Statistically parameterizing and evaluating a positive degree-day model to estimate surface melt in Antarctica from 1979 to 2022

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We are grateful to the Editor and Reviewers for the time they spent reading and reviewing our manuscript. We have carefully considered each of their comments, which are presented below. The comments from the Editor and Reviewers are shown in **bold text**, our replies are shown in normal text, text from the original manuscript are shown in blue, and proposed changes to the manuscript are shown in red.

Editor decision by Brice Noël:

Dear Yaowen Zheng and co-authors,

Thank you very much for submitting your revised manuscript, which has been reviewed by our referees. The editor joins the referees to acknowledge the great effort you put into revising the manuscript. However, the paper remains too detailed/wordy in places, and sometimes overly technical, which can distract the reader. The manuscript also requires additional clarifications, notably on the selection of a grid-cell parameterisation approach, which should be better motivated. As noted by referee #2, it is currently unclear how the latter parameterisation remains valid for independent applications, i.e., future projections.

As a general comment, the introduction should be more focused. For instance, comparing Greenland to Antarctica is not strictly necessary (L17-19, L26). As suggested by referee #2, I recommend elaborating on the impact of surface melt on ice shelf viability, e.g., via hydrofracturing, and AIS mass balance (L24-25). The research question/objectives should be more clearly formulated: this study consists in a statistical exercise assessing the robustness of the PDD method to estimate AIS present-day melt.

Sections 3.3.1 and 3.3.2 are currently too technical. I invite the authors to reformulate these sections with a more appropriate level of detail. Referee #1 provides constructive ideas about this. Both referees spotted inconsistencies in the result section that should be checked. L270 states that the PDD model is "particularly well suited" to estimate melt over the Peninsula sector. L289-292 and L298-299 draw the opposite conclusion.

Based on the above, I deem that major revisions are required. Note that referee #2 and the editor will re-assess the revised manuscript before acceptance in TC.

Below, the authors can find additional minor suggestions.

Thank you for your constructive comments. We will take into account both your suggestions and those of the Reviewers to improve our manuscript. Specifically, we will work on refining our wording and phrasing, and streamlining the sections that were recommended. In addition, we plan to conduct additional experiments to investigate the use of single combination parameters and the applicability of PDD to warmer temperatures. We will also modify the color scheme for Figure 3 and Figure 8 to ensure they meet the accessibility requirements of the Coblis – Color Blindness Simulator.

Minor suggestions by Brice Noël:

Section 2.2: Here the authors should mention that satellites detect the presence of surface liquid water, not necessarily surface melt.

Thank you for pointing this out. We agree. We will change Lines 89–92 from: "It contains daily estimates as a binary of melt or no-melt on a 25×25 km southern polar stereographic grid. It is obtained by applying the melt detecting algorithm (Torinesi et al., 2003; Picard and Fily, 2006) on the scanning Multichannel Microwave Radiometer (SMMR) and three Special Sensor Microwave Imager (SSM/I) observed passive-microwave data from the National Snow and Ice Data Center (NSIDC) (Picard and Fily, 2006)." with "The dataset contains daily estimates as a binary of melt or no-melt on a $25\times25\ \mathrm{km}^2$ southern polar stereographic grid. The dataset is obtained by applying the melt detecting algorithm (Torinesi et al., 2003; Picard and Fily, 2006) to detect the presence of surface liquid water on the scanning Multichannel Microwave Radiometer (SMMR) and three Special Sensor Microwave Imager (SSM/I) observed passive-microwave data from the National Snow and Ice Data Center (NSIDC) (Picard and Fily, 2006).".

L110: Remove "the" in front of "RACMO2.3p2". This holds for the whole manuscript.

Thank you for pointing this out. We will remove "the" in front of "RACMO2.3p2" for the whole manuscript.

Section 3.1: Here the authors should (at least briefly) mention limitations of the PDD method. Otherwise, the reader only learns about shortcomings at the very end of the manuscript (Section 4.3).

Thank you for pointing this out. We will change at Lines 133–135: "If appropriately parameterized, the temperature-index approach offers accurate performance (Ohmura, 2001) and provides a robust surface melt representation. However, because of the temperature dependency, the robustness of the temperature-index approach is therefore attributed to the temperature-melt correlation.".

L190: "The cross-validation (CV) technique ..."

Thank you for pointing this out. We agree. We change at Lines 190–191: "The cross-validation (CV) 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).".

L217: Here you use the acronym CMS, which is defined for the first time in L277. Please define CMS here first.

Thank you for pointing this out. We agree. We will change at Lines 215–217: "To explore the sensitivity of PDD parameters and model outputs to biases in both the satellite and RACMO2.3p2 products, we perform two sensitivity experiments. In the first sensitivity experiment, we explore the response of T_0, and the PDD melt-day ~~(and CMS)~~ and cumulative melting surface (CMS) outputs, to perturbations in satellite estimates. The CMS which is also known as a melt index (e.g. Trusel et al., 2012), is calculated by multiplying the cell area (km^2) by the total annual melt days (day) in that same cell (Trusel et al., 2012). "

We will replace Lines 277–280 from: "To do this, we calculate the cumulative melting surface (CMS) (day km^2) for satellite estimates and PDD outputs, respectively. The CMS which is also known as a melt index (e.g. Trusel et al., 2012), is calculated by multiplying the cell area (km^2) by the total annual melt days (day) in that same cell (Trusel et al., 2012)." with "To do this, we calculate the CMS (day km^2) for satellite estimates and PDD outputs, respectively.".

L224-227: These lines could be removed as they anticipate on results discussed later in the text. For instance, you state that PDD parameters remain stable in the contemporary climate, which is discussed much later in the text.

Thank you for this suggestion. We agree. We will remove the Lines 224–227.

L257-262: These lines are unclear. Could you remove or reformulate?

Thank you for this suggestion. We agree. We will remove Lines 257–262: "Figure 3d summarizes the statistics of DDFs. The probability distribution of the DDFs is asymmetrical and strongly left skewed (Figure 3d). ~~We see that nearly 50% of the DDFs are in the range 1 to 2.5 $\mathrm{mm\ w.e.\ ^\circ C^{-1}\ day^{-1}}$. That the majority of the DDFs are low may be associated with the negative T_0s defined in the T_0 experiments. This is because, (1) the parametrization of the T_0 and DDF is sequential. The optimal T_0s are substituted into the Equation 2 (Section 3.2.2) as a predefined variable for the DDF experiments, which means our decision on the optimal T_0 will influence the decision making for the optimal DDF; (2) a low negative optimal T_0 may cause more degrees above the T_0 leading to a low optimal DDF that works in conjunction with the sum of the degrees above a vey low T_0.~~".

L311: Here you use the acronym SAM, which is defined for the first time in L345. Please define SAM here first.

Thank you for pointing this out. We agree. We will change at Lines 311-313: "It is suggested to be driven by the ~~SAM~~ Southern Annular Mode (SAM), because of an inverse relationship between the number of melt days in Dronning Maud Land and the southward migration of the southern Westerly Winds (Johnson et al., 2022).".

We will change at Lines 344–346: "This could be explained by other players driving surface melting, such as the ~~Southern Annular Mode (SAM)~~ SAM (Torinesi et al., 2003; Tedesco and Monaghan, 2009; Johnson et al., 2022) which explains ∼ 11%–36% of the melt day variability (Johnson et al., 2022).".

From Section 4.2 onward: consider using “bias” instead of “mismatch” in the main text and figures/captions.

Thank you for this suggestion. We agree. We will replace "mismatch" with "bias" in the main text and figures/ captions.

Major comments by Anonymous Referee #1:

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. In general, the authors responded carefully to the reviewers’ questions. I found that they improved the manuscript by specifying the missing/unclear elements. I would like to thanks the authors for all the work they did.

My only main remaining comment is that the manuscript remains long with unnecessary too detailed information. For instance, section 2.3 L107-L11 is relatively useless. L176-182: the important is to know the test you use, the hypothesis and the p-level. Only maximum 2 sentences are needed, for instance I could summarize by: We use two-sample Kolmogorov–Smirnov test (hereafter two-sample KS test) to evaluate the dissimilarity between the PDD results and RACMO2.3p2 melt outputs at a confidence level of 5%. This would even summarize a significant part of L183-L188. L190-192 : Could be removed. L231: Does the number of cells matter (ie, is it a relevant information especially if you mention it again a few sentences later)? ... I would suggest the authors to make the same exercise into the whole manuscript, it won’t change/reduce the quality of the work but should increase the readability of the manuscript.

Thank you very much for your time and for your very constructive comments. We agree that some sentences are unnecessary.

According to your comments, we will change at Lines 107–109: "~~SEB modeling is a physics-based numerical approach used to calculate the surface energy budget in order to estimate how much energy is available for snow/ice melting. A number of studies have used SEB modeling forced by climate model outputs and AWS data to assess surface melting on GrIS and AIS (e.g. Van den Broeke et al., 2011; Zou et al., 2021).~~ ".

We will replace at Lines 176–188 from: "The two-sample Kolmogorov–Smirnov test (hereafter two-sample KS test) has been used in testing for significant difference between two non-Gaussian climatic distributions when parametric tests are inappropriate (e.g. Deo et al., 2009; Zheng et al., 2021). It has also been used as an alternative way to test the dissimilarity of climatic data as a validation of tests on statistical parameters such as the mean (Zheng et al., 2021). The two-sample KS test non-parametrically tests the distributional dissimilarity between two samples by quantifying the distance between two sample-derived empirical distribution functions (Lanzante, 2021). The null hypothesis is that the two samples are from the same continuous distribution. The test result returns a logical index that either accepts or rejects the null hypothesis at the 5% significance level ($p < 0.05$).

Limited by the duration of satellite era and reanalysis data, the time series of annual data for each computing cell is no larger than 45 years with non-normality. To test the goodness-of-fit of the parameterized PDD model, we therefore perform the two-sample KS tests between the time series of annual number of melt days/ melt amount from the satellite estimates/ RACMO2.3p2 and from the parameterized PDD model outputs. We define a 'same distribution cell' as a cell with no statistically significant evidence from the two-sample KS test for the rejection of the null hypothesis (that the two samples are from the same continuous distribution)." with "Limited by the duration of satellite era and reanalysis data, the time series of annual data for each computing cell is no larger than 45 years with non-normality. We use two-sample Kolmogorov–Smirnov test (hereafter two-sample KS test) to evaluate the dissimilarity between the PDD results and RACMO2.3p2 melt outputs at a confidence level of 5%. We define a 'same distribution cell' as a cell with no statistically significant evidence from the two-sample KS test for the rejection of the null hypothesis (that the two samples are from the same continuous distribution).".

We will remove Lines 190–192: "~~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 statistical models that are calibrated and evaluated on the same data (Maraun and Widmann, 2018).~~".

We will change at Line 231: "...computing cell ~~(there are 4515 computing cells in total)~~. The optimal T_0 for almost...".

We will change at Line 237: "...given the large sample size of the T_0s ~~(4515 computing cells)~~. There is...".

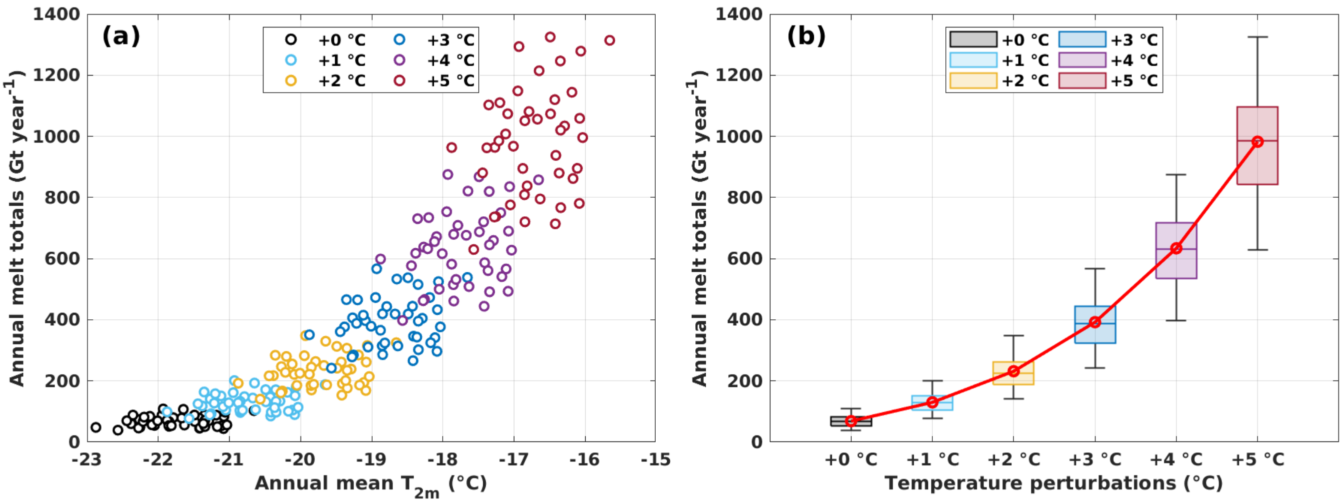
Minor comments by Anonymous Referee #1:

Caption figure 1 : Consider to remove 'Map of', we know it's a map. (Also for Figure 3, Figure 4)

Thank you for this suggestion. We agree. We will change caption figure 1: "~~Map of t~~The research domain and 27 Antarctic drainage basins (Zwally et al., 2012) used in this study.". We will change caption figure 3: "(a) ~~Spatial map of t~~The optimal T_0 (°C) of each computing cell. (b) ~~Spatial map of t~~The optimal DDF (mm w.e. $°C^{-1}$ day^{-1}) for each computing cell." and caption figure 4: "~~Spatial maps for t~~The two-sample KS test results....". We will also remove the "Spatial map of" for Figure 7 and 8.

L224: Not sure why? Because in a warmer climate, the forcing would also be warmer while here you kept ERA5 constant.

Thank you for pointing this out. We agree that our sensitivity experiments do not provide enough evidence for the applicability of the PDD model to warmer climate scenarios. We will conduct additional temperature-melt sensitivity experiments by adding constant temperature perturbations to ERA5 2-m temperature field and use the changed 2-m temperature to force the PDD model.



New Figure 9. (a) scatter plot between annual mean 2-m temperature (T_{2m}) and Antarctic annual melt totals for each temperature-melt sensitivity experiment for the period from 1979/1980 to 2021/2022. (b) boxplot of Antarctic annual melt totals for each temperature-melt sensitivity experiment for the period from 1979/1980 to 2021/2022.

We will replace in Lines 11–14 from: "We conduct sensitivity experiments by adding ±10% to the training data (satellite estimates and SEB model outputs) used for PDD parameterization. We find that the PDD estimates change analogously to the variations in the training data with steady statistically significant correlations, suggesting the applicability of the PDD model to warmer and colder climate scenarios." with "We conduct a sensitivity experiment by adding ±10% to the training data (satellite estimates and SEB model outputs) used for PDD parameterization, and a sensitivity experiment by adding constant temperature perturbations (+1 °C, +2 °C, +3 °C, +4 °C, and +5 °C) to the 2-m air temperature field to force the PDD model. We find that the PDD estimates change analogously to the variations in the training data with steady statistically significant correlations, and the PDD estimates increase nonlinearly with the temperature perturbations, suggesting the consistency of our parameterization and the applicability of the PDD model to warmer climate scenarios. "

We will change at Lines 224–227: "~~In addition, these sensitivity experiments enable us to explore potential applications of our PDD model to predict Antarctic surface melt in the future. Although our PDD parameters remain stable for the contemporary climate, it is uncertain how they could change in a warmer climate. Exploring the variations in PDD parameters~~

~~by performing the above sensitivity experiments provides some insights on the model ability to simulate melt under future warming scenarios.~~ To assess the applicability of our PDD model in simulating melt under warmer climate scenarios, we conduct temperature-melt sensitivity experiments. To do this, we add constant temperature perturbations of +1 °C, +2 °C, +3 °C, +4 °C, and +5 °C to the whole 43-year (1979/1980 to 2021/2022) ERA5 2-m temperature field to force our PDD model.".

We will change at Lines 421–425: "...with the same order of magnitude to both the satellite estimates and RACMO2.3p2 simulations, suggesting that ~~the PDD is also applicable to future climate change scenarios where surface melting is predicted to increase (Trusel et al., 2015).~~ our parameterization method is consistent to both the high and low melt scenarios. ~~Overall, the PDD model is less sensitive than the satellite estimates and RACMO2.3p2 simulations, which indicates that our PDD model can reduce the bias that the satellite and RACMO2.3p2 have on the melt products, even though their biases are unclear (Picard et al., 2007; Mottram et al., 2021).~~

Figure 9 shows the results from our temperature-melt sensitivity experiments. We see a nonlinear increase in our dist-PDD estimates of Antarctic surface melt totals as the temperature perturbation gradually rises from +0 °C to +5 °C. It is not surprising that both the mean and standard deviation increase, given the anticipated nonlinear growth in melt volume resulting from the expansion of both the melt area and amount. The nonlinearity of temperature-melt sensitivity of our dist-PDD model is consistent with the nonlinearity temperature-melt relationship that reported by other studies (Trusel et al., 2015; Bell et al., 2018), further implying the applicability of our dist-PDD model to warmer climate scenarios. "

L242: Do you know why there is this feature around the Amery Ice Shelves (presence of local rocks?

Thank you for pointing this out. It is possibly related to the presence of local rocks as visible on satellite images. For example, Figure 1 from Fricker et al. (2021) and Figure 1 from Spergel et al. (2021). Future work and potential improvement for our PDD model is therefore to consider the elevation correction of the 2-m temperature and the topographic features such as the presence of local rocks, ice free areas, etc.

Another reason might be that melt occurs frequently over the Amery Ice Shelf, but the total amount of meltwater remains low. Our parameterization result suggests low T0s (Figure 3a in the manuscript) agree well (KS test results from Figure 4a and low bias on mean from Figure 5e) with the satellite estimates. However, the PDD melt amount over Amery Ice Shelf does not agree well with RACMO2.3p2 simulations (KS test results from Figure 4b and positive bias on mean from Figure 6e). Figure 6e suggests a significant positive bias on PDD melt amount to RACMO2.3p2 melt amount over Amery Ice Shelf. This is probably because the T0 is too low to lead more sum of the degrees above the T0. Even with a DDF=1 $\mathrm{mm\ w.e.\ ^{\circ}C^{-1}\ day^{-1}}$ will cause much more melt compared to RACMO2.3p2. A future goal and potential improvement for our PDD model is to set a smaller range for the parameterization experiments to limit the parameters to be more physically realistic.

We will change at Line 242: "...The other area is the central Amery Ice Shelf (Figure 3a). We speculate that this feature may be related to the presence of local rocks (e.g., Fricker et al., 2021; Spergel et al., 2021), or it could be a result of frequent surface melt events over the central Amery Ice Shelf (as suggested by the low $\mathrm{T_0}$ value), which are likely to have a low intensity (as indicated by the low DDF value).".

L270 vs L291 and L298: Could you comment here the apparent opposition between these two sentences?

Thank you for pointing this out. This comment overlaps with the 20th Minor comment by the Reviewer Devon Dunmire: "**Figure 5 e-f (and 6e-f): Please put a border around the ice shelves as well as it is difficult to see the ice-shelf edge in some places (e.g. Ross, Ronne-Filchner). Additionally, please more explicitly define what the "difference" represents: is it observations – PDD or PDD – observations? Finally, I wonder if it would also be helpful to show relative difference maps. The largest bias appears to be on the Antarctic peninsula (which is in contradiction to Figure 4 and lines273-275) and I imagine this is just because more melt occurs on the peninsula than elsewhere and thus the bias naturally appears greater.**"

We copy part of our replies to this comment: "The largest absolute bias appears to be on the Antarctic Peninsula and you are correct that this is because more melt occurs in that region. By looking at the relative bias we could indeed see that it is low on the Antarctic Peninsula. This is in agreement with our two-sample KS test results in Figure 4. We will add the following two new figures in Appendix C."

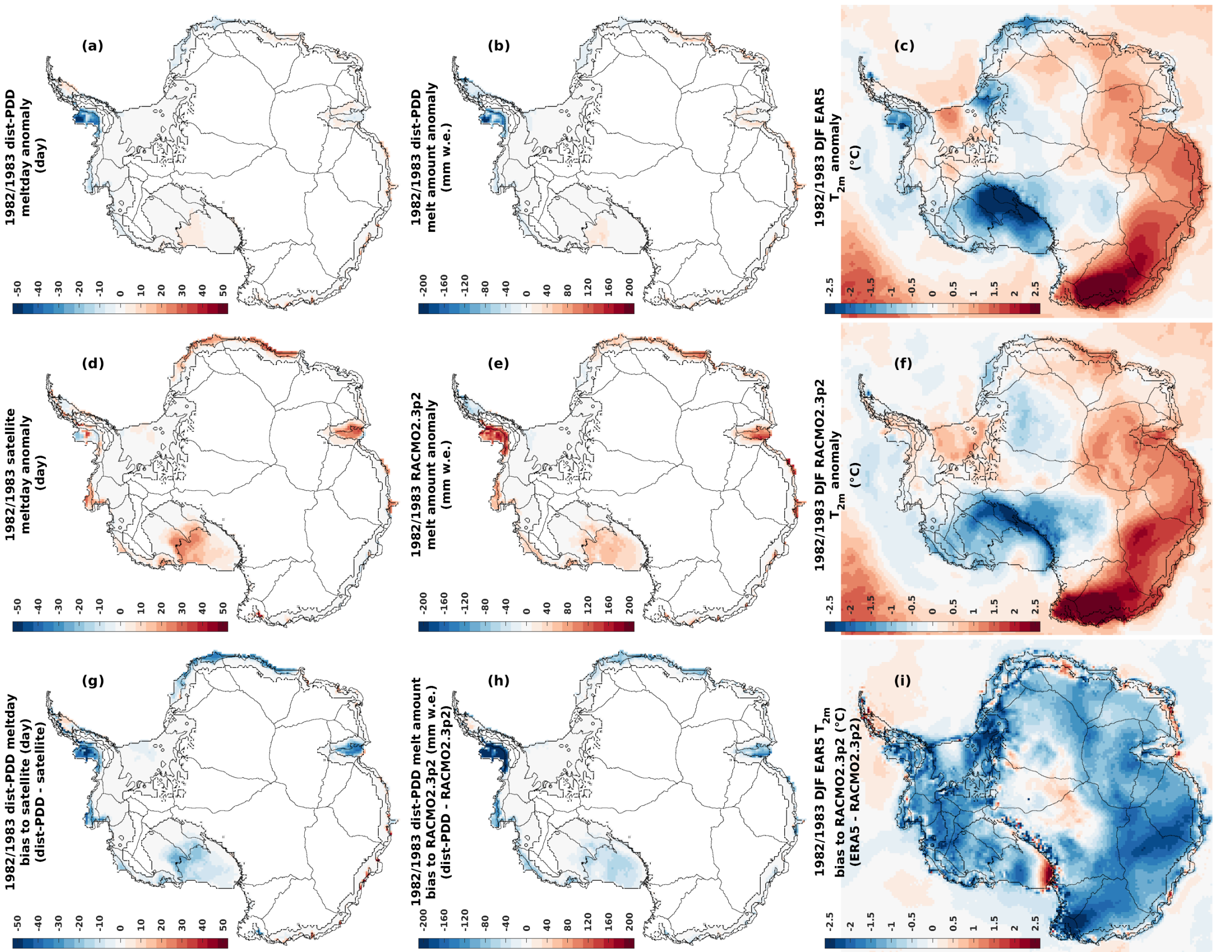
We will change at Lines 270–273: "Our parameterized PDD model is particularly well-suited for estimating surface melt over the ice shelves in the Antarctic Peninsula, while cells located in other ice shelves, such as the Filchner-Ronne Ice Shelf, ice shelves in Dronning Maud Land, Amery Ice Shelf and Ross Ice Shelf, are ~~either in a good agreement on estimating the surface melt days or amount~~ not in a good agreement when estimating both the surface melt days and amount (Figure 4c and d).".

We will change at Lines 289–295: "The computing cells that have relatively large ~~disagreement~~ absolute differences between the mean annual melt days of PDD outputs and of satellite estimates are mainly located over the ice shelves in the Antarctic Peninsula (∼ -2.5 to -22.5 days), over the Abbot Ice Shelf (∼ -5.5 to -12.5 days over the marine edge and ∼ +2.5 to +7.5 days over the interior) and over the Shackleton Ice Shelf (∼ +7.5 to +12.5 days). ~~However, these cells with relatively large disagreement in mean only amount to around 5% of the total computing cells (Figure 5h), and overall for all computing cells, the mean of mismatches in means between the PDD and satellite annual melt days is approximately zero (-0.12 days, Figure 5h).~~ However, these cells with large absolute differences experience frequent surface melt (Figure 2a and d in the Appendix-D), meaning that the relative differences in melt are low (Figure 2g). In addition, these cells only amount to around 5% of the total computing cells (Figure 1b), and overall for all computing cells, the mean of average differences between the dist-PDD and satellite annual melt days is approximately zero (-0.12 days, Figure 1b)."

We will change at Lines 298–301: "The computing cells that have relatively large ~~disagreement~~ absolute differences on STD are mainly located over the Wilkins Ice Shelf (∼ +4.5 to +13.5 days) and over the south of Larsen C Ice Shelf (∼ -7.5 to -10.5 days). Similar to the cells that have relatively large ~~disagreement~~ absolute differences in their means, the relative differences are low (Figure D2h) and these cells amount to only a negligible proportion (less than 5%) of the total number of the computing cells.".

L312-L314: Could you prove that ERA5 is not suited for this summer? Since RACMO is forced by a reanalysis (ERA5 or ERA-Interim), it is likely that the reanalysis actually represents the events leading to higher melt.

Thank you for pointing this out. We will explore this significant PDD melt bias in both the satellite and RACMO2.3p2 data in the year 1982/1983.



New Figure E 1. (a) and (d) 1982/1983 dist-PDD/ satellite meltday anomaly to the dist-PDD/ satellite mean meltday over the period 1979/1980–2020/2021 (with 1982/1983, 1986/1987, 1987/1988, 1988/1989 and 1991/1992 omitted). (g) absolute differences between 1982/1983 dist-PDD and satellite meltday. (b) and (e) 1982/1983 dist-PDD/ RACMO2.3p2 melt amount anomaly to the dist-PDD/ RACMO2.3p2 mean melt amount over the period 1979/1980–2019/2020 (with 1982/1983 omitted). (h) absolute differences between 1982/1983 dist-PDD and RACMO2.3p2 melt amount. (c) and (f) 1982/1983 DJF ERA5/ RACMO2.3p2 2-m air temperature anomaly to the DJF ERA5/ RACMO2.3p2 mean 2-m air temperature over the period 1979/1980–2019/2020 (with 1982/1983 omitted). Note that for all panels the satellite estimates from 2002/2003 to 2010/2011 are the average of SMMR and SSM/I, and AMSR-E. The satellite estimates from 2012/2013 to 2020/2021 are the average of SMMR and SSM/I, and AMSR-2.

New Figure E1 shows that both the satellite and RACMO2.3p2 have a significant positive surface melt anomaly during the 1982/1983 period over the ice shelves in the Amundsen Sea, Ross Ice Shelf, Amery Ice Shelf, and Dronning Maud Land, while PDD does not detect this event. Although both RACMO2.3p2 and ERA5 2-m temperature exhibit similar spatial patterns for the anomaly, ERA5 2-m temperature demonstrates a negative bias in the regions where PDD has lower melt days and amounts than both the satellite and RACMO2.3p2 (New Figure E1).

L315-316: If this does not represent too much work, you could test this second justification by training the PDD over only high melt years, or maybe just refer to section 4.2.2?

Thank you for pointing this out, but we do not fully agree. Using only the high melt years will considerably reduce the sample size, and thus will likely cause the PDD model to overfit to those data (i.e. the high melt year data). Intentionally selecting the high melt years will also remove the signals of multi-decadal climate variability in the timeseries. Therefore, the PDD model will very likely be overfitted to those specific high melt years and will lack the ability to estimate melt when the temperatures are lower. Instead, we propose a new approach to explore our PDD applicability to warmer climate by temperature-melt sensitivity experiments. Please see our reply to your second minor comment.

L459: Following Wille et al., 2019, the authors detected the atmospheric river using ERA-Interim. I guess that we can assume that the new version (ERA5) certainly reflects atmospheric river if its predecessor did.

Thank you for pointing this out. Collow et al. (2022), the authors used ERA5 to detect the atmospheric river. We agree that it is more appropriate to remove "atmospheric river". We will change at Lines 457–459: "We suggest this underestimation corresponds to SAM-influenced climatic conditions, and that the PDD lacks the ability to accurately capture melt if it arises from effects such as föhn winds ~~or atmospheric rivers~~ that are not reflected in the input ERA5 2-m temperature fields used to force the calculations (e.g. Turton et al., 2020~~; Wille et al., 2019)~~.".

Major comments by Devon Dunmire:

The authors made a great deal of changes to the manuscript from it's original version and I commend them for all the work they did. A few more concerns remain for me, particularly with regard to the utility of the PDD model. Can you show that it's better than already existing models? Can it really be used into the future? Additionally, I still think that the results section should be condensed and clarified. It is fairly wordy which makes it sometimes unclear. Hopefully my comments can be helpful in guiding the future direction of this manuscript. Once my more major concerns are addressed, I am happy for the paper to be accepted in the Cryosphere.

My biggest concern is with the applicability of the PDD model to periods outside 1979-2022 (for which melt estimates are already available from satellite observations or RCMs. The authors mention in the conclusion (lines 467-469) the PDD model may be used "to explore Antarctic surface melt in a longer-term context into the future and over periods of the geological past when neither satellite observations nor SEB components are available." However, I worry that the PDD model is too parameterized to the specific observations/RACMO melt estimates from 1979-2022 to have much applicability outside this time, and especially into the future with expected warming. I understand that the authors attempt to address this in section 4.2.2 but I am not entirely convinced by this work, especially as the PDD cumulative melt seems to get worse compared to observations/RACMO from Member 1 to 3. I think it would be more convincing if the authors parameterize 2 different models: 1) using the full 1979-2022 period and 2) using only data from 1979-1989 and compared PDD-derived melt (spatially) from 2012-2022 for these two different models. I'm afraid that if spatial maps of PDD derived melt look substantially different between these two models then the applicability of this PDD is extremely limited. I think some more work needs to be done to prove that this model, which is highly parameterized, can be applied to future periods.

I am also still missing a quantified justification for calculating spatially varying parameters for your PDD. For example, it would be really interesting to see how figures 4, 5, and 6 differ if you do not determine spatially varying parameters and use the same parameters for each grid cell (or use an older PDD). If you can show that melt estimates improve when you utilize spatially varying PDD parameters, this would help justify your method.

Thank you very much for your time and constructive comments. While we understand the rationale for using the first decade for model parameterization, we believe that it is more meaningful to consider the multi-decadal temperature variability over Antarctica. Temperature can decrease in one decade and increase in another due to the influence of internal climate variability. For instance, Turner et al. (2020) reported a positive temperature trend in the Antarctic Peninsula from 1979 to 1997, followed by a negative trend from 1999 to 2018 (referred to Figure 10, Turner et al. 2020). Using only one decade of temperature data for the PDD model may not allow us to include such influences of multi-decadal climate variability. Studies have suggested that the multi-decadal climate variability such as the Amundsen Sea Low, Southern Annular Mode and Interdecadal Pacific oscillation plays an important role on Antarctic temperature variability (e.g. Abram et al., 2014; Stenni et al., 2017; Turner et al., 2020). We therefore argue that using a longer period of temperature data provides a more accurate representation of the overall temperature trends in Antarctica and that the resulting PDD model parameterization therefore provides a more accurate representation of the overall surface melt estimations in Antarctica.

We note that the PDD cumulative CMS (Figure 5b) starts to diverge from the satellite record around the beginning of the first decade, but that they then converge again by the end of the same decade. The significant underestimation of PDD CMS is mainly attributed to the year 1982/1983, as depicted in Figure 5a. Additionally, when comparing the PDD melt amount to RACMO2.3p2, a significant PDD melt bias towards RACMO2.3p2 also occurred during the same year 1982/1983, as shown in Figure 6a.

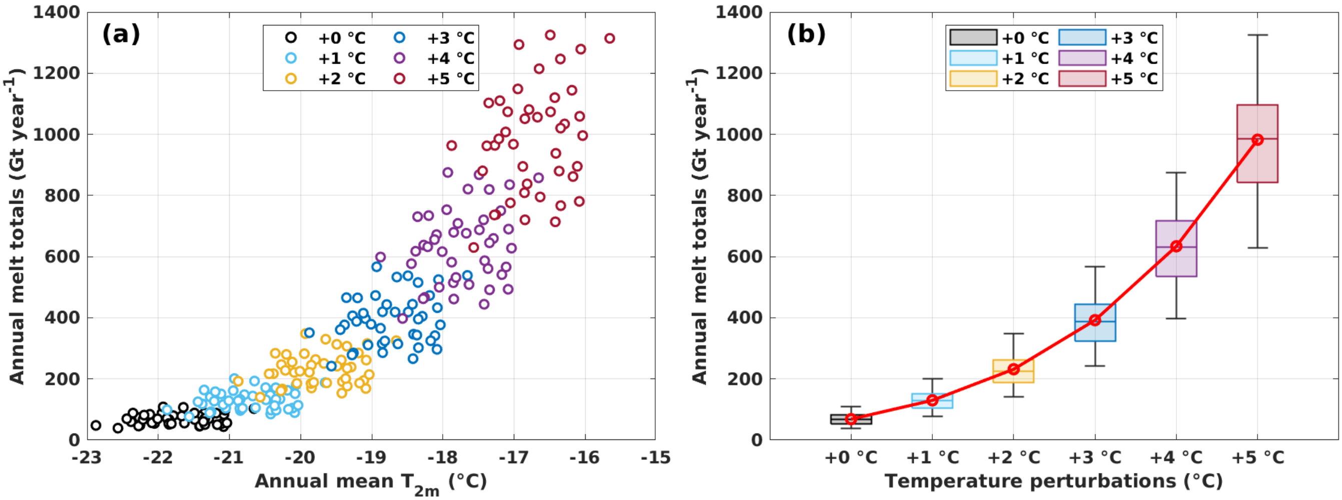
To investigate the applicability of the PDD model beyond the 1979-2022 period, we propose two new methods: (1) exploring the temperature-melt sensitivity for our PDD model by introducing constant temperature perturbations to the ERA 2-m temperature field, which would force the PDD model, and (2) comparing the PDD model outputs with and without including this period.

The nonlinearity of the temperature-melt sensitivity in our PDD model, resulting from our temperature-melt sensitivity experiments, is consistent with the nonlinear temperature-melt relationship reported by other studies (Trusel et al., 2015; Bell et al., 2018). Additionally, a latest paper published in The Cryosphere, Vincent and Thibert (2023) confirms that "temperature-index models are able to capture non-linear responses of glacier mass balance (MB) to high deviations in air temperature and solid precipitation" and suggests "Given that detailed meteorological variables are highly unpredictable in the future, most glacier-mass projections in response to climate change in large-scale studies spanning the 21st century are still today based on temperature-index models with simple temperature and precipitation variables. It follows that the questions raised here relative to the non-linear responses of surface SMB to meteorological variables are crucial."

The temperature-melt sensitivity experiment (1) overlaps with the second minor comment by Anonymous Referee #1. We copy our reply below: "

Thank you for pointing this out. We agree that our sensitivity experiments do not provide enough evidence for the applicability of the PDD model to warmer climate scenarios. We will conduct an additional temperature-melt sensitivity experiments by adding constant temperature perturbations to ERA5 2-m temperature field and use the changed 2-m temperature to force the PDD model.

We will replace in Lines 11–14 from: "We conduct sensitivity experiments by adding ±10% to the training data (satellite estimates and SEB model outputs) used for PDD parameterization. We find that the PDD estimates change analogously to the variations in the training data with steady statistically significant correlations, suggesting the applicability of the PDD model to warmer and colder climate scenarios." with "We conduct a sensitivity experiment by adding ±10% to the training data (satellite estimates and SEB model outputs) used for PDD parameterization, and a sensitivity experiment by adding constant temperature perturbations (+1 °C, +2 °C, +3 °C, +4 °C, and +5 °C) to the 2-m air temperature field to force the PDD model. We find that the PDD estimates change analogously to the variations in the training data with steady statistically significant



New Figure 9. (a) scatter plot between annual mean 2-m temperature (T_{2m}) and Antarctic annual melt totals for each temperature-melt sensitivity experiment for the period from 1979/1980 to 2021/2022. (b) boxplot of Antarctic annual melt totals for each temperature-melt sensitivity experiment for the period from 1979/1980 to 2021/2022.

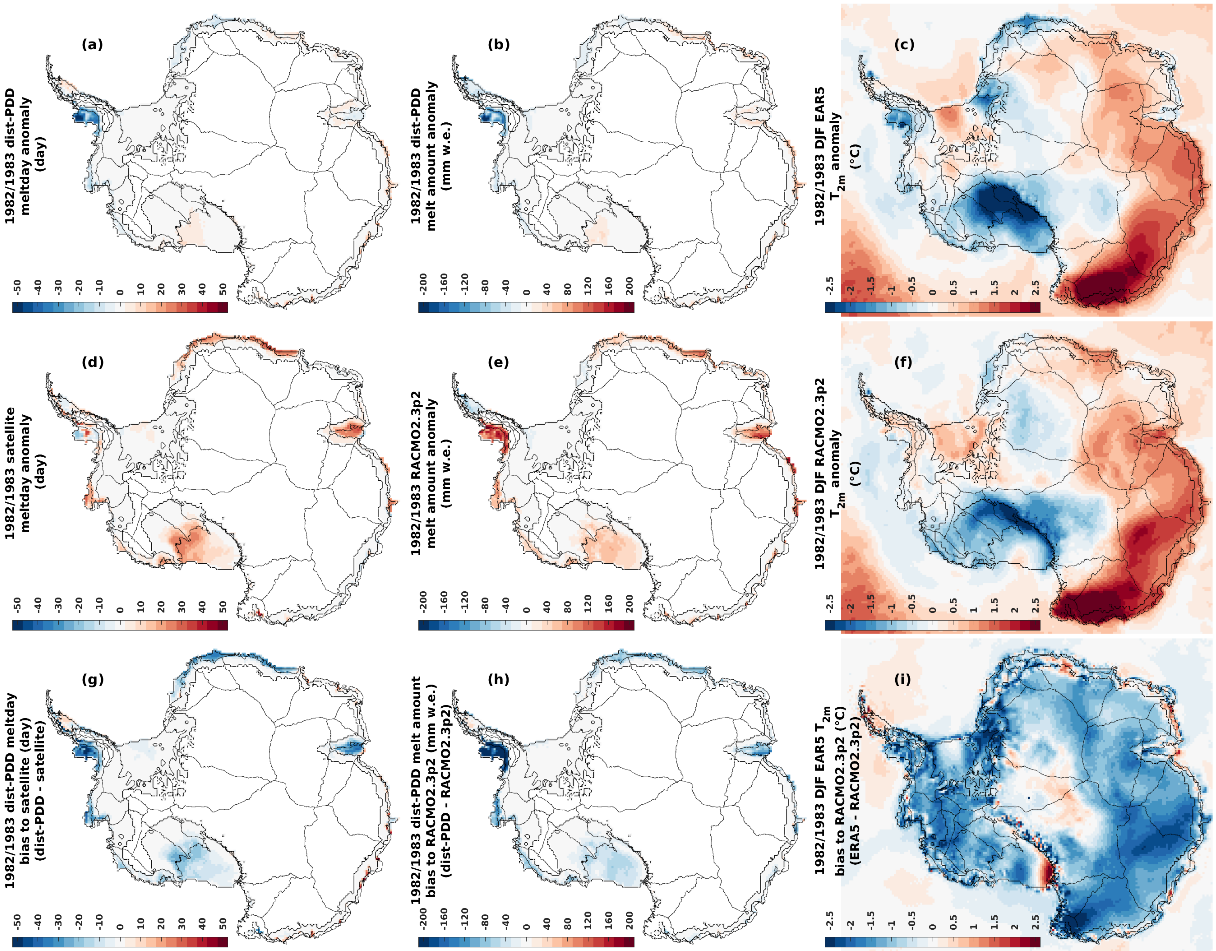
correlations, and the PDD estimates increase nonlinearly with the temperature perturbations, demonstrating the consistency of our parameterization and the applicability of the PDD model to warmer climate scenarios. "

We will change at Lines 224–227: "~~In addition, these sensitivity experiments enable us to explore potential applications of our PDD model to predict Antarctic surface melt in the future. Although our PDD parameters remain stable for the contemporary climate, it is uncertain how they could change in a warmer climate. Exploring the variations in PDD parameters by performing the above sensitivity experiments provides some insights on the model ability to simulate melt under future warming scenarios.~~ To assess the applicability of our PDD model in simulating melt under warmer climate scenarios, we conduct temperature-melt sensitivity experiments. To do this, we add constant temperature perturbations of +1 °C, +2 °C, +3 °C, +4 °C, and +5 °C to the whole 43-year (1979/1980 to 2021/2022) ERA5 2-m air temperature field to force our PDD model.".

We will change at Lines 421–425: "...with the same order of magnitude to both the satellite estimates and RACMO2.3p2 simulations, suggesting that ~~the PDD is also applicable to future climate change scenarios where surface melting is predicted to increase (Trusel et al., 2015).~~ our parameterization method is consistent to both the high and low melt scenarios. Overall, the PDD model is less sensitive than the satellite estimates and RACMO2.3p2 simulations, which indicates that our PDD model can reduce the bias that the satellite and RACMO2.3p2 have on the melt products, even though their biases are unclear (Picard et al., 2007; Mottram et al., 2021).

Figure 9 shows the results from our temperature-melt sensitivity experiments. We see a nonlinear increase in our dist-PDD estimates of Antarctic surface melt totals as the temperature perturbation gradually rises from +0 °C to +5 °C. It is not surprising that both the mean and standard deviation increase, given the anticipated nonlinear growth in melt volume resulting from the expansion of both the melt area and amount. The nonlinearity of temperature-melt sensitivity of our dist-PDD model is consistent with the nonlinearity temperature-melt relationship that reported by other studies (Trusel et al., 2015; Bell et al., 2018), further implying the applicability of our dist-PDD model to warmer climate scenarios. " "

Next, we explore why there is a significant PDD melt bias to both the satellite and RACMO2.3p2 data on the year 1982/1983.



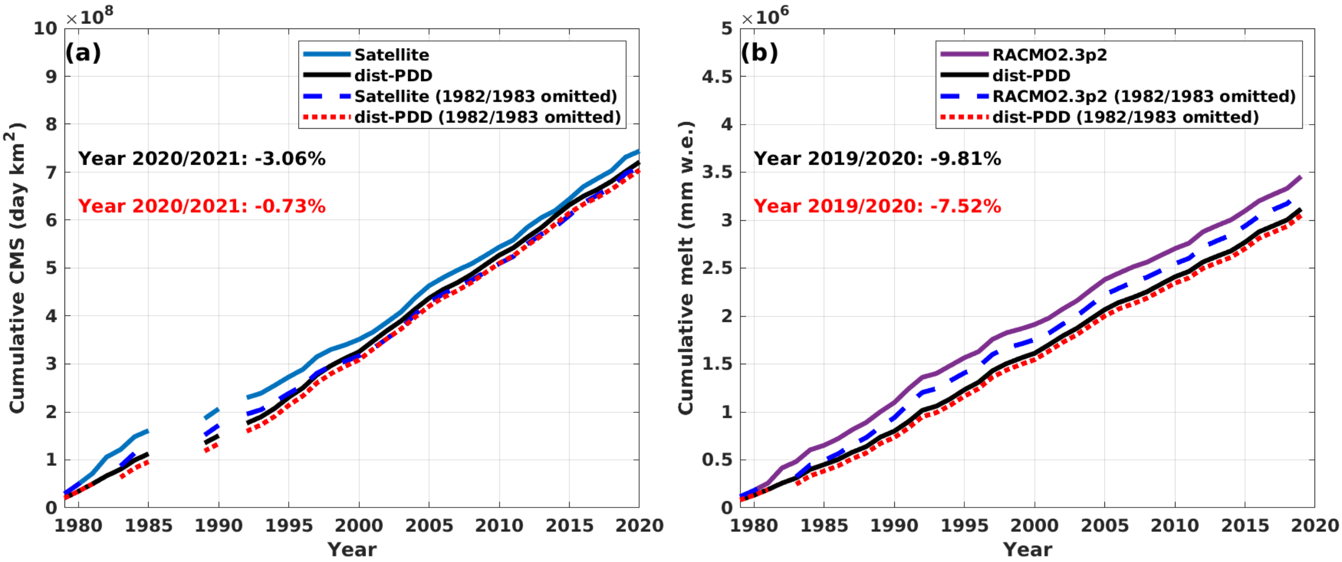
New Figure E 1. (a) and (d) 1982/1983 dist-PDD/ satellite meltday anomaly to the dist-PDD/ satellite mean meltday over the period 1979/1980–2020/2021 (with 1982/1983, 1986/1987, 1987/1988, 1988/1989 and 1991/1992 omitted). (g) absolute differences between 1982/1983 dist-PDD and satellite meltday. (b) and (e) 1982/1983 dist-PDD/ RACMO2.3p2 melt amount anomaly to the dist-PDD/ RACMO2.3p2 mean melt amount over the period 1979/1980–2019/2020 (with 1982/1983 omitted). (h) absolute differences between 1982/1983 dist-PDD and RACMO2.3p2 melt amount. (c) and (f) 1982/1983 DJF ERA5/ RACMO2.3p2 2-m air temperature anomaly to the DJF ERA5/ RACMO2.3p2 mean 2-m air temperature over the period 1979/1980–2019/2020 (with 1982/1983 omitted). Note that for all panels the satellite estimates from 2002/2003 to 2010/2011 are the average of SMMR and SSM/I, and AMSR-E. The satellite estimates from 2012/2013 to 2020/2021 are the average of SMMR and SSM/I, and AMSR-2.

We will add a new Appendix E: "New Figure E1d and e suggest that there is a positive surface melt anomaly in the ice shelves around Amundsen Sea, Ross Ice Shelf, Amery Ice Shelf, and ice shelves in Dronning Maud Land during the period 1982/1983. However, our dist-PDD model does not capture this event (New Figure E1a and b). Our dist-PDD model is significantly negatively biased towards both surface melt days and surface melt amounts compared to satellite estimates and RACMO2.3p2 simulations for this 1982/1983 event (New Figures E1g and h).

Both ERA5 and RACMO2.3p2 exhibit similar spatial patterns for the 1982/1983 DJF 2-m air temperature anomaly (New Figure E1c and f). Although RACMO2.3p2 is forced by ERA5 2-m air temperature, its 2-m air temperature is consistently warmer than that of ERA5 during the 1982/1983 DJF period. This is particularly noticeable in the computing cells over the ice shelves around the Amundsen Sea, Ross Ice Shelf, Amery Ice Shelf, and Dronning Maud Land, where we see significant negative biases for dist-PDD surface melt days and amounts compared to satellite and RACMO2.3p2. These cells also align with the cells where negative ERA5 2-m air temperature biases towards RACMO2.3p2 are found.

We then assess the goodness-of-fit of the dist-PDD model after removing the 1982/1983 period for dist-PDD, satellite, and RACMO2.3p2. The exclusion of the 1982/1983 period significantly improves the accuracy of the dist-PDD model in comparison to satellite and RACMO2.3p2 (New Figure E2). Although there is a slight negative bias of dist-PDD (excluding 1982/1983) cumulative CMS compared to satellite data (excluding 1982/1983) in the first decade, the two cumulative CMS curves converge after approximately the first decade and remain almost completely overlapped for the rest of the time period (New Figure E1a). Similarly, the cumulative melt curves for dist-PDD (excluding 1982/1983) and RACMO2.3p2 (excluding 1982/1983) show a slight divergence in the first decade but remain parallel for the rest of the time period (New Figure E2b). By the end of the integration period, the relative difference between dist-PDD and satellite CMS decreased from -3.06% to -0.73% (New Figure E2a), while the relative difference between dist-PDD and RACMO2.3p2 melt amounts decreased from -9.81% to -7.52% (New Figure E2b). These improvements are consistent across correlations and OLS linear regression analyses, as shown in New Table E1, indicating the enhanced performance of the dist-PDD model in estimating both surface melt days and amounts compared to satellite and RACMO2.3p2 after excluding the 1982/1983 period.

On the basis of this additional experimentation we are able to confidently conclude that our model is accurate for the vast majority of the time series, and that any previously apparent bias was almost entirely due to the anomalous conditions of a single year."



New Figure E 2. (a) cumulative CMS for satellite estimates and PDD/ PDD (1982/1983 omitted) outputs from 1979/1980 to 2020/2021 (with 1986/1987 to 1988/1989 and 1991/1992 omitted. (b) cumulative annual melt amount for RACMO2.3p2 simulations and PDD/ PDD (1982/1983 omitted) outputs from 1979/1980 to 2019/2020.

New Table E 1. The Spearman's ρ and P-value for PDD/ PDD (1982/1983 omitted) CMS/ melt amounts with the satellite CMS/ RACMO2.3p2 melt amounts. Slope, R^2, RMSE and P-value for the OLS fit between PDD/ PDD (1982/1983 omitted) CMS/ melt amounts and satellite CMS/ RACMO2.3p2 melt amounts. Note that the satellite estimates from 2002/2003 to 2010/2011 are the average of SMMR and SSM/I, and AMSR-E. The satellite estimates from 2012/2013 to 2020/2021 are the average of SMMR and SSM/I, and AMSR-2. All the PDD with satellite statistics are calculated over the period from 1979/1980 to 2020/2021 (with 1986/1987 to 1988/1989 and 1991/1992 omitted). All the PDD with RACMO2.3p2 statistics are calculated over the period from 1979/1980 to 2019/2020.

Member	Spearman's ρ	P-value	OLS slope	R^2	RMSE (day km^2/ mm w.e.)	P-value
PDD v.s. satellite	0.5203	$P < 0.01$	0.3004	0.229	3.38×10^6	$P < 0.01$
PDD[a] v.s. satellite[a]	0.5778	$P < 0.01$	0.3894	0.325	3.19×10^6	$P < 0.01$
PDD v.s. RACMO2.3p2	0.8052	$P < 0.01$	0.5307	0.55	1.42×10^4	$P < 0.01$
PDD[a] v.s. RACMO2.3p2[a]	0.8486	$P < 0.01$	0.6582	0.712	1.15×10^4	$P < 0.01$

[a] 1982/1983 is omitted.

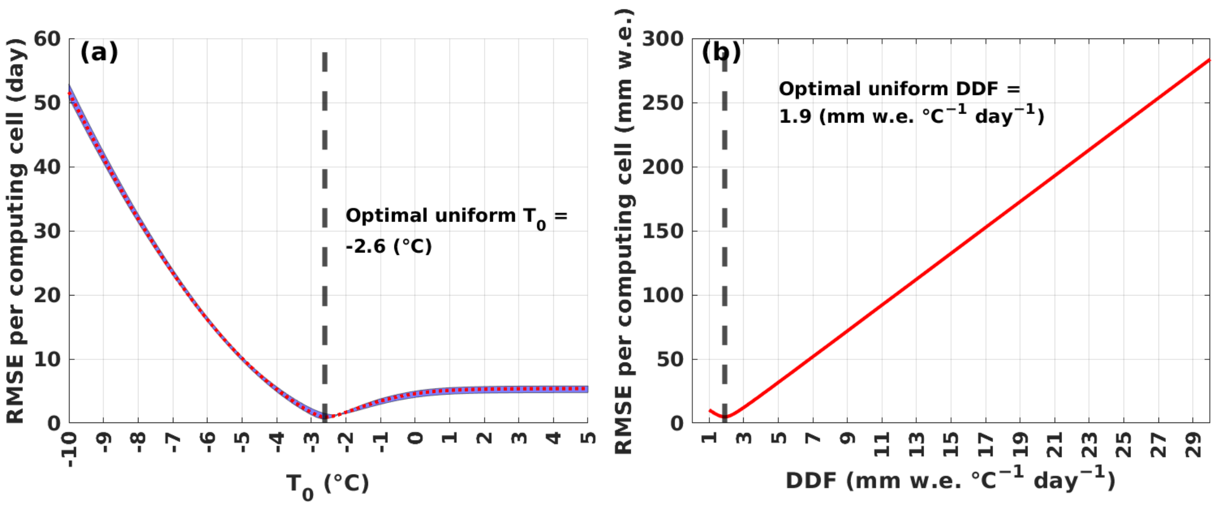
We will use the same parameterization method to generate spatially uniform threshold and melt coefficient for the PDD model, used for all computing cells (hereafter, "uni-PDD"). We will then compare the uni-PDD with the PDD (dist-PDD) obtained by using spatially varying parameters in order to estimate the added value of spatially varying the PDD parameters. In New Figure 4, we calculate the two-sample KS test for the uni-PDD outputs and add the results as panels (a) and (b) to the New Figure 4. By comparing panels (a) and (c) of the New Figure 4, we can see that the proportion of cells with the same distribution for melt days increased. The same trend is observed for the melt amount (panels (b) and (d) of New Figure 4).

We will also add results from uni-PDD to our New Figure 5 and 6. We will move the statistics from New Figure 5c and 6c to New Table 3 and 4. We will calculate the OLS slope, R^2, and RMSE for both the dist-PDD v.s. satellite/ RACMO2.3p2 and uni-PDD v.s. satellite/ RACMO2.3p2.

We will change in Lines 62–69: "In this study, we focus on constructing a computationally efficient cell-level (spatially variable) PDD model to estimate surface melt in Antarctica through the past four decades, by statistically optimizing the parameters of the PDD model individually in each computing cell. We use the European Centre for Medium-Range Weather Forecasts Reanalysis v5 (ECMWF ERA5) (Hersbach et al., 2018a, b) 2-m air temperature as input and compare the simulated presence of melt to satellite estimates of melt days from three satellite products and the Regional Atmospheric Climate Model version 2.3p2 (RACMO2.3p2) surface melt amount simulations. We also use the same data and method to parameterize a spatially uniform PDD model. We then examine the distributions of melt days and melt amount from ~~PDD experiments that use varying model parameters against satellite-based and RACMO2.3p2 estimations~~ PDD outputs against satellite melt day estimates and RACMO2.3p2 melt amount simulations, respectively. Following this, we perform a 3-fold cross validation, together with sensitivity experiments, to evaluate our parameterization method and the PDD model."

We will add in Line 262: "We also use the same method and data to parameterize a spatially uniform PDD (hereafter, "uni-PDD") model (one T_0 and DDF for all computing cells, Appendix C). For convenience, we name the grid cell-level spatially-distributed PDD “dist-PDD”. The optimal T_0 for uni-PDD is -2.6 $°\mathrm{C}$ and the optimal DDF is $1.9\ \mathrm{mm\ w.e.\ °C^{-1}\ day^{-1}}$ (Figure C1 in the Appendix C)."

We will change in Lines 265–275: "We evaluate the parameterized PDD model outputs (melt day and melt amount) for each computing cell by testing the statistical significance of the similarity between the satellite estimates or RACMO2.3p2 simulations and the dist-dist-PDD/ uni-PDD model-derived empirical distribution functions. Figure 4 shows the two-sample KS test results for each computing cell. The dist-PDD model improves the proportion of cells with the same distribution for melt days/ amount from 60.04%/ 65.94% to 86.07%/ 71.16%, respectively, compared to the uni-PDD model. Overall, the parameterized PDD model shows good agreement with the satellite estimates and RACMO2.3p2 simulations both in estimating the annual total of melt days and melt amount, indicated by 86.07% and 71.16% same melt day and amount distribution cells, respectively (Figure 4c and d). Our parameterized PDD model is particularly well-suited for estimating surface melt over the ice shelves in the Antarctic Peninsula, while cells located in other ice shelves, such as the Filchner-Ronne Ice Shelf, ice shelves in Dronning Maud Land, Amery Ice Shelf and Ross Ice Shelf, are ~~either in a good agreement on estimating the surface melt days or amount~~ not in a good agreement on estimating both the surface melt days and amount (Figure 4c and d). It is especially encouraging that the PDD model performs well in the Antarctic Peninsula, given the fact that it is the region of



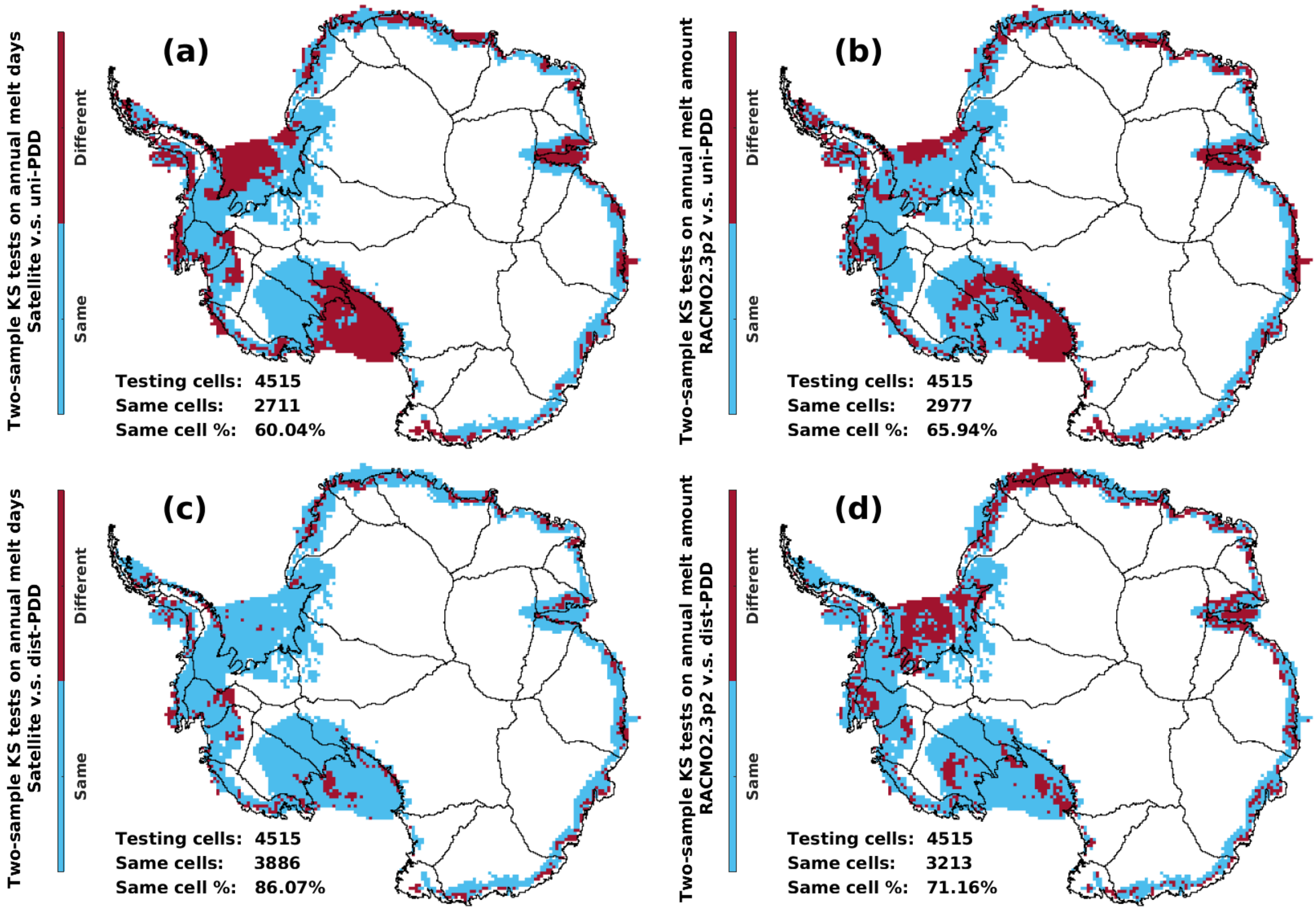
New Figure C 1. (a) red dotted curve is the average of the RMSE across all satellites along each uni-PDD T_0 experiment. In each uni-PDD T_0 experiment, we calculate the RMSE between the time series of annual sum of melt days over all computing cells between uni-PDD model and each satellite estimate. Blue envelope covers the span of the three individual satellite results. Black vertical dash line marks the optimal uni-PDD T_0 suggested by the minimal RMSE. (b) red curve is the RMSE along each uni-PDD DDF experiment. In each uni-PDD DDF experiment, we calculate the RMSE between the time series of annual sum of melt amount over all computing cells between uni-PDD model and RACMO2.3p2. Black vertical dash line marks the optimal uni-PDD DDF suggested by the minimal RMSE.

Antarctica experiencing most intense surface melting both at the present (Trusel et al., 2013; Johnson et al., 2022) and in future projections (Trusel et al., 2015).".

New Table 3. Summary of the statistics for Figure 5c. The Spearman's ρ and P-value for uni-PDD/ PDD CMS with the satellite CMS. Slope, R^2, RMSE and P-value for the OLS fit between uni-PDD/ PDD CMS and satellite CMS. Note that the satellite estimates from 2002/2003 to 2010/2011 are the average of SMMR and SSM/I, and AMSR-E. The satellite estimates from 2012/2013 to 2020/2021 are the average of SMMR and SSM/I, and AMSR-2. All the statistics are calculated over the period from 1979/1980 to 2020/2021 (with 1986/1987 to 1988/1989 and 1991/1992 omitted).

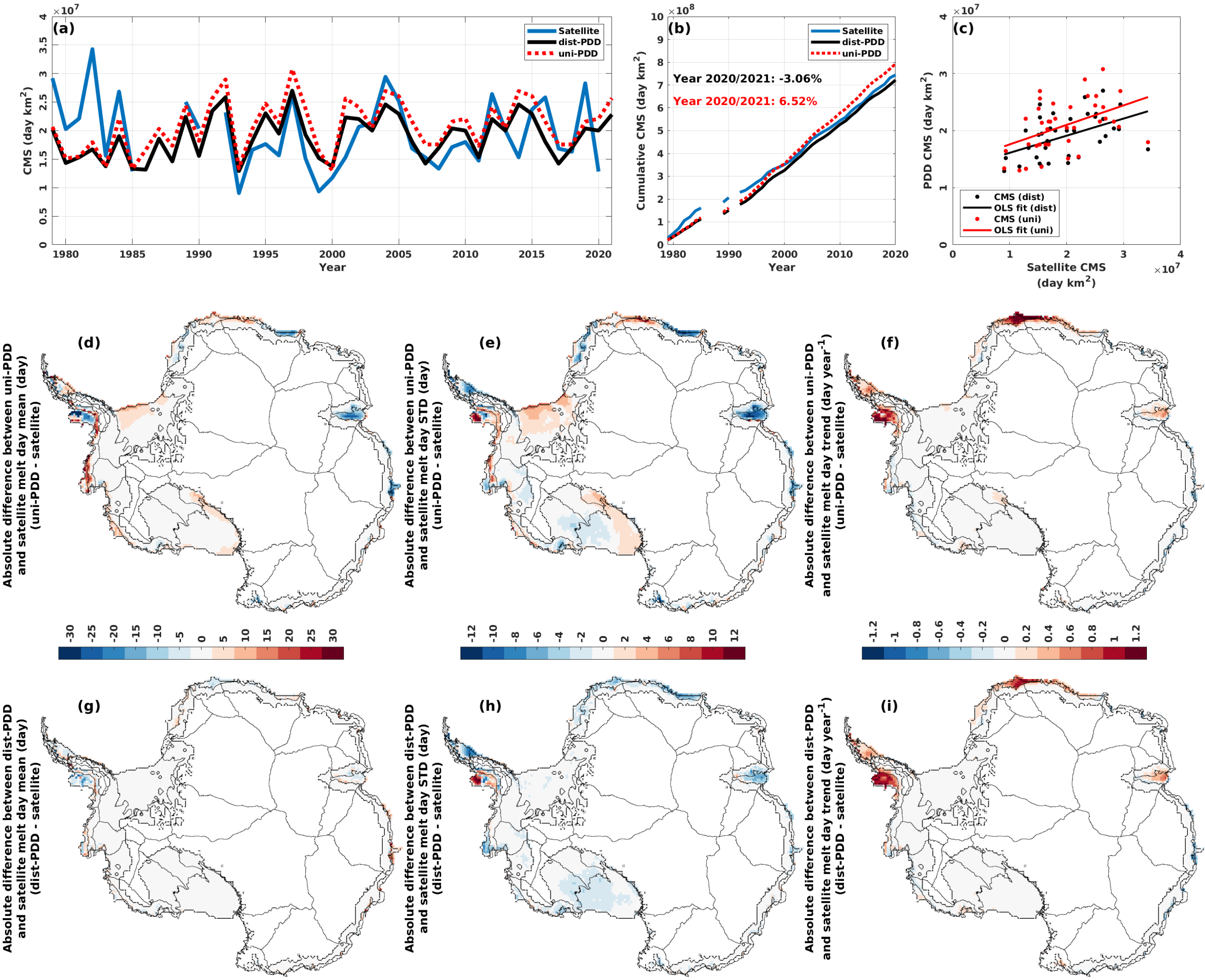
Member	Spearman's ρ	P-value	OLS slope	R^2	RMSE (day km^2)	P-value
uni-PDD v.s. satellite	0.4881	$P < 0.05$	0.3421	0.208	4.09×10^6	$P < 0.05$
PDD v.s. satellite	0.5203	$P < 0.01$	0.3004	0.229	3.38×10^6	$P < 0.05$

We will replace in Lines 276–287 from: "Next, we evaluate the parameterized PDD model outputs for the whole of Antarctica. Firstly, we evaluate the parameterized optimal T0 and its related PDD outputs on the surface melt day. To do this, we calculate the cumulative melting surface (CMS) (day km2) for satellite estimates and PDD outputs, respectively. The CMS which is also known as a melt index (e.g. Trusel et al., 2012), is calculated by multiplying the cell area (km2) by the total



New Figure 4. The two-sample KS test results. The two-sample KS tests are performed individually for each of the 4515 computing cells. The test result "Same" means the tested cell is a same distribution cell where there is no statistically significant evidence for the rejection of the null hypothesis that the testing two samples are from the same continuous distribution (Section 3.3.1). Otherwise, the cell is a different distribution cell ("Different"). (a) and (c) the two-sample KS test results for testing the annual number of melt days between the satellite estimates and the dist-PDD/ uni-PDD model outputs. (b) and (d) the two-sample KS test results for testing the annual melt amount between RACMO2.3p2 simulations and the dist-PDD/ uni-PDD model outputs.

annual melt days (day) in that same cell (Truselet al., 2012). We see in Figure 5a that two CMS time series are in a generally good agreement on both the amplitude and the temporal variability, apart from a small number of years including a period from 1979/1980 to 1982/1983, the year 2014/2015, the year 2016/2017 and the year 2019/2020. Although there is a PDD underestimation for the first decade (1980 to 1990), the cumulative CMS of PDD at the end of the 38-year period is in a good agreement with the cumulative CMS of satellite estimates (-3.06% PDD cumulative CMS underestimation compared to the satellite cumulative CMS, Figure 5b). The positive correlation between the satellite CMS and the PDD CMS is statistically significant (Spearman's $\rho = 0.52$, $p < 0.05$, Figure 5c). The probability histogram for mismatches between the PDD and satellite CMS also



New Figure 5. (a) time series for the cumulative melting surface (CMS) (day km^2) for satellite estimates during the period from 1979/1980 to 2020/2021 (with 1986/1987 to 1988/1989 and 1991/1992 omitted), and for uni-PDD/ PDD outputs during the period from 1979/1980 to 2021/2022. (b) cumulative CMS for satellite estimates and uni-PDD/ PDD outputs from 1979/1980 to 2020/2021 (with 1986/1987 to 1988/1989 and 1991/1992 omitted). (c) scatter plot and ordinary least squares (OLS) fit between satellite CMS and uni-PDD/ PDD CMS. (d) to (i) absolute differences between mean, standard deviation (STD) and trend of uni-PDD/ PDD outputs and satellite estimates on the annual melt days. Mean, STD and trend for the uni-PDD/ PDD outputs and satellite estimates are calculated over the period from 1979/1980 to 2020/2021 (with 1986/1987 to 1988/1989 and 1991/1992 omitted), respectively. Note that for all panels the satellite estimates from 2002/2003 to 2010/2011 are the average of SMMR and SSM/I, and AMSR-E. The satellite estimates from 2012/2013 to 2020/2021 are the average of SMMR and SSM/I, and AMSR-2.

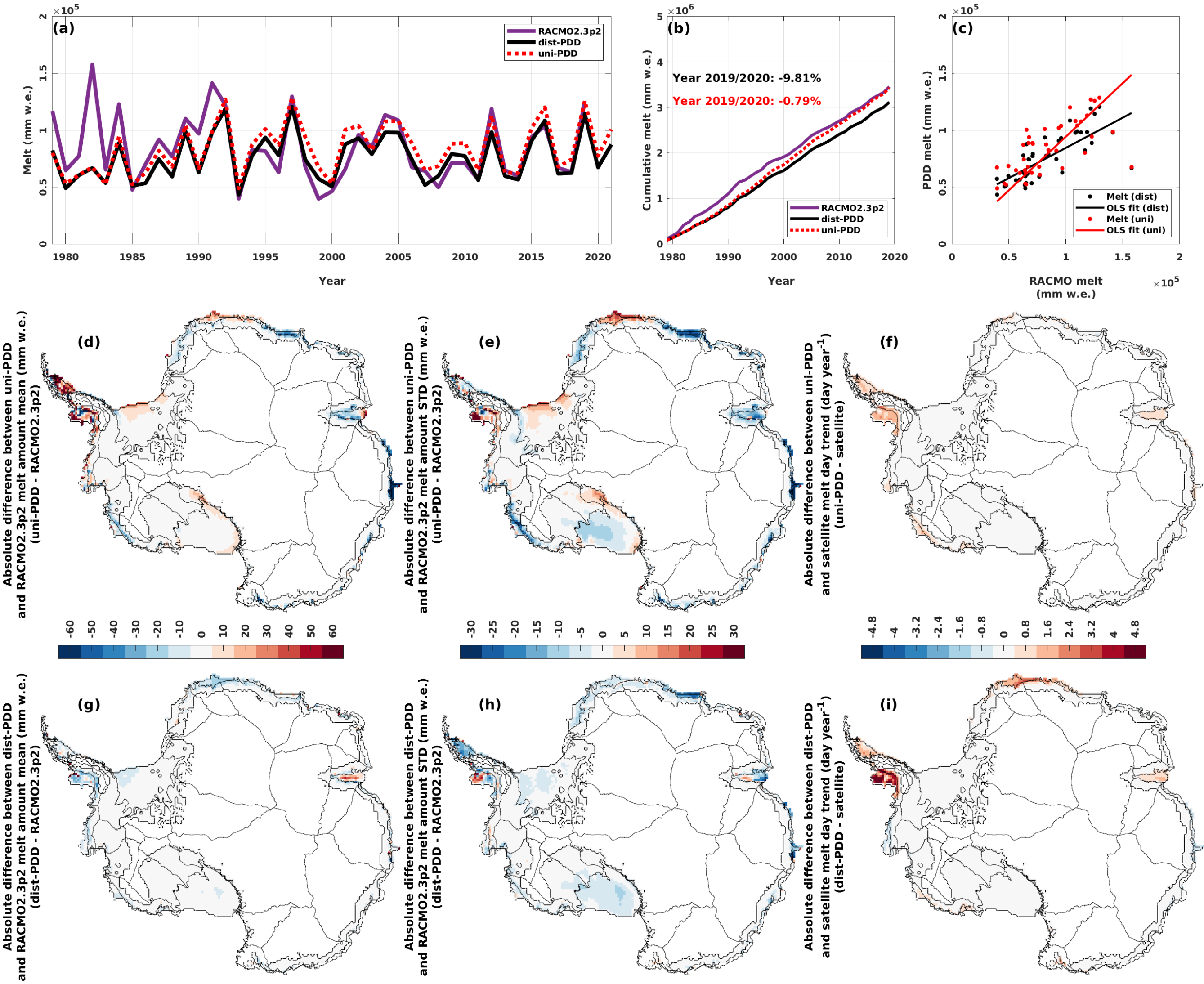
indicates a good agreement between the PDD and satellite CMS (Figure 5d). The mismatches are distributed symmetrically to the mean which is approximated to zero. with "Next, we evaluate the parameterized dist-dist-PDD/ uni-PDD model outputs for the whole of Antarctica. Firstly, we evaluate the parameterized optimal T_0 and its related dist-PDD/ uni-PDD outputs on the surface melt day. To do this, we calculate the CMS (day km^2) for satellite estimates and dist-PDD/ uni-PDD outputs, respectively. We see in Figure 5a that the dist-PDD and satellite CMS time series are generally in good agreement on both the amplitude and the temporal variability, apart from a small number of years including from 1979/1980 to 1982/1983, the year 2014/2015, the year 2016/2017 and the year 2019/2020. Although there is a dist-PDD underestimation of cumulative CMS for the first decade (1980 to 1990), the cumulative CMS of dist-PDD at the end of the 38-year period is in a good agreement with the cumulative CMS of satellite estimates (-3.06% PDD cumulative CMS underestimation compared to the satellite cumulative CMS, Figure 5b). The positive correlation between the satellite CMS and the dist-PDD CMS is strongly statistically significant (Spearman's $\rho = 0.5203$, $p < 0.01$, Table 3). The probability histogram for biases between the dist-PDD and satellite CMS also indicates a good agreement between the dist-PDD and satellite CMS (Figure D1 in the Appendix D). The biases are distributed symmetrically around the mean which is approximated to zero (Figure D1)."

We will replace in Lines 288-289 from: "Globally, we see the PDD model has the ability to capture the main spatial patterns of surface melt days when compared to the satellite estimates for a majority of the computing cells (Figure 5e, f and g)...." with "Globally, we see the accuracy of the PDD model on estimating the surface melt days has improved from a spatial uniformed PDD model to a grid cell-level PDD model (Table 3 and Figure 5), and the latter has the ability to capture the main spatial patterns of surface melt days when compared to the satellite estimates for a majority of the computing cells (Figure 5)".

New Table 4. Summary of the statistics for Figure 6c. The Spearman's ρ and P-value for uni-PDD/ PDD melt amount with the RACMO2.3p2 melt amount. Slope, R^2, RMSE and P-value for the OLS fit between uni-PDD/ PDD melt amount and RACMO2.3p2 melt amount. All the statistics are calculated over the period from 1979/1980 to 2019/2020.

Member	Spearman's ρ	P-value	OLS slope	R^2	RMSE (mm w.e.)	P-value
uni-PDD v.s. RACMO2.3p2	0.7052	$P < 0.01$	0.9416	0.091	2.16×10^4	$P < 0.01$
PDD v.s. RACMO2.3p2	0.8052	$P < 0.01$	0.5307	0.55	1.42×10^4	$P < 0.01$

We will replace in Lines 307–317 from: "Secondly, we evaluate the parameterized optimal DDF and its related PDD outputs on the surface melt amount. Similar to the negative mismatches between PDD and satellite estimates on the CMS for the period from 1979/1980 to 1982/1983 (Figure 5a), negative mismatches of PDD against the RACMO2.3p2 are also present on the annual melt amount for 1982/1983 (Figure 6a). The abnormally extensive melt in 1982/1983 has been reported by previous studies (Zwally and Fiegles, 1994; Liu et al., 2006; Johnson et al., 2022). It is suggested to be driven by the SAM, because of an inverse relationship between the number of melt days in Dronning Maud Land and the southward migration of the southern Westerly Winds (Johnson et al., 2022). The disagreement of the PDD model for this extensive melt event is most likely explained by the absence of any substantial temperature anomaly in the input ERA5 2-m temperature, because of the temperature-dependency of the PDD model (Equation 2) and the temperature-melt relationship (Figure B1). It could also



New Figure 6. (a) time series for the annual melt amount (mm w.e.) for RACMO2.3p2 simulations during the period from 1979/1980 to 2019/2020, and for uni-PDD/ PDD outputs during the period from 1979/1980 to 2021/2022. (b) cumulative annual melt amount for RACMO2.3p2 simulations and uni-PDD/ PDD outputs from 1979/1980 to 2019/2020. (c) scatter plot and ordinary least squares (OLS) fit between satellite annual melt amount and uni-PDD/ PDD annual melt amount. (d) to (i) absolute differences between mean, standard deviation (STD) and trend of uni-PDD/ PDD outputs and RACMO2.3p2 simulations on the annual melt amount. Mean, STD and trend for the uni-PDD/ PDD outputs and satellite estimates are calculated over the period from 1979/1980 to 2019/2020, respectively.

partly be explained by the fact that the PDD parameters were defined based on fitting multi-decadal timeseries between PDD experiments and satellite/ RACMO2.3p2 (Section 3.2.1 and 3.2.2), meaning that some inter/inner- annual signals may not be fully captured." with "Secondly, we evaluate the parameterized optimal DDF and the simulated surface melt amount. Similar to the negative biases between the dist-PDD and the satellite estimates for the CMS for the period from 1979/1980 to 1982/1983 (Figure 5a), the negative biases of dist-PDD against RACMO2.3p2 are also present when compared to the annual melt amount for 1982/1983 (Figure 6a). The abnormally extensive melt in 1982/1983 has been reported by previous studies (Zwally and Fiegles, 1994; Liu et al., 2006; Johnson et al., 2022). It is suggested to be driven by the Southern Annular Mode (SAM), because of an inverse relationship between the number of melt days in Dronning Maud Land and the southward migration of the southern Westerly Winds (Johnson et al., 2022). The disagreement of the dist-PDD model for this extensive melt event is most likely explained by the absence of any substantial temperature anomaly in the ERA5 2-m temperature input (New Figure E1 in the Appendix E), because of the temperature-dependency of the PDD model (Equation 2) and the temperature-melt relationship (Figure B1). It could also partly be explained by the fact that the dist-PDD parameters were defined based on fitting multi-decadal timeseries between dist-PDD experiments and satellite/ RACMO2.3p2 (Section 3.2.1 and 3.2.2), meaning that some inter/intra- annual signals may not be fully captured.".

We will replace in Lines 318–330 from: "Apart from the 1982/1983 event, other negative mismatches from PDD are also evident in the period from 1991/1992 to 1992/1993 (Figure 6a). However, we cannot compare this PDD melt amount mismatch period to the PDD CMS mismatch as the year 1991/1992 is omitted for all the analysis related to the satellite estimates due to the missing satellite data. Notwithstanding, excluding these periods, we see the time series of annual melt amount of the PDD outputs and RACMO2.3p2 simulations are generally in good agreement, especially after 1992/1993 when the two curves start overlapping (Figure 6a) whilst the PDD-satellite CMSs show some disagreement (e.g. 1995/1996, 1999/2000, 2014/2015, 2016/2017 and 2019/2020, Figure 5a). That the PDD is in a good agreement with RACMO2.3p2 on the annual melt amount is also evident by the statistically significant strong positive correlation (Spearman's $\rho = 0.81$, $p < 0.05$, Figure 6c). However, the probability histogram of PDD melt mismatches is slightly left-skewed with a negative mean (-0.08 × 105 mm w.e., Figure 6d) and the PDD model underestimates around 9.81 % for the 41-year integrated annual melt amount compared to the RACMO2.3p2 (Figure 6b). Nevertheless, this underestimation on the 41-year integrated annual melt amount is not evolving through the past four decades, as we see in Figure 6b: the two curves differ in the first decade (i.e. the gap between the two curves is increasing from $\sim$ 1980 to $\sim$ 1990) and becomes parallel for the following three decades." with "Apart from the 1982/1983 event, other negative biases are also evident in the period from 1991/1992 to 1992/1993 (Figure 6a). However, we cannot compare this dist-PDD melt amount bias period to the dist-PDD CMS bias as the year 1991/1992 is omitted for all the analysis related to the satellite estimates due to the missing satellite data. Excluding these periods, the time series of annual melt amount of the dist-PDD outputs and RACMO2.3p2 simulations are generally in good agreement, especially after 1992/1993 when the two curves start to overlap (Figure 6a) whilst the dist-PDD-satellite CMSs show some disagreement (e.g. 1995/1996, 1999/2000, 2014/2015, 2016/2017 and 2019/2020, Figure 5a). It is also evident by the statistically significant strong positive correlation (Spearman's $\rho = 0.8052$, $p < 0.01$, Table 4) that the dist-PDD is in a good agreement with RACMO2.3p2 annual melt amount. However, the probability histogram of dist-PDD melt biases is slightly left-skewed with a negative mean (-0.08×10^5 mm w.e., Figure D3 in the Appendix D) and the dist-PDD model underestimates around 9.81% for the 41-year integrated annual melt amount compared to RACMO2.3p2 (Figure 6b). Nevertheless, this underestimation on the 41-year integrated annual melt amount does not change through the past four decades, as we see in Figure 6b: the two curves differ in the first decade (i.e. the gap between the two curves is increasing from ∼ 1980 to ∼ 1990) and becomes parallel for the following three decades. Although the 41-year integrated annual melt amounts for 2019/2020 between uni-PDD and RACMO2.3p2 show very good agreement (-0.79%, as shown in Figure 6b), the two cumulative curves are not parallel. The uni-PDD curve diverges from the RACMO2.3p2 curve for around 15 years and then converges to RACMO2.3p2 for the rest of the time period (as shown in Figure 6b). This indicates that the uni-PDD model is not sufficiently flexible to accurately estimate surface melt amount.".

We will replace in Lines 331–351 from: "Figure 6e, f and g show the spatial maps for the difference between the mean, STD and trend of the PDD annual melt amount and RACMO2.3p2 mean annual melt amount for the period from 1979/1980 to 2019/2020. As shown in Figure 6e, f and g, the differences over most of the computing cells are equal to or close to zero, which is similar to the spatial difference maps between the PDD outputs and satellite estimates in Figure 5e, f and g. This indicates that the PDD model has the ability to capture the main spatial patterns of both the surface melt days and amount, when compared to the satellite estimates and RACMO2.3p2 simulations, for the majority of the computing cells. There are less than 5% computing cells with mismatches in the mean of lower than -15 mm w.e. or larger than +15 mm w.e. (Figure 6h). These cells are spatially distributed over the western Antarctic Peninsula, ice shelves in Dronning Maud Land, and the Amery Ice Shelf. For the disagreement on the STD, around 10% of the computing cells mismatch -5 to -15 mm w.e. (Figure 6h). The computing cells that have relatively large disagreement on STD are spatially distributed over the Antarctic Peninsula, ice shelves in eastern Dronning Maud Land, the Amery Ice Shelf and ice shelves in western Wilkes Land (Figure 6f). The mismatch in trends between the PDD and RACMO2.3p2 annual melt amount is similar to the mismatch in trends between the PDD and satellite annual melt days, as they both have the same positive mismatch spatial patterns (Antarctic Peninsula, Dronning Maud Land and Amery Ice Shelf, Figure 5g and Figure 6g) and similar right-skewed probability histograms with positive means (Figure 5i and Figure 6i). This could be explained by other players driving surface melting, such as the Southern Annular Mode (SAM) (Torinesi et al., 2003; Tedesco and Monaghan, 2009; Johnson et al., 2022) which explains ∼ 11%–36% of the melt day variability (Johnson et al., 2022). However, these mismatches in trends do not necessarily require that we reject the PDD model, as the trend presented by the PDD model is a reflection of the trend of the input temperature (Figure C1 in the Appendix C), because of the linear relationship between air temperature and surface melt (Figure B1). The disagreement in trends, therefore, is actually between the satellite/RACMO2.3p2 and ERA5 2-m temperature, rather than between the satellite/RACMO2.3p2 and the PDD model itself." with "Figure 6d to i show the spatial maps for the difference between the mean, STD and trend of the dist-PDD/ uni-PDD annual melt amount and RACMO2.3p2 mean annual melt amount for the period from 1979/1980 to 2019/2020. Consistent with the PDD melt day estimates, using the dist-PDD model improves the accuracy of estimating surface melt amount compared to using spatially uniform PDD parameters. As shown in Figure 6g, h and i, the differences over most of the computing cells are equal to or close to zero, which is similar to the spatial difference maps between the dist-PDD outputs and satellite estimates in Figure 5g, h and i. This indicates that the dist-PDD model has the ability to capture the main spatial patterns of both the surface melt days and amount, when compared to the satellite estimates and RACMO2.3p2 simulations, for the majority of the computing cells. Less than 5% of the total number of all computing cells are 15 mm w.e. below or above the bias on mean (Figure 6g). These cells are distributed over the western Antarctic Peninsula, ice shelves in Dronning Maud Land, and the Amery Ice Shelf. For the disagreement on the STD, around 10% of the total number of the computing cells bias -5 to -15 mm w.e. (Figure 6h). The computing cells that have relatively large disagreement on STD are spatially distributed over the Antarctic Peninsula, ice shelves in eastern Dronning Maud Land, the Amery Ice Shelf and ice shelves in western Wilkes Land (Figure 6h). The bias in trends between the dist-PDD and RACMO2.3p2 annual melt amount is similar to the bias in trends between the dist-PDD and satellite annual melt days, as they both have the same positive spatial bias patterns (Antarctic Peninsula, Dronning Maud Land and Amery Ice Shelf, Figure 5i and Figure 6i) and similar right-skewed probability histograms with positive means (Figure D1c and Figure D3c). This could be explained by other players driving surface melting, such as the SAM (Torinesi et al., 2003; Tedesco and Monaghan, 2009; Johnson et al., 2022) which explains ∼ 11%–36% of the melt day variability (Johnson et al., 2022). However, these biases in trends are a reflection of the trend of the input temperature (Figure D5 in the Appendix D), because of the linear relationship between air temperature and surface melt (Figure B1). The disagreement in trends, therefore, is actually between the satellite/RACMO2.3p2 and ERA5 2-m temperature, rather than between the satellite/RACMO2.3p2 and the dist-PDD model itself.".

We will replace in Lines 444–452 from:" We have constructed a PDD model based on the temperature-melt relationship (e.g. Hock, 2005; Trusel et al., 2015), and used it to estimate surface melt in Antarctica through the past four decades. We parameterized the PDD model by running numerical experiments on each individual computing cell to iterate over various combinations of the threshold temperature and the DDF (Section 3.2). We individually selected an optimal parameter combination by locating the minimal RMSE between the PDD and satellite estimates, and SEB simulations, for each computing cell. We independently performed two-sample KS tests on each computing cell in order to assess the goodness-of-fit for the parameterized PDD model. We also temporally and spatially compared the PDD estimations, satellite estimates and RACMO2.3p2 simulations to evaluate the parameterized PDD model. We found that the PDD model has the ability to capture the main spatial and temporal features for a majority of cells in Antarctica under a range of melt regimes (Section 4.2.1)." with "We have constructed a dist-PDD model and a uni-PDD model based on the temperature-melt relationship (e.g. Hock, 2005; Trusel et al., 2015), and used them to estimate surface melt in Antarctica through the past four decades. We parameterized the dist-PDD and uni-PDD models by running numerical experiments on each individual computing cell to iterate over various combinations of the threshold temperature and the DDF (Section 3.2). We individually selected an optimal parameter combination by locating the minimal RMSE between the dist-PDD/ uni-PDD and satellite estimates, and SEB simulations, for each/ all computing cell(s). We independently performed two-sample KS tests on each computing cell in order to assess the goodness-of-fit for the parameterized dist-PDD and uni-PDD models. We also temporally and spatially compared the dist-PDD/ uni-PDD estimations, satellite estimates and RACMO2.3p2 simulations to evaluate the parameterized dist-PDD/ uni-PDD model. We found that our dist-PDD model improves accuracy on Antarctic surface melt estimations from using spatially uniform PDD parameters (uni-PDD), and has the ability to capture the main spatial and temporal features for a majority of cells in Antarctica under a range of melt regimes (Section 4.2.1).".

Minor comments by Devon Dunmire:

In general, I would not recommend starting sentences with "That". For example (L232): "That the dominant number of cells show a negative sign indicates that using T 0 = 0 o C as a melt threshold may significantly underestimate melt events" can be changed to "The majority of cells have a negative T0 ,indicating that using T0 = 0 o C as a melt threshold may substantially underestimate melt events..." I would recommend re-wording other places with this issue as well (L236, L257, L273, L295, L323, L407)

Thank you for this suggestion. We agree. We will replace at Lines 232–233: "That the dominant number of cells show a negative sign indicates that using T0 = 0 ◦C as a melt threshold may significantly underestimate melt events,..." with "The majority of cells have a negative T0, indicating that using T0 = 0 o C as a melt threshold may substantially underestimate melt events,...".

We will replace at Lines 236–237: "That the probability distribution of T0s is close to the normal distribution is not surprising,..." with "It is not surprising that the probability distribution of T0s is close to the normal distribution,...".

L257 is overlapped with the 7th minor suggestion by the Editor. We will remove the Line 257.

We will replace at Line 273 from: "That the PDD model performs well in the Antarctic Peninsula is exciting,..." with "It is especially encouraging that the PDD model performs well in the Antarctic Peninsula".

We will replace at Line 295 from: "That the PDD model captures the main spatial patterns of melt is not surprising,..." with "It is not surprising that the PDD model captures the main spatial patterns of melt,...".

We will replace at Lines 323–325 from: "That the PDD is in a good agreement with RACMO2.3p2 on the annual melt amount is also evident by the statistically significant strong positive correlation (Spearman's $\rho = 0.81$, $p < 0.05$, Figure 6c)." with "It is also evident by the statistically significant strong positive correlation (Spearman's $\rho = 0.8052$, $p < 0.01$, Table 4) that the dist-PDD is in a good agreement with RACMO2.3p2 annual melt amount".

We will replace at Lines 407–408 from: "That the T0 decreases/ increases with the increase/ decrease of the satellite estimates is expected,..." with "It is expected that the T0 decreases/ increases with the increase/ decrease of the satellite estimates,...".

Also, I am slightly confused by the use of the term "mismatches" used throughout. Is this essentially the bias in each grid cell? For example, is Figure 5d showing a probability distribution of the bias between the PDD and satellite CMS for all the grid cells? If this is the case, I recommend using the word "bias" as it likely much more familiar and intuitive for the reader. If not, please explain what exactly is meant by "mismatches"

Thank you for pointing this out. We agree that the term "mismatches" is unclear. This comment is overlapped with the last minor comment by the Editor. We will replace "mismatch" with "bias" in the main text and figures/ captions.

L5/6 – “current understanding of surface melt in Antarctica remains limited”. This statement is a bit too vague... Please specify what aspect of surface melt has limited understanding.

Thank you for pointing this out. We will replace at Lines 5–6 from: "However, current understanding of surface melt in Antarctica remains limited in past, present and future contexts." with "However, the current understanding of surface melt in Antarctica remains limited in terms of the uncertainties of quantifying surface melt and understanding the driving processes of surface melt in past, present, and future contexts.".

Introduction – I think it is important to still mention the potential impact meltwater has on ice-shelf stability (e.g. hydrofracture, ice-shelf disintegration), just perhaps not as extensively as you did at Lines 29-46 of the previous version.

Thank you for this suggestion. We will replace at Lines 25–27: "...Studies have suggested that Antarctic surface melt can impact ice sheet mass balance through surface thinning and runoff, surface meltwater draining to the bed, and increasing ice shelf vulnerability (Bell et al., 2018; Stokes et al., 2022)....". with "Studies have suggested that Antarctic surface melt can impact ice sheet mass balance through surface thinning and runoff, and increasing ice shelf vulnerability that potentially influenced by the production of meltwater which can pond, drain and contribute to the structural weakness of ice shelves (Glasser and Scambos, 2008; Bell et al., 2018; Stokes et al., 2022).".

L26 – “However, these currently less understood...” Please specify what these refers to.

Thank you for pointing this out. We apologize that the text is not clear. Here we cite the "To move beyond simple projections of modern Greenland hydrology to a warmer Antarctica requires an improved understanding of surface hydrology on ice shelves and ice sheets. There are profound knowledge gaps in our understanding of the role of firn densification, the roles of hydrofracture and meltwater-loading-induced-flexure on ice-shelf fracture and calving, and how effective surface rivers are in buffering ice shelves from collapse —these must be addressed to inform our grasp of surface hydrology." from Bell et al. (2018). We will replace at Line 26 from: "However, these are currently less understood over Antarctica than Greenland, either in the past or at present." with "However, the roles of surface meltwater production in relation to ice shelf hydrofracture, surface rivers acting as buffers and ice shelf surface hydrology, are currently less understood over Antarctica than Greenland (Bell et al., 2018).".

L27 – Please be more specific with regards to how meltwater will become an “increasingly important player to the Antarctic environment”.

Thank you for pointing this out. We apologize that the text is not clear. Here we will cite "The impact of surface hydrology on ice-sheet mass balance in other parts of Antarctica will grow as the extent and intensity of surface melt increases. The ponding of meltwater on ice shelves could contribute to their collapse. Whether water is exported by ice-shelf rivers will depend on surface slope, surface conditions and the ice-shelf stress state. If predictions of increased melting are accurate, by 2100 ice shelves in the Antarctic Peninsula will probably have collapsed and all remaining ice shelves including the large Ross, Filchner-Ronne and Amery ice sheets will undergo firn densification due to the increased surface melt." and "On the grounded portions of East and West Antarctica, surface lowering due to runoff and connectivity to the bed (modes 1 and 2, Fig. 3) could become significant by 2100 in certain regions. Regions where 2100 melt rates similar to those observed in Greenland today develop on grounded Antarctic ice include the Pine Island catchment and portions of Wilkes Land, East Antarctica. " from Bell et al. (2018). We will also cite Lee et al. (2017) to include the information of potential impact of future surface melt on Antarctic terrestrial biodiversity.

The surface melting will not only impact the ice dynamics (through the influence to the collapse of ice shelves), but also the ecosystems. Therefore surface melting will likely play an increasingly important role in the Antarctic environment.

We will replace at Lines 26–28 from: "This is concerning as surface melting will likely become an increasingly important player to Antarctic environment through this century and the next." with "This is concerning as surface melting will likely become an increasingly important player in the Antarctic environment through this century and the next. Surface melting will not only impact the dynamics of the ice shelves and ice sheet through meltwater production (e.g. Bell et al., 2018), but will also impact the habitat of the Antarctic biodiversity (Lee et al., 2017).".

L29 – 35 – I'm sorry but I really have no clue what the point of this paragraph is! It jumps around from the Antarctic Peninsula to the melt-albedo feedback to the potential impact of clouds and atmospheric rivers. Please provide a clarified version of this paragraph with the point you are trying to make.

Thank you for this suggestion. We apologize that the text is not clear. We discuss some information about the potential impact of clouds and atmospheric rivers in Section 4.3. We will remove this paragraph at Lines 29–35: "~~Although the warming taking place over the Antarctic Peninsula has not been consistent over the past two decades (Turner et al., 2016), the global mean surface temperature is predicted to increase (Meinshausen et al., 2011). Moreover, the positive feedback of albedo, in which the absorption of shortwave radiation increases when snow melts to water, amplifies this melting (Lenaerts et al., 2017). However, recent studies have found large inter-annual variability of surface melt in Antarctica with no statistically significant trend (Kuipers Munneke et al., 2012; Johnson et al., 2022). Projecting Antarctic surface melt is therefore still a challenge, partly because of uncertainties introduced by clouds (Kittel et al., 2022), atmospheric rivers (e.g. Clem et al.,2022), or other localized climate phenomena.~~".

L51-53: "Topographic influences, such as... (Hock 2005)". This sentence should be reworded for clarity. Perhaps something like: "Spatial and temporal variability in DDF can result from topographic variation, such as the gradient of elevation which affects albedo and direct input solar radiation (Hock, 2003), and seasonal variations in radiation."

Thank you for this suggestion. We apologize that the text is not clear. We will replace at Lines 51–53 from: "Topographic influences, such as the gradient of elevation which affects albedo and direct input solar radiation (Hock, 2003), are generally strongest in mountainous terrain, together with seasonal variations in radiation, and can introduce spatial and temporal variabilities of DDF, respectively (Hock, 2005). " with "Spatial and temporal variability in DDF can result from topographic variation, such as the gradient of elevation which affects albedo and direct input solar radiation (Hock, 2003), and seasonal variations in radiation.".

L158 – Perhaps I am missing something but what are the "three satellite products"? I thought there was one product from SMMR and SSM/I and another one from AMSR-E and AMSR-2?

Thank you for pointing this out. We apologize for that the text is not clear. The three satellite products are: (1) SMMR and SSM/I for the period 1979–2021; (2) AMSR-E for the period 2002–2011; (3) AMSR-2 for the period 2012–2021.

We will change at Lines 157–159: "...Although these three satellite products have different time periods (Table 1), we assume their comparability as these satellite products are derived from the same algorithm and threshold (Picard and Fily, 2006)....".

Figure 2 – please describe in the caption how panel a) and b) are different.

Thank you for this suggestion. We will replace the Figure 2 caption from: "Schematic overview of the time periods for each CV folders and the HIGH, LOW sensitivity experiments." with "Schematic overview of the time periods for each CV folders and the HIGH, LOW sensitivity experiments. (a) is for satellite estimates and PDD melt day calculations. (b) is for RACMO2.3p2 simulations and PDD melt amount calculations.".

Section 3.3.2 – do you average the results from the 3 different folds or look at each fold individually?

Thank you for pointing this out. We don't average the results from the 3 different folds. The three members of our cross-validation are independent. We look at each member of the cross-validation individually.

We will change at Lines 189–192: "The 3-fold CV has three independent members. ~~the first membercontains the first and second fold used to parameterize the PDD model, and the third fold is used to test the model.~~ In Member 1, we take the first and second fold to parameterize the PDD model and test the model on the third fold. 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.".

L213 – it is unclear to me what you mean by "biases in satellite products are likely due to frequent equipment replacements". Has this been reported in other studies? Or do the biases mostly come from some process in the development of the satellite products?

Thank you for pointing this out. As end users of the satellite products, we are not experts in satellite retrievals routines and their biases and refer to papers documenting these biases, authored by developpers of these satellite products. We reference Picard and Fily (2006): "However, the period 1979–2005 includes observations from 4 different sensors whose characteristics vary. As a consequence, sensor replacement may induce artifacts in the derived melting information which may, in turn, bias the climatic analysis of the series. " and Picard et al. (2007): "As a consequence, a pixel experiencing no climatic change would have a slightly negative trend in melt duration, due to the satellite replacements (Picard and Fily, 2006). As a corollary, observed melt duration trends are negatively biased.", which points out that the satellite replacements can introduce biases to the satellite melt products.

We will change at Lines 213–214: "However, biases in satellite products are likely due to the inconsistency in the characteristics of satellite sensors caused by frequent equipment replacements, i.e., 4 times in the period 1979–2005 (Picard and Fily, 2006; Picard et al., 2007).".

L164/165 – Perhaps combine these two sentences to something like: "The DDF is a scaling parameter that controls the meltwater production and is related to all terms of the SEB...". I am a bit thrown off by the usage of "lumped parameter" in L164.

Thank you for this suggestion. We will replace at Lines 164–166 from: "The DDF is a scaling number that controls meltwater production. It is a lumped parameter that relates to all terms of the SEB (Hock, 2005; Ismail et al., 2023) and is suggested not to be considered as a constant number in PDD models (Ismail et al., 2023)." with "The DDF is a scaling parameter that controls the meltwater production and is related to all terms of the SEB (Hock, 2005).".

L234-237: I think these lines can be summed up by something like "The probability distribution of T0 across all grid cells is approximately normal.".

Thank you for this suggestion. We agree. We will replace at Lines 234–237 from: "Figure 3c summarizes the T_0 statistics across all grid cells. The skewness of T_0s is -0.63 indicating a slight left asymmetry of the probability distribution of T_0s. The kurtosis is slightly larger than 3 which is the kurtosis of a normal distribution. We fit a normal distribution with the same mean and standard deviation (STD) (red curve in Figure 3c). It is not surprising that the probability distribution of T_0s is close to the normal distribution, given the large sample size of the T_0s." with "The probability distribution of T_0 across all grid cells is approximately normal (Figure 3c).".

L238: Instead of saying "less than 5% probability", I think it is more intuitive to say something like "more than X standard deviations lower than the mean". I'm left wondering "less than 5% probability than what?"

Thank you for this suggestion. We agree. We will replace in Line 237–238 from: "There is a small number of cells distributed below -5.5 °C with less than 5% probability (Figure 3c)." with "There is a small number of cells distributed below -5.5 °C which is around 1.96 standard deviations lower than the mean (-5.57 °C, Figure 3c).".

L243: Replace "optimal DDFs identified by the minimal RMSE from 291 DDF experiments on each computing cell" with "optimal DDFs identified for each computing cell".

Thank you for this suggestion. We will replace at Lines 243–244 from: "Figure 3b shows the spatial map of the optimal DDFs identified by the minimal RMSE from 291 DDF experiments on each computing cell." with "Figure 3b shows the spatial map of the optimal DDFs identified for each computing cell.".

L256: Do you mean right-skewed?

Thank you for pointing this out. We apologize for the mistake. It should be "right-skewed". We will change at Lines 256–257: "Figure 3d summarizes the statistics of DDFs. The probability distribution of the DDFs is asymmetrical and strongly ~~left skewed~~ right-skewed (Figure 3d).".

L272: This phrase is a bit confusing (and misleading): "are either in a good agreement on estimating surface melt days or amount"

Thank you for pointing this out. We will change at Lines 270–273: "Our parameterized PDD model is particularly well-suited for estimating surface melt over the ice shelves in the Antarctic Peninsula, while cells located in other ice shelves, such as the Filchner-Ronne Ice Shelf, ice shelves in Dronning Maud Land, Amery Ice Shelf and Ross Ice Shelf, ~~are either in a good agreement on estimating the surface melt days or amount~~ do not perform as well for both the surface melt days and amount (Figure 4).".

Figure 5c (and 6c): It would be helpful to provide some statistics for this scatter plot. For example, RMSE, R2, slope of the line of best fit.

Thank you for this suggestion. We will calculate the RMSE, R2 and slope of the line of best fit. However, because Figure 5c and Figure 6c are already quite busy, we propose to move the statistics to two new tables:

New Table 3. Summary of the statistics for Figure 5c. The Spearman's ρ and P-value for dist-PDD/ uni-PDD CMS with the satellite CMS. Slope, R^2, RMSE and P-value for the OLS fit between dist-PDD/ uni-PDD CMS and satellite CMS. Note that the satellite estimates from 2002/2003 to 2010/2011 are the average of SMMR and SSM/I, and AMSR-E. The satellite estimates from 2012/2013 to 2020/2021 are the average of SMMR and SSM/I, and AMSR-2. All the statistics are calculated over the period from 1979/1980 to 2020/2021 (with 1986/1987 to 1988/1989 and 1991/1992 omitted).

Member	Spearman's ρ	P-value	OLS slope	R^2	RMSE (day km^2)	P-value
uni-PDD v.s. satellite	0.4881	$P < 0.05$	0.3421	0.208	4.09×10^6	$P < 0.05$
dist-PDD v.s. satellite	0.5203	$P < 0.01$	0.3004	0.229	3.38×10^6	$P < 0.05$

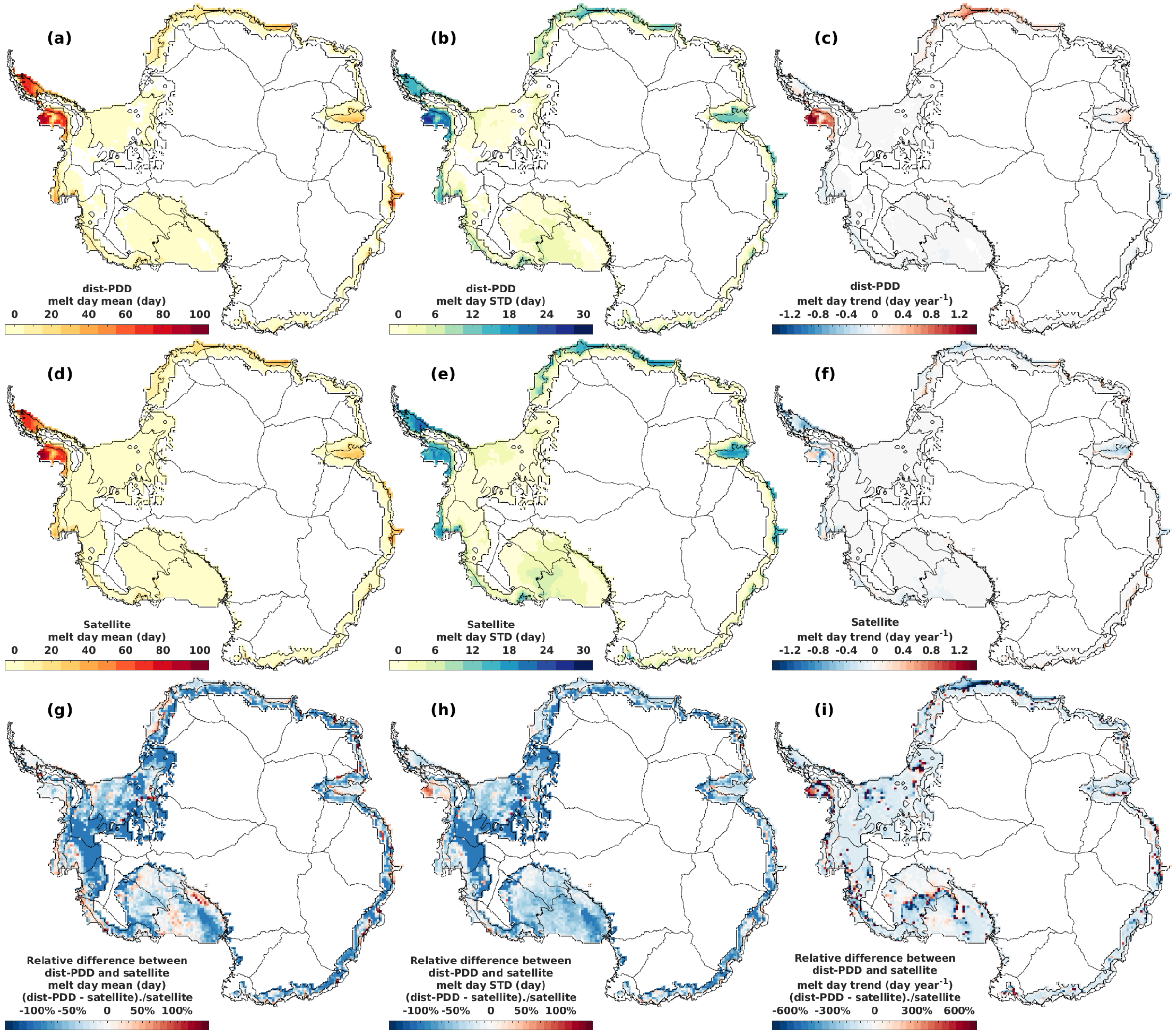
New Table 4. Summary of the statistics for Figure 6c. The Spearman's ρ and P-value for dist-PDD/ uni-PDD melt amount with the RACMO2.3p2 melt amount. Slope, R^2, RMSE and P-value for the OLS fit between dist-PDD/ uni-PDD melt amount and RACMO2.3p2 melt amount. All the statistics are calculated over the period from 1979/1980 to 2019/2020.

Member	Spearman's ρ	P-value	OLS slope	R^2	RMSE (mm w.e.)	P-value
uni-PDD v.s. RACMO2.3p2	0.7052	$P < 0.01$	0.9416	0.091	2.16×10^4	$P < 0.01$
dist-PDD v.s. RACMO2.3p2	0.8052	$P < 0.01$	0.5307	0.55	1.42×10^4	$P < 0.01$

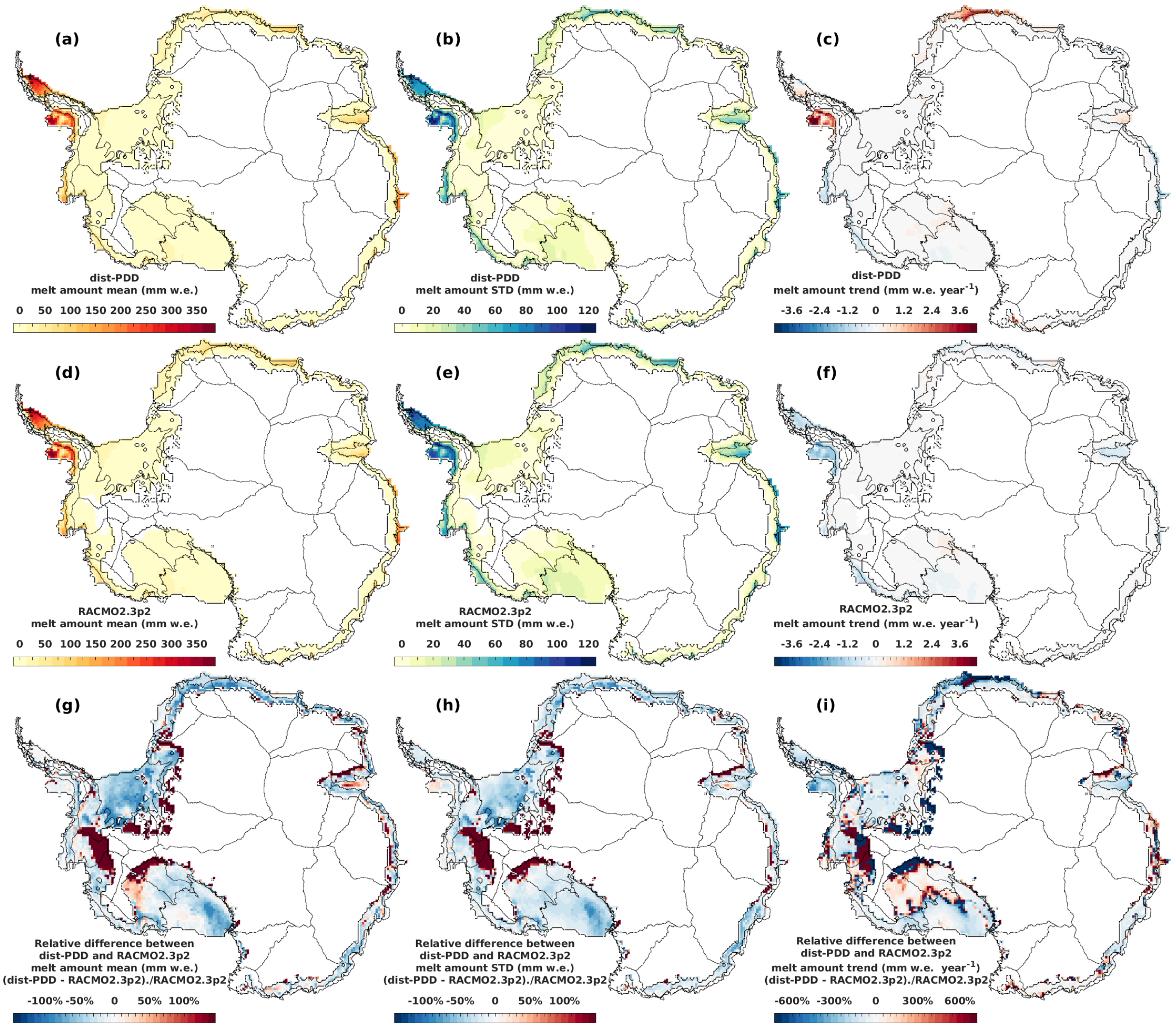
Figure 5 e-f (and 6e-f): Please put a border around the ice shelves as well as it is difficult to see the ice-shelf edge in some places (e.g. Ross, Ronne-Filchner). Additionally, please more explicitly define what the "difference" represents: is it observations – PDD or PDD – observations? Finally, I wonder if it would also be helpful to show relative difference maps. The largest bias appears to be on the Antarctic peninsula (which is in contradiction to Figure 4 and lines 273-275) and I imagine this is just because more melt occurs on the peninsula than elsewhere and thus the bias naturally appears greater.

Thank you for this suggestion. We will add a border of mask area to the spatial maps in Figure 5 and 6 (Figure 5 and Figure 6 above). The "difference" represents the absolute difference between the PDD outputs and satellite/ RACMO2.3p2 (PDD - satellite/ RACMO2.3p2). We will change the title of the colorbar for clarification.

You are correct that the relative difference explains the opposition between Line 270, Line 291 and Line 298, as the Anonymous Referee #1 also pointed out. The largest absolute bias appears to be on the Antarctic Peninsula and you are correct that this is because more melt occurs on the peninsula. Plotting the relative bias actually reduces the bias on the Peninsula in relation to the ther areas. This is in agreement with our two-sample KS test results in Figure 4. We will add the following two new figure in Appendix C.



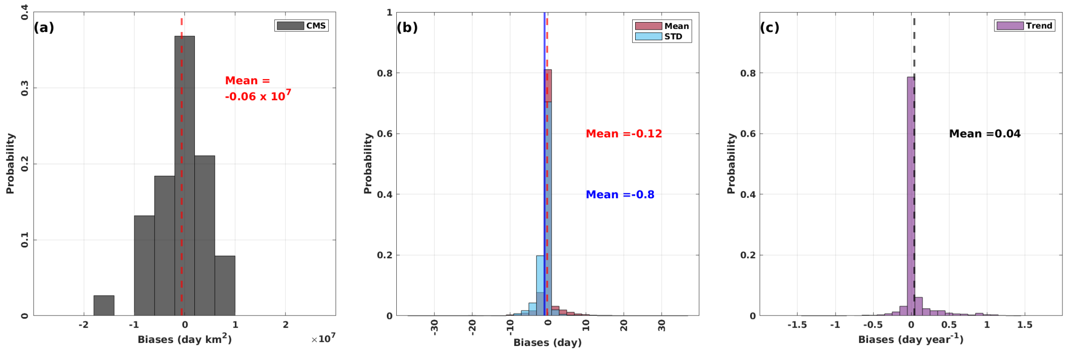
New Figure D 2. (a) to (f) mean, STD and trend of dist-PDD/ satellite melt days for the period 1979/1980 to 2020/2021, respectively. (g) to (i) relative difference between dist-PDD and satellite melt day mean, STD and trend for the period 1979/1980 to 2020/2021, respectively. Note that for all panels the satellite estimates from 2002/2003 to 2010/2011 are the average of SMMR and SSM/I, and AMSR-E. The satellite estimates from 2012/2013 to 2020/2021 are the average of SMMR and SSM/I, and AMSR-2. For all panels the period 1986/1987, 1987/1988, 1988/1989 and 1991/1992 are omitted.



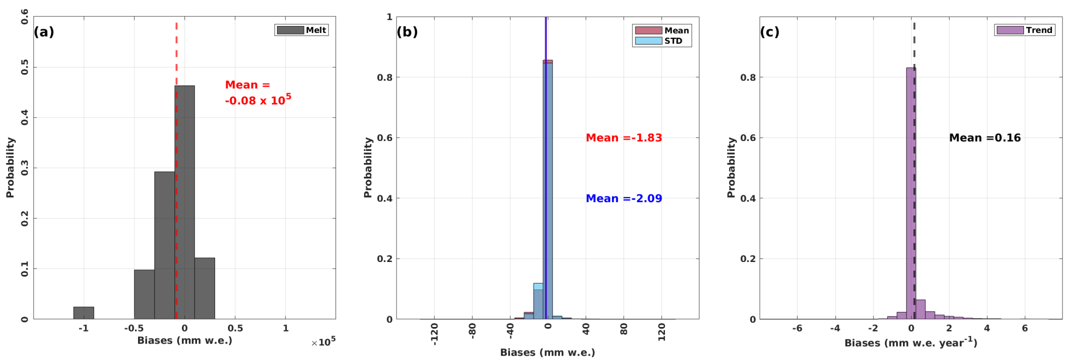
New Figure D 4. (a) to (f) mean, STD and trend of dist-PDD/ RACMO2.3p2 melt amounts for the period 1979/1980 to 2019/2020, respectively. (g) to (i) relative difference between dist-PDD and RACMO2.3p2 melt amount mean, STD and trend for the period 1979/1980 to 2019/2020, respectively.

Figure 5 h/i (and 6 h/i): These figure panels are quite small and have a lot going on in a relatively small area. I would recommend making them bigger or perhaps making them their own figure and moving to the Supplemental material.

Thank you for this suggestion. We agree. We will move these panels to their own figures and move them to Appendix C.



New Figure D 1. (a) probability histogram for the biases between the dist-PDD and satellite CMS. Red dashed vertical line indicates the mean of all biases. (b) and (c) probability histograms for the biases between the dist-PDD outputs and satellite estimates on mean, STD and trend. Red dashed vertical line indicates the mean of all biases between means. Blue vertical line indicates the mean of all biases between STDs. Black dashed vertical line indicates the mean of all biases between trends. Note that for all panels the satellite estimates from 2002/2003 to 2010/2011 are the average of SMMR and SSM/I, and AMSR-E. The satellite estimates from 2012/2013 to 2020/2021 are the average of SMMR and SSM/I, and AMSR-2.



New Figure D 3. (a) probability histogram for the biases between the dist-PDD and RACMO2.3p2 melt amounts. Red dashed vertical line indicates the mean of all biases. (b) and (c) probability histograms for the biases between the dist-PDD outputs and RACMO2.3p2 simulations on mean, STD and trend. Red dashed vertical line indicates the mean of all biases between means. Blue vertical line indicates the mean of all biases between STDs. Black dashed vertical line indicates the mean of all biases between trends.

L329-330: What changed to cause a greater difference between the PDD and RACMO melt amounts before 1990 than after?

Thank you for this question. We believe this is related to the melt event of 1982/1983. Please refer to our response to your major comments and our proposed new Appendix E. In addition, one of the reasons could be the decadal climate variability. Turner et al. (2020) reported that there was a positive temperature trend in Antarctic Peninsula for the period 1979–1997 and a negative temperature for the period 1999–2018 (referred to Figure 10, Turner et al. 2020). Because the Antarctic Peninsula is one of the most intensive melting regions in Antarctica, changes in that area can therefore influence the changes of our PDD annual Antarctic melt totals.

We also list some limitations of the PDD model in Section 4.3 which might be helpful to explain the bias of the PDD model to satellite/ RACMO2.3p2. We assume some climatic phenomena that might be able to influence the surface melt that cannot be captured by the PDD model.

L336: "There are less than 5% computing cells with mismatches in the mean of lower than -15 mm w.e. or larger than +15 mm w.e. (Figure 6h)." – What do you mean by this? Is it "Less than 5% of all computing cells are 15 mm w.e. below or above the mean"?

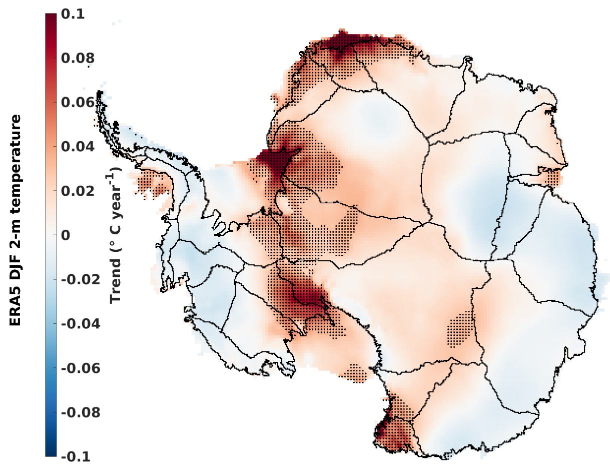
Thank you for pointing this out. We will replace at Lines 336–337 from: "...here are less than 5% computing cells with mismatches in the mean of lower than -15 mm w.e. or larger than +15 mm w.e. (Figure 6h). T..." with "...Less than 5% of the total number of all computing cells are 15 mm w.e. below or above the bias on mean....".

L349-351 "The disagreement in trends, therefore, is actually between the satellite/RACMO2.3p2 and ERA5 2-m temperature, rather than between the satellite/RACMO2.3p2 and the PDD model itself." Can you create a figure to demonstrate this?

Thank you for pointing this out. Please refer to our Figure C6 in the Appendix C. New Figure C3c and New Figure C5c show a positive trend of PDD melt day and amount over ice shelves in West Antarctic Peninsula and Dronning Maud Land, and the Amery Ice Shelf. This spatial pattern of the positive trend is in agreement with the spatial pattern of the positive trend of mean DJF ERA5 2-m temperature (Figure C6).

L355-367: I think this paragraph needs to be simplified and condensed. Essentially, you train on two folds to determine the optimal PDD parameters and test on the third by comparing PDD melt with observations/RACMO, correct? I think shortening this section to would help clarify and make it easier for the reader to follow.

Thank you for pointing this out. Yes, you are correct. We train on two folds to determine the optimal PDD parameters and test on the third by comparing PDD melt with observations/RACMO. According to your comment above on the Section 3.2.2,



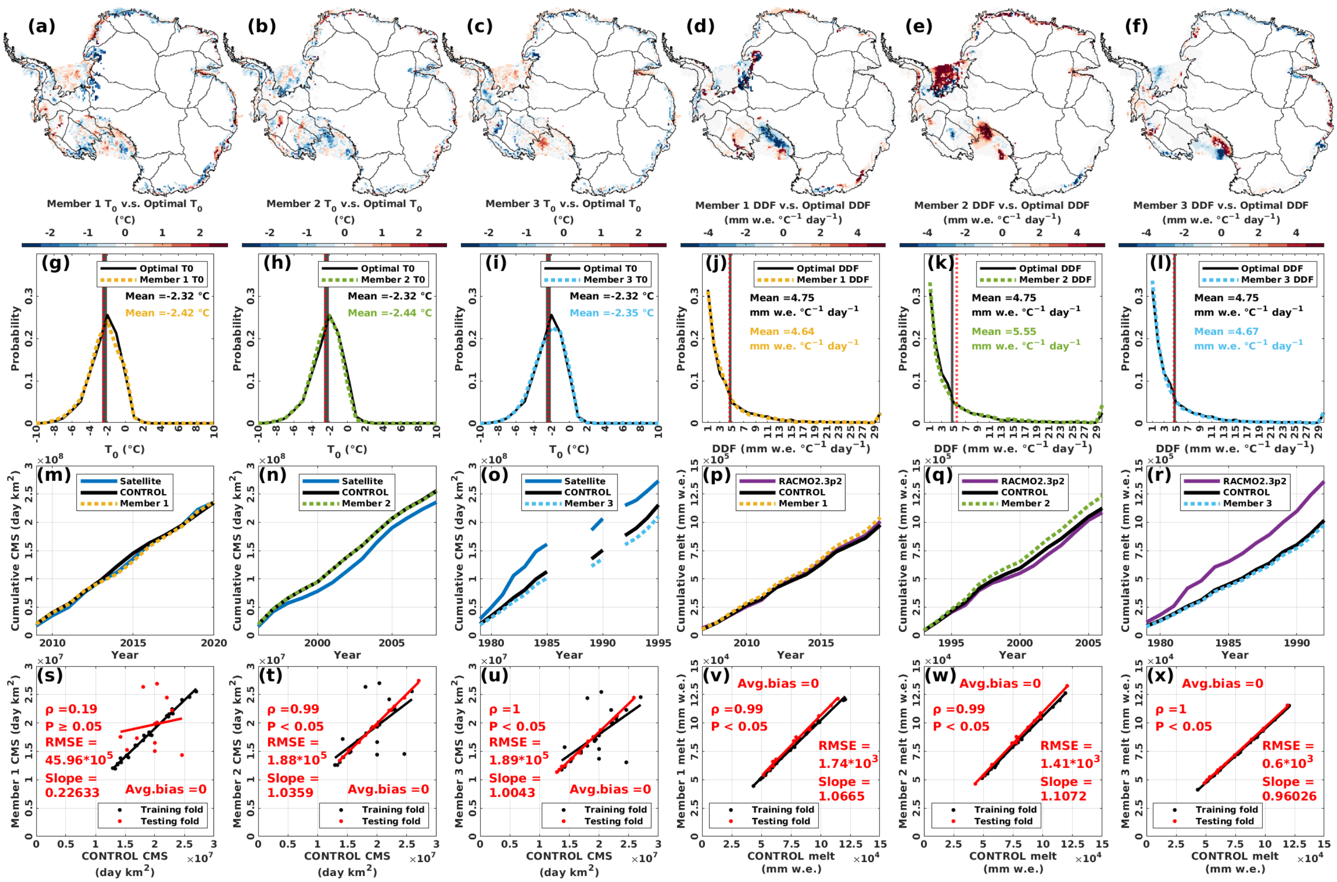
New Figure D 5. Trend of the mean DJF ERA5 2-m temperature on each computing cell during the period 1979/1980–2019/2020. Black dots mark the trends that are statistically significant ($p < 0.05$).

we will change at Lines 189–192: "The 3-fold CV has three independent members. ~~the first membercontains the first and second fold used to parameterize the PDD model, and the third fold is used to test the model.~~ In Member 1, we take the first and second fold to parameterize the PDD model and test the model on the third fold. 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.". This information given in Section 3.2.2 overlaps with the information at Lines 354–363. We therefore remove Lines 354–363 to streamline the manuscript and to improve its readability: "~~Table 2 lists the periods for the training folds and testing folds for each T_0 and DDF member. The training fold is used to parameterize the PDD model parameters. For example, in T_0 Member 2, we use the satellite estimates over the periods 1979/1980–1995/1996 (1986/1987–1988/1989 and 1991/1992 are omitted) and 2009/2010–2020/2021 to run 151 T_0 experiments (similar to the Section 3.2.1, but using different time period of satellite estimates) to parameterize the optimal T_0 for Member 2 (see also Figure 2)). The testing fold is used to evaluate the PDD model parameterized only on the training fold. For example, in DDF Member 3, the Member 3 DDF is parameterized by the training fold which is over the period from 1993/1994 to 2019/2020 (see also Figure 2)). Once the Member 3 DDF is parameterized, we run the PDD model with the Member 3 DDF for the whole 41-year time period. Then we extract the PDD model (the Member 3 DDF PDD model) outputs for the testing fold period (1979/1980–1992/1993) from the whole 41-year model outputs, for testing (evaluating) the DDF Member 3.~~". We think the Table 2 should be in the "Methods" Section instead of the "Results and discussion" Section. We will move the Table 2 to Section 3.3.2.

Figure 7g-l: The histograms are not super helpful for me here. Is there a better way to visualize this? The colors for each subpanel are a bit hard to distinguish.

Thank you for pointing this out. We agree that the histograms are a bit hard to visually distinguish because they mostly overlap. The overlapping of these histograms indicates that the distribution of parameters of each CV member are analogous to the distribution of the CONTROL parameters.

In order to better visualize this, we convert the histograms to curves (Figure 7).



New Figure 7. (a) to (f) 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 distributions 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, and the slope, RMSE and average bias for the OLS fit, for the testing fold between each member and the CONTROL are calculated, respectively.

Figure 7s-x: It would be helpful to include other statistics for these scatter plots (RMSE, average bias, slope of line of best fit).

Thank you for this suggestion. We will add RMSE, average bias and slope of the line of best fit to the Figure 7s-x ((Figure 7) above). The average bias for each panel from (s) to (x) are: 2.1731e-09, -6.1611e-09, -2.2925e-09, 4.3096e-11, -5.1971e-13, 2.2348e-11. The biases are distributed symmetrically to zero therefore the average bias for each CV member are very close to zero.

Figure 7o and r: I am confused why the CONTROL line is so different from RACMO2.3p2. Should this not look the same as the PDD line in Figure 5 and 6b? Maybe I am misunderstanding what the CONTROL is.

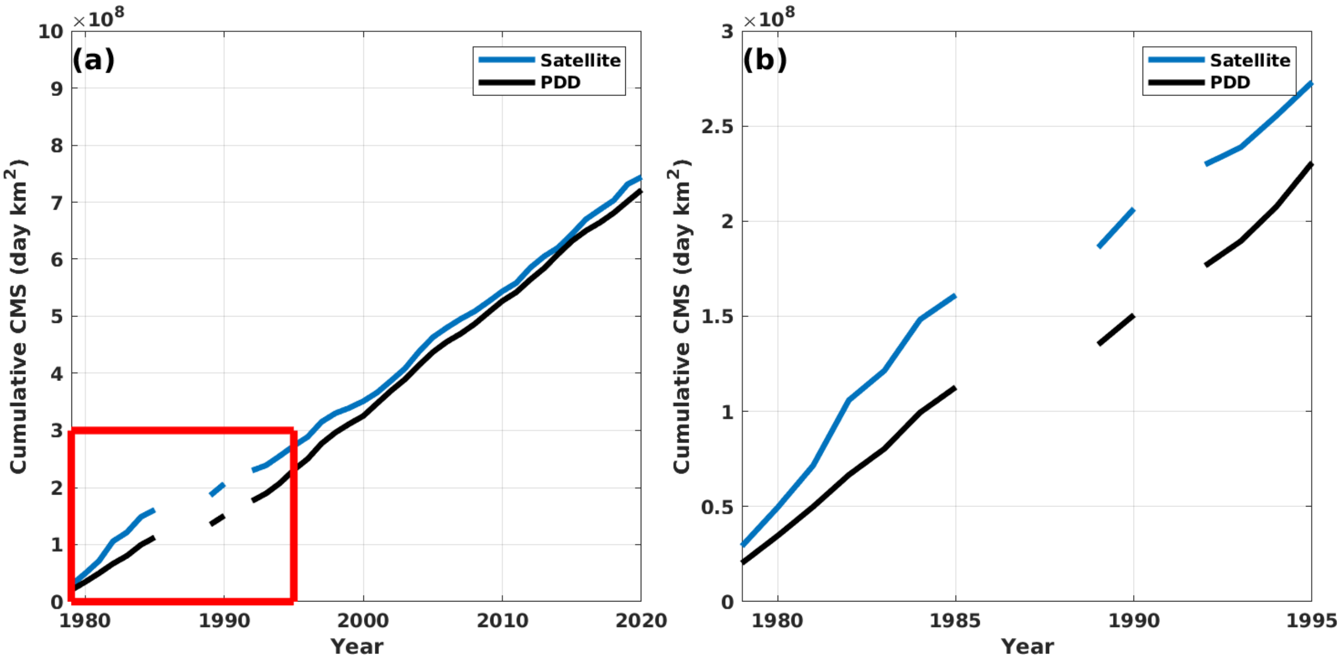


Figure 0. (a) cumulative CMS for satellite estimates and PDD outputs from 1979/1980 to 2020/2021 (with 1986/1987 to 1988/1989 and 1991/1992 omitted. (a) cumulative CMS for satellite estimates and PDD outputs from 1979/1980 to 1995/1996 (with 1986/1987 to 1988/1989 and 1991/1992 omitted

Thank you for pointing this out. You are correct that the CONTROL line on Figure 7o and r should look same as the PDD line in Figure 5 and 6b, and they are exactly the same. The size of the figure and the range of x and y axis introduce the visual bias: zooming into the red box area of Figure 0a and setting the x and y axis to be exactly the same x and y axis of Figure 7o reveals that the PDD line on Figure 0b is exactly the same as the CONTROL line on Figure 7o. Same as the Figure 6a and Figure 7r.

Technical corrections by Devon Dunmire:

L6 – Add “grid” before “cell-level”

Thank you for this suggestion. We will change in Line 6: "...Here, we construct a novel grid cell-level positive degree-day...".

L10 – delete “to” in “independently of to the time window...”

Thank you for this suggestion. We will change in Line 10: "...computing cells as a whole, independently of ~~to~~ the time ...".

L39 – add “better” before “suited”. Also make sure your spelling of “therefor” is consistent throughout the paper. In L54 you use “therefore”.

Thank you for pointing this out. We will change in Line 39: "...input and computational requirements and is therefore better suited...".

L58: change “the spatial variability of PDD parameters are rarely considered” to “the spatial variability of PDD parameters is rarely considered”.

Thank you for pointing this out. We will change in Line 58: "...the spatial variability of PDD parameters ~~are~~ is rarely considered...."

L68: Change “varying” to “our spatially varying”

Thank you for this suggestion. We will change in Line 68: "...our spatially varying model parameters agains...".

L129: change “most used” to “most commonly used”

Thank you for this suggestion. We will change in Line 129: "...temperature-index models are the most commonly used method...".

L161 – Change “multi” to “multiple”

Thank you for this suggestion. We will change in Line 161: "...there are multiple T0 experiments that...".

L164 – Change “the amount of melt” to “meltwater production”. (perhaps do this elsewhere too).

Thank you for this suggestion. We will change in Line 164: "...number that controls ~~the amount of melt~~ meltwater production....". We will also change in Line 42: "...which controls ~~the amount of melt~~ meltwater production....".

L169 – Change “address” to “determine”

Thank you for this suggestion. We will change in Line 169: "In order to ~~address~~ determine the optimal DDF,...".

L186 – Add either “melt volume” or “meltwater production” after RACMO2.3p2

Thank you for this suggestion. We will change in Line 186: "...RACMO2.3p2 melt volume and from the...".

L190 – I think you can delete “has been developed since the 20th century (Stone, 1974) and”

Thank you for this suggestion. This comment overlaps with the Major comments by Anonymous Referee #1. We will delete the whole paragraph.

L205 – change “foldis” to “fold is”

Thank you for pointing this out. We will change in Line 205: "...the third ~~foldis~~ fold is used...".

L232 – replace “dominant number” with “majority”

Thank you for this suggestion. We will change in Line 232: "...the ~~dominant number~~ majority of cells...".

L234: Change “statistics of T0 s” to “T0 statistics across all grid cells”

Thank you for this suggestion. We will change in Line 234: "...the ~~statistics of T0s~~ T0 statistics across all grid cells....".

L280: Add “the” before “two CMS time series” and change “are in a generally” to “are generally in”

Thank you for this suggestion. We will change in Line 280: "...that the two CMS time series are ~~in a~~ generally in good agreement...".

L287: Change “symmetrically to the mean” to “symmetrically around the mean”

Thank you for this suggestion. We will change in Line 287: "...distributed symmetrically ~~to~~ around the mean which...".

L288: There are two “the”s before “PDD model”

Thank you for pointing this out. We will change in Line 288: "...see the ~~the~~ PDD model...".

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