Response to Editor and Reviewers minor comments to:

Spatially and temporally resolved ice loss in High Mountain Asia and the Gulf of Alaska observed by CryoSat-2 swath altimetry between 2010 and 2019

Dear Editor,

Thank you for providing us with additional feedback. We have taken the valuable comments on board and modified the manuscript accordingly. Besides stylistic comments and smaller clarifications we have added a separate section explaining the methods used for uncertainty assessment as well as a section discussing uncertainties and limitations.

Yours sincerely,

Livia Jakob

Reviewer

Main comments:

Overall, the authors addressed the comments thoroughly, so that have only few minor comments left.
Most important is that the manuscript would highly benefit from an explicit section in the main manuscript where you clearly describe how the uncertainty was assessed. The authors may then refer to the supplement for more details if needed. The uncertainty and error sources should then also explicitly discussed in a seperate part of the discussion section. You can then also better argue regarding possible deviations from other studies.

Answer: We have expanded the description on how the uncertainty is assessed in the paper and also added a section about uncertainties in the discussion. See more details in the specific comments (L. 162ff).

Specific comments:

L27: The number is true for the past and a specific period. I ask you therefore to use the past tense and be more specific about the period for which this statements is true.The glacier contribution to sea level rise.

Answer: We have changed this accordingly:
"Glaciers store less than 1% of the mass (Farinotti et al., 2019) and occupy just over 4% of the area (RGI Consortium, 2017) of global land ice, **however their rapid rate of mass loss**

has accounted for almost a third of the global sea level rise during the 21st century (Gardner et al., 2013; WCRP Global Sea Level Budget Group, 2018; Wouters et al., 2019; Zemp et al., 2019), the largest sea level rise (SLR) contribution from land-ice (Bamber et al., 2018; Slater et al., 2021)."

L.40: I suggest to update the reference with Immerzeel et al. (2020) as whole HMA is covered.

Answer: We have updated this.

L78: Include an additional reference. Neither Bolch et al. (2019) nor Maurer et al. (2019) cover the Tien Shan.

Answer: We have changed this accordingly:

"As a result of atmospheric forcing, the vast majority of glaciers in the HMA region have been losing mass during the satellite records (Bolch et al., 2019; **Farinotti et al., 2015**; Maurer et al., 2019) which has led to widespread glacier slowdown (Dehecq et al., 2019)."

L. 162ff. This section contains already some results of the uncertainty estimates "our error bounds are similar to …" and reads also partly like a discussion. In this section you should clearly describe what you did and why. While you should discuss the potential sources of errors and uncertainty and the impact in the discussion section. The sentence "In general, these limitations are known and efforts are currently underway in the community to improve uncertainty analysis, and develop new glaciers outlines products" needs some more details and references.

Answer: We agree with the reviewer and have therefore added a separate paragraph about uncertainty calculation in the methods as well as a section on uncertainties in the discussion.

<u>In the methods section:</u>

"2.5 Uncertainty assessment

The error budget on mass change has three uncertainty sources, which are assumed to be independent and uncorrelated: uncertainty on time-dependent elevation change ($\sigma_{\Delta h}$), uncertainty on glacierised area (σ_A) and uncertainty on mass-volume conversion (σ_p).
The rate of elevation change uncertainty for each 100 x 100 km bin is based on the standard error of the regression model. We conservatively use a factor of five (Berthier et al., 2014; Brun et al., 2017) for uncertainties on areas without coverage of swath measurements:

$$\sigma_{\Delta h} = \sigma_{\Delta z}(g + 5u) \ , \qquad (1)$$

where g is the proportional coverage of glacierised area at 400-metre postings, u is $(1 - g)$ and $\sigma_{\Delta z}$ is the standard error of the regression. To retrieve the uncertainty on extrapolated bins we calculate the differences of all non-extrapolated bins between elevation changes using the plane fit approach and elevation changes using the hypsometric averaging method. The standard deviation of these differences is the uncertainty on elevation change ($\sigma_{\Delta h}$) for all extrapolated bins. We retrieve an uncertainty on elevation change for extrapolated bins of 0.34 m yr^{-1} and 0.47 m yr^{-1} respectively for High Mountain Asia and the

Gulf of Alaska. To account for errors due to temporal changes in glacier extents and polygon digitization (Shean et al., 2020) we use an error of 10% ($\sigma_A = 0.1A$) on the glacierised area A in a bin, even though the reported uncertainty of the RGI is ~8% (Pfeffer et al., 2014). Assuming independence between the two error components (σ_A, $\sigma_{\Delta h}$), volume change uncertainty ($\sigma_{\Delta V}$) of a bin is:

$$\sigma_{\Delta V} = \sqrt{(\sigma_{\Delta h}\, A)^2 + (\sigma_A\, \Delta h)^2}\,, \qquad (2)$$

where Δh is the elevation change rate of the respective bin. To generate the region-wide volume uncertainty ($\sigma_{\Delta V_{tot}}$) we combine all the values (including extrapolated bins) in quadrature. We use a density uncertainty of $\sigma_p = 60$ kg m^{-3}, and a density mass conversion of p = 850 kg m-3 (Huss, 2013). The total mass balance uncertainty is:

$$\sigma_{\Delta M_{tot}} = \sqrt{(\sigma_{\Delta V_{tot}}\, p)^2 + (\sigma_p\, \Delta V_{tot})^2}\,, \qquad (3)$$

where ΔV_{tot} is the total volume change for the region."

In the discussion section:

“**4.1 Uncertainty**

While our uncertainty methods follow existing approaches and our error bounds are similar in magnitude to Brun et al. (2017), Kääb et al. (2012) and Shean et al. (2020) but lower than GRACE-based estimates, several additional potential sources of errors could impact the results. Radar altimetry, and delay-doppler radar in particular, has been shown to be sensitive to surface slopes, and in particular to slope in the direction of the satellite’s flight path, in regions like HMA and GoA this impact will also be seen in the performance of the onboard tracker as for large slopes the system is expected to “lose lock”. While we do observe a decreased coverage compared to other, less mountainous, glaciated regions, we also demonstrated here that measurements do cover the entire elevation range of glaciers in the HMA and GoA regions allowing us to match the glaciers’ hypsometry. We also do not observe significant coverage bias in function of glacier orientation with respect to the satellite’s track path. The spatial coverage is such that we demonstrably resolve spatial, altitudinal, and temporal evolution of glacier elevation.
It is a well-known observation that microwave pulses scatter from the surface as well as the subsurface, which can lead to elevation change bias in regions of historically anomalous melt events (Nilsson et al., 2015); or at seasonal time-scale (Gray et al., 2019). Over most regions however, it has been shown that surface elevation change from CryoSat over annual and pluri-annual time scale are consistent with in-situ, airborne, and meteorological observations (Gourmelen et al., 2018; Gray et al., 2015, 2019; McMillan et al., 2014a; Zheng et al., 2018). Using static glacier masks can also lead to errors in regions of rapid dynamic changes. In general, these limitations are known and efforts are currently underway in the community to improve uncertainty analysis, and develop new glaciers outlines products (RAGMAC, 2019).
Although time series are generally reflecting the actual change in surface elevation, there are a number of limitations that are important to keep in mind when interpreting the results from radar altimetry. For the reasons stated above, scattering properties can induce elevation biases at seasonal time-scale (Gray et al., 2019). In addition, integrating changes over large regions can lead to spatial heterogeneity in the successive time steps, in

particular when the data volume becomes too low. These limitations may explain some of the observed patterns, and in particular the few cases where seasonal variability is larger than what is expected from our knowledge of SMB in the regions."

L176: Did you consider the +-60 as suggested by Huss et al. in the uncertainty estimate? Yes, but this should be clear from the main manuscript.

Answer: Yes, we considered the ± 60 as suggested by Huss (2013) in the uncertainty estimate. We have clarified this:

"We assume the standard bulk density of 850 **± 60** kg/m^3 (Huss, 2013) to convert volume changes to equivalent mass changes."

L. 327: Include a discussion about the deviation of your study and previously published results in Eastern Pamir.

Answer: We have included a discussion and changed the paragraph accordingly:

"Contrasting estimates have also been published for the Pamir and Pamir Alay mountains (Hissar Alay), where high (Kääb et al., 2015), moderate (this study; **Ciracì et al., 2020; Gardner et al., 2013**), slight mass losses (Brun et al., 2017; Shean et al., 2020), and even mass gains (Gardelle et al., 2013) have been reported. **Part of the discrepancy can be attributed to time variability in mass loss (Brun et al., 2017) and driven by fluctuation in winter precipitation (Smith and Bookhagen 2018). CryoSat time series indeed suggest near-balance between 2011 and 2015 and increased mass loss from 2015 onwards, which could account for the higher mass loss estimates in comparison to the DEM differencing studies covering the last two decades (Brun et al., 2017; Gardelle et al., 2013; Shean et al., 2020).**"

Replies to editor comments

Note that we have taken all minor stylistic comments on board and do not discuss them in the answers here.

Specific comments (not including stylistic comments):

L131 and L145: It is important to clarify over which time period your processing refers

Answer: We have clarified this accordingly:

"Rates of elevation change are then calculated for each 100 x 100 km bin individually based on elevDiff measurements from mid-2010 to mid-2019."

L194: What about the end date? Does this apply to linear rates of change too?

Answer: The end of the time series is in April 2019, with the latest data from June 2019 due to the 90 days window. As opposed to the timeseries, the linear trends start with the earliest data in mid-2010.
We have changed accordingly:

"Note that as opposed to the linear rates the regional and sub-regional time series displayed in this publication start in January 2011 (with the earliest data from November 2010 using the 90 days window), since we retrieve less swath measurements for the first few months of CryoSat-2's life cycle, impacting the quality of the time series pre-2011. The time series in this paper end in April 2019, with the latest data from June 2019 due to the 90 days window."

L265: Clarify the exact start/end dates of these estimates

Answer: We have clarified accordingly:
"We record an acceleration of thinning from –0.06 ± 0.33 m yr–1 (January 2011 to January 2013) to –1.1 ± 0.06 m yr–1 (January 2013 to January 2019)."

L303: The authors need to state that this is in contradiction to their own results using CS2. So their overall value agrees but not the temporal evolution.

Answer: We stated this accordingly:

"Besides the differences in data and methodology, a part of these disagreements can be explained by the time periods. Maurer et al. (2019) and King et al. (2019) find that the thinning rates in the Himalayas have increased from the interval 1975–2000 to 2000–2016. This trend seems to have continued in more recent years, **with Ciracì et al. (2020) observing significant variation in rates of mass loss during the period between 2002 to 2019, with mean rates of loss 35% larger during the CryoSat period than between 2002 and 2010,** which could explain our more negative mass balance in comparison to Brun et al. (2017) [2000 to 2016] and Shean et al. (2020) [2000 to 2018]."

L640: (Figure 3): tell that the authors are splitting up glaciers into different tiles

Answer: We have mentioned this in the result section:

"Surface elevation change maps (Figure 3) display an expected pattern with more negative trends towards lower elevations close to the coast. Note that some of the lower rates observed in the St Elias Mountain are likely the result of the presence of accumulation areas of large glaciers e.g. Hubbard and Bering glaciers in these particular grid cells."

SI L135: Clarify if plot is for a specific site.

Answer: We have clarified this:

"Differences between the TanDEM-X 90m DEM (German Aerospace Center [DLR], 2018) and the swath elevation measurements in Hissar Alay for different along-track and across-track slopes, including median average deviation (MAD) and mean (MEAN) of the elevation differences (referred to as elevDiff)."