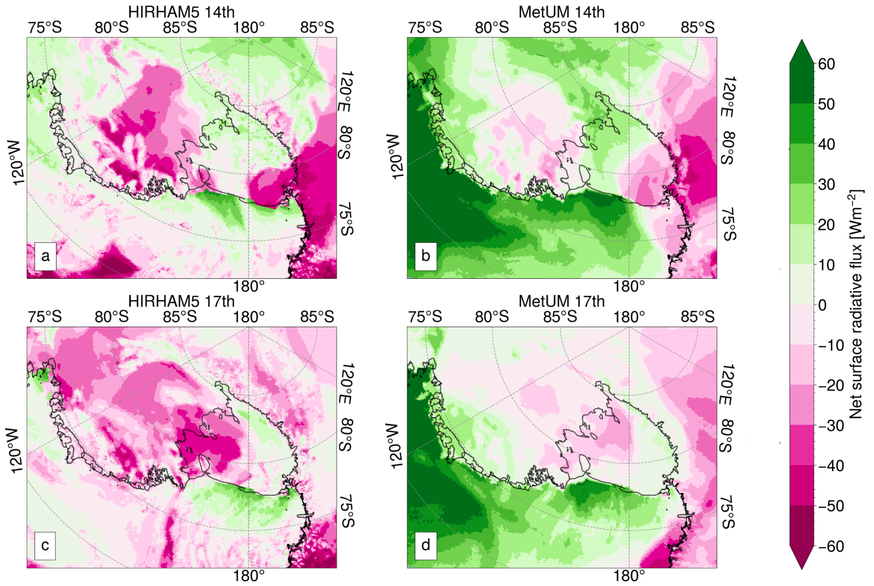
- **The two major observational datasets used in the article are contradictory with respect to melt in western RIS** : passive microwave melt extent shows no melt in western RIS during the event, whereas CERES radiative fluxes would lead to more melt than in models, as indicated by the authors in Section 4. Indeed, CERES shows larger net surface radiative fluxes than in models (Fig5a), consistent with larger liquid water path in CERES than in MetUM in western RIS during the event (Fig 11 and 12).

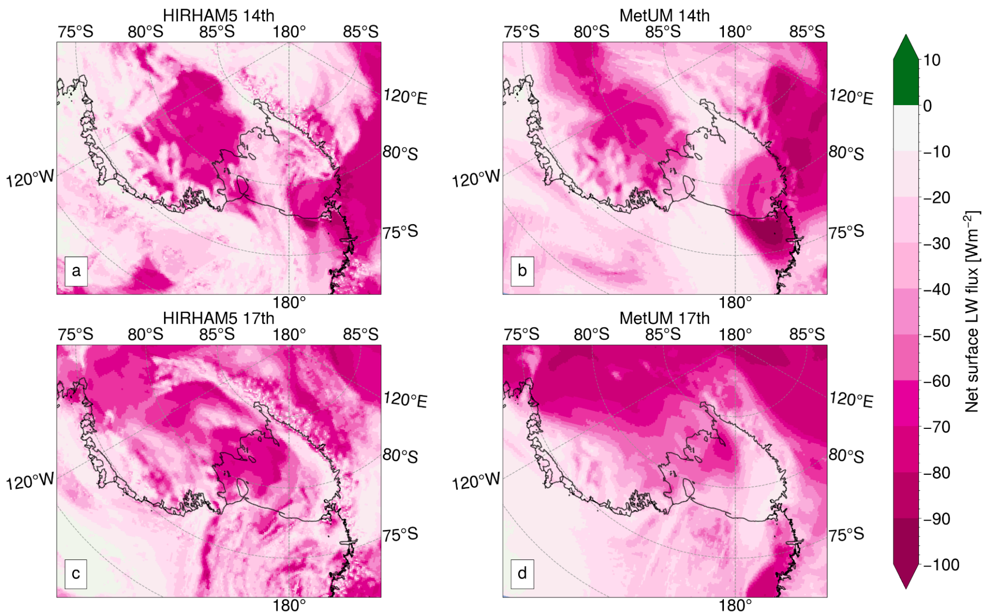
  Thanks for the comment. We have removed CERES data from figures 5-8. This has been done because CERES measures fluxes and cloud properties at the top of the atmosphere. So the surface fluxes are a derivative of the top of the atmosphere observations, Futhermore, Hinkelman and Marchand (2020) suggested a potential positive bias in SW radiation and a negative bias in LW radiation over the Southern Ocean. However, we keep figure 11 and 12 as it is a more direct observation.

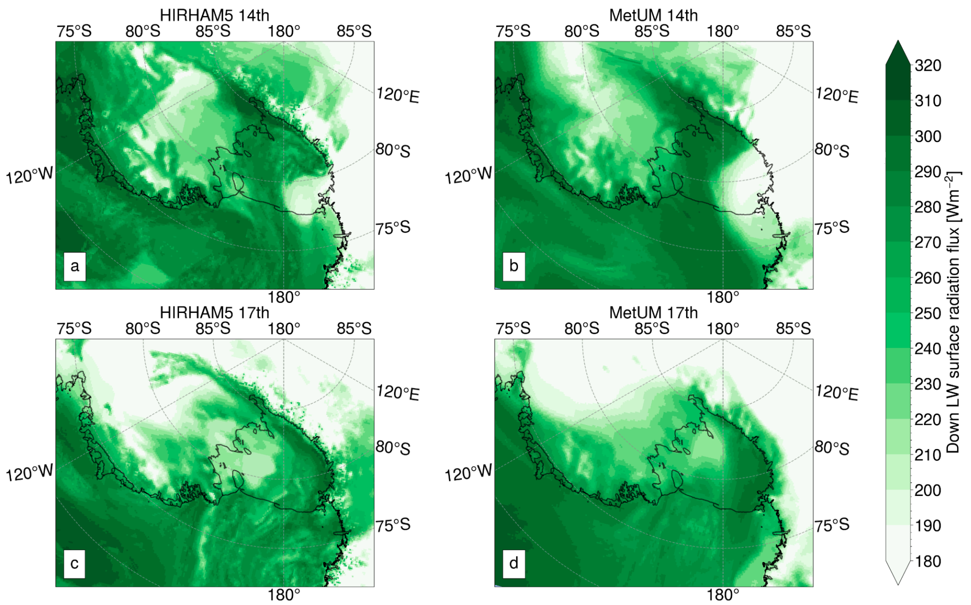


Danish Meteorological Institute

Hansen et al 2023 doi.org/10.5194/tc-2023-145







- The manuscript shows that models simulate too few liquid clouds with respect to ice clouds, using both CERES and CALIPSO satellite products. This means that **correcting the ice-to-liquid mass partitioning would induce more downward longwave radiation toward the surface, hence more melt**. As the authors rely on the passive microwave melt extent rather than on CERES (point above), **this result contradicts the statement in the introduction that *"The models (…) seemingly struggle to correctly represent the ice-to-liquid mass partitioning associated with the cloudy conditions, which we suggest is responsible for the radiative flux errors"*.** This statement is repeated in the discussion, where a large emphasis is given on liquid-ice cloud partitioning. But in the discussion, the authors also state that fixing this partitioning would actually increase melting, in contradiction with passive microwave observations: *"However, the larger amounts of liquid-water clouds observed by CALIPSO and CERES would be expected to produce even larger downwelling surface LW fluxes (Zhang et al., 1996). This is not the case, suggesting that other factors influencing the LW radiative effect of the clouds, such as cloud temperature, altitude, and cloud microphysical properties like the size of water droplets or ice crystals, may be impacting surface LW fluxes."*. **So why this emphasis on ice-liquid partitioning, which contradicts the results of the study?**
- From the two points above, I think that a conclusion of this study is that either **(1) properties other than ice-to-liquid partitioning of cloud water influence the radiative effects of the clouds**, or that **(2) melt extent from passive microwave might be wrong.** Can the authors clarify these points?

  Thank you for these comments. We do trust the passive microwave data, as it has been validated multiple times. We will make sure that this is clear in the conclusion. We agree with your conclusion that the ice-liquid partitioning cannot be solely responsible for the radiative flux biases, since correcting it in line with satellite cloud observations would adjust the downwelling LW fluxes in the wrong direction relative to what is required for agreement with passive microwave melt observations. Rather, we intended to emphasise that the incorrect ice-liquid phase partitioning in the simulated clouds is evidence of broader problems with the cloud microphysics schemes. Model deficiencies affecting the ice-liquid partitioning can be expected to impact other cloud properties as well, such as cloud height and temperature, or the vertical distribution of ice relative to liquid within the cloud. These other variables will have an impact on the surface radiative fluxes as well as the simple phase partitioning. So we hypothesise that cloud microphysics, including but not limited to phase, is biased in the model and that this is responsible for the radiative fluxes. We have made several changes to the text, especially in the discussion section, to make our meaning more clear on this subject.

More details are given bellow.

 # Specific comments

1 Introduction

"Therefore, to realistically capture local climate variability and simulate ice shelf melt patterns, it is essential to utilize regional atmospheric models at high spatial resolution, i.e., grid box sizes of the order 10 km or less."

- In case of synoptic-scale events, 10 km resolution might not be needed over large ice shelves. It depend on the ice shelves ?
  Thank you for this comment. However, we believe that a 10km resolution is needed as the margin of the ice shelves can show complex wind and temperature pattens.
- Which of the numerous papers cited L25-35 does use "10km or less" resolution ?

  Thank you for this comment. Lenaerts et al., 2017a, Heinemann et al., 2019, Zou et al., 2021, 2023, Gilbert et al., 2022, Bozkurt et al., 2018, and Wille et al., 2022 all have a horinzotal resolution of less than 10 km.

"Here we investigate the benefits of applying the sophisticated offline coupled firn model described by Langen et al. (2017) that represents key aspects such as the melt-albedo feedback to improve regional atmospheric model simulations of a prolonged and extensive episode of surface melt that occurred during January 2016 over the Ross Ice Shelf (RIS), West Antarctica. The RIS frequently experiences major surface melt events due to both synoptic- and local-scale processes (Nicolas et al., 2017; Zou et al., 2021; Li et al., 2023; Orr et al., 2023), with this particular event attributed to an influx of warm and moist marine air, likely linked to a concurrent strong El Niño episode (Nicolas et al., 2017). The regional atmospheric model simulations examined were initially produced for Antarctic CORDEX (Antarctic COordinated Regional Downscaling EXperiment), and are based on HIRHAM version 5 (HIRHAM5) and MetUM version 11.1 (Orr et al., 2023). In these simulations, HIRHAM5 employed a relatively sophisticated multi-layer snow scheme (Langen et al., 2015), while the MetUM utilized a simple composite snow/soil layer (Best et al., 2011)."

- This paragraph should be moved to the method section. It could be replaced by a final paragraph in the introduction presenting the outline of the article, with much less detail on the models as they will be presented in the Method section.

  Thank you for this comment. We have removed the model description of the paragraph and put it into the Methods section, this is still in the intro (as we think this outlines the article) :
  "Here we investigate the benefits of applying the sophisticated offline coupled firn model described by Langen et al. (2017) that represents key aspects such as the melt-albedo feedback to improve regional atmospheric model simulations of a prolonged and extensive episode of surface melt that occurred during January 2016 over the Ross Ice Shelf (RIS), West Antarctica. The RIS frequently experiences major surface melt events due to both synoptic- and local-scale processes (Nicolas et al., 2017; Zouet al., 2021; Li et al., 2023; Orr et al., 2023), with this particular event attributed to an influx of warm and moist marine air, likely linked to a concurrent strong El Niño episode (Nicolas et al., 2017)."

2 Methods and materials

This section should be divided in (at least) 2 subsections : Observations and Models.

Good idea, we now have a subsection called *Models* and one called *Observations.* On that occasion we have also added some more information on the CALIPSO and CERES data products (suggested by the other reviewer).

"This consists of 6-hourly averaged values of solid precipitation, liquid precipitation, surface evaporation, surface sublimation, surface downwelling SW radiative flux, surface downwelling LW radiative flux, sensible heat flux, and latent heat flux"

- Why this models need surface evaporation, surface sublimation **and** latent heat flux as input?
  Thank you for this comment. The model uses evaporation and sublimation to calculate the surface mass balance, the model does not calculate the evaporation and sublimation. The model uses the latent heat flux to calculate the surface energy balance.

"These are compared with daily melt extent estimates from satellite passive microwave measurements at a grid spacing of 25 km (Picard et al., 2007; Nicolas et al., 2017), using the same melt threshold of 3 mm."

- I don't find a 3 mm threshold in Picard et al., 2007 nor in Nicolas et al., 2017. Can you justify the choice of this threshold?

  Thank you for the comment, the 3 mm threshold is the Donat-Magnin et al 2020, we will insert the reference.

4 Cloud radiative effects

Comparison with CERES

"This raises concerns over the reliability of these measurements, as this would also presumably be associated with (erroneous) melt over the western RIS region, i.e., contradicting the satellite passive microwave measurements of daily melt extent (Figs. 2 and 3)." And to the end of the section, including Fig 5, 6, 7 and 8

- You state that CERES might give erroneous radiative budget at the surface (Fig 5 + sentence above), so we are not sure if we can trust maps from CERES or not (Fig 6, 7, 8). Consequently, what is the objective of this full section?

  Thank you for this comment. As written above, we have removed CERES from figures 5 to 8. Although we have removed CERES from this section, we still think that this section is nice to keep in the paper, as there are some interesting things happening with the energy fluxes. To accommodate for the changes, we have changed the section title to "Surface radiative fluxes"

"Figure 7 also shows that CERES semi-captures the transition from large negative net surface LW values over the western RIS during nighttime on the 14th to smaller negative values on the 17th, in agreement with the models."

- Do you use CERES to evaluate the models, or do you use the models to validate CERES? With this formulation, it seems that you use the models to validate CERES, which is confusing as the initial objective was to evaluate the models. Can you clarify?

  Thank you for this comment. As written above, we have removed CERES from figures 5 to 8. We will make sure to update the text accordingly.

5 Cloud properties and 6 Discussion

From Section 5 and 6, I conclude that **partitioning between liquid and ice cannot be the reason for the supposed too high melt in models versus passive microwave melt extent:**

Thanks for this comment. We agree it is more complex than just the cloud phase as measured earlier.

- **Section 5 : Liquid cloud are observed on western RIS during the event** *"More noteworthy is that CALIPSO shows liquid-water and ice-water clouds extending up to 7 km above the surface in the same region on the 17th of January (Fig. 10) coincident with the (erroneous) spike in modelled melt."* "the same region" being western RIS according to Fig. 10 legend.

  Thank you for this comment. We have changed "liquid-water and ice-water clouds" to "mixed-phase clouds" – the presence of mixed-phase clouds is a more complex regime for the models to simulate, which is why we highlight it.

- **Section 5 : MetUM models much less LWP that CERES and CALIPSO in western RIS during the event** *"However, CERES suggests that clouds with high liquid-water content and ice-water content occur at 12 UTC on the 17th over this region, with values of cloud ice water path up to 0.5 kg m-2 (i.e., similar to the MetUM) and cloud liquid water path up to 1 kg m-2 (i.e., two orders of magnitude larger than the MetUM). Moreover, it's noteworthy that CALIPSO also observed liquid-water and ice-water clouds over the western region of the RIS (Fig. 10), which substantiates the CERES results."*

  Thank you for this comment. We have left this text as it is to highlight the model cloud biases that can be evaluated against the observations.

- **Section 6 : Partitioning between liquid and ice cannot be the reason for discrepancies in LWD.** *"However, the larger amounts of liquid-water clouds observed by CALIPSO and CERES would be expected to produce even larger downwelling surface LW fluxes (Zhang et al., 1996). This is not the case, suggesting that other factors influencing the LW radiative effect of the clouds, such as cloud temperature, altitude, and cloud microphysical properties like the size of water* *droplets or ice crystals, may be impacting surface LW fluxes." "In reality, multiple possible cloud properties (in addition to ice-to-liquid partitioning of cloud water) could be influencing the radiative effects of the clouds to produce smaller downwelling LW fluxes than are being simulated."*

Thanks for this comment. We have edited the text related to cloud microphysics in this section. We hope that the new text makes our conclusions clearer.

- From this, I think that a conclusion of this study is that either **(1) properties other than ice-to-liquid partitioning of cloud water influence the radiative effects of the clouds**, or that **(2) melt extent from passive microwave might be wrong.**

  Thank you for this comment. We agree that ice-liquid partitioning cannot be solely responsible and have edited the text to emphasise this point.

"as would repeating the MetUM simulations using its recently developed double-moment microphysics scheme to examine whether this increased the amount of liquid- water cloud and limited its conversion to ice (Field et al., 2023)."

"Previous studies have already shown that the MetUM has deficiencies in its representation of cloud phase, particularly re- lated to it simulating Antarctic clouds that contain too much ice-water content and not enough liquid-water content (Abel et al., 2017)."

- Here, more liquid cloud would induce more melt, so more model bias compared to passive microwave melt extent. Can you clarify what you expect to improve by increasing the liquid water content?

  Thank you for this comment. We believe that improving model cloud microphysics schemes would improve cloud properties generally, including phase partitioning but also affect other variables that could be causing biases in the radiative fluxes in this case study.

 # Technical corrections

The number of references L25-35 is too large (25 references)

Thank you for the comment, we have removed some of the references

Figure 1 : Orgraphy

Thank you for your comment, we have corrected the typo

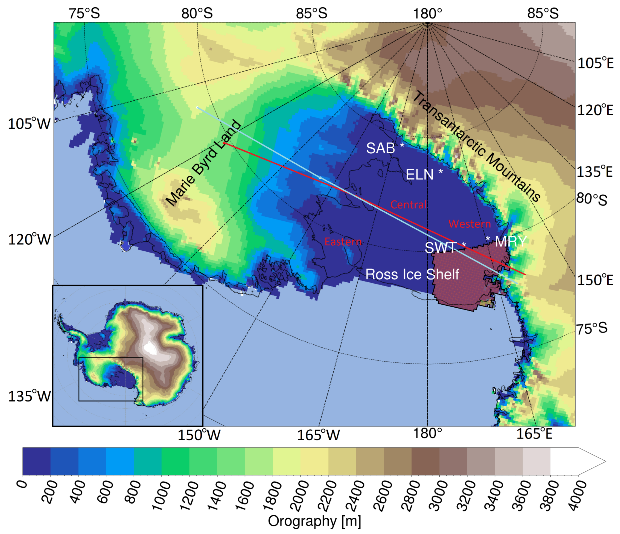
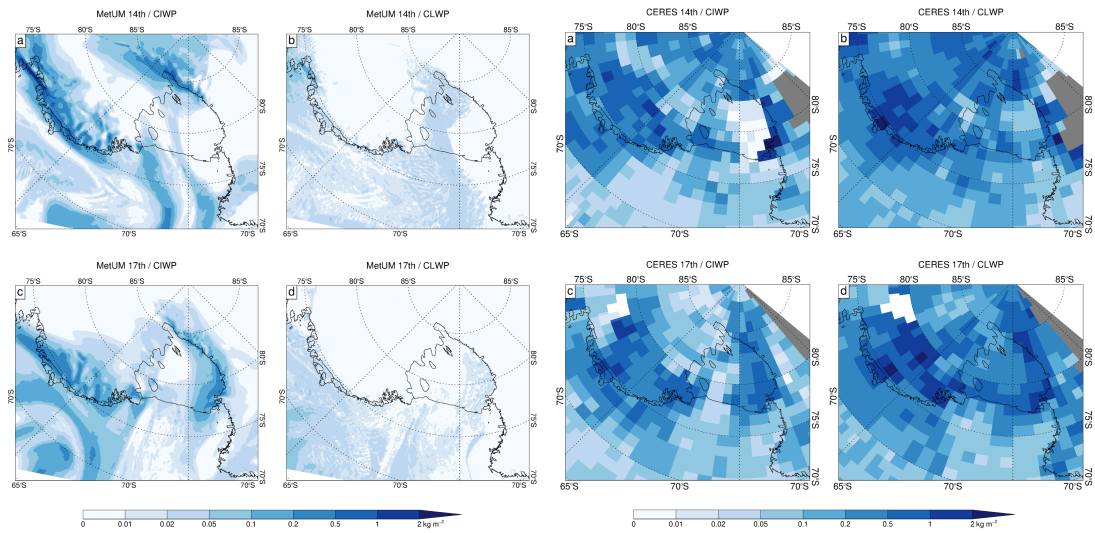


Figure 11 and Figure 12 : Use a continuous colormap instead of the divergent Blue/Red colormap curenlty used.

Thank you for this comment. We have updated the colormap.



Reviewer 2:

Although the fundamental atmospheric result is not entirely new, it is useful to see that applying the most sophisticated firn model does not compensate for the radiative errors related to cloud phase. The manuscript needs some additional detail and clarification regarding some of the satellite remote sensing products.

1. It is not stated what CERES product is used. There are several available from NASA Langley Research Center (LaRC) and other NASA facilities. CERES does not measure surface radiative fluxes. It only measures top-of-atmosphere radiances over broad spectral intervals, and these are then combined with angular dependence

models to get top-of-atmosphere fluxes, and then these fluxes are combined with various other satellite data sets and/or radiative transfer models to get estimates of the surface radiation components. Given that CERES is showing such great discrepancy here, it is important to identify which CERES product has been used and discuss potential sources of error with reference to the underlying algorithms (most of which are published by NASA LaRC in the open literature).

Thank you for pointing this out. We have removed the CERES surface fluxes from figures 5-9, and focus on ice- and liquid-water phases from CERES. We have also added more information about the data product in section 2.2 “Observations” and included a discussion about the uncertainties.

2. Similarly, CALIPSO provides excellent active-sensor detection of cloud vertical extent, but the phase partitioning algorithms have some built-in assumptions and temperature thresholds. The manuscript should give a brief discussion of how the CALIPSO algorithm might lead to uncertainties in what is presented in Figure 10, with the specific vertical temperature profiles over the study domain.

   Thank you for this comment. The CALIPSO dataset distinguishes between ice (depolarizing) and water clouds (spherical) based on backscattered light. However, uncertainties in cloud phase identification can arise from multiple scattering by water clouds, which exhibit significant depolarization, and horizontally oriented ice particles that are nearly nondepolarizing (Hu et al. 2009). Therefore, the vertical profile of cloud phases in Fig. 10 may be influenced by the presence of water clouds, resulting in ice/unknown phases above the surface melting area over the RIS (Fig. 10b). Unfortunately, temperature profile observations over the RIS during the 2016 melt event are unavailable, precluding the provision of additional information on cloud phases.
   We have added some of the above-written text in section 2.2, and in the discussion

3. The vertical temperature profiles and the vertical profiles of the simulated cloud properties should also be presented and discussed for the two days (14 and 17 January) and the relevant locations. This would make the discussion section (around lines 285-299) less qualitative and speculative. For example, if the temperatures in the lower temperature are only slightly below freezing over several km, then extensive ice phase cloud is obviously ridiculous as we expect supercooled liquid water in these pristine conditions.

   Thank you for this comment. Unfortunately, we have no temperature profiles from CALIPSO or the models.

4. Regarding the deficiencies of single-moment cloud microphysics, RACMO simulations of West Antarctic surface melt (e.g., see papers by Jan Lenaerts) have “tuned” the microphysical scheme to give high enough cloud liquid water, yielding good geographic representations of surface melt. This should be mentioned somewhere in the later sections of this paper.

Thanks for pointing this out, we actually already cite papers that deal with tuning/updating cloud schemes, to make that clear we have added this line just before the references
"and global atmospheric models despite work to improve parameterisations"

5. Why is ERA-Interim reanalysis used to initialize the regional models and not the more current ERA5?

   Thank you for this comment. Neither MetUM nor HIRHAM5 has been run using ERA5 yet.

References:

CERES, N.: CERES and GEO-Enhanced TOA, Within-Atmosphere and Surface Fluxes, Clouds and Aerosols 3-Hourly Terra-Aqua Edition4A, https://doi.org/10.5067/TERRA+AQUA/CERES/SYN1DEG-3HOUR_L3.004A, 2017.

Donat-Magnin, M., Jourdain, N. C., Gallée, H., Amory, C., Kittel, C., Fettweis, X., Wille, J. D., Favier, V., Drira, A., and Agosta, C.: Interannual variability of summer surface mass balance and surface melting in the Amundsen sector, West Antarctica, The Cryosphere, 14, 229–249, https://doi.org/10.5194/tc-14-229-2020, 2020

Hinkelman, L. M. and Marchand, R.: Evaluation of CERES and CloudSat Surface Radiative Fluxes Over Macquarie Island, the Southern Ocean, Earth Space and Science, 7, e2020EA001 224, https://doi.org/10.1029/2020EA001224, 2020

Hu, Y., Winker, D., Vaughan, M., Lin, B., Omar, A., Trepte, C., Flittner, D., Yang, P., Nasiri, S. L., Baum, B., et al.: CALIPSO/CALIOP cloud phase discrimination algorithm, Journal of Atmospheric and Oceanic Technology, 26, 2293–2309, https://doi.org/10.1175/2009JTECHA1280.1, 2009.