Author comment to the Referee comment by Anonymous Referee #1 on the manuscript

Estimating surface melt in Antarctica from 1979 to 2022, using a statistically parameterized positive degree-day model

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We gratefully thank the reviewer for the time that they spent reading and reviewing the manuscript. We respond to each of the major and minor comments below. The reviewer's comments are shown in **bold text**, replies are shown in normal text, text from the original manuscript is shown in blue, and proposed changes to the manuscript are shown in red.

Zengh et al., 2022 estimate the melt over the Antarctic Ice Sheet using a PDD model. They also carefully parametrize their model to produce similar results than satellite and RACMO estimations. The calibration of the model is particularly complete and nothing seems to be omitted for a reproducibility of the results. Obtaining a correct PDD model is interesting and important because, as the authors mention, the efficiency of the PDD in terms of computation time allows long simulations where other more complex models do not enable it. However, most of the manuscript focuses on the calibration and the evaluation of the PDD, and only a limited part is dedicated to the new information about melt. From this point of view, the scientific issue of the manuscript could be more emphasized in the title and might have deserved a submission to another journal like GMD (this does not, however, question the quality and robustness of the study. I would add that while being comprehensive is a quality, some passages are difficult to read because too much information is given when that information is sometimes obvious. I also have some more comments listed hereafter. In general, I don't have much to say except to advise to simplify/summarize some passages (introduction, result) and to add some nuances (see major comments).

Major comments:

One major limitation of the PDD is that all the calibration is done over present climate where melt is only limited to margins and weak. One could question the validity of the calibration in warmer climates, i.e. for projections. For instance, how could the melt computed by PDD take into account the snow albedo feedback (which is a process often not represented by PDD due to their simplicity)? Or could the PDD correctly represent areas where no melt currently occurs and will likely occur in warmer climates as it was calibrated to reproduce current surface melt? Maybe you could compare the results of a PDD calibrated over only low melt years but evaluated over high melt years (even high present-day melt years will be considered as low melt years in the future).

Furthermore, the calibration of the quantity of melt is solely based on the RCM RACMO, what is the impact of RACMO biases on the PDD? Although Mottram et al, 2021 showed that RACMO is one of the best models to represent the Antarctic climate, they also suggested that RACMO underestimates near-surface air temperature which could also influence melt computed by RACMO. Note that the calibration and evaluation is also not independent as you use the same values.

Thank you for this very inspiring and constructive comment. Practically, the Antarctic surface melt data are limited for only around 40 years. This limited time period prevents us from exploring the PDD model via the selection of low/ high melt years. This, because the training and testing samples in that case would be really small (which reduces the reliability of the parameterization as the number of data points used for training is small). We agree that we did not explore the biases on the RACMO and the satellite, and there is also the question of the independence of the calibration and evaluation in our study. To address these questions: Whether the PDD model has applicability to the warmer climates? What do the training biases impact on the PDD model? How to calibrate and evaluate the PDD model from the limited datasets? Here, we conduct a number of new testings and experiments. We will add two new subsections in the Methods section and will change the entire Results and discussion section, and parts of the Abstract and Conclusions accordingly.

Here, we show our proposed changes regarding to the new methods. Please refer to our proposed new manuscript for the according results, discussions and conclusions.

We will add two new subsections (Section 3.3.2 and Section 3.3.3) in the Methods section to describe our new tests and experiments:"

3.3.2 K-fold cross-validation

The cross-validation technique has been developed since the 20th century (Stone, 1974) and has became a standard technique in the field of climate and weather predictions (e.g. Mason, 2008; Maraun and Widmann, 2018). It is especially suitable for the usage of statistical models that are calibrated and evaluated on the same data (Maraun and Widmann, 2018).

We consider the spatial variability of PDD parameters by parameterizating the model in each computing cell for the whole time period. However, this does not allow us to explore the variability of the PDD parameters on a temporal scope, as Ismail et al. (2023) suggest that the temporal variability of DDF should also be considered. Due to the short period of the satellite-era

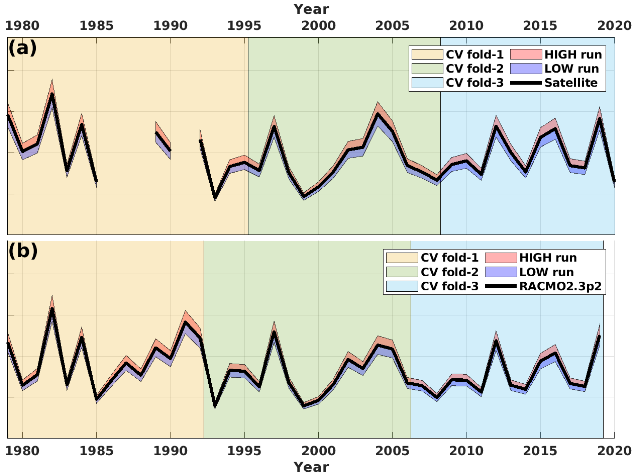

Figure 1. Schematic overview of the time periods for each CV folders and the HIGH, LOW sensitivity experiments.

and the scarcity of the in situ Antarctic surface melt data (Gossart et al., 2019), our PDD model is parameterized and evaluated using the same dataset covering the past four decades.

To assess the temporal dependency of the PDD parameters, we perform an adjusted 3-fold cross-validation (hereafter 3-fold CV). The satellite melt occurrence estimates used in this study cover 38 years (four years have been omitted). Therefore, we sequentially divide the satellite estimates into two 13-year folds and a 12-year fold (Figure 1a). Note that in Section 3.2.1 we calculate the RMSE between the PDD and three satellite estimates on their overlapped period, respectively, and calculate the mean of those three RMSE. However, the second fold has actually only 7 years of overlap between the satellite SMMR and SSM/I, and satellite AMSR-E. Here, we firstly calculate the mean of satellite estimates between their overlapping periods prior to the 3-fold CV and then, we perform the 3-fold CV. The 3-fold CV has three members. the first membercontains the first and second fold used to parameterize the PDD model, and the third foldis used to test the model. In Member 2, we take the first and third fold to parameterize the PDD model and test the model on the second fold. In Member 3, we take the second and third fold to parameterize the PDD model and test the model on the first fold. Similarly, we repeat the calculations for the RACMO2.3p2 surface melt amount but the folds are divided into two 14-year folds and a 13-year fold (Figure 1b).

3.3.3 Sensitivity experiments

Although RACMO2.3p2 is suggested to be one of the best models on replicating Antarctic climate, a cold bias of -0.51 K for the near-surface temperatures is also reported (Mottram et al., 2021). However, it is unclear how much this cold bias influences the output of RACMO2.3p2 snowmelt simulations, at least on the spatial scale. Satellite estimates are more direct products for Antarctic surface melt. However, bias is suggested to be existed as a corollary due to the frequent replacements of satellites that happened at least four times since the satellite-era (Picard et al., 2007).

In order to explore how much the biases from satellite estimates and RACMO2.3p2 simulations will influence on the parameterization of the PDD model and the outputs from the parameterized PDD model, or in other words, how sensitive the parameterization and PDD model to the satellite estimates and RACMO2.3p2 simulations, we perform two sensitivity experiments. In the first sensitivity experiment, we explore how sensitive the T_0 and the PDD melt-day (and CMS) outputs to the satellite estimates. We increase (HIGH run) and decrease (LOW run) 10% of the satellite estimates (Figure 1a) for each computing cell then repeat the T_0 parameterization as described in Section 3.2.1, respectively. In the second sensitivity experiment, we explore how sensitive the DDF and the PDD melt amount outputs to the RACMO2.3p2 simulations. We increase and decrease 10% of the RACMO2.3p2 simulations (Figure 1b) for each computing cell then repeat the DDF parameterization as described in Section 3.2.2, respectively. Note that in the context of the sensitivity experiments, out optimal parameterization of T_0 and DDF in Section 3.2.1 and Section 3.2.2 therefore refers to the CONTROL run.

In addition, these sensitivity experiments can also allow us to explore the validity of our PDD model for the application on the future Antarctic surface melt. Even if our PDD parameters are temporally stable for the period that we investigate in this study, the validity of our PDD model for the application on the future Antarctic surface melt will still be uncertain given that the future predictions of Antarctic climate is warmer than the current. Therefore, accessing the PDD model behaviours between these HIGH/ LOW runs will shed a light on the applicable of the PDD model to the warmer climate scenarios.

We will include these two new figures into the main text. The corresponding changes in the discussions and conclusions will also be added into the new version of the manuscript.

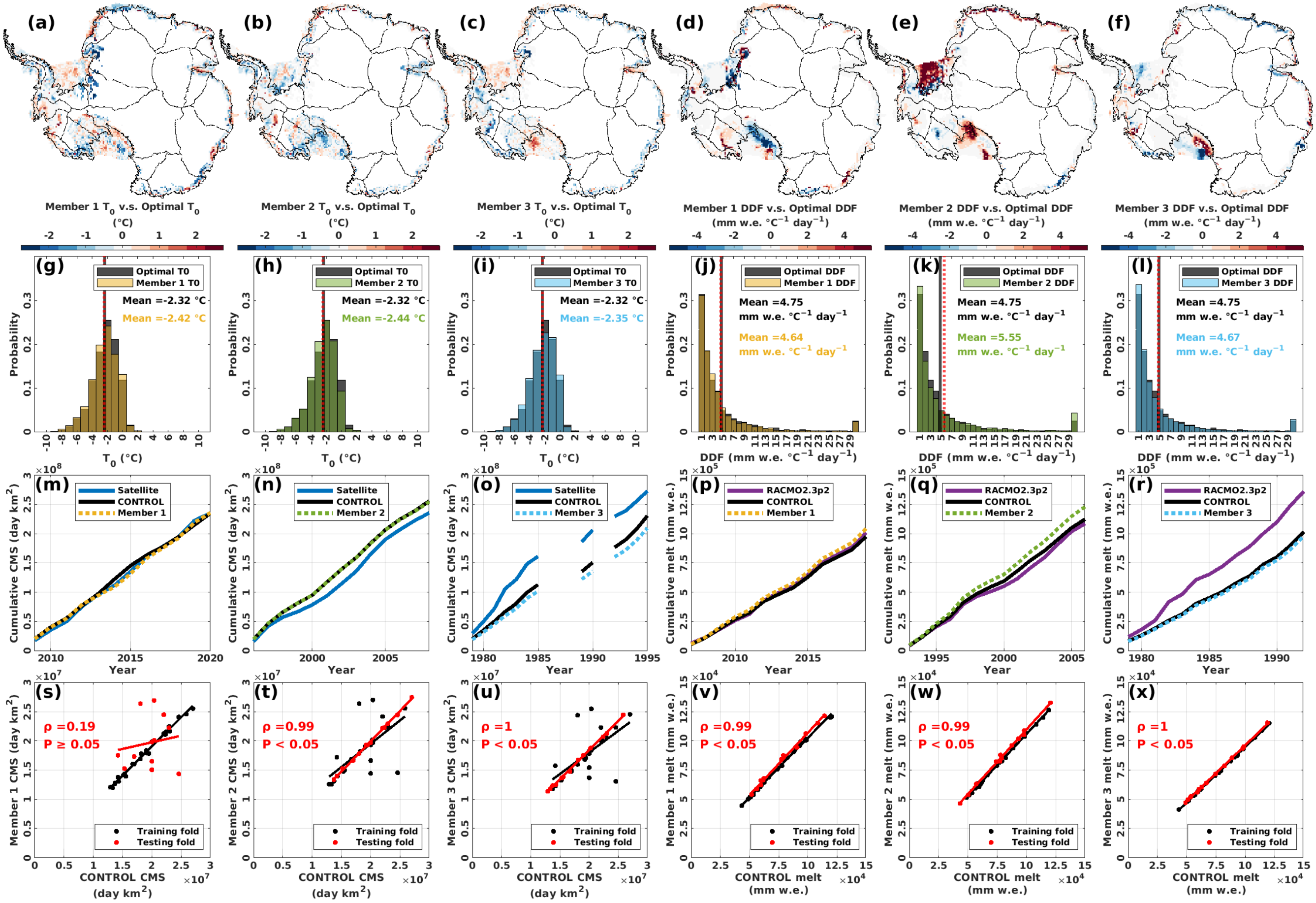

Figure 2. (a) to (f) spatial maps for the differences between the T_0/ DDF parameterized in each member of the T_0/ DDF 3-fold CV and the optimal T_0/ DDF, respectively. (g) to (l) probability histograms for the T_0/ DDF of each T_0/ DDF 3-fold CV and the optimal T_0/ DDF, respectively. Black vertical lines indicate the mean of optimal T_0s/ DDFs. Red dotted vertical lines indicate the mean of T_0/ DDF for each member, respectively. (m) to (r) cumulative CMS/ annual melt amount for satellite estimates/ RACMO2.3p2 simulations, CONTROL (which is the PDD model run with optimal T_0 and DDF) and each member for the period of the testing-fold, respectively. We calculate the difference of cumulative CMS/ annual melt amount between each member and the CONTROL, at the end of the testing fold, respectively. (s) to (x) scatter plots for the CMS/ annual melt amount of each 3-fold CV member against the CONTROL, respectively. The Spearman's ρ and its statistical significance for the testing fold between each member and the CONTROL are calculated, respectively.

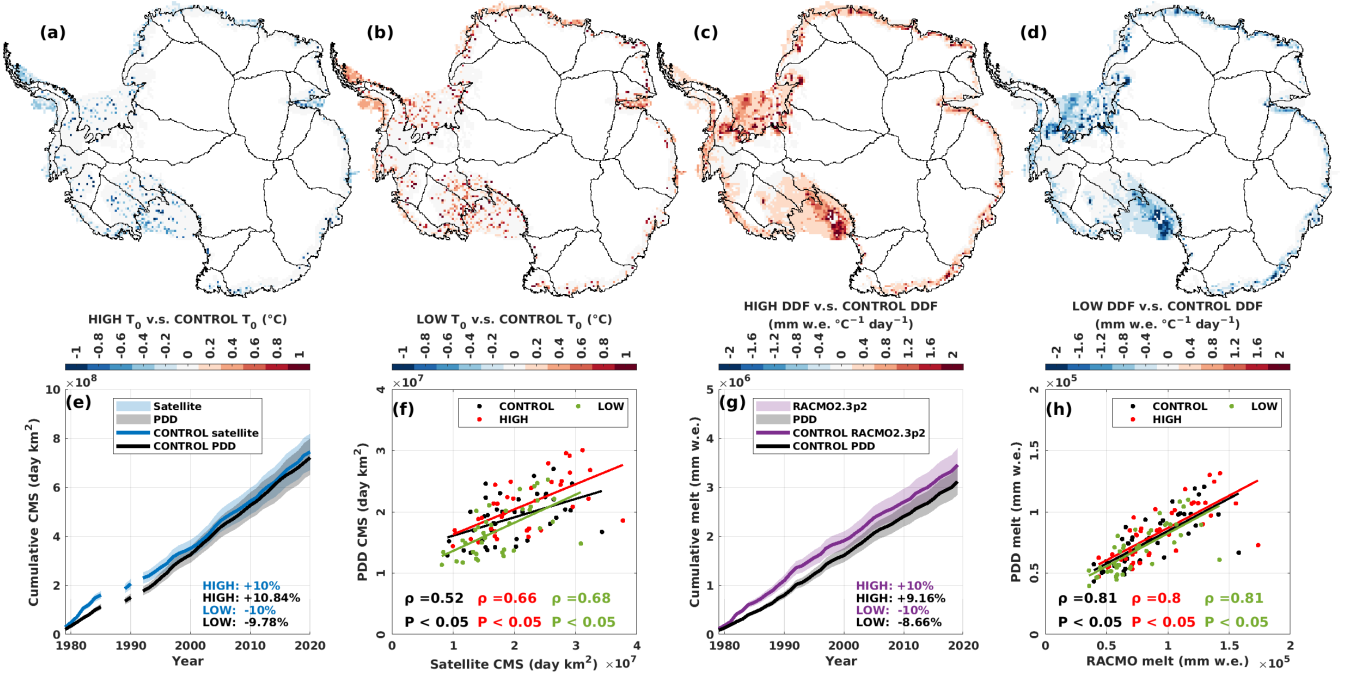

Figure 3. (a) and (b) spatial maps for the difference between the T_0 parameterized in the HIGH/ LOW experiment and the CONTROL (optimal) T_0. (c) and (d) spatial maps for the difference between the DDF parameterized in the HIGH/ LOW experiment and the CONTROL (optimal) DDF. (e) and (g) cumulative CMS/ annual melt amount for the satellite estimates/ RACMO2.3p2 simulations and PDD outputs. Note that the period for (e) is from 1979/1980 to 2020/2021 (with 1986/1987 to 1988/1989 and 1991/1992 omitted). The period for (g) is from 1979/1980 to 2019/2020. The upper and lower boundaries of the semi-transparent shaded areas indicates the HIGH/ LOW satellite estimates and the HIGH/ LOW PDD outputs. The percentage difference annotated in the left-bottom corner is calculated between the HIGH/ LOW and the CONTROL for each variable (by "variable", we mean satellite melt occurrence data/ PDD melt occurrence and amount data/ RACMO2.3p2 melt amount data), respectively. (f) and (h) scatter plots and the Spearman's ρ (with its statistical significance) for PDD outputs and satellite/ RACMO2.3p2, from each sensitivity experiment (HIGH, LOW and CONTROL).

Minor comments:

1 P1L4: Consider to nuance since this will only be the case if the firn cannot absorb the additional water

Thank you for pointing this out. We will change it accordingly in Line 4: "temperature and melt. Enhanced surface melt will ~~negatively~~ impact the mass balance of the Antarctic Ice Sheet (AIS) and,".

2 P1L13: Satellite observation, I suggest to replace observation by estimates as melt is not directly observed by satellite but derived from brightness temperatures or absorptivity of the surface under the assumption that the presence of water at the surface is newly-produced melt. (also for P3L81)

Thank you for pointing this out. We agree using the term "satellite estimates" is better than "satellite observations". We will replace the term "satellite observations" with "satellite estimates" for the entire manuscript.

3 P1 L26-27: Is this 100% valid? Surface melt is projected to remain limited to ice shelves (Kittel et al., 2021) beyond 2100 where basal melt should have a much higher influence (Seroussi et al., 2020). Consider nuance.

Thank you for pointing this out. This suggestion overlaps with the sixth comment by the other reviewer Devon Dunmire. We copy our response to that comment below:

Thank you for your suggestion. We agree. We will change Lines 21-28 from: "Surface melting is common and well-studied over the Greenland Ice Sheet (GrIS) (e.g. Mernild et al., 2011; Colosio et al., 2021; Sellevold and Vizcaino, 2021), and is known to play an important role in the net mass balance of the ice sheet and changes in global mean sea level (GMSL), both now and in the past (e.g. Ryan et al., 2019). It is likely to become even more important in the future. Even though Antarctica is currently much colder than Greenland, projected Antarctic near-surface warming (e.g. Kittel et al., 2021) means that increased surface melting is to be expected over coming decades – both in terms of area and frequency of melting. However, these are currently less understood over Antarctica than Greenland, either in the past or at present. This is concerning as surface melting will likely become an increasingly important component of Antarctic Ice Sheet (AIS) mass balance through this century and the next." to "Surface melting is common and well-studied over the Greenland Ice Sheet (GrIS) (e.g. Mernild et al., 2011; Colosio et al., 2021; Sellevold and Vizcaino, 2021), and is known to play an important role in the net mass balance of the ice sheet and changes in global mean sea level (GMSL), both now and in the past (e.g. Ryan et al., 2019). It is likely to become even more important in the future. Antarctica is currently much colder than Greenland. Antarctic ice shelves show no statistically significant trend for the annual melt days (Johnson et al., 2022) and also no significant increase in melt amount in East Antarctica in the past 40 years (Stokes et al., 2022). However, climate projections have suggested that the surface melt will increase in the next century (e.g. Trusel et al., 2015; Kittel et al., 2021; Stokes et al., 2022) – both in terms of area and volume of melting (Trusel et al., 2015; Lee et al., 2017). Studies have suggested that the Antarctic surface melt can impact the ice sheet mass balance through the surface thinning and runoff, surface meltwater injecting to the bed and increasing ice shelf vulnerability (Bell et al., 2018; Stokes et al., 2022). However, these are currently less understood over Antarctica than Greenland, either in the past or at present. This is concerning as surface melting will likely become an increasingly important player to Antarctic environment through this century and the next.".

4 P1 L29-L46: I would shorten these two paragraphs which, although interesting in historical terms for the evolution of ice shelves, do not bring much information directly related to your topic. This is only a suggestion, feel free to keep as it is.

Thank you for pointing this out. We think it is better to include such information to emphasise that Antarctic surface melting is important. We will keep these paragraphs but will change the wording of the Introduction section to make the structure of the Introduction more logical.

5 P4L105: observation => values/estimates

Thank you for this suggestion. We agree. We will change at P4L104: "It contains daily ~~observations~~ estimates as a binary of melt and no-melt on a $25{\times}25\ \mathrm{km}^2$ southern...".

6 P8L179-181: Is the ERA5 mean also computed between 6am and 6pm in local time for each grid point?

Thank you for pointing this out. We agree that this text is unclear. The ERA5 mean for comparing to the SMMR and SSM/I estimates is computed between the data at 6am and at 6pm in local time for each grid point, and the ERA5 mean for comparing to the AMSR-2 and AMSR-E estimates is computed between the data at 12am and at 12pm in local time for each grid point. For clarity, we will replace Lines 179-182: "Because the satellite melt day product of SMMR and SSM/I (Table 1) is retrieved from the local acquisition times around 6 am and 6 pm, we select the 6 am and 6 pm ERA5 2-m air temperature data and calculate the daily averages of the 6 am and 6 pm. For the satellite product from AMSR-E and AMSR-2 (Table 1), we repeat the calculations using the daily averages of the 12am and 12pm ERA5 2-m air temperature data as of their local acquisition times." with "Because the satellite melt day product of SMMR and SSM/I (Table 1) is retrieved from the local acquisition times at around 6am and 6pm, we compute the mean of 6 am and 6 pm ERA5 2-m air temperature data for the input T for the PDD model (Equation 3). For the satellite product from AMSR-E and AMSR-2 (Table 1), we compute the mean of 12am and 12pm ERA5 2-m air temperature data as of their local acquisition times.".

7 P8 L186-192: These sentences can be considered as an example of too much provided details that can make the manuscript hard to read. I'd say that the only necessary information is that the RMSE from each pixel is averaged to produce a RMSE per region. All the other information seems obvious and may be non necessary. Also Figure 7 for instance, not necessary how the surface elevation is obtained.

We thank the reviewer for these suggestions. We will change in Lines 184-197 from:

"In order to obtain the optimal T_0, we calculate the RMSE between the time series of the annual number of melt days for the satellite observations and the model experiments. As we treat each computing cell individually, all calculations are carried out on each cell independently in each iteration (T_0 experiment).

Next, we explore the optimal T_0 for the whole continent and by region. To do this, we multiply the mask matrices (cells inside the region have a value of one, and cells outside the region have a value of zero) by the RMSE of each T_0 experiment to generate the RMSE for each T_0 experiment on each region. The mask matrices for those regions are defined by multiplying each mask matrix of the 38 regions of interest (Figure 1) by the mask matrix of the satellite observational area (Figure A2 in the Appendix A). Then we calculate the average of RMSE across all computing cells (RMSE per computing cell) in each targeted region in each T_0 experiment. Although these three satellite products have different time periods (SSMI and SSM/I covers the period from 1979/1980 to 2020/2021 (1986/1987–1988/1989 and 1991/1992 omitted), AMSR-E covers the period from 2002/2003 to 2010/2011 and AMSR-2 covers the period from 2012/2013 to 2020/2021), we assume their comparability as these satellite products are derived from the same algorithm and threshold (Picard and Fily, 2006). We therefore calculate the average of the regional-average RMSE across three satellites (hereafter, the regional RMSE). Finally, we define the optimal T_0 of each targeted region where the T_0 experiment has the minimal regional RMSE.".

to

"In order to obtain the optimal T_0, we calculate the root-mean-square error (RMSE) between the time series of the annual number of melt days for the satellite estimates and the model experiments in their overlapped years. As we treat each computing cell individually, all calculations are carried out on each cell independently in each iteration (T_0 experiment). Although these three satellite products have different time periods, we assume their comparability as these satellite products are derived from the same algorithm and threshold (Picard and Fily, 2006). Therefore, we calculate the mean of RMSE between three satellite estimates for each cell. Finally, we define the optimal T_0 of each computing cell where the T_0 experiment has the minimal RMSE. If there are multi T_0 experiments that have same minimal RMSE for their computing cell, we calculate the mean of those T_0 as the optimal T_0 (this only happened on the cells that have very low melt days). "

8 P10 L229: Could this melt associated with relative apparent cold conditions be related to katabatic winds in that area, maybe not correctly represented by ERA5? (ie, could ERA5 actually underestimate temperature in that region leading to suspicious values).

Thank you for this comment. Yes, it is possible. We will cite the "Katabatic winds warm and mix the air as it flows downward and cause widespread snow erosion, explaining >3 K higher near-surface temperatures in summer and surface melt doubling in the grounding zone compared with its surroundings." from Lenaerts et al. (2017), and change in Lines 372–374: "A primary limitation of the PDD model is systematically introduced by the temperature-dependency, making it difficult to accurately estimate surface melt strengthened/ weakened or triggered by other components of the surface energy budget that may accompany katabatic winds (Lenaerts et al., 2017) and climatic phenomena such as the...".

9 P14 L283: Instead of surface temperature, use air temperature as it is the input variable of the PDD.

Thank you for this suggestion. We agree using the term "air temperature" is better than "surface temperature". We will change at P14 L283: "...decreasing ~~surface~~ air temperature...".

10 P16 L320-321: How do you obtain the quantity of melt from the satellite? Should it be melt area * melt days (instead of melt quantity?). Could you also compute the CMS from RACMO to add a comparison?

Thank you for pointing this out. We meant to calculate the CMS by the product of pixel area (km^2) and the total annual melt duration in that pixel as Trusel et al. (2012) described. In the context of our paper, the CMS is computed by the product of cell area (km^2) and the total annual melt days (day) in that cell. We apologize that the text is not clear. For clarity, we will change in Line 320: "...calculated by ~~multiplying the annual number of melt cells by the cell area (30×30 km^2)~~ the product of cell area (km^2) and the total annual melt days (day) in that cell,... ".

The current RACMO2.3p2 data are Antarctic surface melt amount on a monthly temporal resolution. In order to calculate the CMS from RACMO2.3p2, we would need the daily temporal resolution RACMO2.3p2 data. We will consider adding the comparison with the RACMO2.3p2 CMS in future work.

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