Author comment to the Referee comment by Devon Dunmire on the manuscript

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

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

This work presents a new method to obtain Antarctic surface melt using only near-surface air temperature and is parameterized for different regions of Antarctica. Overall, the work presented is of high quality and will improve our understanding of AIS surface melt. However, I think the presentation of the methods, results and contribution of this work needs to be modified throughout the paper to clarify how this work fits into previous studies and contributes to ongoing efforts to better understand AIS surface melt. Many of the paragraphs are a bit confusing and difficult to read because unnecessary information is present. I feel confident that once the writing is clarified and condensed a bit that this work will be a great contribution! Nice job on the figures as they are all very clear.

Major revisions:

I think the main thing that is missing for me is a quantified justification for calculating parameters for your PDD in each region or basin. What do you gain from the by-region parameterization of your PDD model? How much better does your model do in each basin/ice-shelf region compared to observations than if you just chose one value for the whole AIS?

Many of the sentences throughout the paper use "this" or "it" without specifying what "this" or "it" is referring to. For example, in Line 164: "It shows that most of the cells in Antarctic…"

You mention that topography can introduce spatial variability in PDD parameterization. In this work, you parameterize a PDD model for each basin, but what about topographic variability within each basin? I am left wondering how variable the optimal PDD model parameters are withing each basin/region?

I think more emphasis needs to be put on why your PDD model is useful throughout the paper(esp. in the intro and discussions sections). This work provides a new method but not really any new information about AIS melt that cannot be obtained from RACMO or satellite observations.To that end, I think the final sentence in the introduction is a bit misleading because really you just compare output from your PDD model with observations and regional climate model output of surface melt. I would suggest focusing on the novelty of the method and potential applications for it, instead of the fact that you use your model to estimate AIS surface melt from 1979-2022 (because this can be and has been done already with satellite observations and RCMs instead).

Thank you for these very inspiring and constructive comments. We apologize that the text is confusing and the decision of using regional parameters is not very convincing. We thank you for making this great point and have decided to explore the PDD parameters on the cell-level in the revised version of the manuscript. We agree that the cell-level PDD parameterization enhances the novelty of our study. We will make sure that the new version of the manuscript, is proofread to make sentences clearer.

Below are some figures that we will add into the new version of the manuscript regarding to the cell-level PDD parameterization. The according results, discussions and conclusions will also be added into the new version of the manuscript.

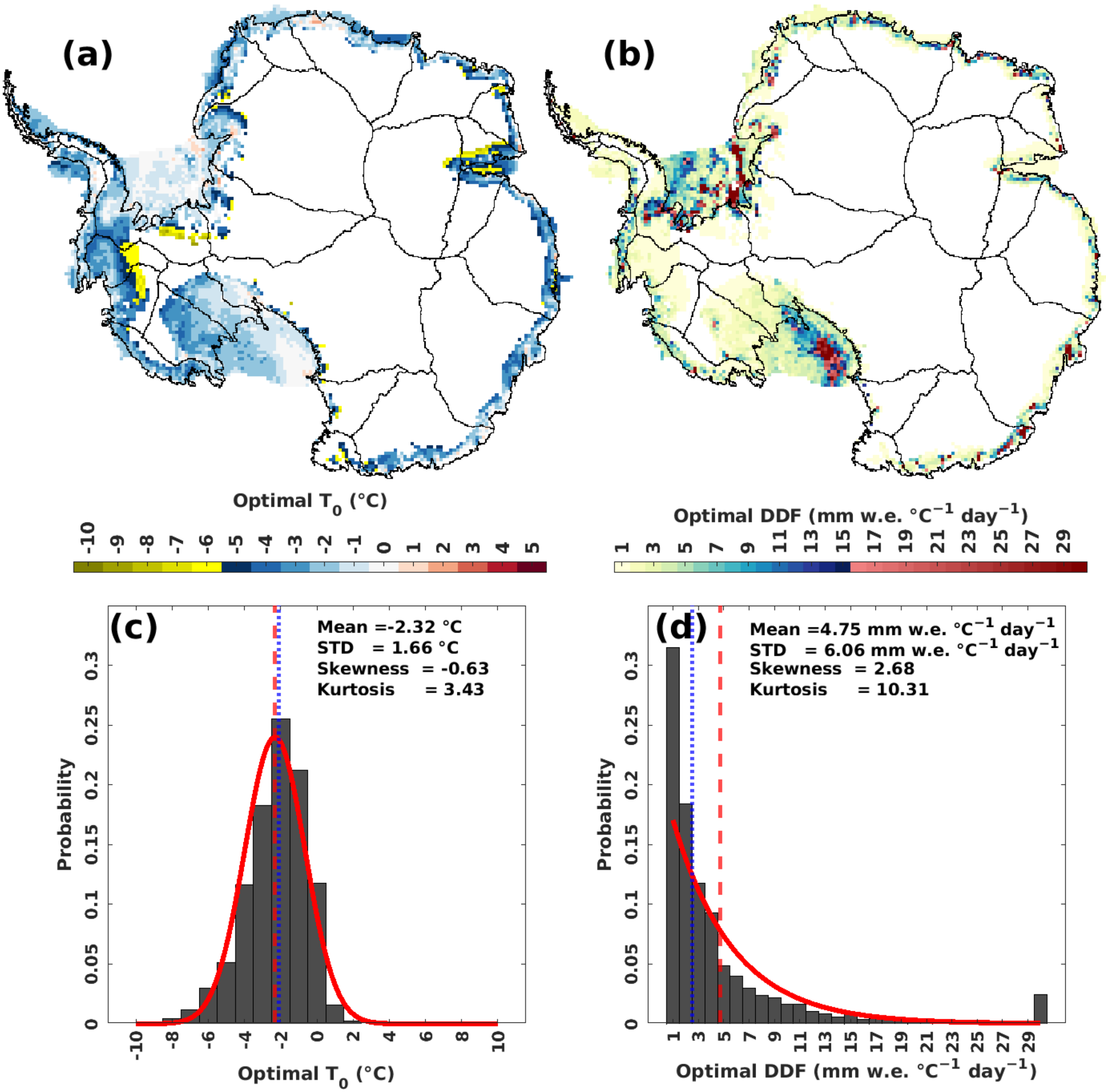

Figure 1. (a) Spatial map of the optimal T_0 (°C) of each computing cell. (b) Spatial map for the optimal DDF (mm w.e. °C^{-1} day^{-1}) for each computing cell. (c) Probability histogram of the optimal T_0 (°C). Red curve is the fitted normal distribution. Red dashed vertical line is the mean of T_0 for all computing cells. Blue dotted line is the median of T_0 for all computing cells. (d) Probability histogram for the optimal DDF (mm w.e. °C^{-1} day^{-1}). Red curve is the fitted exponential distribution. Red dashed vertical line is the mean of DDF for all computing cells. Blue dotted line is the median of DDF for all computing cells.

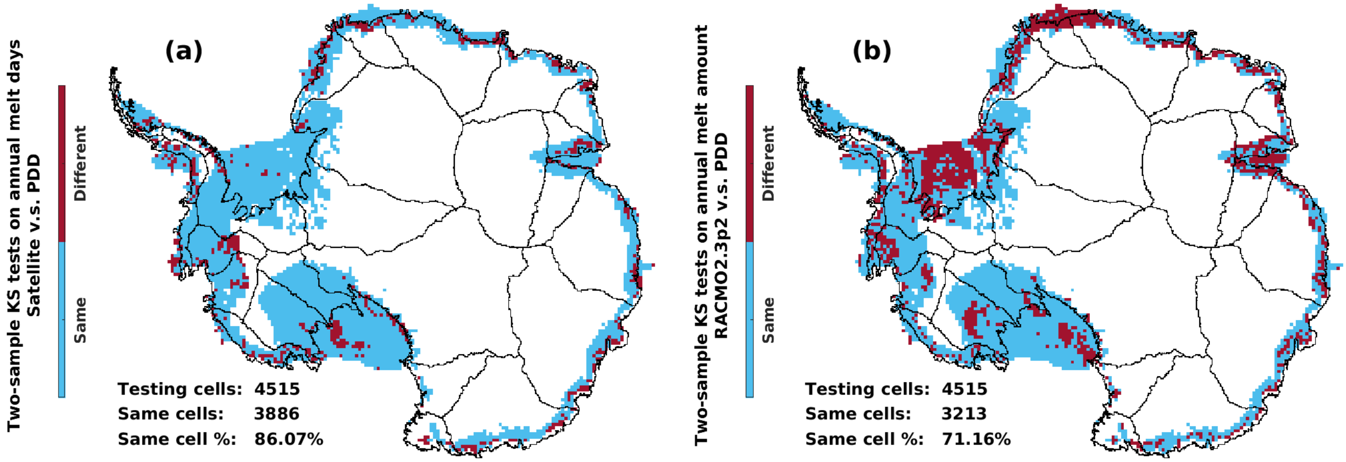

Figure 2. Spatial maps for the two-sample KS test results. The two-sample KS tests are performed individually for each of the 4515 computing cells. The test result "Same" means the tested cell is a same distribution cell where there is no statistically significant evidence for the rejection of the null 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) is the two-sample KS test results for testing the annual number of melt days between the satellite estimates and the PDD model outputs. (b) is the two-sample KS test results for testing the annual melt amount between the RACMO2.3p2 simulations and the PDD model outputs.

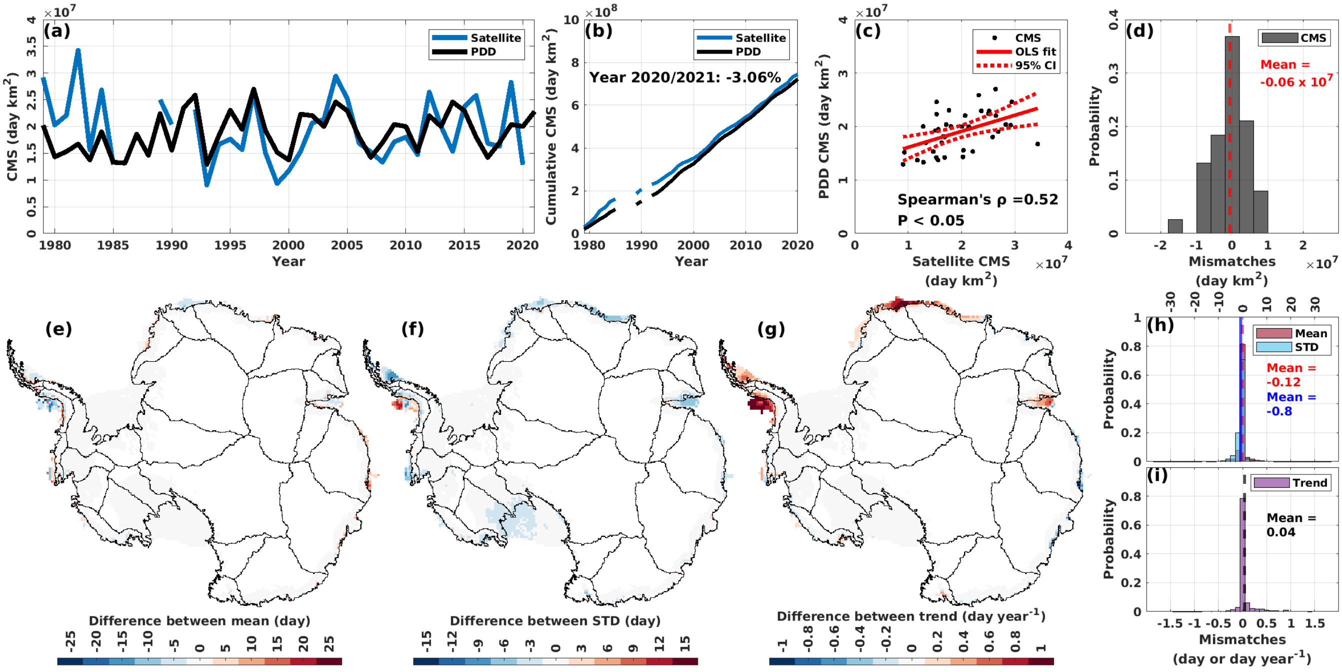

Figure 3. (a) time series for the cumulative melting surface (CMS) (day km^2) for satellite estimates during the period from 1979/1980 to 2020/2021 (with 1986/1987 to 1988/1989 and 1991/1992 omitted), and for PDD outputs during the period from 1979/1980 to 2021/2022. (b) cumulative CMS for satellite estimates and 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 PDD CMS. (d) probability histogram for the mismatches between the PDD CMS and satellite CMS. Red dashed vertical line indicates the mean of all mismatches. (e) to (g) spatial maps for the differences between mean, standard deviation (STD) and trend of PDD outputs and satellite estimates on the annual melt days (day). Mean, STD and trend for the 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. (h) and (i) probability histograms for the mismatches between the PDD outputs and satellite estimates on mean, STD and trend (histograms for (e) to (g)). Red dashed vertical line indicates the mean of all mismatches between means. Blue vertical line indicates the mean of all mismatches between STDs. Black dashed vertical line indicates the mean of all mismatches 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.

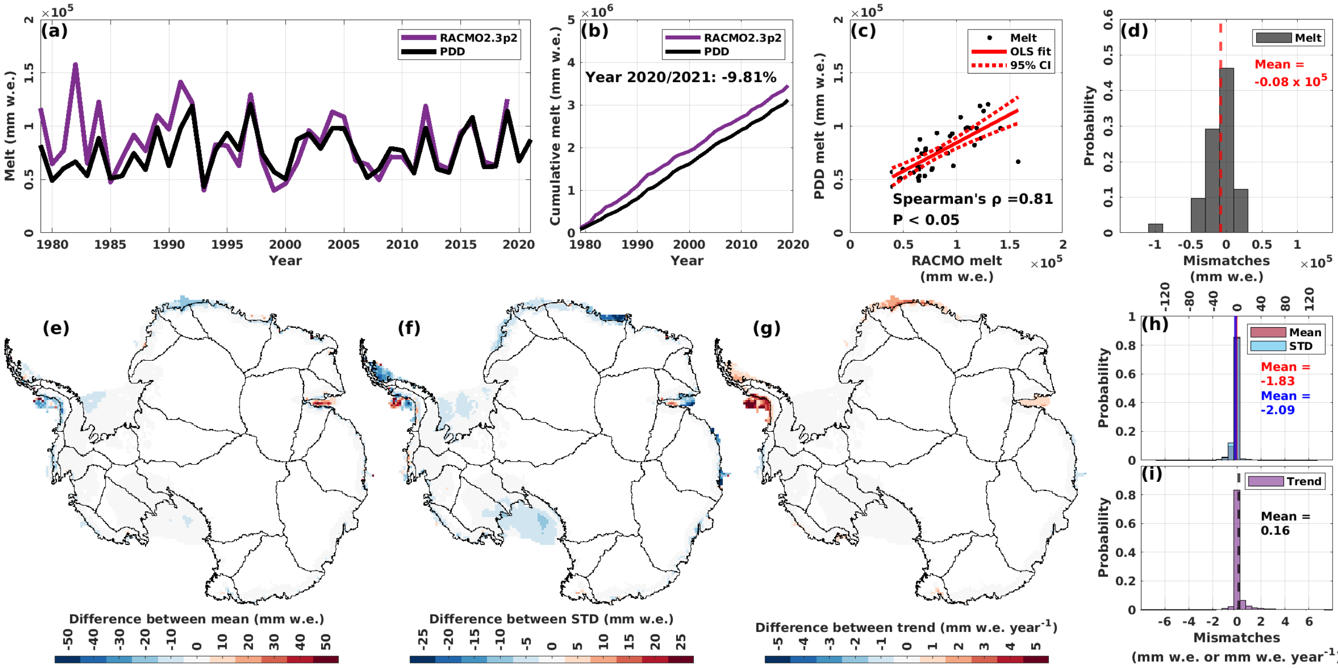

Figure 4. (a) time series for the annual melt amount (mm w.e.) for RACMO2.3p2 simulations during the period from 1979/1980 to 2019/2020, and for PDD outputs during the period from 1979/1980 to 2021/2022. (b) cumulative annual melt amount for RACMO2.3p2 simulations and PDD outputs from 1979/1980 to 2019/2020. (c) scatter plot and ordinary least squares (OLS) fit between satellite annual melt amount and PDD annual melt amount. (d) probability histogram for the mismatches between the PDD annual melt amount and satellite annual melt amount. Red dashed vertical line indicates the mean of all mismatches. (e) to (g) spatial maps for the differences between mean, standard deviation (STD) and trend of PDD outputs and RACMO2.3p2 simulations. Mean, STD and trend for the PDD outputs and RACMO2.3p2 simulations are calculated over the period from 1979/1980 to 2019/2020. (h) and (i) probability histograms for the mismatches between the PDD outputs and RACMO2.3p2 simulations on mean, STD and trend (histograms for (e) to (g)). Red dashed vertical line indicates the mean of all mismatches between means. Blue vertical line indicates the mean of all mismatches between STDs. Black dashed vertical line indicates the mean of all mismatches between trends.

Minor revisions:

1 I find the abstract a bit vague. There is too much emphasis on introductory material (lines 1-12) while only one sentence touches on the results (lines 16,17) and this sentence does not make sense within the rest of the abstract (e.g. what epoch?). I think this sentence does not do a good job of summarizing your results in the abstract and I am left wondering what to take away from the paper.

Thank you for pointing this out. We agree and will replace the Abstract from: "

Surface melt is one of the primary drivers of ice shelf collapse in Antarctica. Surface melting is expected to increase in the future as the global climate continues to warm, because there is a statistically significant positive relationship between air temperature and melt. Enhanced surface melt will negatively impact the mass balance of the Antarctic Ice Sheet (AIS) and, through dynamic feedbacks, induce changes in global mean sea level (GMSL). However, current understanding of surface melt in Antarctica remains limited in past, present or future contexts. Continental-scale spaceborne observations of surface melt are limited to the satellite era (1979–present), meaning that current estimates of Antarctic surface melt are typically derived from surface energy balance (SEB) or positive degree-day (PDD) models. SEB models require diverse and detailed input data that are not always available and require considerable computational resources. The PDD model, by comparison, has fewer input and computational requirements and is therefor suited for exploring surface melt scenarios in the past and future. The use of PDD schemes for Antarctic melt has been less extensively explored than their application to surface melting of the Greenland Ice Sheet, particularly in terms of a spatially-varying parameterization. Here, we construct a PDD model, force it only with 2-m air temperature reanalysis data, and parameterize it by minimizing the error with respect to satellite observations and SEB model outputs over the period 1979 to 2022. We compare the spatial and temporal variability of surface melt from our PDD model over the last 43 years with that of satellite observations and SEB simulations. We find that the PDD model can generally capture the same spatial and temporal surface melt patterns. Although there were at most four years over/under- estimation on ice shelf regions in the epoch, these discrepancies reduce when considering the whole AIS. With the limitations discussed, we suggest that an appropriately parameterized PDD model can be a valuable tool for exploring Antarctic surface melt beyond the satellite era.

" to"

Surface melt is one of the primary drivers of ice shelf collapse in Antarctica. Surface melting is expected to increase in the future as the global climate continues to warm, because there is a statistically significant positive relationship between air temperature and melt. Enhanced surface melt will impact the mass balance of the Antarctic Ice Sheet (AIS) and, through dynamic feedbacks, induce changes in global mean sea level (GMSL). However, current understanding of surface melt in Antarctica remains limited in past, present and future contexts. Here, we construct a novel cell-level positive degree-day (PDD) model, force it only with 2-m air temperature reanalysis data, and parameterize it spatially by minimizing the error with respect to satellite estimates and SEB model outputs on each computing cell over the period 1979 to 2022. We evaluate the PDD model by performing a goodness-of-fit test and cross-validation. We assess the fidelity of our parameterization method, based on the performance of the PDD model when considering all computing cells as a whole, independently of to the time window chosen for parameterization. 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. Within the limitations discussed, we suggest that an appropriately parameterized PDD model can be a valuable tool for exploring Antarctic surface melt beyond the satellite era.

"

2 Lines 24-28: You talk about future projects of Antarctic surface melt but what about current Antarctic melt? I think it will help to add a sentence or two that covers the current state of knowledge of AIS melt (i.e. Stokes 2021, Arthur 2022, Corr 2022).

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

3 Line 28 – Explain how AIS melt impacts ice sheet mass balance.

Thank you for pointing this out. We agree. Please see our response to the comment above.

4 Lines 29 – 47: Much of these paragraphs is unnecessary. I think that these paragraphs draw focus away from the main topic of this paper (which is not hydrofracture and ice-shelf collapse as it may seem by reading these two paragraphs). I think this can be summarized in a few sentences related to why surface melt is important in Antarctica.

Thank you for this suggestion. We agree. This suggestion is overlapped with the sixth comment by the Anonymous Referee #1. We copy our response to Reviewer #1 comment below:

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

5 Line 48: "surface melt has most likely been accelerated by the rapid increase of atmospheric temperatures…". I do not believe that this statement is correct as I don't think that AIS surface melt has accelerated. Alison Banwell recently reported results at the Cryosphere 2022 conference in Reykjavik showing a statistically significant decrease in surface melt across the AIS (will be published soon). Also, the observational trends reported in Figures 5 and 6 disagree with this statement.

Thank you for pointing this out. However, this statement is not about the AIS, but it refers to the Antarctic Peninsula. We reference the "Analyses of 50-year meteorological records have since revealed atmospheric warming on the Antarctic Peninsula, and a number of ice shelves have retreated." and "We conclude that ice-shelf extent may well be a sensitive indicator of regional climate change. The pattern of retreat provides evidence of warming in both climate regimes on the Antarctic Peninsula, but due to the high spatial gradients of mean annual air temperature, the warming was achieved by a modest migration of the climate pattern. We have still, however, to determine the precise mechanisms whereby the atmospheric warming had such a catastrophic effect on the ice shelves of the Antarctic Peninsula but it is clear that ice shevles cannot survive periods of warming that last more than a few decades." from Vaughan and Doake (1996), "The Antarctic Peninsula has experienced a major warming over the last 50 years, with temperatures at Faraday/Vernadsky station having increased at a rate of 0.56°C decade^{-1} over the year and 1.09°C decade^{-1} during the winter; both figures are statistically significant at less than the 5% level. Overlapping 30 year trends of annual mean temperatures indicate that, at all but two of the 10 coastal stations for which trends could be computed back to 1961, the warming trend was greater (or the cooling trend less) during the 1961–90 period compared with 1971–2000." from Turner et al. (2005), "Therefore all these studies suggest that the rapid warming on the AP since the 1950s and subsequent cooling since the late-1990s are both within the bounds of the large natural decadal-scale climate variability of the region." from Turner et al. (2016) and "The Antarctic Peninsula experienced rapid warming through the second half of the twentieth century, but so far this trend has not been sustained during the twenty-first century" from Hogg and Gudmundsson (2017).

For clarity, we have changed at Lines 47-49: "Although the warming taking place over the Antarctic Peninsula has not been consistent over the past two decades (Turner et al., 2016), surface melt there has ~~most~~ likely been accelerated during that period by the rapid increase of local atmospheric temperatures through the late 20th century (Vaughan and Doake, 1996; Turner et al., 2005, 2016; Hogg and Gudmundsson, 2017)."

6 One thing that I think is missing from the introduction – Why are PDD models helpful? What do they add? I think perhaps some of the info from the abstract on PDD models would be better in the introduction.

Line 59 – "The PDD model calculates. . . " All PDD models or just one in particular?

Line 60 – ". . . based on the temperature-melt relationship". Earlier (line 57) you mention that PDD models also use the precipitation field. Is this just some PDD models? Or are you talking about the ice sheet models that use precipitation fields to determine SMB?

Lines 65-67 – "Wake and Marshall (2015). . . " I find this sentence to be a bit distracting and confusing. I think you could just simplify to: "Wake and Marshall (2015) suggest that Antarctic surface melt can be estimated solely from monthly temperature".

Line 69 – What do you mean by "universal usage"?

Line 71 – "Topographic influences" such as what?

Line 79 – ". . . ice shelf region. . . ". Refer to Figure 1.

Lines 81 – Specify that you take melt volume from RAMCO.

Thank you for these eight suggestions. As they are all related to the Introduction section, we will address all of them at once by changing Lines 56–84 from :"

Positive degree-day (PDD) schemes have been used in many Antarctic numerical ice sheet models (e.g. Winkelmann et al., 2011; Larour et al., 2012) as empirical approximations to compute surface mass balance based on temperature and precipitation fields. Several studies have been conducted with PDD models to explore surface melt in Antarctica, particularly in the Antarctic Peninsula (e.g. Golledge et al., 2010; Barrand et al., 2013; Costi et al., 2018). The PDD model calculates surface melt based on the temperature-melt relationship (Hock, 2005). Although it is empirical, it is often sufficient for estimating melt on a catchment scale (Hock, 2003, 2005) because of its two physical bases: (a) the majority of the heat required for snow and ice melt is primarily a function of near-surface air temperature, and (b) the near-surface air temperature is correlated with the longwave atmospheric radiation, shortwave radiation and sensible heat fluxes (Ohmura, 2001).

A typical PDD model has two parameters: (1) the threshold temperature (T_0), which controls the decision of melt or no-melt, and (2) the degree-day factor (DDF), which controls the amount of melt. Wake and Marshall (2015) reported that using the Gaussian distribution sigma as a linear function of the monthly temperature can improve the performance of the PDD approach in terms of accurately capturing surface melt on the AIS, compared to the traditional fixed sigma value. This suggests that Antarctic surface melt can be estimated solely from monthly temperature. However, as the DDF is related to all terms of the surface energy balance (SEB) (Hock, 2005), the PDD model may not be appropriate for universal usage unless the model can incorporate DDFs that vary spatially and temporally (e.g. Hock, 2003, 2005; van den Broeke et al., 2010). This is because topographic influences that are generally strongest in mountainous terrain, together with seasonal variations in radiation, can introduce spatial and temporal variabilities of DDF, respectively (Hock, 2005). Spatial and temporal parameterisation of DDF (model calibration), as well as model verification, therefore need to be considered. Moreover, compared to PDD model approaches established (e.g. Reeh, 1991; Braithwaite, 1995) and improved (Fausto et al., 2011; Jowett et al., 2015; Wilton et al., 2017) for Greenland over many decades, such assessments for the PDD approach for the Antarctic domain are limited and a spatially parameterized Antarctic PDD model has not yet been achieved.

In this study, we focus on constructing a computationally efficient 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 Antarctic drainage basin (Zwally et al., 2012) and ice shelf region. 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 observations of melt days from three satellite products and the Regional Atmospheric Climate Model version 2.3p2 (RACMO2.3p2) surface melt simulations. We then examine the distributions of melt days and melt volume from PDD experiments that use varying model parameters against satellite-based and RACMO2.3p2 estimations. Following this, we use the PDD model to estimate and analyse the surface melt in Antarctica in terms of occurrence and amount from 1979 to 2022.

" to "

Continental-scale spaceborne observations of surface melt are limited to the satellite era (1979–present), meaning that current estimates of Antarctic surface melt are typically derived from surface energy balance (SEB) or positive degree-day (PDD) models. SEB models require diverse and detailed input data that are not always available and require considerable computational resources. The PDD model, by comparison, has fewer input and computational requirements and is therefor suited for exploring surface melt scenarios in the past and future. PDD models calculate surface melt based on the temperature-melt relationship (Hock, 2005). A typical PDD model has two parameters: (1) the threshold temperature (T_0), which controls the decision of melt or no-melt, and (2) the degree-day factor (DDF), which controls the amount of melt.

Although PDD models are empirical, they are often sufficient for estimating melt on a catchment scale (Hock, 2003, 2005) because of their two physical bases: (a) the majority of the heat required for snow and ice melt is primarily a function of near-surface air temperature, and (b) the near-surface air temperature is correlated with the longwave atmospheric radiation, shortwave radiation and sensible heat fluxes (Ohmura, 2001). Wake and Marshall (2015) suggest that Antarctic surface melt can be estimated solely from monthly temperature.

However, as the DDF is related to all terms of the surface energy balance (SEB) (Hock, 2005), a robust PDD model needs to incorporate DDFs that vary spatially and temporally (e.g. Hock, 2003, 2005; van den Broeke et al., 2010), not simply a uniform value that covers a wide region. This is because of the variability of energy partitioning, which is affected by the different climate, seasons and surfaces (Hock, 2003). 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). Spatial and temporal parameterisation of DDF (model calibration), as well as model verification, therefore need to be considered.

Although PDD schemes have been used in many Antarctic numerical ice sheet models (e.g. Winkelmann et al., 2011; Larour et al., 2012) as empirical approximations to compute the ice ablation for the computation of surface mass balance, and in several studies for exploring surface melt in Antarctica, particularly in the Antarctic Peninsula (e.g. Golledge et al., 2010; Barrand et al., 2013; Costi et al., 2018), the spatial variability of PDD parameters are rarely considered. Moreover, compared to PDD model approaches developed(e.g. Reeh, 1991; Braithwaite, 1995) and improved (Fausto et al., 2011; Jowett et al., 2015; Wilton et al., 2017) for Greenland over many decades, such assessments for the PDD approach for the Antarctic domain are limited and a spatially parameterized Antarctic PDD model has not yet been achieved.

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 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. Following this, we perform a 3-fold cross validation, together with sensitivity experiments, to evaluate our parameterization method and the PDD model.

"

7 Line 92 – Specify that you use hourly 2-m air temperature ERA5 data in the text (also on line 174).

Thank you for this suggestion. We will change at Line 92: "...is the hourly 2-m air temperature data which...", and at Line 174: "...ERA5 hourly 2-m air temperature data...".

8 Line 95 – ERA5 performs better at what than those other models?

Thank you for pointing this out. ERA5 performs better at the "near-surface temperature" referred to Gossart et al. (2019). We will add it at Line 95: "...ERA5 performs better at the near-surface temperature than its predecessor ERA-Interim...".

9 Line 109 – "around 6 am and 6 pm" – How close to 6 am and 6 pm? Does the acquisition time vary each day?

Thank you for pointing this out. According to the Picard and Fily (2006), the SSMR and SSM/I are carried by sun-synchronous satellites. These satellites are designed to be observing convergence of their orbits twice per day with consistent local acquisition times. However, because of the convergence of satellite orbits near the poles, there might be additional observations introduced by the passing of the satellite (Picard and Fily, 2006). Therefore, there might be other observations rather than the 6 am and 6 pm satellite ascending and descending passes. Nevertheless, Picard and Fily (2006) only proceed two passes for simplicity, and the SSMR and SSM/I satellite products we use (https://snow.univ-grenoble-alpes.fr/melting/), are derived from the average of 6am and 6pm. For consistency, to compare the PDD model output with the satellite estimates, we use the 2-m temperature data that have the same time as the satellite products.

10 Line 110 – "This dataset is being continually updated..." Consider moving this sentence to your Data Availability statement.

Thank you for this suggestion. We agree and will move this sentence to the Data Availability statement.

11 Line 115 – "We therefore omit those periods from our analysis" – Which analysis in particular? These periods are not omitted from the trend analysis in section 4.2. I would probably suggest to omit these no-data periods from the trend analysis as well (for both satellite and PDD model trends).

We thank the reviewer for this comment. For clarity, we will change at Line 115: "...We therefore omit those periods from our ~~analysis~~ comparison to the satellite estimates..". Regarding to the Section 4.2. In the new version of the manuscript, the entire Section 4.2 will be rewritten.

12 Line 116 – For readability, change "More recently, there is a newly developed..." to "We also use a more recently developed...".

Thank you for this suggestion. We agree. We will change in Line 116: "~~More recently, there is a newly~~ We also use a more recently developed satellite melt day dataset which uses a similar algorithm...".

13 Lines 119-120 – It is not necessary to specify that this product has a "twice finer spatial resolution than satellite SMMR and SSM/I product" since you mention the resolution of both products.

Thank you for pointing this out. We agree. We will change Lines 119-120: "...This dataset is on a 12.5×12.5 km^2 southern polar stereographic grid~~, which has a twice finer spatial resolution than satellite SMMR and SSM/I product~~....".

14 Line 123 – Consider changing the section heading to "Regional climate model melt output". Additionally, I believe that much of this section is unnecessary. You are just using the melt output from RACMO not doing any of the SEB calculations, correct? Therefore I think this section should focus on describing the RACMO product used instead of explaining SEB modeling as this description is a bit confusing because you do not actually do this in the paper.

Thank you for pointing this out, but we do not fully agree. We agree that we are only using the melt output from RACMO2.3p2 and are not doing any of the SEB calculations. However, the point here is to tell the reader that the data we use to parameterize the PDD model is obtained using a SEB model. The usage of the section heading "Surface energy balance model data" emphasises that the data we use is from the SEB module/routine of the model. As we mention in the earlier text that the two numerical approaches on estimating the Antarctic surface melt are SEB and PDD models. One of the novelties of this study is that we use a more sophisticated model data (the SEB model data) to parameterize another simple and computationally efficient model (the PDD model). We will replace the section heading from "Surface energy balance model data" to "Regional climate model SEB output".

We think it is better to include the information about the terms of the SEB as the DDF of the PDD model is related to all terms of the SEB (Hock, 2005). Showing the equation of the SEB and description of its terms could somehow indicate that the SEB is more sophisticated than the PDD (if the reader compare the Equation 1 and Equation 2).

15 Line 147 – Specify that the 27 drainage basins you use are grounded ice. I would also specify that you consider "all ice shelves", "all grounded ice" and "all AIS ice (both floating and grounded)" as regions in this study as well.

Thank you for pointing this out. We agree. In the new version of the manuscript, we focus on the cell-level PDD parameters which makes it not not applicable to the new version. These sentences will be deleted.

16 Line 157 – "..., which are multiplied...". What is this referring to?

Thank you for pointing this out, it indeed lacks a reference. This is referring to the PDD model described in the Hock (2005):

$$\sum_{i=1}^{n} \mathrm{M} = \mathrm{DDF} \sum_{i=1}^{n} \mathrm{T}^{+} * \Delta t \tag{1}$$

where DDF is the degree-day factor.

We will add a citation in Line 157: "...which are multiplied by the empirical DDF ($\mathrm{mm\ w.e.\ {}^{\circ}C^{-1}\ day^{-1}}$) (e.g. Hock, 2005)....".

17 Lines 161-170 – It is unclear to me why this paragraph (and Fig. 2) is necessary. Has this relationship between melt and temperature already been shown in other work (ie Trusel 2015)?

Thank you for this comment. We agree. Although this temperature-melt relationship has been discussed in other studies, we include such information derived from the data we use for the rigour of this study and the discussions of our results in Section 4. Nevertheless, we agree that this paragraph and the Figure 2 are not necessary in the main text. We will move this paragraph and the Figure 2 into the Appendices as the "Appendix B: Temperature-melt relationship".

18 Line 173 – add "binary" before "melt/no-melt signal"

Thank you for this suggestion. We agree. We will add it in Line 173: "...we firstly focus on the binary melt/no-melt signal...".

19 Line 180 – Do you use all ERA5 data or just the hours of 6am and 6pm? I am confused because Eq. 3 sets MD* = 1 if at least one hour has T-T0 > 0, but in the line below it sounds like you are only using those two hours (6am and 6pm)?

Thank you for pointing this out. Theoretically we would use the hourly ERA5 data, but in reality, the hourly satellite estimates for Antarctic surface melt are not available. For consistency, we use the input ERA5 data that have the same time as the satellite estimates as we described in the lines below. For clarity, we will change Lines 173-178 from: "

To parameterize the threshold temperature (T_0) for our PDD model, we firstly focus on the melt/no-melt signal. We use the ERA5 2-m air temperature data to force the model and run 101 numerical experiments with a set of T_0 ranging from -5.0 °C to +5.0 °C with 0.1 °C intervals. We define a melt day ($MD^\star$) as a day during which there is at least one hour of ERA5 2-m air temperature exceeding the T_0. In each T_0 experiment, we calculate the total number of melt days from the 1st April of that year to the 31st March of the following year as the "annual number of melt days". The modified Equation 1 can be written as:

$$\text{Annual number of melt days} = \sum_{i=t_1}^{t_2} \text{MD}^\star$$

$$t_1 = 01 - \text{April} - \text{Year}$$

$$t_2 = 31 - \text{March} - (\text{Year+1}) \tag{2}$$

$$\text{MD}^\star = \begin{cases} 1 & \text{if at least one hour } \text{T} - \text{T}_0 > 0 \\ 0 & \text{otherwise} \end{cases}$$

" to

"To parameterize the threshold temperature (T_0) for our PDD model, we firstly focus on the binary melt/no-melt signal. We use the ERA5 2-m air temperature data to force the model and run 101 numerical experiments with a heuristic set of T_0 ranging from -5.0 °C to +5.0 °C with 0.1 °C intervals. Practically, we find a number of cells that exceed the low boundary at -5.0 °C, we therefore expand the lower boundary to -10.0 °C and add another 50 numerical experiments to traverse from -10.0 to -5.1 °C. We define a melt day ($\mathrm{MD}^\star$) as a day in which the daily input of the ERA5 2-m air temperature (T) exceeds the T_0. Note that the T is either the daily mean of 6 am and 6 pm or the daily mean of 12 am and 12 pm depending on the satellite estimates we compare to (detailed in the paragraph below). In each T_0 experiment, we calculate the total number of melt days from 1st April of that year to 31st March of the following year as the "annual number of melt days". The modified Equation 1 can be written as:

$$\text{Annual number of melt days} = \sum_{i=t_1}^{t_2} \mathrm{MD}^\star$$
$$t_1 = 01 - \text{April} - \text{Year}$$
$$t_2 = 31 - \text{March} - (\text{Year}{+}1) \tag{3}$$
$$\mathrm{MD}^\star = \begin{cases} 1 & \text{if } \mathrm{T} - \mathrm{T}_0 > 0 \\ 0 & \text{otherwise} \end{cases}$$

".

20 Line 184 – I believe this is the first time you use the "RMSE" acronym so you should define it here.

Thank you for pointing this out. We agree. We have changed Line 184: "...we calculate the root-mean-square error (RMSE) between...".

21 Line 187 – It might be helpful to introduce the concept of "mask matrices" for each region in Section 2.4.

Line 190 – I think it is a bit confusing how you use the work "region". Here you say there are 38 regions which I understand to be the 27 drainage basins + ice shelf regions + all ice shelves + all grounded ice + all of Antarctica? This is not entirely clear in all places in the text because the word "region" is also used to describe the ice shelf regions. Maybe consider changing to "area of interest" when talking about the 38 "regions of interest".

Lines 192 – 194 – The text in parenthesis can be deleted because it clutters up the sentence and is mentioned in the data section.

Thank you for pointing this out. We agree. These three comments are overlapping with the 7th minor comment by the Anonymous Referee #1. We copy our response to that comment below:

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

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

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

to

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

22 Section 3.2.2 – Perhaps provide an introductory sentence to define the DDF and explain why it is necessary. (I know this is in the intro but might be useful to mention briefly again here)

Thank you for your suggestion. We agree. We have changed Line 199: "The DDF is a scaling number that controls the amount of melt. 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). To parameterize the DDF for our PDD model, we...".

23 Section 3.3 – What exactly are you testing here? I find this section to be very confusing!

Line 213 - "45" This number has no context in this sentence. 45 what?

Thank you for pointing this out. These two comments are related to the Section 3.3. which we will replace as follows: "

Significance testing

The two-sample Kolmogorov–Smirnov test (hereafter two-sample KS test) has been used in testing the 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 of 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 annual data for each computing cell is no larger than 45 with non-normality. To test the significance of the optimal T_0 and DDF, we therefore perform the two-sample KS tests between the annual number of melt days/ melt amount from the satellite observations/ RACMO2.3p2 and from the PDD model T_0/ DDF experiments. 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). To quantify the test result in each targeted region, we calculate the percentage of the same distribution cells for each T_0/ DDF experiment on each targeted region. We specifically discuss and interpret the results of this test approach in Appendix B.

" with "

Goodness-of-fit testing

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 of 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).

"

24 Line 224 – change “AIS and ice shelves” to “whole AIS and all ice shelves”.

Figure 3 (and 4) – Your y-label is “RMSE per computing cell”. Is this correct or should it be the regional RMSE?”

Line 225 – “Lower ability” – what exactly do you mean by this?

Lines 226 – 230 – I believe that these sentences can be more succinct and that the part describing the Jakobs et al 2020 study is largely unnecessary and confusing (ie what is “unrecognizability”. I think you could shorten this to something like: “In Fig. 3a-a the RMSE at T0=0 oC is larger than at T0=-1.8 oC (our optimal threshold temperature). This finding indicates that using T0=0 oC as a melt threshold may miss events, a finding consistent with other work (Jakobs et al 2020).

Lines 230 – 234 – What exactly are you trying to say with this sentence? Overall, I think this paragraph can be made much shorter. You are just explaining why you round the DDFs right? I would consider mentioning that you choose to round the DDFs at the beginning of the paragraph (right now it is a bit lost at the end of a long paragraph), and then using the rest of the paragraph to explain why you do this.

Line 253 – “the optimal DDF better estimates…” Which DDF? DDF = 2.8 mm… or the one that is calculated for each basin?

Line 259-260 – “This may lead to a single…” I am confused why you mention this because in your work you do not use a singly parameterization for all drainage basins (Table 2).

Section 4.2 – In this section the analysis of melt days and melt volume are intermixed throughout. I would consider separating these two analyses because they use completely different products (satellite obs. Vs RACMO). This section is also really just further evaluation of how your PDD model captures trends/variability in surface melt. You aren’t really providing any new information here about AIS melt variability and trends (that cannot be obtained from already existing products). Hence, I think it might be useful to re-frame the results from this section as model evaluation.

Figure 5 & 6 – I think it would be helpful to also provide difference maps between the observations/RACMO output and the PDD results.

Line 299 – Why do you think that the PDD model does not capture some of the trends seen in the observations?

Line 304 – 306 – "It is worth noting that on the marine edge…". Make the distinction between melt days trend and melt volume trend in this sentence as these are really two different things.

Figure 7 – Is this figure necessary in the main text? It is simply ERA5 output so why is it important?

Line 308 – "West Ice Shelf (part of the ice shelves in Wilkes Land"). By this do you mean to say that West ice shelf is located in Wilkes Land?

Lines 315 – 318 – What do you mean by "temporal stability" and what sort of "time series analysis" do you perform? What do you mean by "We gather all 27 drainage basins for the next stage of analysis"?

Figure 8 (and in-text analysis) – I mentioned this before but I would consider only performing the trend analysis from 1992-2022 so you do not include any of the years with missing satellite data.

In this section (4.2) you mention "residuals" many times. What are the residuals? What do you mean by this? I was a bit confused what you meant every time I read the word "residuals"which I think limited my understanding of the last part of section 4.2.

We thank the reviewer for those 16 comments above. These comments are all related to the Section 4.1 and Section 4.2. In the new version of the manuscript, these sections will not exist. We will re-write the whole Section 4.1 and 4.2 based on the new results on the cell-level PDD model. Please refer to the new version of the manuscript for the Section 4.1 and Section 4.2.

25 Section 4.3 – While RACMO and satellite observations are perhaps closer to the truth than a PDD model there are biases that exist in these products too. Are there studies that mention these biases that you could also discuss in this section?

Thank you for this comment. We agree. This comment is partly overlapping with the major comments by the Anonymous Referee #1. Here i copy our response to that comment below:

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

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

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

For the new subsection, please see our response to the comments by Anonymous Referee #1.

26 Line 391 – "same surface melt distributions" – what do you mean by this?

Thank you for pointing this out. In the new version of the manuscript, the first paragraph of the Conclusions: "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 in 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 selected an optimal parameter combination by locating the minimal RMSE between the PDD and satellite observations, and SEB simulations. We independently performed two-sample KS tests in each experiment in order to quantify the percentage of cells that have statistically significant ($p < 0.05$) same surface melt distributions for each targeted region. We have found that rounding the PDD optimal parameters not only simplifies the calculations, without introducing considerable differences either on the RMSE or two-sample KS percentage, but also avoids suggesting a level of precision defined by the parameterisation experiments that may not be physically realistic." will be replaced with: "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). ".

Technical corrections:

27 Line 6 – "Past, present or future contexts": replace "or" with "and"

Thank you for pointing this out. We have changed in Line 6: "...remains limited in past, present ~~or~~ and future...".

28 Line 60 – Change "it is" in "Although it is empirical…" to "PDD models are". Doing this will clarify what "it" is referring to throughout that sentence.

Thank you for pointing this out. We have changed in Line 60: "... Although ~~it is~~ PDD models are empirical, it is often sufficient for estimating...".

29 Line 103 – change "(once in two days before 1988)" to "(once every two days before 1988)"

Thank you for pointing this out. We have changed in Line 103: "... We use the satellite 42-year daily (once ~~in~~ every two days before 1988) Antarctic surface...".

30 Line 104 – change "melt and no-melt" to "melt or no-melt"

Thank you for pointing this out. We have changed in Line 104: "...as a binary of melt ~~and~~ or no-melt on a...".

31 Line 144 – change "we use" to "products used"

Thank you for pointing this out. We have changed in Line 143: "...~~we use~~ products used in this study...".

32 Line 151 – change "requires" to "require"

Thank you for pointing this out. We have changed in Line 151: "...approach enable fast run times and ~~requires~~ require low computational...".

33 Line 184 – Change "in" to "for"

Thank you for pointing this out. We have changed in Line 183: "...~~in~~ for each T_0 experiment.".

34 Line 225 – Change "at the point which T0 equals 0C" to "where T0 = 0C"

Line 288 – "That the PDD model…". Beginning this sentence differently will help the sentence read better.

Thank you for pointing these out. These two suggestions are related to the Section 4.1 and Section 4.2. We will re-write the entire Section 4.1 and Section 4.2.

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