Dear Editor,

Thank you for considering our manuscript entitled "A new Greenland digital elevation model derived from ICESat-2" [essd-2021-183], for publication in the Earth System Science Data.

For this submission, we have revised the manuscript according to the comments of reviewers and editor. The point-to-point responses can be found in the Response letter. Please find below point by point our responses (BLUE) to the comments (BLACK) from reviewers. In the revised manuscript, the amendment texts are highlighted in RED color.

All the co-authors have approved this round of submission.

Once again, we thank you so much for the effort in our manuscript.

Yours sincerely,

Changqing Ke and co-authors

Reviewers' Comments:
Reviewer: #1
This study utilizes ICESat-2 data from November 2018 to November 2019 to generate a new DEM over Greenland, and validates the newly generated DEM with IceBridge ATM data obtained in May 2019. This study also presents a comparison of different DEM products. I think that this paper is interesting and the topic is suitable to ESSD. However, several major comments should be seriously considered.

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

Major comments:

1. The present language quality is not good enough and needs to be improved throughout. For example, Page 1 Line 10-11, "but long temporal coverage introduced additional time uncertainty to scientific research", what does time uncertainty mean? Line 11-12 "with a definite time", what does it mean? Page 2 Line 49, "Hence"? Page 3 Line 97, "by different beams"? Page 9 Line 253, "Of these" should be "Among them".

Responses: We have changed the structure of the article and some statements in the article, and these parts are shown in red in the revised version.

(a) Page 1 Line 10-11, "but long temporal coverage introduced additional time uncertainty to scientific research", what does time uncertainty mean?
Responses: Time uncertainty refers to temporal resolutions. The long timespan of applied source data leads to the low temporal resolutions of previous DEMs. When it was applied to calculate elevation and mass changes, it is hard to quantify the years when these changes occurred.

Line 11-12 "with a definite time", what does it mean?
With a definite time means that ICESat-2 DEM has a specific time-stamp (e.g May 2019).

(b) Page 2 Line 49, "Hence"?
Responses: We changed the sentence to 'In addition, owing to the wide coverage (86°N-86°S), high single-point accuracy (0.1-0.15 m), and small footprint size (70 m) (Zwally et al., 2002), ICESat has the ability to measure the elevation of entire Greenland.'

(c) Page 3 Line 97, "by different beams"?
Responses: We changed the sentences to 'Hence, we included weak beams to increase spatial coverage and data point utilization due to no systematic errors were found in strong and weak beams in ICESat-2 elevation measurements.'

(d) Page 9 Line 253, "Of these" should be "Among them"

2. The resample resolution of IceBridge is about 25 m, how to validate the ICESat-2 DEM with different spatial resolution (namely, 500 m, 1 km, 2 km). Please clarify.

3. Please rewrite the Method part in Page 6, Line 164-173, which is different to understand. When the ICESat-2 data were gridded to fine resolution (i.e. 500 m), there would be many gaps. These gaps will be filled with values from coarse-grid data (i.e. 1 km or 2 km)?

months ...＂? What does this sentence mean and how the values of 10 and 2 were determined? ＂In addition, we introduced thresholds to remove outliers, which are RMSE≥10 m, the uncertainty of elevation change ≥10 m ...＂ Please clarify how these thresholds were calculated?

Responses: The minimum number of points in the grid is 7, because the quadratic function based on the local surface terrain used in the text has 7 unknowns. We set the minimum number of points as 10 to ensure the quality of the least square fitting. The minimum number of months is 2 months is also used to make sure the model fit can derive a result. If there is only one month's data in one grid, the fitting equation will have an infinite number of solutions.

We assumed that the maximum elevation change is 10 m/yr and its uncertainty is impossible to exceed 0.4 m/yr as Slater et al. (2018). Furthermore, we assumed that DEM uncertainty is less than 10 m and the maximum RMSE in each grid is 10 m. After this filter procedure, the elevation range is feasible since it is within the elevation range of published Greenland DEM products.

The above statement has also been added into the manuscript.

References: 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.

4. Please rewrite the conclusions in Section 5.2 and Section 6. Due to time discrepancy between different DEM products, I don't think it is possible to validate ICESat/GLAS DEM (2003~2005), ArcticDEM (2015~2018), TanDEM (2011~2014), CryoSat-2 DEM (2011~2014) using IceBridge data acquired in May 2019 and current results can support the conclusion that the ICESat-2 DEM showed significant improvements in accuracy compared with other altimeter-derived DEMs (in Page 1 Line 20~25). If possible, I suggest selecting areas with little elevation changes and doing the comparison.

Responses: We are sorry that our statement caused your misunderstanding.

The data to evaluate other DEMs are the spatiotemporally matched IceBridge data. The IceBridge data to evaluate ArcticDEM were during 2015~2018, TanDEM during 2011~2014, CryoSat-2 DEM during 2011~2014, and the IceBridge data to evaluate ICESat/GLAS DEM were from 2009 since no data can be found in 2003~2005, so we used the data from the nearest year instead.

As you suggest, we selected areas with little elevation changes (-0.05~0.05 m/yr) (Smith et al, 2020) and did a further comparison.

DEM (grid numbers)	MED(m)	MD(m)	MAD(m)	STD(m)	RMSE(m)	R
ICESat-2 DEM (15983)	-0.20	-0.43	0.74	3.05	3.08	0.9999
ICESat DEM (6903)	0.63	0.35	1.10	4.15	4.16	0.9999
CryoSat-2 DEM (27268)	-0.63	0.87	1.42	6.05	6.11	0.9999

500 m ArcticDEM (54235)	-0.14	0.04	0.77	2.19	2.19	0.9999
1 km ArcticDEM (25675)	-0.04	0.06	0.82	2.67	2.67	0.9999
TanDEM (50656)	-4.26	-4.43	4.26	1.97	4.85	0.9999

The conclusion still stands that the ICESat-2 DEM showed significant improvements in accuracy compared with other altimeter-derived DEMs in areas with little elevation changes. The performance is also comparable to the stereo-photogrammetry-derived DEMs and is better than TanDEM.

The above statement has also been added into the manuscript.

Reference: Smith, B., Fricker, H. A., Gardner, A. S., et al. Pervasive ice sheet mass loss reflects competing ocean and atmosphere processes, Science, 368, 1239-+, https://doi.org/10.1126/science.aaz5845, 2020.

5. Since the ICESat-2 data is available from 2018 to present, two years' DEM products could be generated and compared. Otherwise, the specific time should be added to the title, for example, "A new Greenland digital elevation model derived from ICESat-2 during 2018-2019".

Responses: Accept and revised.

General comments:

Page 2 Line 37: "The previously published Greenland DEM dates back to the 1980s ...". "previously" would be "first", since "previously published" would have several DEM products?

Responses: Accept and revised.

Page 2 Line 38-40: "However, the data acquisition was limited by the low-visibility contrast between snow and ice surfaces (Noh and Howat, 2015), which introduced large time uncertainty into the DEM." How the low-visibility contrast introduced large time uncertainty. Please clarify.

Responses: We meant large elevation uncertainty here. We rewrote the sentence as 'However, the low-visibility contrast between snow and ice surfaces may affect the radiometric and geometric quality of stereoscopic DEMs (Noh and Howat, 2015), which may introduce considerable uncertainty to the elevation.'

Page 3 Line 78-79: "IceBridge data were used to evaluate the accuracy for all of Greenland and for different basins."

According to Figure 1 in Page 16, the IceBridge data didn't coverage all the Greenland, please rewrite this sentence.

Responses: We rewrote this sentence to 'The overall accuracy of ICESat-2 DEM was evaluated by comparing to the spatiotemporally matched IceBridge data.'.

Page 3 Line 91-92: "However, for strong and weak beams in the ATL06 product, both beams in one pair show similar performance, with a median difference of -0.08 cm and -0.13 cm for strong beam2 and weak beam1"

The statement is confusing. "a median difference", compared with what? The results is for strong beam2 and weak beam1, what about the other beams? Please clarify.

Responses: We are sorry that our confusing statement. The median difference is compared with contemporaneous IceBridge data. The median difference between strong beam4 and weak beam3 are -0.07m and -0.08m, and the median differences of the strong beam6 and the weak beam5 are the same, -0.03m. Beam2 and beam1 have the largest difference.

We also concluded the result in the text to 'Brunt et al (2019) compared the elevation of ICESat-2 ATL06 product and GPS data, and found that ICESat-2 is currently accurate to better than 3 cm with better than 9 cm of surface measurement precision. Shen et al. (2021) compared the altitudes of weak and strong beams with IceBridge data, and the result indicated that the height difference between them is trivial. Hence, we included weak beams to increase spatial coverage and data point utilization due to no systematic errors were found in strong and weak beams in ICESat-2 elevation measurements.' to clarify the statement.

Reference:
Brunt, K. M., Neumann, T. A., Smith, B. E. (2019). Assessment of ICESat-2 ice sheet surface heights, based on comparisons over the interior of the Antarctic ice sheet. Geophysical Research Letters, 46, 13,072–13,078. https://doi.org/10.1029/2019GL084886.
Shen, X. Y., Ke, C. Q., Yu, X. N., et al. Int. J. Remote Sens., 42, 2556-2573, https://doi.org/10.1080/01431161.2020.1856962, 2021.

Page 4 Line 107-112, what do α, β, αs,n, αw,e, β0 stand for? Please clarify.
Responses: The calculation methods of slope and aspect have been deleted as the suggestion of reviewer#2, the detailed calculation can be referred from Shen et al. (2021). α is the slope, β is the aspect, $\alpha_{s,n}$ is the south-to-north slope, $\alpha_{w,e}$ is the west-to-east slope, β_0 stands for the aspect in degree value in the original text.

Reference: Shen, X. Y., Ke, C. Q., Yu, X. N., et al. Int. J. Remote Sens., 42, 2556-2573, https://doi.org/10.1080/01431161.2020.1856962, 2021.

Page 5 Line 145-150, what does h, a0 to a4 stand for? Please clarify how to get a0 to a4 and dh/dt.

Responses: h_i means the elevation of each ICESat-2 footprint in one grid, h means the modelled elevation of the grid. a_0 to a_4 stand for surface elevation fluctuations (the fitting coefficients of a two-dimensional surface) and term t stands for seasonal changes.

All the coefficients were retrieved from an iterative least-squares fit to the observations in each grid. t is the month difference between May 2019 and ICESat-2 acquisition time, which adds a term of time, so the monthly elevation change can be derived.

The above statement has also been added into the manuscript.

Reviewer: #2

DEMs are the basic datasets for digital hydrology, watershed analysis, quantification of remote sensing, glacier change, etc. Compared with the optical stereo images (photogrammetric method) and radar interferometry (microwave band), the DEM data obtained by laser altimetry satellite data has higher reliability, especially for the surface elevation of glaciers and snow cover. In this paper, a new Greenland DEM is derived from ICESAT-2 with a definite time (13 months), which is very meaningful and practical. However, the paper still has many problems, and substantial revisions are required before the acceptance of this manuscript can be recommended.

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

Specific comments:

1. There are some problems with cryosat-2 satellite orbit description in the article. Some parameter values have inconsistencies or errors, please check carefully. For example, "which is a great improvement over CryoSat-2's along-track distance of 1.5 km and cross-track distance of 3 km".

Responses: We have checked the CryoSat-2 satellite orbit description, and changed the sentence to 'A much finer observation can be obtained owing to its along-track distance of 0.7 m and cross-track distance of 3.3 km, which is a significant improvement compared with CryoSat-2's along-track distance of 0.3 km and cross-track distance of 1.5 km'

2. Each parameter in the formula needs to be defined, but there are no explanations for many parameters in the paper, such as formula (1)-(4). In formula (5), what does "h" mean and how to input its parameter values?

Responses: We have removed the formula (1)-(4) of slope and aspect calculation in the text as you suggest in comment #3. 'h' in the original formula 5 (now formula 1) means the modelled elevation, and h_i is the elevations from ICESat-2 measurement points in one grid. The 'h' in one grid was calculated by performing an iterative least-squares fit model using all ICESat-2 measurements in this grid.

The above statement has also been added into the manuscript.

3. There is no need to write specific formulas for commonly used parameters in the paper, such as slope and aspect.

Responses: We have removed the calculated formulas of slope and aspect in the text as you suggest.

4. How to use ICESAT-2 laser point cloud data to simulate DEM data at 500m grid scale is the focus of this paper, but the paper does not describe it clearly. How to achieve "To improve ICESat-2 data utilization, DEMs with 1 km and 2 km resolution across all of Greenland and an additional 5 km resolution in southernmost Greenland were used to

fill the DEM gaps. Kriging interpolation was used to fill the remaining 2% of void grids that were insufficiently observed by ICESat-2 measurements."

Responses: We expanded the DEM simulation description in section 3.1, the rewritten texts are as follows 'After the aforementioned process, we have acquired Greenland DEM in four resolutions (500 m, 1 km, 2 km, and 5 km). However, these four types of DEM all include voids area thus we need to incorporate them to obtain final Greenland DEM results with the minimal gaps. Firstly, we used Greenland DEM with 500 m resolution as our primary DEM source. Afterwards, Greenland DEMs with 1 km, 2 km, and 5 km resolution were resampled to 500m by applying a bilinear method to fill the gaps in this DEM and the finer resolution as our first option. Unavoidably, there are still some voids in the final Greenland DEM, but this has a minor impact.

And how to get calculated grids and interpolated grids in Figure 6. Therefore, it is recommended to expand the content of section 3.1.
Responses: In this study, we described the unvoided area (98%) in the final Greenland DEM as 'calculated grids' and termed the rest (2%) as 'interpolated grids'. For the rest, an ordinary kriging approach was used to interpolate. The ICESat-2 DEM was posted at the modal resolution of 500 m after gap filling and interpolation. '.

5."We set the minimum number of grid points to 10 and the minimum timestamp to 2 months", are you sure it is 2 months timestamp here? Generally speaking, the revisit period of icesat-2 is 91 days.

Responses: One grid may contain several tracks, especially at high latitudes. The acquisitions time difference of these tracks is uncertain, and 91 days is the revisit cycle of one orbit. 2 months is the minimum requirement to solve the term dh/dt in the model fit.
Taking one 500m grid as an example, this grid contains 3 tracks, the left track (red one) was acquired in December,2018, and the right track (blue one) was acquired in January, 2019. These two tracks came from different Ground Reference Tracks of ICESat-2.
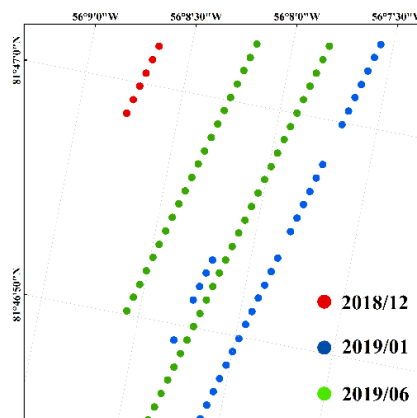
6.Some descriptions in the paper are not clear. For example, in Figure 4(b) and (d), how

is the elevation uncertainty calculated and which index is used?

Responses: For the calculated grids, the regress function in MATLAB can return a matrix 'bint' that gives the range corresponding coefficient will be in with 95% confidence intervals, and the elevation uncertainty was described as equation below. For interpolated grid uncertainty estimation, we just used kriging variance error calculated by ArcGIS 10.6. There is a 95.5 percent probability that the actual elevation at the grid is the predicted raster value ± two times the square root of the variance error of the corresponding cell by assuming the kriging errors are normally distributed. Hence, the two times the square root of the value in the variance error was taken as the elevation uncertainty in the interpolated grids.

$$\text{elevation uncertainty} = t\,(1\text{-}0.025,\ n\text{-}p)\ \times SE\,(b_i)$$

where b_i is the elevation, SE (b_i) is the standard error of the elevation, and t (1-0.025, n-p) is the 95% percentile of t-distribution with n-p degrees of freedom, n is the number of ICESat-2 measurements in one grid, p is the number of regression coefficients (7) in the text.

The slope was calculated by the method of Horn et al. (1994). Based on the law of propagation, the slope uncertainty was calculated as follows:

$$\text{slope} = \frac{\sqrt{[(e_1 + 2e_4 + e_6) - (e_3 + 2e_5 + e_8)]^2 - [(e_6 + 2e_7 + e_8) - (e_1 + 2e_2 + e_3)]^2}}{8d}$$

$$\text{slope uncertainty} = \sqrt{\sum_{i=1}^{8} (\frac{\partial_{slope}}{\partial_{e_i}} \times \sigma e_i)^2}$$

where e_2, e_4, e_5, e_7 are the elevation values adjacent to the central pixel, e_1, e_3, e_4, e_6 are the elevation values on the diagonal of the central pixel, σe_i is the elevation uncertainty of the corresponding pixel.

The above statement has also been added into the manuscript.

7.In general, the labels of the figures are arranged in the paper from small to large, please check the order of Figure 4 and Figure 5.
    Responses: We have checked the order of figures, and exchanged Figure 5 and Figure 6 according to the revised manuscript.

8.The structure of the conclusion and discussion section is a bit confusing, please reorganize it. Generally speaking, accuracy verification is part of the results.
    Responses: We have moved the accuracy verification to the results, and reorganized

the text as you suggest.