

# Response to the Referee 2 comments (RC2 – Neil Ross) on manuscript TC-2020-51: Temporal and spatial variability in surface roughness and accumulation rate around 88° S from repeat airborne geophysical surveys

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We use the following color and font coding scheme in our response:

## **Referee's comments**

*Response:* authors' response to comments.

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*We thank referee Neil Ross for the positive general comments and the many and very helpful specific suggestions. We have revised our manuscript accordingly.*

## **Broad comments:**

**1. A lack of discussion about the wider implications of the study. I would encourage the authors to consider the broader implications of this work (e.g. implications for satellite-derived accumulation rates, implications for ice core research at South Pole, Hercules Dome etc.) and incorporate these aspects into the abstract, discussion and conclusions sections.**

*Response:* Section 3.2 "Relevance of surface roughness and slope for altimetry and surface mass balance" already addresses the wider implications of our work. Since we don't present specific results in our paper other than for radar altimetry we feel any statements on potential impacts on other areas of research we could make will be speculative and don't belong into a scientific paper.

**2. A lack of information about the geographical setting of the area of investigation (e.g. which Antarctic drainage basins and ice stream catchments does the 88°S survey line intersect and survey?). A 'study area' section to the manuscript may help in this regard.**

*Response:* We have added a survey area section to the manuscript and moved some of the text in sections 3 and 4 into the new section. We have tried and plotted the drainage basins in Fig. 1 but feel the basin outlines are too distracting and don't add much context to the figure. Instead we have described the geophysical setting. Given the low ice surface velocities in our survey area (< 10 m yr<sup>-1</sup>) we don't think drainage basins are relevant for the work presented in the paper.

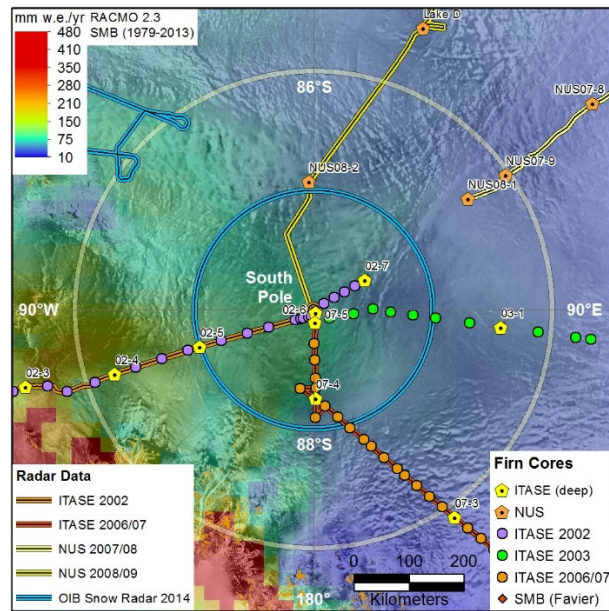
**3. A somewhat awkward structure to the paper, with inter-mixing of study area, methods, results, and background information. There is no clear delineation between description of results and discussion/interpretation of those results. To me the current structure is not that logical, but this may reflect my training/background discipline. However, a decision on what section 3 is needs to be made. Is it a methods section, or something else? Currently it is an amalgamation of background, methods and**

results. Section 4 also seems to be predominantly methods, with sections 5-7 results/discussion intermingled. My recommendation is to restructure the manuscript to more clearly delineate between background/methods/results/discussion & interpretation. Without this restructuring it will not be clear whether the manuscript is a 'methods' paper or a 'results' paper.

*Response:* We agree with the referee that the structure of the manuscript can be clarified. Our paper is a synthesis of several different data types (laser altimetry, optical imagery, subsurface radar) that explores relationships between several geophysical parameters that can be derived from these data. The nature of our analysis complex and this complexity is reflected in the manuscript. In order to help the reader understand the organizational structure and flow of our manuscript we have added several sentences at the end of the introduction that describe the outline of our paper. We have change the title of several sections to better reflect their contents. We have chosen to keep background, method, results and discussions together with roughness and accumulation sections to avoid the paper becoming repetitive.

**4. A lack of citation to previous, potentially relevant, surface accumulation/roughness investigations in study area (e.g. results from the South Pole-Queen Maud Land traverses of 1964-65 and 1965-66), and potentially to Antarctic-wide surface accumulation literature (e.g. Arthern et al. 2006 <https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2004JD005667>).**

*Response:* The work presented in this paper is part of a larger NASA funded project. As part of this wider effort we have extensively looked at all available accumulation, radar, ice core and snow pit data in the survey area (see figure below) and have only referenced data sets and publications that we consider relevant to the work presented in the paper. Firn cores and snow pits shown on the map below mostly don't have published accumulation rates. Our paper describes spatial variations in accumulation rates and does not focus on absolute values, because there are no existing data that we could use to tie our radar-derived accumulation rates to firn cores or snow pits in the area. Instead, we use MERRA-2 for that as described in the paper.



Other than Das et al. (2013) and Gow (1965) we have not found any surface roughness related work. We have included several of these data sets in the survey area description in Section 2 although we are not convinced of their relevance.

There seems to be general agreement in the surface mass balance community that re-analysis models such as RACMO2.3 and MERRA-2 are now better than the Arthern et al. (2006) accumulation estimates. This is the reason why we have chosen to use a re-analysis model over the Arthern et al. (2006) data. We use MERRA-2 since unlike RACMO2.3 it is publicly available. We have added a reference to Arthern et al. (2006) in the survey area section but are not convinced of its relevance to our work. We have also added a reference to the surface mass balance data set from Favier, V., Agosta, C., Parouty, S., Durand, G., Delaygue, G., Gallee, H., et al. (2013). An updated and quality controlled surface mass balance dataset for Antarctica. *Cryosphere*, 7(2), 583-597.

**5. Statistics are not my strongest suite, so I am not terribly well qualified to comment on the validity of those aspects. The statistics used seem simple and relatively unsophisticated however (e.g. lines 391-409), and I do wonder if a more sophisticated and rigorous statistical analysis has the potential to tease out more insights from the data set. Perhaps the current statistical analysis does the job however (i.e. ‘reviewer 2’ is simply scaremongering unnecessarily), and there is no requirement for introducing more complexity in this regard. I was a little unsure as to why it was so important to assess the correlation of the standard deviation (lines 391-409) however. Perhaps this could be explained a little more?**

*Response:* This is an excellent point that the authors have discussed at length and with colleagues while doing the analysis. We don’t think that more sophisticated or rigorous statistical methods would reveal any meaningful relationships in the data. The Pearson’s correlation coefficient may not be the most sophisticated method but it is widely accepted and certainly robust, which is the reason why we decided to use it as a metric. Using the standard deviation for quantifying variability is a commonly used method. We have explained in lines 390 – 391: “To quantify the relationship between variability in surface slope, wind direction and accumulation rates we use the standard deviation  $\sigma$  of the MSWD and snow accumulation....”

**Specific comments:**

**Line 23: “overall” instead of “entire”?**

*Response:* We have changed the wording.

**Lines 26-28: Implications of this study for developing elevation bias corrections is stated, but I’d encourage the authors to include other broader implications (e.g. for quantification of surface mass balance and for ice core studies) here.**

*Response:* We feel that our section 3.2 already addresses the broader implications. Since we don’t present specific results in the paper we feel any statements we could make will be speculative and don’t belong into this paper.

**Line 46: “...ice surface, volume...”?**

*Response:* We have inserted a comma after surface.

**Line 47: “Radio-wave signal detection below the noise floor...”? Line 50: “...azimuth dependent elevation ....”?**

*Response:* We have changed line 50. We are not sure what is meant by the comment on line 47.

**Line 52: “...we specifically studied....”?**

*Response:* Using present tense is generally considered better writing style than using past tense and most of our manuscript is written in present tense. We’ll leave this up to the copy editor.

**Line 62: Change title to “Data sets and methods”? Line 85: no comma after “both”?**

*Response:* We have deleted the comma in line 85. Section 2 does not contain a description of methods. The methods we apply to the data sets are described in Section 3. We have followed the referee’s second broad comment and added a study area section to Section 2.

**Line 86: “...a ground speed...”**

*Response:* we have change “an” to “a”.

**Line 105-108: Change to: “The difference in geolocation between distinct elongated topographic snow surface features (sastrugi) between overlapping orthorectified images is on the order of several metres. The DMS images.....”?**

*Response:* We have already changed this sentence based on RC1’s suggestion.

**Lines 119-123: More detail on the survey flights would be helpful. For example, what was terrain clearance, and was it consistent each year?**

*Response:* We have added a column to Table 1 that shows the flight elevation in meters above ground level (AGL) for each survey flight, which was the same for all 6 flights. Ground speed and other flight parameters are already listed in the text.

**Line 127: Section “3.1 Background”: It is unclear to me why this section is titled background, and why it is positioned here. If the section is background, then it should probably come before datasets/methods. This section seems to be a mix of background (lines 128-137 & 150-157) and surface roughness results (137-144).**

*Response:* We have addressed this point in previous comments.

**Line 134: “Elongated....sastrugi” is repetition of line 105-108.**

*Response:* We have already reworded line 134 based on RC1’s comments.

**Line 155: Use of Gow reference is really effective. Engagement with more literature of this age could benefit the paper, e.g. publications from the South Pole-Queen Maud Land traverses of 1964-65 and 1965-66. Lots of the results of these traverses are published in “Antarctic Snow and Ice Studies II” <https://agupubs.onlinelibrary.wiley.com/doi/book/10.1029/AR016>**

*Response:* We have added the SP-QML reference to the new survey area section. The SP-QML traverse has very sparse accumulation measurements but no discussion of roughness or slope to our knowledge. We therefore think it is lacking the relevance to our work that would warrant

more discussion. The Gow paper, on the other hand cover all these topics and is therefore relevant.

**Line 158: Section “3.2. Relevance of surface roughness.....”:** This seems to be background material rather than results.

*Response:* We have addressed this point in previous comments.

**Line 170: No need for an acronym for bidirectional reflectance distribution function. It is only used once after this in the entire manuscript.**

*Response:* We have deleted the acronym and spelled out BRDF in line 175.

**Line 172: “the relationships”**

*Response:* We prefer “then” since the 2007 work is a follow up to the 2002 work.

**Line 180: Section “3.3. Surface roughness estimates”:** The entirety of section 3.3 seems to be methods, or assessment of methods (lines 207-216) rather than results or discussion. An overall decision needs to be made about what section 3 is (see ‘broad comments’ above).

*Response:* We have addressed this point in previous comments.

**Line 234: year of Mougnot reference (2019?) is missing.**

*Response:* We have added the missing year in the reference.

**Line 239-249: Description of the longitudinal ranges of features of interest. I did find it tricky when reading the text to think about compass bearings in both westerly and easterly compass directions in a single sentence. I understand why the authors have done this (i.e. to describe what is shown in figures 3 and 4), but it is a little jarring and non-intuitive when reading a single sentence. For example, for me it is much easier to comprehend “between 175° W and 60 °E” when written as “between 60-185°E”. As currently written, it is also not clear without reference to the figure whether the smooth area is clockwise or anti-clockwise between 175° W and 60 °E. It may also be worth considering annotating the area described in figure 3 (&4)?**

*Response:* Describing compass bearings in the vicinity of the pole is inherently challenging because of the longitudinal convergence. There are no good solutions to this challenge in our view. The authors are having the same difficulties as the referee when discussing results among ourselves or describing them and we are aware that the readers will face those same challenges. Two conventions are in use to describe longitudes: 180° W/180° E and 0°/360°. Strictly speaking the longitude is defined as an angular measurement ranging from 0° at the Prime Meridian to 180° E eastward and 180° W westward. We have therefore chosen the 180° E/W convention. It also provides a hemisphere distinction that the 0°/360° convention does not have. As the referee points out the words in the text need to be consistent with the figures and we have followed that rule.

The referee describes the challenges when describing features that go over a singularity. These challenges are the same in both the 180° W/180° E and 0°/360° conventions.

To help the reader comprehend the spatial setting we have use the same SCAR-recommended polar stereographic map projection (EPSG:3031) for Figs 1-3 that many people are familiar with.

We are not clear what is meant with the last sentence of the referee's comment.

**Line 250: I am not sure what "...appears to have less of a roughness anomaly...." means. Why not just "..the surface of this dunefield is less rough in 2017 compared to 2014 and 2016"?**

*Response: We have changed the sentence accordingly.*

**Line 253: "beyond" rather than "out of"?**

*Response: We prefer "out of".*

**Lines 254-257: this paragraph seems a little 'bolted-on' to this section and is a little perfunctory. Does it need a few more sentences to describe the data presented in figure 4e a little more fully? This section is entitled "3.4 Surface roughness, slope and elevation..." but is very much dominated by roughness.**

*Response: We have moved the last sentence into the new survey area section.*

**Line 254: Why "...slope of the ATM ICESSEN nadir platelets..."? Why not just "ATM-derived surface slope"?**

*Response: We prefer to be precise here and state that the slope from the ICESSEN data product was used and that we used only the nadir platelet.*

**Line 262: A, B & C are labelled in 4b, rather than 4a.**

*Response: We have corrected that error.*

**Lines 265: "simultaneously" or "concurrently" rather than "at the same time"? Line 267: no comma after "Both"**

*Response: We have changed line 265 already based on RC1's comments and have deleted the comma after "Both".*

**Line 268: "...seems to be even slightly lower..." – recommend rewording to either quantify this statement, or to make it more certain. Perhaps "...are slightly lower..."?**

*Response: We have reworded the sentence accordingly.*

**Lines 282-318: "Section 4" – this all seems to be method description here, rather than description of data or results? Perhaps a re-structuring of the paper is required to make it clear to the reader which sections are methods, results and interpretation? If the manuscript is a methods development paper then that's fine, but that's not the impression currently given by the abstract.**

*Response: We have addressed this point in previous comments.*

**Lines 320-340: "Section 5" – the first part of this section is a mix of background information (i.e. lines 320-329) and further description of methods (i.e. lines 329-340). It does not describe "Spatial variability in snow accumulation rates". I would suggest that the opening line of section 5 is not the best place to state "Accumulation of snow on the Antarctic ice sheet is primarily the result of precipitation of snow".**

Such a sentence should be on the 1st page of a manuscript. The entirety of Lines 320-324 should be much earlier in the manuscript.

*Response:* We have moved lines 320 – 326 into the new survey area section. We have revised the title of this section to better reflect its contents.

**Line 347:** rather than “several”, can the authors provide a range (e.g. 0-3 cm w.e. yr-1)?

*Response:* We have included a number.

**Line 349:** again, here it would be good to quantify the statement made (e.g. “the highest accumulation rates (xx cm w.e. yr-1) near....”

*Response:* We have included a number.

**Line 352-353:** Good to cite original paper locating the bedrock low (i.e. Studinger et al. 2006). Authors could also add an up-to-date reference here to reflect new bed data acquisition in this area. Either Paxman et al., 2019 <https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2018GC008126> or Morlighem et al., 2019 <https://www.nature.com/articles/s41561-019-0510-8> ? Perhaps also move the reference to figure 3a to earlier in the sentence as it only shows surface depression, rather than the subglacial topographic low?

*Response:* We have added a reference to Morlighem et al. (2020) in the new survey area section. The ice thickness and bedrock data that are relevant to our study are the one that have been collected along our survey line on the 6 flights we discuss. These data sets are shown and referenced in our manuscript.

**Line 354-360:** this is an extensive description of previous work that is not directly linked into the data description/interpretation here. Could it be moved to a ‘study area’ section earlier in the manuscript? It might be more effective there, and can then simply be referred to at its current location?

*Response:* We have moved some of the wording into the new survey area section.

**Line 362:** suggest insert an  $r^2$  value after “correlates”.

*Response:* We don’t have  $r^2$  values calculated for geographic segments and don’t think it would make much sense.

**Line 365:** “highly variable” – requires some quantification in the text (i.e. range of values should be quoted).

*Response:* We have quantified the variability.

**Line 369:** Reword to “However, several peaks in snow accumulation rate still correlate...”?

*Response:* We have changed the wording.

**Line 370:** again, insert an  $r^2$  value after “correlates”? **Line 372:** “topographic” rather than “topography”?

*Response:* We have changed the wording. Figure A3 shows a visual correlation without  $r^2$  values.



**Line 372-373: change to “..lowest part of the depression where it reaches it’s highest point.”? Perhaps quantify the “highest point” too? How high was it? Such statements should be quantified in the text.**

*Response: We have changed the sentence accordingly, but have replaced “it’s” with “its”.*

**Lines 373-374: change to “...with lows in topography results in an overall negative correlation coefficient of....”**

*Response: We have changed the sentence accordingly.*

**Lines 393-394: insert an  $r^2$  value after “The correlation is strongest”? I note that in-text quantification of data description is much better in the following section 6.**

*Response: We don’t have  $r^2$  values calculated for geographic segments and don’t think it would make much sense.*

**Line 432: is there really a requirement to say “ESA’s CryoSat-2”? Why not just CryoSat-2? Line 466: change to “...MERRA-2, which have low spatial resolutions.”?**

*Response: We have deleted “ESA’s” to make this CryoSat-2 mentioning consistent with previous mentioning of CryoSat-2 in the manuscript. We have changed line 466 following the suggestion.*

**Lines 467-471: this is a very important finding.**

*Response: None required*

#### **Figures:**

**Figure 1: Cite source of rock outcrop polygons (Antarctic Digital Database?)**

*Response: We have added the Antarctic Digital Database to the caption of Fig. 1 and data availability section at the end of the manuscript.*

**Figure 2: I found it difficult to orient myself between figures 2 and 3. Where is figure 2 located on figure 3?**

*Response: Figure 2 is located at 135° E and 88° S. We have added the location of Fig. 2 to Fig. 3b and updated the caption to Fig. 2. The same SCAR-recommended polar stereographic map projection (EPSG:3031) is used for Figs 1-3.*

**Table 1: This is table is really useful.**

*Response: None required.*