Interactive comment on "TanDEM-X PolarDEM 90 m of Antarctica: Generation and error characterization"

Authors: Wessel, B., Huber, M., Wohlfart, C., Bertram, A., Osterkamp, N., Marschalk, U., Gruber, A., Reuß, F., Abdullahi, S., Georg, I., and Roth, A., The Cryosphere Discuss., https://tc.copernicus.org/preprints/tc-2021-19/

Referee comments are shown in *black*, our response in blue. Line numbers refer to the manuscript version (pdf) of 21 January 2021.

Authors' response to Referee#1 Ted Scambos

General comments:

The study describes the assembly and processing of a new DEM of Antarctica produced by X-band interferometry using the TanDEM-X and TerraSAR-X satellites, with a gridding scale of 90 m. The DEM is exceptionally complete (99.991% of the continent mapped) and has a new derived ice sheet edge (coastline). Validation of the DEM over blue ice areas shows that in regions of near-zero radar penetration into the snow-ice surface (and little surface elevation change), the new DEM matches ICESat data very well. The paper is fairly well-written and well-described, and the authors are very clear about how they build the DEM.

Response: First, we want to thank the Referee for the time and effort put in this detailed and thorough review. We are impressed about the deep understanding and careful reading of the reviewers. We thoroughly evaluated all comments and suggestions, which are very valuable in improving this paper and we are glad about the positive feedback.

We particularly value the Referee#1's appreciation of the following main aspects that we will incorporate into the manuscript: 1) a better explanation of the reflective surface of X-Band SAR DEM for ice/firn areas; 2) some more glaciological processes but also some explanations, why the authors think that these are not in detailed needed for an error characterization; 3) more explanations and examples of the benefits of the presented DEM; and 4) the insertion of some selective profiles plots.

However, the DEM is intentionally left unadjusted for X-band penetration below the snow surface, although the offset between ICESat and the TanDEMX DEM is well described and has interesting regional variations. However, it's unclear what surface is being measured – how would this surface be described? Firn level at which a large fraction of X-band radar energy is scattered back? This makes the DEM hard to use for things not related to radar studies. It also calls into question the nature of the local topography (scales of 1 – 5 ice thicknesses, horizontally) that is being measured. In many areas of East Antarctica, this is unlikely to be parallel to the air-snow interface because of strong variations in backscatter associated with local variations in deposition and sublimation.

Response: (surface of X-Band SAR DEMs for ice/firn areas) Many thanks for stressing this topic. We recognized that the physical scattering surface for X-Band SAR for ice/firn surfaces was not well enough explained. Also, both reviewers raised this topic. In fact, the scattering surface is not air-ice but somewhere in the ice resp. in the firn varying due to the ice/firn characteristics, what makes it variable and complicated.

First of all, the measured InSAR height represents an elevation corresponding to the average penetration when firn is present. Over pure dry firn (no melting or physical effects present) the radar waves at X-band penetrate inside the snow pack and are gradually absorbed with increasing depth, while only a fraction is backscattered toward the SAR instrument. The individual scattered returns stem from varying depth, that are aggregated to a mean "scattering phase center". In Antarctica as well as on the Greenland ice sheet no more "mean scattering depth" than 10m below the air-ice surface were observed (ICESat-1 as reference) in case of TanDEM-X. Compared to Greenland ice sheet, the InSAR penetration bias in Antarctica is smaller, because the ice masses are affected by strong wind effects that changes the microstructure and density of the snow and ice layer. Such densified layers influence the backscattering as they often act like a strong backscatter layer for X-band SAR, where a large part of the scattering takes place. In general, the layer-structure and therewith the corresponding X-band penetration bias is unknown. A hint about the reflective surface is given by the amplitude image (Fig. 10). Strong backscatter indicates the presence of such densification processes which lead to a predominant reflection at this layer. To improve the usability of the TanDEM-X DEM in the future, this relationship will be further investigated by the authors to be able to model the penetration bias to achieve a corrected version that represents at least an approximation of the surface (Abdullahi et al. 2019).

The authors need to consider some glaciological processes that they may not be aware of

– sub-glacial lake drainages in the Recovery Ice Stream explain some of the shifts they see; Thickening in the LarsenC and thnning along the George VI southern coast and Amundsen Sea coast should be discussed as indicators of major mass balance changes --- also the Dotson Ice Shelf region.

Response: (glaciolgical processes) The reviewer's observation is correct and we intentionally avoided to attribute the affects to glaciological processes. For a DEM error characterization, we chose stable regions in height and over time for a proper absolute height validation. This was the reason to select the stable blue-ice areas (ICESat comparisons) or the Recovery glacier or South Pole comparisons with IceBridge. Areas with larger height variations were excluded from a detailed analysis as the height differences can be attributed to both "real" change phenomena caused by height variations during the time-span between ICESat (-2009) and TanDEM (2013-2014) or to calibration errors. The latter are of main interest here. Nevertheless, we agree to mention regions with some well-known effects like the most obvious explanation for the differences at the Peninsula down to Getz glacier or the thickening in LarsenC (zoom here in the review). Also, in the inner Antarctica different snow characteristics play a mayor role for the variations between ICESat and TanDEM-X DEM. Here, we are very pleased about the hint of the Referee regarding an explanation for the inner ray-like structure (Scambos et al., 2016)

Recovery Glacier: We investigated your assumption that subglacial drainage might be partly responsible for the height differences over the Recovery glacier in more detail. We added to Figure 16 (height differences TanDEM-X minus IceBridge) the outlines of the known subglacial lakes (source Quantarctica3, Smith et al. 2009). The subglacial lakes deliver no clear indication for the larger height errors present at this glacier. So, we had a closer look at the TanDEM-X input data, the TanDEM-X DEM mosaic represents mean values of May 2013 and May 2014 at this part; IceBridge was taken in October 2014. In the TanDEM input data there are indeed mayor differences at some locations outside the lakes, these are marked with a red star in the updated Figure 16, indicating, the same depression like IceBridge does. These might stem from potentially active subglacial lakes, but could also be caused by other effects (wind, incidence angle, change of ice characteristics). For us, the reason remains unclear, but there really seem to exist some depressions that explain the larger discrepancies between TanDEM-X mosaic and Icebridge. Apart of these spots, most of the Recovery Glacier main trunk shows the expected correlation between the amplitude backscatter (which is related to ice characteristics) and the measured penetration bias: high amplitude values = no/small penetration bias, low amplitude values = high penetration bias (Floricioiu et al, 2016). This area is quite complicated and show that active areas that are the observing goal of IceBridge are not well suited for a DEM validation even if the time span covers just 1.5 years.

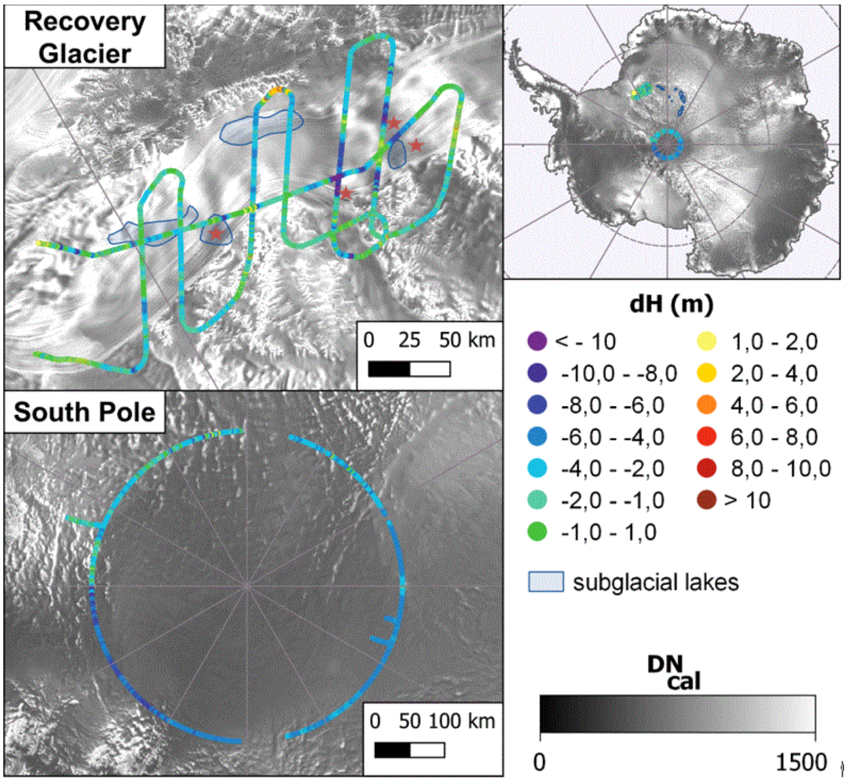
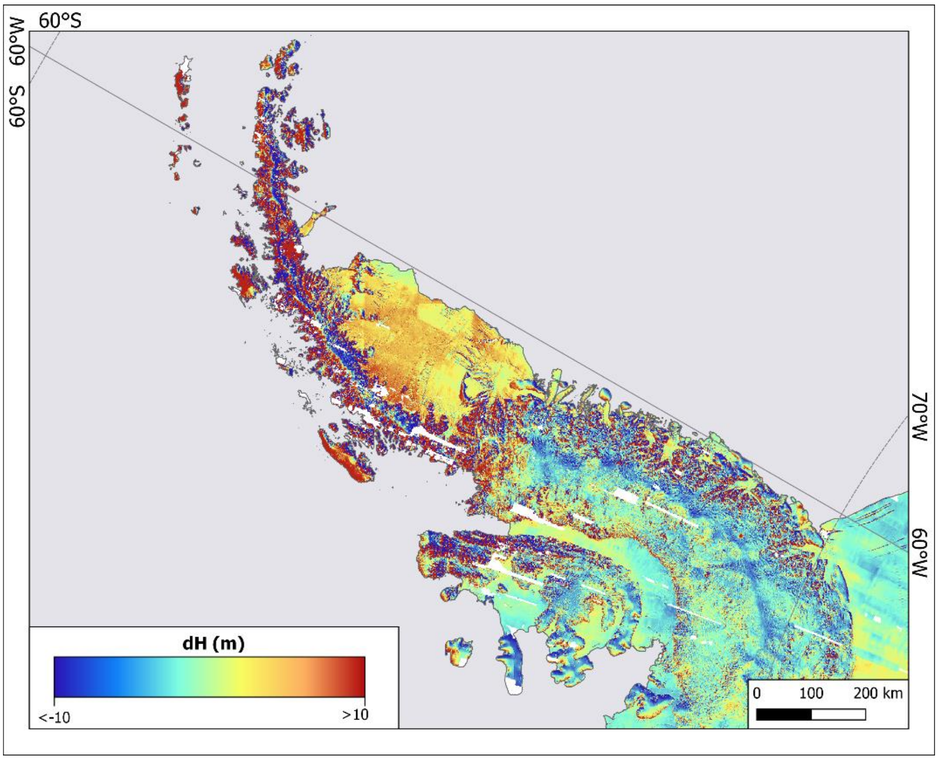


Fig. 16 updated: Height differences TanDEM-X PolarDEM 90m minus IceBridge; with subglacial lakes outlines for the Recovery glacier and spots where TanDEM-X input data from 05-2013 and 05-2014 differ marked with a red star.

The paper is fine as it stands, with minor edits; but the authors need to make clear how the DEM can be used. It is not suitable for mass-balance related change detection studies, because of the fuzzy nature of the correlation surface measured in the DEM; even a comparison with a repeat DEM by TanDEM-X would be more a study of backscatter changes at depth than elevation. Also not suitable for determining the surface slope for ice velocity studies, at least not in detail.

Response: (Use of the DEM)

We agree that the use of the TanDEM-X DEM over ice sheets is not straight forward. However, SAR sensors are well established and widely used in cryosphere applications. They all have in common that the SAR signal penetrates and the derived information is not related purely to the upper surface. From that point of view the TanDEM-X DEM could serve as an ideal basis DEM e.g. for applications like the interferometric SAR velocity estimation and also the ortho-rectification of SAR data. They benefit from a similar penetration bias as well as from a complete, gap-free coverage that is prerequisite for these applications. The almost gap-free coverage of TanDEM-X is also a big plus. In the zoom you see the gaps in the REMA DEM at the Peninsula, which are filled with valid values in the TanDEM-X DEM).



Zoom: Difference TanDEM-X minus REMA for the Antarctic Peninsula, in white no data areas in REMA.

Nevertheless, elevation change or mass balance change are important topics that require two or more DEMs. For DEM to DEM comparison the penetration bias should be handled adequately. For example (Huber et al. 2020) used the TanDEM-X DEM of Greenland in comparison with aerial photogrammetric DEMs over a 28-years period and therefore decided to neglect the penetration. In contrast, Malz et al. used the TanDEM-X DEM for a comparison with SRTM and roughly estimate the different penetration biases in advance. In both cases, the (residual) unknown penetration bias was regarded and modelled as an additional uncertainty for the heights. For X-band DEM to X-band DEM comparisons the penetration bias could be regarded as an uncertainty assuming similar biases or- for higher accuracies – has to be compensated first (Abdullahi et al. 2019). We will add these aspects and the examples.

It would be good to see detailed profile comparisons between this DEM and ICESat elevations, REMA elevations, CryoSat-2 elevations in several key areas – a good figure to add.

Response: (Profile comparison) Thank you for this suggestion. We decided to introduce some elevation profiles of TanDEM, REMA and CryoSAT-2 in several key areas. The new Fig. Y will be included. In its first profile (Fig. Ya), there is a relatively homogenous penetration bias between TanDEM-X and REMA or CryoSAT-2, except for some crevasses. The profiles in Fig. Y b), d), and e) illustrate the capability of the DEMs to capture fine-scale topography and its limitations especially in the case of the 1km data set of CryoSAT-2. In the difference images TanDEM-X minus REMA in Fig. Y b) and c) some rectangular

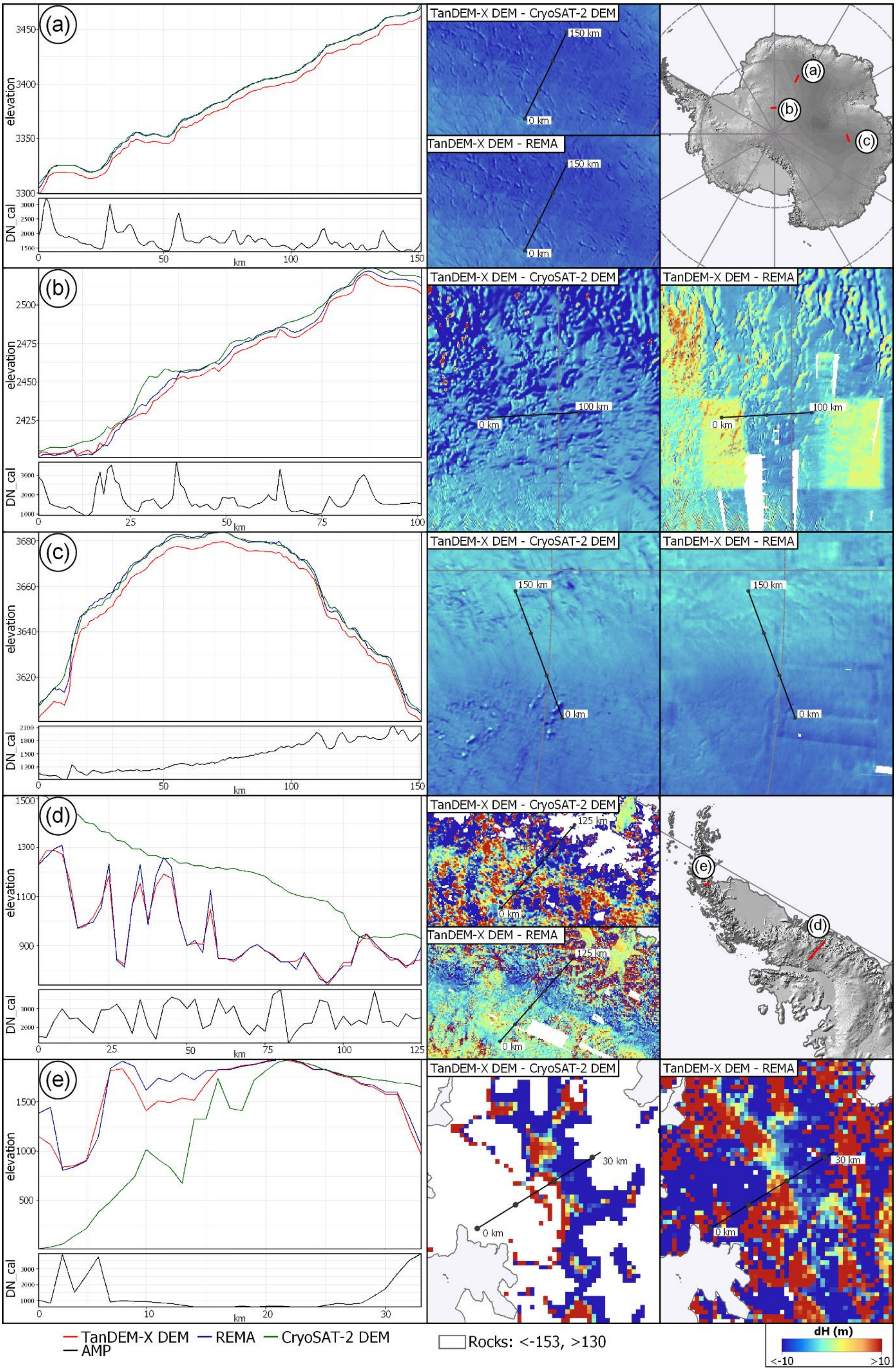


Fig. Y elevation profiles of TanDEM, REMA and CryoSAT-2 in several key areas features from the REMA DEM can be observed, where REMA is close to or even below TanDEM-X DEM. We will elaborate the description in more detail and incorporate it into the next version of the paper.

But the careful processing and blending of the data -do- make the data set useful. Figure 10 and 11 are worth more analysis and comparison with other backscatter data sets (e.g. Radarsat or ERS-1, 2 at C-band, PALSAR-2 at L-band)

The validation of the backscatter map is not the topic of this paper, but definitely interesting! We will add your statement regarding comparison with other backscatter maps as a potential future research.

I suggest that the paper could be acceptable with 'major' revisions, but mostly in terms of how the result is described and what it might be used for.Numerous short comments are in the annotated .pdf file uploaded with this review.Please also note the supplement to this comment:https://tc.copernicus.org/preprints/tc-2021-19/tc-2021-19-RC1-supplement.pdf

Further Referee's comments from annotated pdf:

Thank you very much for taking the time and proposing so many improvements regarding minor remarks and wordings. All minor remarks or rewordings are accepted and will be changed in the final manuscript. Where necessary, we provide some additional information below:

Line 5. suggest that you include the range of observations that are included in the DEM

We will add the acquisition period of April 2013 to October 2014 in the abstract.

Line 180. I don't understand this paragraph. You determine the homogeneous bias in several regions, but then set the adjusted heights back to a mean InSAR height below the surface?

Correctly understood, but we will improve this paragraph to make this clearer.

Line 188. would it have been better to complete the circle in both directions, re-unifying in East Antarctica and somehow averaging or blending the results?

Your suggestion of a double estimation and averaging the results would have been a technical easy solution to average out some errors. Unfortunately, we had some time constraints in processing as the goal of the TanDEM-X processing was the generation of a global DEM. At least a smoothing is applied on local scale in the range of some 200m, so no hard step was introduced.

Line 328. These ray-like areas around the pole are due to variations in net accumulation and the fraction of 'wind glaze' regions. Wind glaze is a high-altitude East Antarctic surface type that is formed in areas that have near-zero accumulation for decades or more, due to sublimation or wind transport off the surface. Megadunes are alternating bands of accumulation stripes (low backscatter) and wind glaze (high backscatter due to subsurface recrystalization). You may want to replace the pers. com. with this paper: Scambos et al., 2016, J. Glaciol, https://doi.org/10.3189/2012JoG11J232

Thank you very much for this explanation and the reference! We will take it from there.

Line 333. I am wondering, though, what the DEM is useful for, since you did -not- attempt to raise it to the level of the ICESat data -- what surface does it define? An unspecified *surface of coherent backscatter at depth -- but what does that mean? How would someone use this DEM? Am I missing something?*

The answer is given above (Use of the DEM)

Line 375. "The higher variance in height differences at Recovery Glacier indicates a higher variability of signal penetration, which is also reflected in the higher variability of backscatter intensity (Fig. 16, lower right). " *->sub-glacial lake drainage?*

The answer is given above (glaciolgical processes /Recovery Glacier)

References:

Abdullahi, S.; Wessel, B.; Huber, M.; Wendleder, A.; Roth, A.; Kuenzer, C. Estimating Penetration-Related X-Band InSAR Elevation Bias: A Study over the Greenland Ice Sheet. Remote Sens. 2019, 11, 2903. https://doi.org/10.3390/rs11242903

Floricioiu. D., Jaber, A.W., Baessler, M., Helm, V., and Jezek, K. (2016), Recovery ice stream: Synergy of satellite and airborne remote sensing for flow dynamics, Proceedings of IGARSS 2016, pp. 7098 – 7100.

Huber J., McNabb R., Zemp M. Elevation Changes of West-Central Greenland Glaciers From 1985 to 2012 From Remote Sensing Frontiers in Earth Science, 8, 2020, https://doi.org/10.3389/feart.2020.00035

Malz, P.; Meier, W.; Casassa, G.; Jaña, R.; Skvarca, P.; Braun, M. H. 2018. "Elevation and Mass Changes of the Southern Patagonia Icefield Derived from TanDEM-X and SRTM Data" *Remote Sens.* 10, no. 2: 188. https://doi.org/10.3390/rs10020188

Scambos, T., Frezzotti, M., Haran, T., Bohlander, J., Lenaerts, J., Van Den Broeke, M., . . . Winther, J. (2012). Extent of low-accumulation 'wind glaze' areas on the East Antarctic plateau: Implications for continental ice mass balance. Journal of Glaciology, 58(210), 633-647. https://doi.org/10.3189/2012JoG11J232

Smith, B. E., H. A. Fricker, I. R. Joughin, and S. Tulaczyk (2009), An inventory of active subglacial lakes in Antarctica detected by ICESat (2003-2008), J. Glaciol., 55(192), 573-595.