We thank the reviewer for the helpful feedback, these suggestions have significantly improved the text and figures, we are appreciative of the help and time.

We have addressed all the comments here, point by point responses to the comments are listed in BLUE.

Here we summarize two major revisions in the revised manuscript:

First, in the revised manuscript we select a 500m posting for the derived ICESat-2 DEM. That is, elevations are firstly estimated at the resolution of 500 m and 1 km, respectively. Then the observation gaps in the 500 m DEM are filled by the resampled 1 km DEM (resampled to the 500 m), and the remaining gaps are filled by using ordinary kriging interpolation. In the original manuscript, we firstly generated four DEMs, i.e., 250m DEM, 500m DEM, 1km DEM and interpolated DEM. We produced a DEM at 250 m posting by resampling DEMs at 500 m and 1 km posting (including the interpolated DEM). However, 250m DEM only has a coverage of 26%, most of the derived DEM were based on resampled coarser DEMs. Hence, as suggested by the reviewers, starting from 500m, refill with 1km and do the kriging would make more sense. In this case the model fitting tends to be more robust as more points are used per grid cell. The updated Figure 4 is listed below (the figure indexes in this text are the same to these in original manuscript):

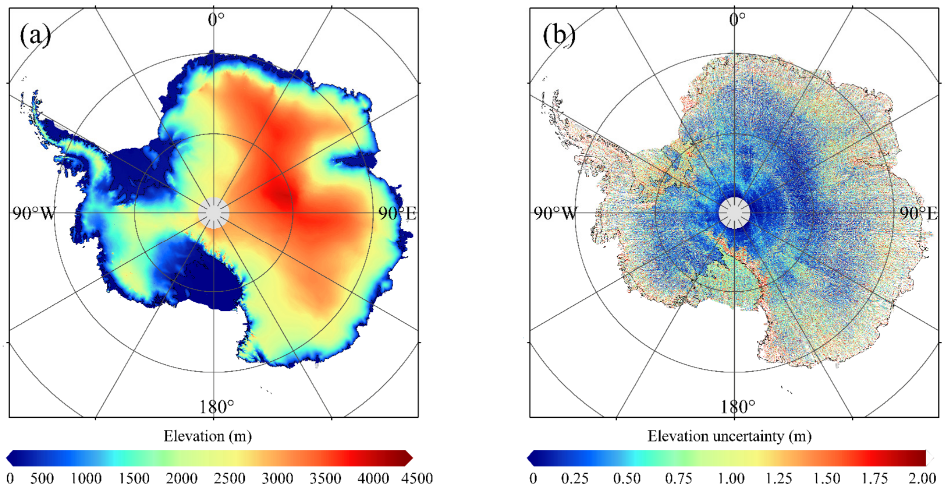

Figure 4. (a) A fine-scale DEM of Antarctica at a posting of 500 m derived from ICESat-2, which covers both the ice sheet and ice shelves with the southern limit of 88°S. (b) Map of the ICESat-2 DEM elevation uncertainty.

Second, in order to provide a robust and reasonable comparison between ICESat-2 DEM and other DEMs, a common OIB data in areas of low elevation change from 2009 to 2019 are used in the revised manuscript. As the same evaluation data are used, all the DEMs can be compared validly. These OIB data are located in the ice sheet interior, as shown in the figure below (Figure 1b). The CryoSay-2 Low Rate Mode (which was designed for flat ice sheet interior measurements) mask is used to extract the regions of low elevation change. CryoSat Geographical Mode Mask (v 4.0, updated in 19 August - 26 August 2019) at https://earth.esa.int/eogateway/news/cryosat-geographical-mode-mask-4-0-released is used here. The averaged elevation change rate in the used

OIB data locations is about -0.0074±0.0821 m/yr from 2003 to 2019, according to elevation change rate data from Smith et al. (2020). Hence, we assume that in these areas the effect of the elevation change on the DEM evaluation can be ignored. It should be noted that, when evaluating ICESat-2 DEM individually, OIB data in areas of low elevation change from 2009 to 2017 and OIB data in all Antarctica from 2018 to 2019 (Figure 1a) are used for a comprehensive evaluation. In addition, published GPS transects (Schröder et al., 2017) are also used here for the DEM comparison (Figure 1c).

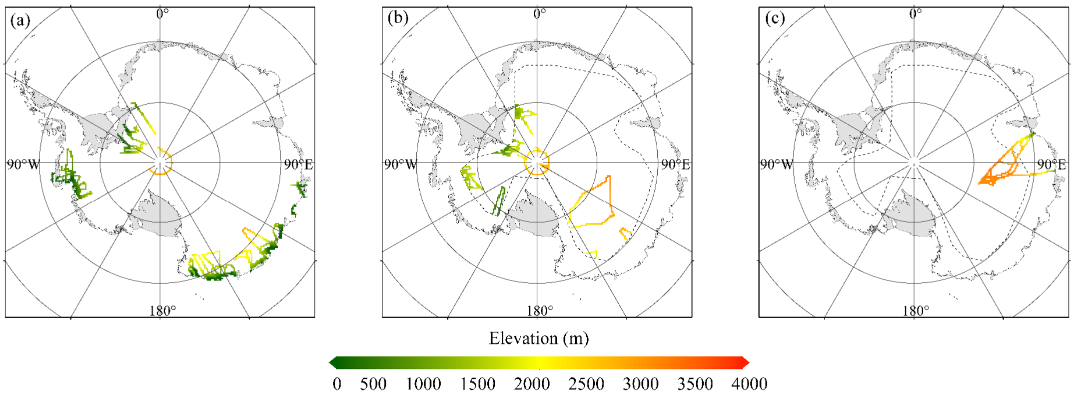

Figure 1. (a) Map of the OIB airborne data in October and November 2018 and October and November 2019 in Antarctica. (b) Map of the OIB airborne data from 2009 to 2019 in Antarctic ice sheet interior. (c) Map of the GPS transects from 2001 to 2015 in Antarctica. The dashed lines in (b) and (c) show the boundary of region where we assume to have low elevation change, it is the mode mask boundary of CryoSat-2 Low Rate Mode data in Antarctica, this data mode was designed for flat ice sheet interior measurements.

In addition, in the revised manuscript we resample all the DEMs to the OIB data locations and calculate the difference and statistics to perform the evaluation. The original approach (calculating a median OIB elevation for each grid cell) will certainly influence the evaluation results as the DEMs have different pixel spacing. Also as pointed out by the reviewers, OIB is the reference elevation and cannot be replaced by the median values. The new approach is also applied for DEM evaluation using GPS data. The related statistics have changed, but the same conclusions are found comparing to original statistics. The updated Tables 3, 5 and 6 are listed in below:

Table 3. Comparisons between the ICESat-2 DEM and OIB airborne elevation measurements (including data in areas of low elevation change from 2009 to 2017 and data in all Antarctica from 2018 to 2019) in observed and interpolated areas for individual regions (i.e., the ice sheet and ice shelves).

	Region	MeD (m)	MeAD (m)	SD (m)	RMSD (m)	Number of used OIB measurement points
Observed	Ice sheet	0.08	1.18	12.75	12.75	3589087
	Ice shelves	0.77	2.60	15.26	15.27	191754
	Total	0.09	1.23	12.89	12.89	3780841
Interpolated	Ice sheet	-0.40	2.50	20.68	20.73	1237416
	Ice shelves	0.36	3.23	24.61	24.65	185613

	Total	-0.33	2.58	21.25	21.28	1423029
Overall	Ice sheet	0.01	1.41	15.20	15.20	4826503
	Ice shelves	0.59	2.88	20.40	20.43	377367
	Total	0.03	1.49	15.64	15.64	5203870

Table 5. Comparisons between the ICESat-2 DEM, ICESat DEM, ICESat/ERS-1 DEM, Helm CryoSat-2 DEM, Slater CryoSat-2 DEM, REMA DEM, TanDEM PolarDEM and OIB airborne elevation measurements in areas of low elevation change from 2009 to 2019.

	MeD (m)	MeAD (m)	SD (m)	RMSD (m)	Number of used OIB measurement points
ICESat-2 DEM	0.10	0.98	5.36	5.38	
ICESat DEM	-2.61	6.35	19.90	20.43	
ICESat/ERS-1 DEM	-0.15	1.84	11.53	11.54	
Helm CryoSat-2 DEM	0.65	2.68	24.97	25.02	1965309
Slater CryoSat-2 DEM	1.22	2.87	23.85	24.14	
REMA DEM	-0.16	0.53	1.75	1.76	
TanDEM PolarDEM	-2.84	2.94	2.76	3.90	

Table 6. Comparisons between the ICESat-2 DEM, ICESat DEM, ICESat/ERS-1 DEM, Helm CryoSat-2 DEM, Slater CryoSat-2 DEM, REMA DEM, TanDEM PolarDEM and GPS elevation data in areas of low elevation change from 2001 to 2015.

	MeD (m)	MeAD (m)	SD (m)	RMSD (m)	Number of used OIB measurement points
ICESat-2 DEM	-0.03	0.41	1.17	1.17	
ICESat DEM	-1.91	2.89	5.21	5.97	
ICESat/ERS-1 DEM	-0.74	0.84	1.39	1.61	
Helm CryoSat-2 DEM	0.07	0.67	1.67	1.71	488963
Slater CryoSat-2 DEM	0.00	0.46	1.65	1.66	
REMA DEM	0.03	0.26	0.57	0.57	
TanDEM PolarDEM	-4.62	4.62	1.33	4.72	

References:

Smith B, Fricker H A, Gardner A S, et al. Pervasive ice sheet mass loss reflects competing ocean and atmosphere processes. Science, 2020, 368(6496): 1239-1242.

Schröder L, Richter A, Fedorov D V, et al. Validation of satellite altimetry by kinematic GNSS in central East Antarctica. The Cryosphere, 2017, 11(3): 1111-1130.

Review of Shen et al, TC 2021

This paper presents a new DEM of Antarctica derived from a year's worth of ICESat-2 data. It is a worthwhile endeavour and, with adequate care and attention to detail, an ICESat-2 DEM could provide a useful additional source of topographic information for Antarctica. There are, however, some misgivings with the approach taken here and lack of clarity about some of the methods.

General comments

In general the paper is well written but there are a significant number of instances of statements that are not accurate and/or misleading possibly because of the terminology used or possibly because of flaws in understanding or misconceptions. Specific details are given below but they start with the very first sentence of the abstract and continue from there and occur frequently.

Thank you very much for your feedback and advice, these suggestions have significantly improved the text and figures. We have revised the manuscript according to all your comments, details are listed in below.

If I understand the approach correctly, the authors produced a DEM at 250 km posting by resampling DEMs at 500 m and 1 km posting. First, the authors confuse resolution and posting (they are not the first to do this). It is misleading or incorrect to claim that a DEM with 26% observed coverage at 250 m posting has a resolution of 250 m as 74% of the grid points are interpolated. It has a 250 m posting and a resolution that is latitudinally dependent. More serious and worrying appears to the fact that there is a bias between elevations interpolated at the three resolutions which amounts to ~100 m at different latitudes (Fig 3b). According to this Figure the mean elevation, say, 80 degs differs by ~150 m from 1 km to 250 m. if the interpolation has been done correctly what is the explanation for this huge difference and how is it possible to combine elevations at these three resolutions when they are so different? I must have missed something but this seems like a fundamental issue? It suggests the distribution of elevations is not Gaussian around the mean, which is entirely possible but the interpolation should account for this unless there is a flaw in the method used.

1. Thank you very much for this essential correction. We have corrected this misleading terminology in the related part of the manuscript.

2. In the Fig. 3, elevations at different latitudes are presented by the region-averaged values. As shown in the Fig. 2 (in below), the coverages of DEMs at three resolutions are different, the observed elevation grid cells at the same region are not completely overlapped, DEM at coarser resolution has more observed grid cells than DEM at fine resolution at the same region, hence the region-averaged elevation values have large difference.

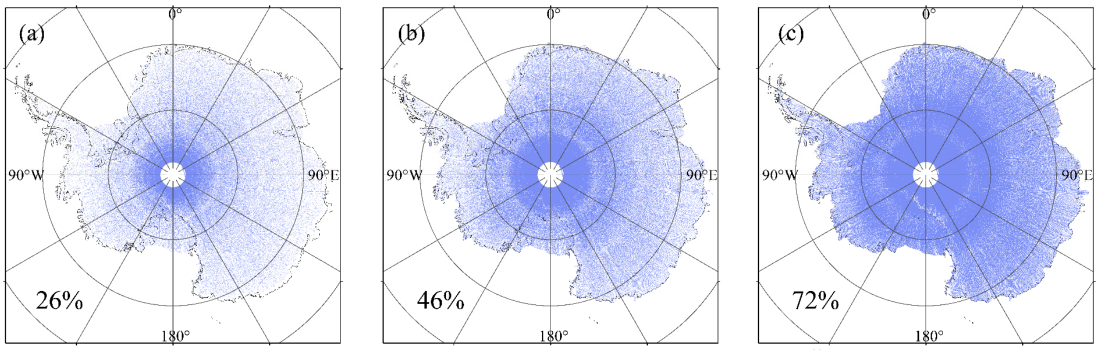

Figure 2. Map of the observed grid cells of DEMs at the spatial resolution of 250 m (a), 500 m (b)

and 1 km (c). The observed grid cells are colored in blue, the overall coverage of each DEM in Antarctica is also presented beside.

In the revised manuscript, we compare the elevations at two resolutions (i.e., 500 m and 1 km, as we mentioned in the very beginning only two resolutions are used in the revised manuscript) in the overlapped regions in Antarctica. The map and histogram of elevation difference between 1km DEM and 500m DEM are shown in Figs. 3b and 3c. An averaged elevation difference of 0.04 ± 2.93 m is found, which is quite small comparing to the estimated elevations. This elevation difference is acceptable and it is valid to combine elevations at these two resolutions.

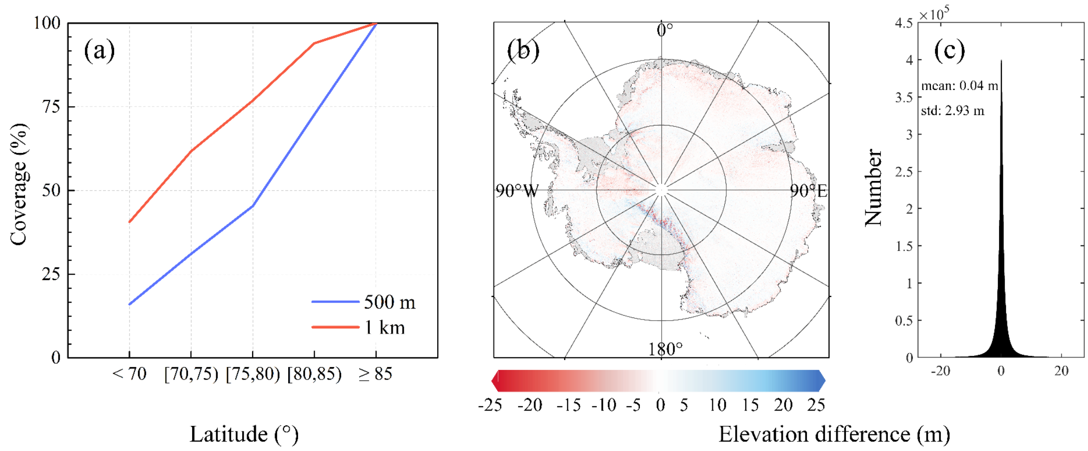

Figure 3. (a) Spatial coverages of observed grid cells in the five latitude ranges when two spatial resolutions, i.e., 500 m (blue) and 1 km (red), are applied. (b) Map of the elevation difference of DEMs at the resolutions of 1 km and 500 m. (c) Histograms of the elevation difference of DEMs at the resolutions of 1 km and 500 m, the average and standard deviation values are also presented.

A second major reservation, which in addition contradicts the brief discussion of the results, is that the largest mean elevation difference with OIB data, standard dev and RMSD is found over the ice shelves. These are the flattest places in Antarctica and so it is worrying and extremely unexpected that the "worst" bias and random error is over the ice shelves. This makes no sense. Without some sound explanation for why this would be, it brings into question the methodology/approach used here. Combined with the strange bias between different resolutions this suggest some issues with the methodology.

As we mentioned in the very beginning, we generate a new DEM at 500 m posting, perform a new evaluation by resampling the DEM into OIB location and calculating the statistics. According to the updated evaluation result, we can still find a slight better performance of DEM in ice sheet than ice shelves. In order to find the explanation, we present the histograms of surface slope and roughness values (derived from OIB data) for ice sheet and ice shelves in below:

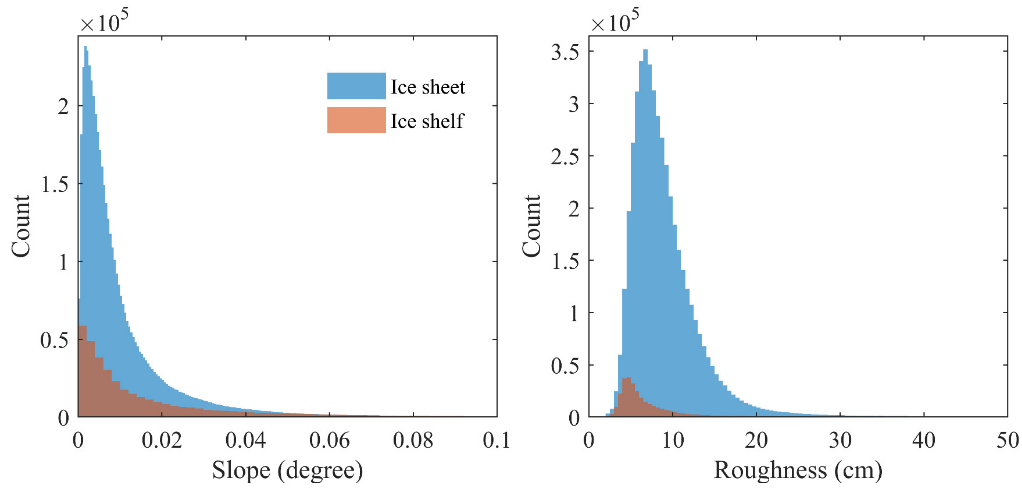

Figure. Histograms of the OIB-derived surface slope and roughness values for ice sheet and ice shelves.

As we can found in this figure, observed ice shelves have overall smaller surface roughness than ice sheet, but have a larger percentage of high-slope areas than ice sheet. For example, approximately 70% of the OIB measurement points which covered ice sheet have slope values of < 0.01°. In comparison, approximately 50% of the OIB measurement points which located in ice shelves have slope values of < 0.01°. Hence, observed ice shelves have a higher percentage of high-slope areas, which may cause larger elevation biases. To test this argument, standardized regression coefficients between surface slope/roughness and the elevation difference (i.e., mean absolute difference between ICESat-2 DEM and OIB elevations) are calculated here by using a multivariate linear regression model (this model is fitted by using an iterative least-squares fit). All OIB data in 2018 and 2019 are used. Standardized values of surface slope, roughness and elevation difference are used for a valid comparison. The regression coefficients for surface slope and roughness are 0.18 and -0.01. Larger regression coefficient indicates that the surface slope has greater effect on elevation difference than roughness. Hence, although ice shelves observed by OIB data have smaller surface roughness than ice sheet, a higher percentage of high-slope areas makes ice shelves have a slight worse DEM performance.

In addition, similar phenomenon can still be found in Table 2 in Slater et al. (2018), their observed DEM also has a slight better performance in ice sheet than ice shelves.

Table 2. Statistics of the comparison between observed and interpolated DEM grid cells and airborne elevation measurements for individual Antarctic regions and mode mask areas. In total, only 5 and 2 % of DEM elevation values are obtained through interpolation for the ice sheet and ice shelves, respectively.

Region	Observed			Interpolated		
	Number of compared grid cells	Median difference (m)	rms difference (m)	Number of compared grid cells	Median difference (m)	rms difference (m)
Ice sheet	230 165	−0.27	13.36	32 933	25.37	138.62
Ice shelves	40 081	−0.42	14.31	4772	1.20	30.96
Antarctic Peninsula	6820	−1.12	22.40	7473	82.21	191.07
West Antarctica	60 452	−0.86	11.43	8783	11.78	96.15
East Antarctica	162 893	−0.17	13.60	14 679	19.62	117.77
LRM	73 867	0.26	7.15	1683	6.51	41.70
SARIn (ice sheet only)	156 298	−0.82	15.45	31 250	28.65	141.97
Total	270 246	−0.30	13.50	37 655	19.84	131.13

Reference:

Slater T, Shepherd A, McMillan M, et al. A new digital elevation model of Antarctica derived from CryoSat-2 altimetry. The Cryosphere, 2018, 12(4): 1551-1562.

Third. The DEM is presented and compared to six existing DEMs but there is no real attempt to discuss what value or use it might have compared to these, how and where it might be better/worse than one or other or why someone might want to use this DEM over, for example, the REMA DEM which has an RMSD that is half of the ICESat-2 one. It could be better for some applications but no attempt is made to consider what these might be. Was this DEM created because it could be or because it should be? The former has limited scientific value, the latter needs to have demonstrated scientific value.

Here we add the related discussion in Section 5 in the revised manuscript:

Generally, the accuracy of ICESat-2 DEM is comparable to these of REMA DEM and TanDEM PolarDEM, which have higher resolutions and accuracies. However, these commercial images (used in REMA DEM and TanDEM PolarDEM) are expensive, significant economic investments are required to derive a large-scale DEM (e.g., for Antarctica) as a large amount of data are needed. More importantly, in this case multi-temporal images are usually used, the derived DEMs hence have various time stamps in different regions, which may cause some uncertainties in their further applications, e.g., numerical ice sheet modelling. ICESat-2 DEM has the same time stamp for all regions. Although the derived ICESat-2 DEM is less accurate than REMA DEM and TanDEM PolarDEM, considering the measurement accuracy of altimetry, these differences are still acceptable. Elevation change rate can be obtained when deriving the ICESat-2 DEM, which can provide an additional reference for ice topography and mass balance estimation. Comparing to altimeter-derived DEMs, ICESat-2 DEM has better (or comparable) performance in accuracy, resolution and coverage.

In addition, ICESat-2 data are easily accessible by the public comparing to high-resolution commercial images. In previous studies, several years of altimeter data are needed to derive the DEM in Antarctica. Due to the high-density measurements of ICESat-2, 13 months of ICESat-2 data can be used to generate a DEM for Antarctica, and the elevation accuracy is superior than other altimeter-derived DEMs. This means that the ICESat-2 DEM can be updated annually, this is still difficult for those DEMs derived from stereo-photogrammetry and interferometry. This study demonstrates the feasibility and reliability of using one-year ICESat-2 data to derive the Antarctic DEM, provides a reference for the processing scheme of DEM (e.g., in higher resolution, regularly updated) based on ICESat-2 in future.

Specific Comments

L9-10. “ice topography monitoring and ice mass change estimation”. First, these two things are almost identical, the difference being a density, so to assert that they are somehow different is misleading. To get mass balance you have to measure an elevation change here. Second, the vast majority of altimetry-derived mass balance and "topography monitoring" approaches published do not use a DEM (partly because of biases in absolute elevation) but use elevation difference either at cross overs or along track.

Agree and accept, we have revised this sentence to avoid the existing misleading information: 'Antarctic digital elevation models (DEMs) are essential for human fieldwork, ice motion tracking and the numerical modelling of ice sheet'.

The original sentence is also listed below:
~~'Antarctic digital elevation models (DEMs) are essential for human fieldwork, ice topography monitoring and ice mass change estimation.'.~~

L10 thirty decades = 300 years.

It should be 30 years, corrected.

L24 "essential addition". This is not demonstrated in the m/s. While the new DEM is an interesting addition to the 6 discussed, it is not the most accurate so to claim it is essential is unjustified.

Accept, the '*essential*' have been deleted.

L27-28. See first comment above. In addition, the two references cited do not use altimetry DEMs for ice motion tracking or mass balance.

Agree and accept, we have revised this sentence to avoid the existing misleading information: 'Knowledge of the detailed surface topography in Antarctica is essential for human fieldwork, ice motion tracking (Bamber et al., 2000) and numerical modelling of ice sheet (Cornford et al., 2015).'

The original sentence is also listed below:
~~'Knowledge of the detailed surface topography in Antarctica is essential for human fieldwork, ice motion tracking and mass balance estimation (Sutterley et al., 2014; Bamber et al., 2009).'.~~

The references have been corrected:
Bamber J L, Vaughan D G, Joughin I. Widespread complex flow in the interior of the Antarctic ice sheet. Science, 2000, 287(5456): 1248-1250.
Cornford S L, Martin D F, Payne A J, et al. Century-scale simulations of the response of the West Antarctic Ice Sheet to a warming climate. The Cryosphere, 2015, 9(4): 1579-1600.

L30 "monitoring the topography". What do the authors mean? Do they mean measuring elevation change? See first comment.

We have revised this sentence to avoid the existing misleading information:
'Digital elevation models (DEMs) of Antarctica, for example, can be used for **presenting** ~~monitoring~~ the topography of ice sheets and ice shelves and …'.

L51-52. KU-band penetration into snowpack is unknown. This statement is misleading at best. There is plenty of literature on Ku band penetration into snow. Further, radar penetration can be corrected for either empirically or theoretically using a waveform fitting approach (see e.g. [Davis, 1996; 1997]).

Agree and accept. We have revised this sentence to avoid the misleading information:
'Although the radar penetration depth of the Ku-band into snowpack can be corrected for either empirically or theoretically using a waveform fitting approach (Davis, 1996; Davis, 1997), the spatial and temporal variations of penetration depth are still difficult to account. As multi-temporal and large-scale satellite altimeter data are usually used, this includes some uncertainties in the elevation estimation.'.

The original sentence is also listed below:
~~'However, the penetration depth of the CryoSat-2 Ku-band into Antarctic dry snowpack is still unknown, which includes some uncertainties in the elevation estimation.'.~~

References:

Davis C H. Temporal change in the extinction coefficient of snow on the Greenland ice sheet from an analysis of Seasat and Geosat altimeter data. IEEE transactions on geoscience and remote sensing, 1996, 34(5): 1066-1073.

Davis C H. A robust threshold retracking algorithm for measuring ice-sheet surface elevation change from satellite radar altimeters. IEEE Transactions on Geoscience and Remote Sensing, 1997, 35(4): 974-979.

L84 Icessn?

IceBridge ATM L2 Icessn elevation, slope and roughness (V002) product (Studinger et al., 2014) is used here for DEM evaluation. According to Studinger et al. (2014), '*... the fundamental form of ATM topography data is a sequence of laser footprint locations acquired in a swath along the aircraft flight track. The **icessn program** condenses the ATM surface elevation measurements by fitting a plane to blocks of points selected at regular intervals along track and several across track. ...*'.
Here, Icessn is a terminology.

Reference:

Studinger, M.: IceBridge ATM L2 Icessn Elevation, Slope, and Roughness, version 2. Boulder, Colorado USA: National Snow and Ice Data Center, Digital media, https://doi.org/10.5067/CPRXXK3F39RV, 2014.

L87-88. This is not reducing "seasonal elevation changes" because any change that occurs in less than a year must be sub-annual, not multi-annual. Second, except for the pensinsula seasonal changes do not really exist over Antarctica, they are sub-annual which is not the same thing.

Agree and accept, the '*seasonal changes*' has been replaced by '*sub-annual changes*' in the revised manuscript.

Table 1, p5. It states the ICESat/ERS-1 DEM has an unclear timestamp but in the paper there is a specific section the DEM time stamp, where it explains that the ICESat data are corrected for any significant dh/dt between 1995 and date of acquisition [Bamber et al., 2009] so the time stamp is extremely clear and spelled out. It may not be perfectly corrected to 1995 but the Table is incorrect for this DEM and, consequently, makes me concerned about the veracity of claims made elsewhere in Table 1. Without carefully studying the methods used to generate each DEM the authors will not be able to support the claims made in Table 1.

Agree and accept, all DEMs have specific time stamps, but the temporal resolutions are different. In order to avoid the misleading information in original Table 1, we delete the column [time stamp] as the column [Time span of applied source data] has provided the information for DEM time stamps. All the information in Table 1 have been checked, the updated Table 1 is also shown below:

Table 1. Detailed introductions to six previously published Antarctic DEMs, including the source data, time span of the source data, spatial posting/resolution.

DEM	Source data	Time span of applied source data	Spatial posting/resolution
ICESat DEM	ICESat	February 2003 to June 2005	500 m
ICESat/ERS-1 DEM	ICESat, ERS-1	1994-1995, 2003-2008	1 km
Slater CryoSat-2 DEM	CryoSat-2	July 2010 to July 2016	1 km
Helm CryoSat-2 DEM	CryoSat-2	A full 369-day-long cycle starting January 2012	1 km
REMA DEM	GeoEye-1, WorldView-1/2/3	As of July 2017	Variable resolutions, 2 and 8 m
TanDEM-X PolarDEM	TerraSAR-X, TanDEM-X	April to November 2013, April to October 2014, mid-2014, July 2016 to September 2017	90 m

L120 replace "seasonal" with sub annual here and elsewhere.

Accept, the related parts have been revised.

L130 neighboring. The preferred spelling convetion for TC is UK English not US. Please follow that convention.

This has been revised.

L153. Strictly speaking the kriging variance is not, and cannot, be used to determine the interpolation error. It is related to the interpolation error but not equal to it.

Here, kriging variance error is not used to determine the interpolation error, but to calculate the elevation uncertainty due to the kriging interpolation (according to Slater et al. (2018)). The interpolation error is evaluated by using OIB data in Table 3.

Reference:

Slater T, Shepherd A, McMillan M, et al. A new digital elevation model of Antarctica derived from CryoSat-2 altimetry. The Cryosphere, 2018, 12(4): 1551-1562.

L171. Nominal resolution. See above. It would be more appropriate to refer to 250 m posting with a resolution of 1 km for latitudes x-y and 250 m from a-b…

We have corrected this misleading terminology, and revised the related parts in the manuscript.

L248. Needs rewording.

We have revised this sentence:

'Larger biases will be included in the ICESat-2 DEM if the coverage of interpolated elevations is high, hence the elevation gaps in the 500 m DEM are firstly filled by the resampled 1 km DEM to reduce the coverage of interpolated elevations.'.

The original sentence is also listed below:

~~'Larger biases are included in the ICESat-2 DEM if the coverage of interpolated elevations is high, which demonstrates the reasonability of the three resolutions used for DEM generation from ICESat-2.'~~

L250 Here the authors claim the bias increases with slope or roughness but that is not borne out by Table 3. See General Comments.

This has been responded in the General Comments (the second one).

L280-281. This is a sweeping generalisation that is incorrect. The accuracy of photogrammetric derived DEMs is a function of the resolution of the sensor and the accuracy of GCPs.

Agree and accept, we have revised this sentence:

'As shown in Table 5, REMA DEM and TanDEM PolarDEM are more accurate than altimeter-derived DEMs; hence, similar elevations indicate the reliability of ICESat-2 DEM in mountain environments.'.

The original sentence is also listed below:

~~'DEMs derived from stereo-photogrammetry have a better performance for high-slope regions (Slater et al., 2018); hence, similar elevations indicate the reliability of ICESat-2 DEMs in mountain environments.'~~

L321. “modal resolution” -> posting.

Done.

References

Bamber, J. L., Gomez Dans, J. L., and Griggs, J. A. (2009), A new 1 km digital elevation model of the Antarctic derived from combined satellite radar and laser data. Part I: Data and methods, The Cryosphere 3(2), 101-111.

Davis, C. H. (1996), Temporal change in the extinction coefficient of snow on the Greenland ice sheet from an analysis of seasat and geosat altimeter data, IEEE Trans. Geosci. Remote Sensing, 34(5), 1066-1073.

Davis, C. H. (1997), A robust threshold retracking algorithm for measuring ice-sheet surface elevation change from satellite radar altimeters, IEEE Trans. Geosci. Remote Sensing, 35(4), 974-979.