

# 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 Reviewer are shown in **bold text**, our 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**.

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## Editor decision by Brice Noël:

Dear Yaowen Zheng and co-authors,

I join the reviewer to congratulate you on a revised manuscript that clarifies remaining concerns and much improves the robustness of the results. The reviewer has a few minor suggestions, that I invite the authors to consider in a revised version. You can find below some additional edits. When the authors have addressed these minor comments, I am in principle happy to accept the manuscript for publication in The Cryosphere.

Thank you very much for your comments. We will take into account both your suggestions and those of the reviewer to improve our manuscript.

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## Editor minor comments:

**L8: I suggest "... (PDD) model, forced with 2-m air temperature reanalysis data, and spatially parameterized by minimizing ..."**

Thank you for this suggestion. We will replace in Line 8 from: "...force it only with 2-m air temperature reanalysis data, and parameterize it spatially by minimizing the error with respect to..." with "...forced with 2-m air temperature reanalysis data, and spatially parameterized by minimizing the error with respect to..."

**L15-16: PDD estimates of what? Please clarify: melt amounts / extent?**

Thank you for pointing this out. We will replace at Lines 14–17 from: "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, demonstrating the consistency of our parameterization and the applicability of the PDD model to warmer climate scenarios." with "We find that the PDD melt extent and amounts change analogously to the variations in the training data with steady statistically significant correlations, and the PDD melt amounts increase nonlinearly with the temperature perturbations, demonstrating the consistency of our parameterization and the applicability of the PDD model to warmer climate scenarios."

**25** **L28-29: Do you mean “that increase ice shelf vulnerability, as meltwater can pond, drain and further contribute to the structural weakness of ice shelves.”?**

Thank you for pointing this out. Yes. We will replace at Lines 27–30 from: "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)." with "Studies have suggested that Antarctic surface melt can impact ice sheet mass balance through surface thinning and runoff that can increase ice shelf vulnerability, as meltwater can pond, drain and further contribute to the structural weakness of ice shelves (Glasser and Scambos, 2008; Bell et al., 2018; Stokes et al., 2022)."

**L36: The authors could in ‘one sentence’ introduce Regional Climate Models that use SEB modules to estimate surface melt. See e.g. Wessem et al. (2018), Agosta et al. (2019) and models presented in the model intercomparison of Mottram et al. (2021).**

Thank you for this suggestion. We agree. We will change at Lines 35–38: "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 are employed in Regional Climate Models such as the Regional Atmospheric Climate Model (RACMO) (Van Wessem et al., 2018) and Modèle Atmosphérique Régional (MAR) (Agosta et al., 2019). PDD models are employed in ice sheet models such as the Simulation COde for POLythermal Ice Sheets (SICOPOLIS) (Nowicki et al., 2013), Ice Sheet System Model (ISSM) (Larour et al., 2012), and Parallel Ice Sheet Model (PISM) (Winkelmann et al., 2011). SEB models require diverse and detailed input data that are not always available and require considerable computational resources."

50 **L65: Please add a reference to the RACMO2 data set.**

Thank you for pointing this out. We agree. We will change in Line 65: "days from three satellite products and the Regional Atmospheric Climate Model version 2.3p2 (RACMO2.3p2) (Van Wessem et al., 2018) surface melt".

**L155: “in the overlapping years.”**

Thank you for pointing this out. We agree. We will replace in Line 155 from: "...in their overlapped years..." with "...in the overlapping years...".

**L219: 0 should be a subscript in ‘To’.**

Thank you for pointing this out. We agree. We will replace in Line 219 from: "...optimal T0 values selected through 151 T0 experiments..." with "...optimal T<sub>0</sub> values selected through 151 T<sub>0</sub> experiments...".

**Table 3 and 4 captions: Please add “Ordinary Least Square” to define the acronym “OLS”.**

60 Thank you for pointing this out. We agree. We will change in Table 3 and 4 captions: "...for the Ordinary Least Squares (OLS) fit..."

**L343: I suggest “... because of the correlation between ...”**

Thank you for this suggestion. We agree. We will replace in Line 343 from: "...because of the linear relationship between air temperature and surface melt..." with "...because of the correlation between air temperature and surface melt...".

65 **L370: Here and elsewhere could you consider “we show that” or “we find that” instead of “we see”.**

Thank you for this suggestion. We agree. There are 13 "we see" in total. We will replace these "we see" with "we show that".

**L370: Replace ‘statistically significantly, strongly’ by ‘significantly’.**

Thank you for this suggestion. We agree. We will replace at Lines 370–371 from: "...dist-PDD estimates are statistically significantly, strongly ( $\rho \geq 0.99$ ,  $p \leq 0.05$ ) correlated..." with "...dist-PDD estimates are significantly ( $\rho \geq 0.99$ ,  $p \leq 0.05$ ) correlated...".

**L373-377: Cut this long sentence into two sentences.**

Thank you for this suggestion. We agree. We will replace at Lines 373–377 from: "Although the  $T_0$  Member 1 dist-PDD estimates and dist-PDD CONTROL estimates are strongly correlated to the training fold (black dots in Figure 7s), which is not surprising as the  $T_0$  Member 1 dist-PDD is parameterized by those dist-PDD CONTROL estimates, the  $T_0$  Member 1 dist-PDD estimates and dist-PDD CONTROL estimates are not statistically significantly correlated ( $\rho = 0.19$ ,  $p \geq 0.05$ ) to the testing fold (red dots, Figure 7s)." with "The  $T_0$  Member 1 dist-PDD estimates and dist-PDD CONTROL estimates are strongly correlated to the training fold (black dots in Figure 7s), which is not surprising as the  $T_0$  Member 1 dist-PDD is parameterized by those dist-PDD CONTROL estimates. The  $T_0$  Member 1 dist-PDD estimates and dist-PDD CONTROL estimates are not statistically significantly correlated ( $\rho = 0.19$ ,  $p \geq 0.05$ ) to the testing fold (red dots, Figure 7s).".

**80 L383: I suggest “might explain” instead of “might be”.**

Thank you for this suggestion. We agree. We will replace in Line 382 from: "...over the testing-fold period might be the disagreement between..." with "...over the testing-fold period might explain the disagreement between...".

**L388-389: “To that is parameterized by ... data sample used to parameterize ... data length used to estimate ...”.**

Thank you for this suggestion. We agree. We will replace at Lines 388–390 from: "optimal  $T_0$  that parameterized by the full 38-year period. However, the data sample that used to parameterize the Member 1  $T_0$  is only 2/3 the full data length which parameterized the optimal  $T_0$ , giving us less confidence on the reliability of the Member 1  $T_0$ s for the full 38-year period." with "optimal  $T_0$  that is parameterized by the full 38-year period. However, the data sample used to parameterize the Member 1  $T_0$  is only 2/3 the full data length used to estimate the optimal  $T_0$ , giving us less confidence on the reliability of the Member 1  $T_0$ s for the full 38-year period.".

**90 Figure 8 caption L5: “shaded areas indicate ...”.**

Thank you for pointing this out. We agree. We will replace Figure 8 caption Line 5 from: "...shaded areas indicates the..." with "...shaded areas indicate the...".

**L396: Do you mean “is expected to increase the occurrence of temperatures above ...”.**

Thank you for this suggestion. Yes. We will replace in Line 396 from: "...is expected to allow more temperatures above the threshold to produce more melt days, and vice versa." with "...is expected to increase the occurrence of temperatures above the threshold to produce more melt days, and vice versa.".

**L401-403: “sensitive ... to” instead of “sensitive ... on”.**

100 Thank you for pointing this out. We agree. We will replace at Lines 401–403 from: "...is less sensitive than the satellite estimates on the low melt scenario, where the dist-PDD estimates only decrease by 9.78% for the integrated 38-year CMS, when the satellite estimates decrease by 10%. Although the dist-PDD model is more sensitive than the satellite estimates on the high melt scenario..." with "...is less sensitive than the satellite estimates to the low melt scenario, where the dist-PDD estimates only decrease by 9.78% for the integrated 38-year CMS, when the satellite estimates decrease by 10%. Although the dist-PDD model is more sensitive than the satellite estimates to the high melt scenario...".

**L402: “while” instead of “when”.**

105 Thank you for pointing this out. We agree. We will replace in Line 402 from: "...38-year CMS, when the..." with "...38-year CMS, while the...".

**L443: “surface melt estimates from using uni-PDD.”**

Thank you for this suggestion. We agree. We will replace at Lines 443–444 from: "...Antarctic surface melt estimations from using spatially uniform PDD parameters (uni-PDD),..." with "...Antarctic surface melt estimates from using uni-PDD,...".

110 **L472-473: The link to IMBIE-3 data does not work, please update.**

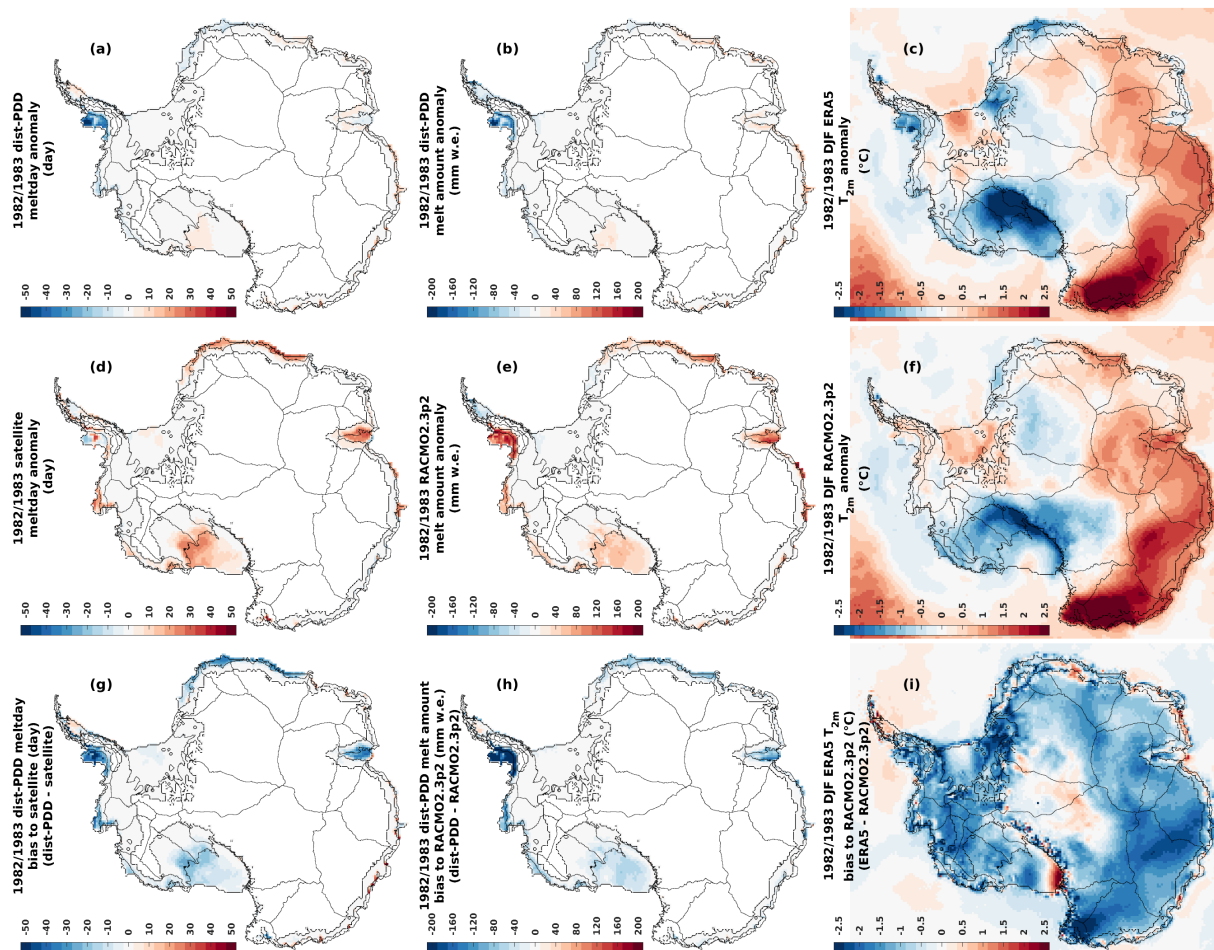
Thank you for pointing this out. We will replace at Lines 472–473 from: "The Zwally Antarctic drainage basin (Zwally et al., 2012) data are available from <http://imbie.org/imbie-3/drainage-basins/>." with "The Zwally Antarctic drainage basin (Zwally et al., 2012) data are available from <http://imbie.org/imbie-3/drainage-basins/> and <https://earth.gsfc.nasa.gov/cryo/data/polar-altimetry/antarctic-and-greenland-drainage-systems> (last access: 18 July 2023).".

115 **Figure E1 c, f and i and caption: ‘ERA5’ instead of ‘EAR5’.**

Thank you for pointing this out. We will replace Figure E1 with the New Figure E1.

**L518: “first decade and almost overlap for the rest”**

Thank you for this suggestion. We agree. We will replace in Line 518 from: "...first decade and remain almost completely overlapped for the rest of the time period..." with "...first decade and almost overlap for the rest of the time period...".



**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). (i) absolute differences between 1982/1983 DJF ERA5 and RACMO2.3p2 2-m air temperature. 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.

## Minor comments by Devon Dunmire:

**L23: Recently published, Banwell et al (2023) (<https://doi.org/10.1029/2023GL102744>) actually found a significant (but small) decrease in AIS ice shelf melt days using a snow model and microwave observations**

125 Thank you for pointing this out. We will replace at Lines 23–24 from: "[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](#))." with "[Antarctic ice shelves show statistically significant negative trend for the annual melt days \(Banwell et al., 2023\)](#) and no significant increase in melt amount in East Antarctica in the past 40 years ([Stokes et al., 2022](#)).".

**L215 – fix T<sub>0</sub> (change to subscript)**

130 Thank you for pointing this out. This comment is overlapped with the seventh comment by the Editor. We will replace in Line 219 from: "[...optimal T<sub>0</sub> values selected through 151 T<sub>0</sub> experiments...](#)" with "[...optimal T<sub>0</sub> values selected through 151 T<sub>0</sub> experiments...](#)".

**L343 – I am confused by the statement “because of the linear relationship between air temperature and surface melt”. Is there a typo here? Doesn’t Figure 9 (and other works) demonstrate a non-linear relationship between air temperature and surface melt?**

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Thank you for pointing this out. This comment is overlapped with the ninth comment by the Editor. We will replace in Line 343 from: "[...because of the linear relationship between air temperature and surface melt...](#)" with "[...because of the correlation between air temperature and surface melt...](#)".

**Figure 7 – Specify in the caption that this is for dist-PDD (same for Figure 8)**

140 Thank you for this suggestion. We agree. We will add '[This analysis is based on dist-PDD.](#)' at the end of the captions for Figure 7 and 8.

**L415 – Please add the Banwell et al 2023 citation with Bell et al and Trusel et al.**

Thank you for this suggestion. We agree. We will replace in Line 415 from: "[... that reported by other studies \(Trusel et al., 2015; Bell et al., 2018\),...](#)" with "[... that reported by other studies \(Trusel et al., 2015; Bell et al., 2018; Banwell et al., 2023\),...](#)".

145 **L435 – I would recommend elaborating that the “dist-PDD” and “uni-PDD” are “spatially varying” and “spatially uniform” PDDs here because it is the start of the conclusion.**

Thank you for this suggestion. We agree. We will replace in Line 435 from: "We have constructed a dist-PDD model and a uni-PDD model based on the..." with "We have constructed a PDD model with spatially varying PDD parameters (dist-PDD) and a PDD model with spatially uniform PDD parameters (uni-PDD) based on the..."

150 **L447 – “Underestimation” of what?**

Thank you for this suggestion. We agree. We will replace in Line 447 from: "...with the exception of an underestimation in the ice shelves of the western..." with "...with the exception of an underestimation of melt days and amounts in the ice shelves of the western..."

**Appendix - Figure D4 is not referenced anywhere and should be referenced somewhere in the text**

155 Thank you for pointing this out. We agree. We will change at Lines 325–327: "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. The spatial maps for the mean, STD and trend of the dist-PDD/ uni-PDD annual melt amount and RACMO2.3p2 mean annual melt amount for the same period are shown in Figure D4 in the Appendix D. Consistent with the PDD melt day estimates, using the dist-PDD model improves the accuracy of estimating surface melt amount compared to".

160



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