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 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):

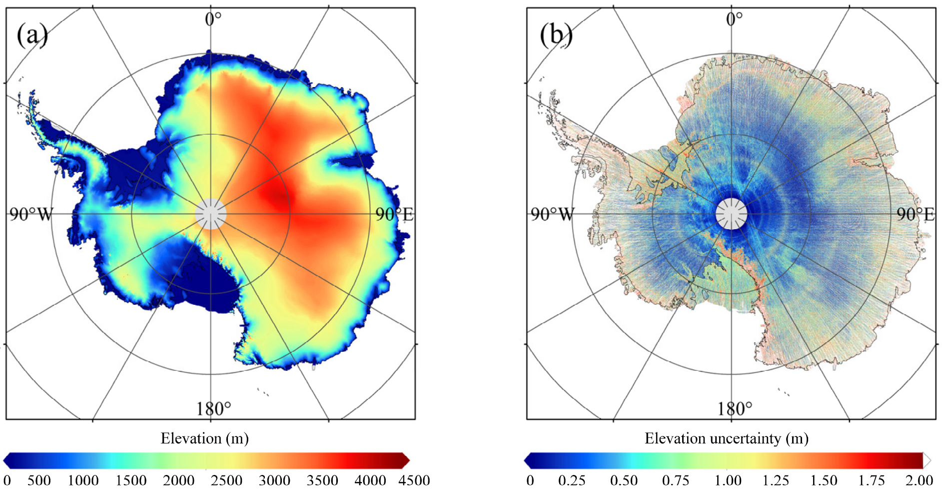

Figure 4. (a) A fine-scale DEM of Antarctica at a posting of 500 m derived from ICESat-2, which covers both the ice sheet and ice shelves with the southern limit of 88°S. (b) Map of the ICESat-2 DEM elevation uncertainty.

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).

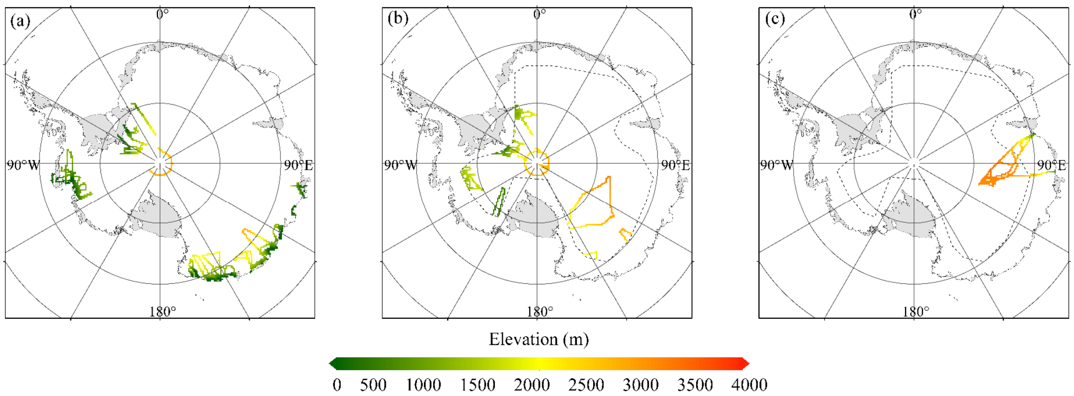

Figure 1. (a) Map of the OIB airborne data in October and November 2018 and October and November 2019 in Antarctica. (b) Map of the OIB airborne data from 2009 to 2019 in Antarctic ice sheet interior. (c) Map of the GPS transects from 2001 to 2015 in Antarctica. The dashed lines in (b) and (c) show the 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.

General comments

Shen et al. describe a new DEM of Antarctica generated from 1 year of IceSat-2 data, using a model fit and blended resolution approach similar to Slater et al., 2018. The DEM is compared to airborne laser altimeter data to assess its accuracy, and compared to other DEMs derived from both radar and laser altimetry, radar interferometry and stereo-photogrammetry. The paper is generally well written and structured, although the readability of most figures could be improved, in terms of resolution and the choice of colour blind friendly colour scales. A new DEM exploiting the high accuracy and density of IceSat-2 data is a welcome product and is worthy of publication. However, I have some concerns relating to the description of the DEM resolution, model fit, and the comparison to both OIB data and other DEMs which I would appreciate if the authors could address.

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, the details can be found in below.

DEM resolution and posting – the authors claim the modal resolution of the DEM is 250 m, but to me this does not seem correct. While the DEM is posted at 250 m, the most commonly used model fit is 1 km, and the majority of the DEM comprises of 500 m and 1 km model fits resampled to 250 m.

Agree and accept. As we mentioned in the very beginning, we produce a new ICESat-2 DEM at 500 m posting, the 500m DEM is refilled with estimated and interloped DEMs at 1 km posting to give a more reasonable and robust elevation estimate. The incorrect statement has been deleted.

Model fit method – I have some concerns with the authors choice of using the model fit method, which I would appreciate if they could address:

A linear component in time is more appropriate for longer time series, not one year of data where this parameter will be poorly constrained. How effective is this model at separating temporal elevation changes with just one year of data?

The map of elevation change rate in this study is shown in below, we also provide the estimation result from 2003 to 2019 in Smith et al. (2019) for a comparison. Overall, similar elevation change patterns can be found between the two figures. For example, larger elevation decreases can be found in the margin of West Antarctica, obvious elevation increases can be found in the interior of West Antarctica (red cycles in the figure). Hence, the elevation change pattern based on one-year ICESat-2 data is reasonable, which indicates that one year of data can give a reliable elevation change map and the elevation estimation is thus reliable. This may due to the much higher measurements density and accuracy of ICESat-2 than previous altimeters. In addition, ICESat-2 DEM has a higher accuracy than other altimeter-derived DEMs by comparing to both airborne and GPS data, which also proves the feasibility of the data and method.

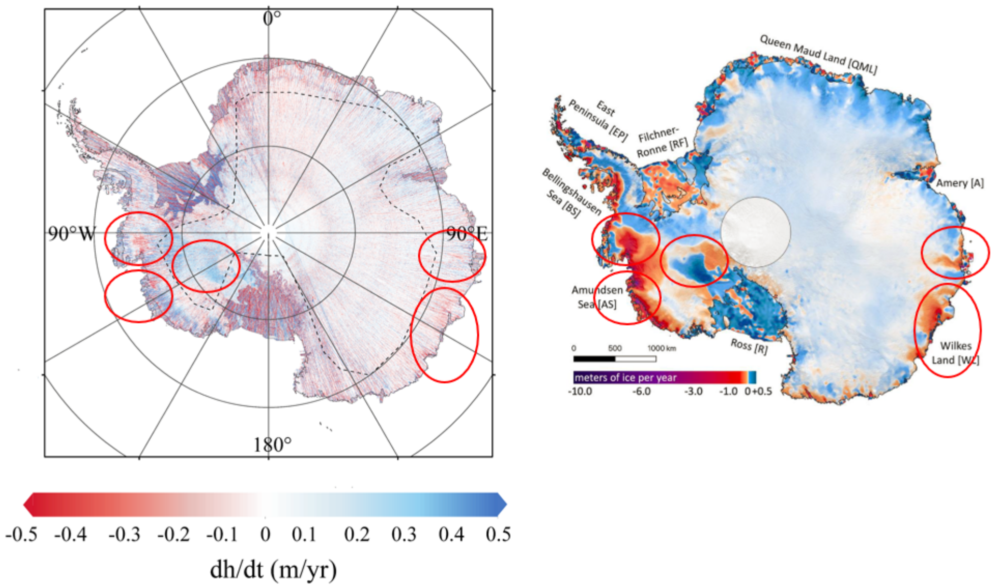

Figure. Map of elevation change rate in Antarctica derived from one year of ICESat-2 data in this study (left) and map of elevation change rate in Antarctica from 2003 to 2019 in Smith et al. (2019) (right).

Reference:

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.

Fitting a model to IceSat-2 data, which is both high accuracy and high density, to me this is degrading the spatial sampling provided by this dataset, which should resolve finer scale features not observed by e.g. a larger radar footprint. The paper would benefit from the author's adding a bit of text to justify why this approach is best for IceSat-2.

Here we add a statement about the choice of model fitting method:

A model fitting method used here is to separate the various contributions to the estimated elevations within each grid cell (Flament and Remy, 2012; McMillan et al., 2014), including local surface terrain and elevation change. This function is fitted in each grid cell by using an iterative least-squares fit to all the elevation measurements to minimize the impact of outliers. A quality control criterion is also used to reduce the effect of any poor fit. This method suits ICESat-2 orbit cycle, which samples dense ground tracks comparing to previous satellite radar altimeters, more measurement points are included in the grid cell and the estimated elevations are more robust. The resolutions of grid cells (i.e., 500 m and 1 km) are appropriate for the used ICESat-2 data in this study. First, most elevations (72%) can be directly estimated based on this method. Second, it is possible for a quadratic form to model the topography at these scales and smaller elevation residuals can be found than using a simple linear fit (Flament and Remy, 2012).

In addition, model fitting method can provide the estimation of elevation change rate, and the estimate agrees well with accurate elevation change estimations from crossover-point method

(Moholdt et al., 2010), which provides an addition reference for the research of ice dynamics and mass balance.

References:

Moholdt G, Nuth C, Hagen J O, et al. Recent elevation changes of Svalbard glaciers derived from ICESat laser altimetry. Remote Sensing of Environment, 2010, 114(11): 2756-2767.

Flament T, Rémy F. Dynamic thinning of Antarctic glaciers from along-track repeat radar altimetry. Journal of Glaciology, 2012, 58(211): 830-840.

McMillan M, Shepherd A, Sundal A, et al. Increased ice losses from Antarctica detected by CryoSat-2. Geophysical Research Letters, 2014, 41(11): 3899-3905.

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.

Comparison to OIB – the authors restrict the OIB comparison of their DEM due to temporal differences between the two datasets. This severely limits the amount of OIB data available for comparison. To my mind, temporal differences in elevation between the two datasets will only be worth considering in regions where elevation trends are high due to either ice dynamics or surface mass balance anomalies - why haven't the authors used OIB data from other time periods in the interior of the ice sheet for example, where the surface height will be stable over time? This would allow more OIB data to be used and the DEM accuracy to be more robustly assessed.

Agree and accept. This has been responded in the very beginning.

Comparison to other DEMs – because the authors have not used a common OIB dataset to compare against the other DEMs, this limits their ability to claim their DEM is the most accurate (please note I am not doubting this is the case). Using a common dataset, or adjusting for temporal changes in elevation would allow for a more robust comparison.

Agree and accept. This has been responded in the very beginning.

Specific comments

L10 – I guess this should be 'thirty years', not 'thirty decades'?

Yes and corrected.

L51 – it is more that spatial and temporal variations in Ku band penetration depth are difficult to account for; I'd suggest re-wording this sentence to better reflect that

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.

L74 – how are 'good quality' data defined – or on which criteria are poor quality data thrown out?

The surface signal confidence metric (i.e., atl06_quality_summary) from ICESat-2 data is used as the data filter criterion. Only ICESat-2 data with atl06_quality_summary values of zero are used. The detailed introduction to atl06_quality_summary can be referred to Smith et al. (2019).

Here we reworded this sentence to give a clear statement:
'… here, only ATL06 data with good quality (according to the surface signal confidence metric from ATL06 data, i.e, those for which atl06_quality_summary equals zero) are used to generate the DEM.'.

The original sentence is:
~~'… here, only ATL06 data with good quality (those for which atl06_quality_summary equals zero) are used to generate the DEM.'.~~

Reference:

Smith B, Fricker H A, Holschuh N, et al. Land ice height-retrieval algorithm for NASA's ICESat-2 photon-counting laser altimeter. Remote Sensing of Environment, 2019, 233: 111352.

L87 – Not sure what the authors are referring to here by 'seasonal elevation changes'? Seasonal elevation changes in Antarctica are only really specific to the Peninsula.

It should be sub-annual changes, all related statements have been revised.

Fig 1 – suggest making the axis labels larger as they're difficult to make out

The resolution of all figures has been improved. As Figs. 1b, c and d do not provide useful information in the text, hence we have removed them in the revised manuscript (also as suggested by another reviewer).

Table 1 – this table is misleading as all the altimeter derived DEMs do have timestamps. Helm et al (2014) is derived from one cycle of data and Bamber et al (2009) correct for elevation changes between acquisition period of the two datasets. Instead of saying 'unclear', it would be more appropriate to state the acquisition periods of the datasets used. I'm also unclear on what is meant by 'Pan-Antarctica', as Bamber et al (2009) includes the ice shelves also?

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.

Thank you for your correction, the column [Coverage] has be removed. 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

L128 'gaps' not 'gasps'

Done.

L141/Figure 2 – why have the authors chosen to show data density at 1 km, and not the posting of the DEM (250 m)?

Accept. Here we show the data density at 500 m for the new DEM (500 m posting).

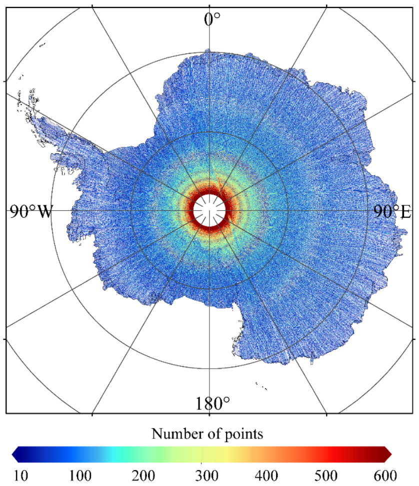

Figure 2. Map of the numbers of valid ICESat-2 measurement points in each 500 m grid cell. The numbers of ICESat-2 measurement points in 1 km grid cells are resampled to the resolution of 500 m.

L163 – I'm confused by the author's claim that the modal resolution of the DEM is 250 m in the abstract – if most spatial coverage is provided by 1 km model fits then is that not the modal resolution?

We have deleted this incorrect statement.

L171 – I would suggest rewording as I feel this sentence is misleading – the DEM is posted at a resolution of 250 m, but the resolution is not 250 m as the most commonly used model fit is 1 km. This should be addressed elsewhere in the text (particularly the abstract) to make this clear to the reader.

Accept. We have reworded this sentence:
'Although two resolutions are applied, 1 km and interpolated elevations are all resampled to a posting of 500 m to provide a consistent DEM dataset; hence, the final ICESat-2 DEM is posted at a resolution of 500 m.'.

The original sentence is:
~~'Although three resolutions are applied, 500 m, 1 km and interpolated elevations are all resampled to a resolution of 250 m to provide a consistent DEM dataset; hence, the final ICESat-2 DEM has a nominal resolution of 250 m.'.~~

The related statements in the text have also been revised.

Fig 3 – I'm surprised to see such large differences (up to ~ 300 m) between the three different resolutions? This could mean that the model fit is not working as intended; if the authors could investigate further into e.g. the spatial distribution of these differences that may help understand what's happening

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 differences.

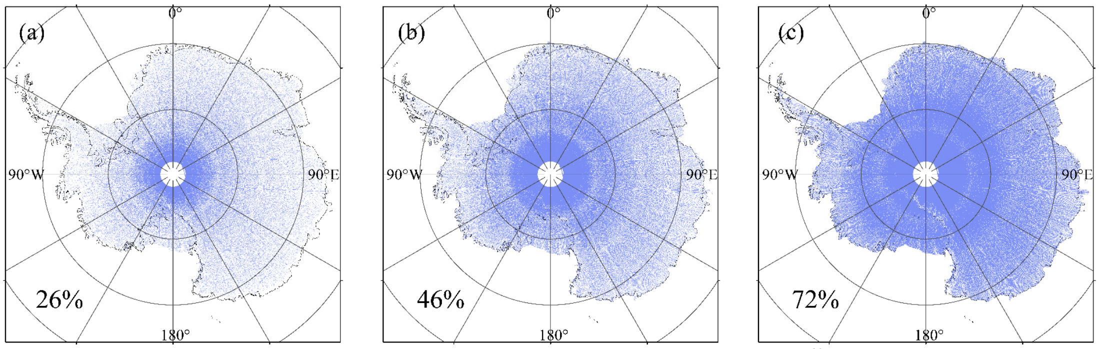

Figure 2. Map of the observed grid cells of DEMs at the spatial resolution of 250 m (a), 500 m (b) and 1 km (c). The observed grid cells are colored in blue, the overall coverage of each DEM in Antarctica is also presented beside.

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.

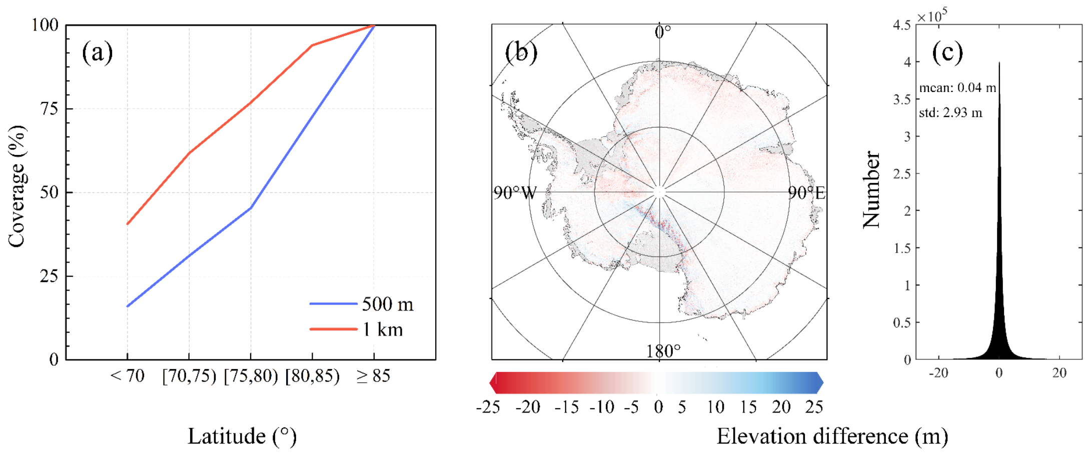

Figure 3. (a) Spatial coverages of observed grid cells in the five latitude ranges when two spatial resolutions, i.e., 500 m (blue) and 1 km (red), are applied. (b) Map of the elevation difference of DEMs at the resolutions of 1 km and 500 m. (c) Histograms of the elevation difference of DEMs at the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

Fig 4 – I'm not sure if the colour scale is playing tricks on me but it seems that the uncertainty is larger for the much of the ice shelves than it is for the ice sheet margins? Could the authors please explain why this is the case? The ice shelves are flat so the uncertainty should be lower here I think?

Most ice shelves are coloured in green/yellow while the ice sheet margins are coloured in yellow/red, hence uncertainties in ice sheet margins are generally larger than these in ice shelves. This has been confirmed by checking the original data, an averaged elevation uncertainty of 0.58 ± 22.67 m is found for ice shelves, while for ice sheet margins (within the CryoSat-2 Low Rate Mode mask) the number is 0.93 ± 21.78 m. In addition, as the finer resolutions and one-year data used in this study, there are some observed elevation gaps in low latitudes (e.g., ice shelves), these elevations are estimated by using interpolation method. The uncertainty values of interpolated elevations are usually larger than these from observed elevation. This explains why similar uncertainty values can be found in some areas of ice shelves and ice sheet margins.

Fig 7 – I find this figure hard to read, improved resolution and particularly the colour scale used in panel c would improve the readability of this figure

The resolutions of all figures in the manuscript have been improved. The colors of 7a and 7c are the same in the updated figure.

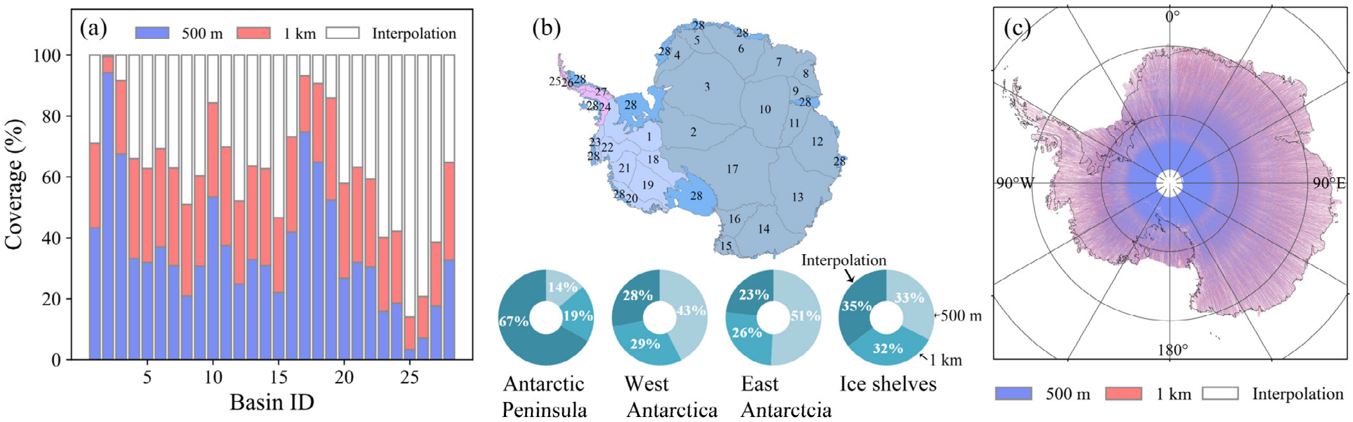

Figure 7. (a) Coverages of observed grid cells at 500 m and 1 km and interpolated grid cells in 27 drainage basins of ice sheets (Zwally et al., 2012) and ice shelves. The boundaries and basin index (ID) of 27 ice sheet drainage basins (Numbers 1 to 27) and ice shelves (Number 28) are shown in (b). The coverages of observed (at two spatial resolutions) and interpolated grid cells in the Antarctic Peninsula, West Antarctica, East Antarctica and ice shelves are also shown in (b). (c) Map of the selected grid cell resolution for deriving the ICESat-2 DEM in all grid cells at a spatial resolution of 500 m. Elevation values derived from 1 km and interpolation (i.e., 1 km) are resampled to a resolution of 500 m.

L246 – remove ‘obviously’

Done.

Fig 8 – Suggest using a colour blind friendly colour scale here

Accept. Red-white-blue like in Figure 9 has been applied in this figure.

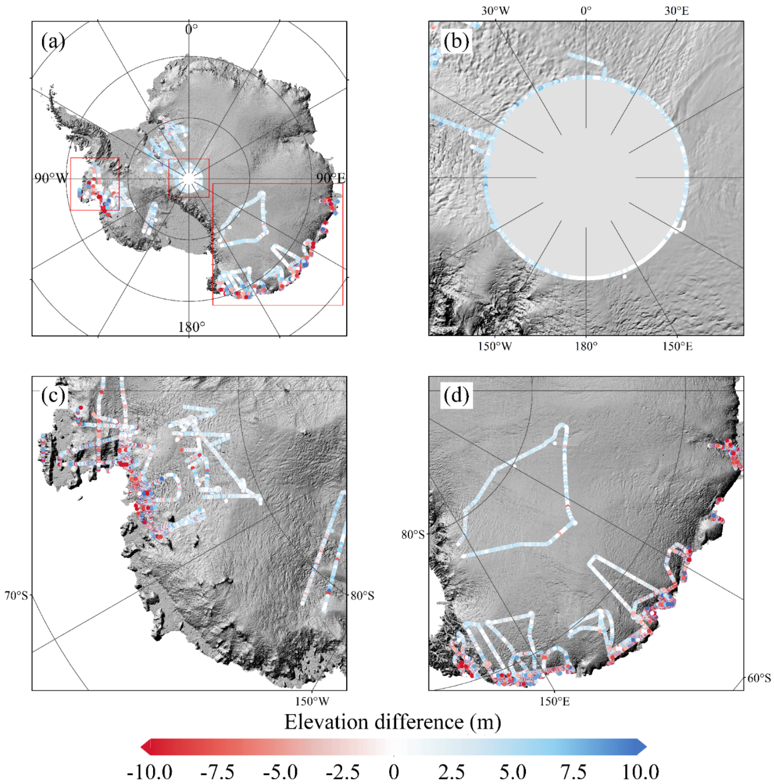

Figure 8. (a) Map of the difference between the ICESat-2 DEM and OIB airborne elevation measurements. Detailed maps of the ice sheet interior, Pine Island Glacier region and ice sheet margin in East Antarctica are shown in (b), (c) and (d), and their locations are also shown in (a) by red rectangular boxes. The background is the shaded relief map of Antarctica derived from the ICESat-2 DEM.

Table 5 – I realise the authors have done this because the DEMs have different timestamps, but this is not a fair comparison as different subsets of OIB data are used for each DEM, so it's not possible to compare between the two. As mentioned previously, I don't see the need for the authors to restrict OIB data in time in areas of low elevation change, so that could be a way to perform a more fair comparison. It may also be possible to e.g. correct for longer term elevation change between the two datasets using contemporaneous elevation trends.

Agree and accept. These comments have been responded in the very beginning.

Table 6 – I noticed the number of grid compared grid cells are different here – does this Table use different subsets of OIB data also?

The same OIB data were used in the original Table 6. As the different grid cell resolutions of listed DEMs, the final grid cells used for comparison are different. In the revised manuscript this table has been removed as we used a common OIB data and GPS data for comparisons. Now we resample all the DEMs into OIB/GPS locations, hence the number of the used OIB/GPS points are the same. Detailed responses can be found in the very beginning.

Best wishes,