Response to comments of reviewer 2 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

The study provides estimations of glacier mass balance of two large glacierized regions: High Mountain Asia and the Gulf of Alaska using CryoSat-2 data. Most important is that the authors show the suitability of the radar altimeter to obtain not only information about one period but to obtain information about seasonal height and mass changes for the period 2010-2019. The method is not entirely novel but for the first time applied over such large areas including smaller mountain glaciers. This is a timely and very relevant work as detailed information about glacier mass changes are important in many aspects. Overall, the manuscript is well written and illustrated. I am not a full expert in processing CryoSat-2 data, but as far as I can judge, the method applied seems sound and also the specific conditions of mountain glaciers are considered to degree possible. However, considering the nature of CryoSat-2 and judging the presented results I am not fully convinced that all results are reliable. As also detailed by the other reviewer there are many error sources and sources of uncertainties which should be better considered. I highlight below first the more general comments and provide then more detailed ones.

General comments:

1. Error/Uncertainty sources:
a. The authors subtract the TanDEM-X 90m DEM from Cryosat-2 swath elevation measurements. The state in their manuscript: “The remaining elevation differences are due to time-dependent elevation change that can be related to glacier thickness change as well as errors in the two data sets, temporal heterogeneity and differences in penetration between the reference DEM and the swath elevation measurements.” Both utilised data are microwave data. Although the KU and X-band penetration is lower than the penetration of larger wavelengths such as the often used SRTM-C band data, it is not negligible especially in dry snow which is common in many parts of HMA. Moreover, the TanDEM-X DEM is composed of different acquisitions of different seasons and years.

Answer: We agree with the reviewer and in effect this corresponds to our statement. We are considering these errors in our current uncertainty analysis, in that the difference in scattering depth and multi-annual composite of the reference DEM will result in a larger spread of the corrected elevation, spread that is accounted for in the standard error of the regression. We therefore rephrase this section as follows:

“The remaining elevation differences (hereinafter referred to as elevDiff) are due to time-dependent elevation change that can be related to glacier thickness change as well as errors in the two data sets, temporal heterogeneity (**TanDEM-X is a composite of acquisitions from different years**) and differences in penetration between the reference

DEM (**X-band**) and the swath elevation measurements. **The errors related to the reference DEM will result in an increase in spread of the elevDiff measurements and is accounted for in the regression model discussed below.**"

b. Density conversion and snow accumulation: The author's apply a constant value of 850 kg/m^3. This value is often applied also in other studies but needs to be applied with caution. First of all Huss (2013) states that the conversion factor can be significantly different for short periods. This is especially important as height changes of snow which has a much lower density can be large. Hence, the authors need to consider these density variations more carefully especially when interpreting short term changes.

Answer: Assuming a volume to mass conversion factor of 850 ± 60 kg m^{-3} is appropriate for a wide range of conditions and longer term trends, however, this factor can differ significantly for shorter term periods (<3 years) (Huss, 2013). In this study we provide time-dependent elevation changes on a monthly basis, however, caution is required converting these elevation change time series to mass changes.

We added this point in the mass balance sub-section of the method section:

"To obtain volume changes we use the glacierised area of the Randolph Glacier Inventory (RGI 6.0) (RGI Consortium, 2017). We assume the standard bulk density of 850 kg/m3 (Huss, 2013) to convert volume changes to equivalent mass changes. **This assumption is considered appropriate for a wide range of conditions and longer-term trends, however, this factor can differ significantly for shorter term periods (<3 years) (Huss, 2013)**."

We also change the title of section 2.4 to:

"2.4 Time series of **surface** elevation changes"

c. These and other sources of uncertainties need to be better acknowledged. I have the feeling that the provided uncertainty ranges of 0.03 and 0.07 m w.e./a are clearly too low. I suggest showing the accuracy of the data and results at few selected test sites with independent data (e.g. the HMA DEM, Shean et al. 2017, ICESat-2 data, detailed comparison to high resolution DEMs or other studies for smaller regions and also in-situ measurements, e.g. as available from WGMS).

Answer: As described in the response to reviewer #1 we have added a discussion about uncertainties to the paper:

"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, and methods to assess them, not currently available, should be developed. Radar altimetry 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". 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."

And also answered specific comments from reviewer#1 that are relevant here.

The datasets mention by the reviewer are not ideal for validation, the HMA DEM is a static dataset, IceSat-2 only overlaps a few months with the time period of this paper and would deserve a dedicated study as the 2 datasets have a very different spatial sampling. Shean et al. (2020) and Brun et al. (2017) cover the time periods 2000–2016 and 2000–2018 and do not provide estimates on their sub-periods. The difficulty with *in situ* measurements list in the very different spatial scales. In general we do agree with the reviewer that this is a key point that is lacking in regions like the himalaya and dedicated validation study should be carried out.

2. Small glaciers and data coverage: The authors state that CryoSat-2 are also able to survey (very) small glaciers, but do not clearly state a size threshold what they consider as small. There are many very small glaciers especially in HMA which can have significant impact on the overall and especially specific mass changes. Please define "small" and show the portion of the size classes covered in comparison the glacier inventory. Moreover, be more specific about the data coverage and the representativeness and show a plot of the data coverage in relation to the total area.

Answer: We have added the total glacierised area vs glacier size in Figure S5b and S5c (see below). In addition, we have quantified the data coverage and glacierised area for (glaciers smaller than 1km^2, glaciers between 1 and 10 km^2, glaciers between 10 and 100 km^2 and glaciers larger than 100 km^2).

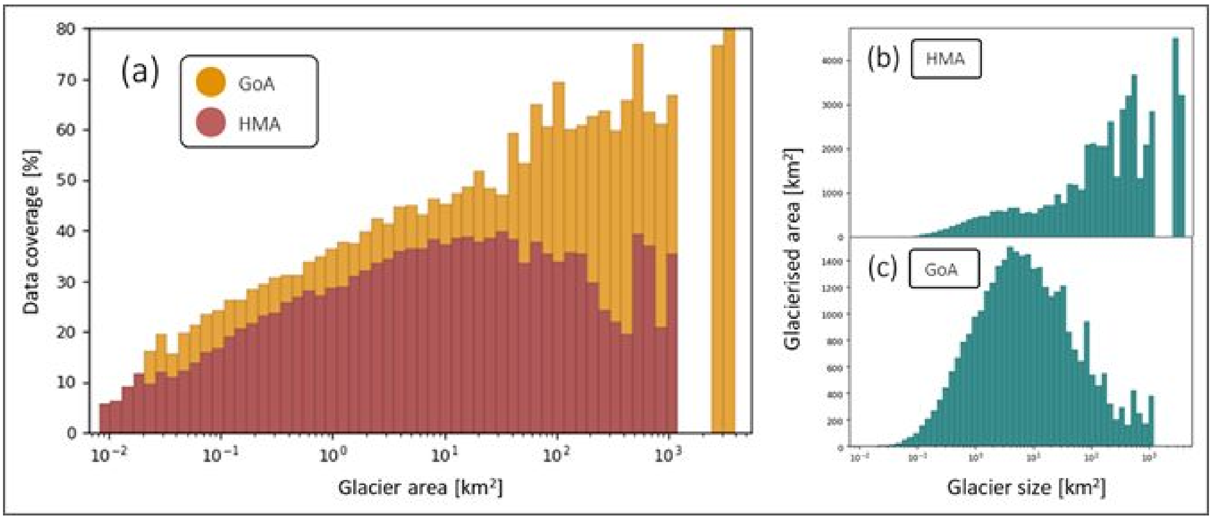

Figure S6: Relation between glacier size and CryoSat-2 swath elevation data coverage in High Mountain Asia and the Gulf of Alaska region (a), hypsometry of glacier sizes in the Gulf of Alaska (b) and in High Mountain Asia (c). For High Mountain Asia we achieve a data coverage of 25% for glaciers smaller than 1 km^2 (representing 21% of total glacierised area), 34% coverage for glaciers between 1 and 10 km^2 (representing 39% of total glacierised area), 37% coverage for glaciers between 10 and 100 km^2 (representing 28% of total glacierised area) and 31% coverage for glaciers larger than 100 km^2 (representing 12% of total glacierised area). For the Gulf of Alaska we achieve a coverage of 31% for glaciers smaller than 1 km^2 (representing 8% of total glacierised area), 42% coverage for glaciers between 1 and 10 km^2 (representing 15% of total glacierised area), 54% coverage for glaciers between 10 and 100 km^2 (representing 21% of total glacierised area) and 68% coverage for glaciers larger than 100 km^2 (representing 56% of total glacierised area).

3. There is no mention of impact of glacier surges and avalanche-fed glaciers which are common in parts of the study regions. The validity of the data for these glacier types should be in an ideal case shown, but at least discussed.

Answer: Dynamic processes such as surges impact our results in two ways. Firstly, we acknowledge that static glacier masks do not capture the temporal evolution of glacier extents induced by dynamic processes, which is one of the limitations of this study, as it currently is for many other studies (described in the section 2.2). To address this issue we recommend using dynamic glacier masks as a step into the future to sample fast changes more accurately. To account for errors due to temporal changes in glacier extents and polygon digitization we use an error of 10% (Shean et al., 2020) on the glacier masks, even though the reported uncertainty of the RGI is ~8% (Pfeffer et al., 2014) (described in the Supporting Information).
Secondly, the hypsometric curves of surging glaciers can differ largely from other surrounding glaciers (Huber et al., 2020), which can affect the results when interpolating surging glaciers with hypsometric averaging on a regional or sub-regional scale. Typically this is addressed by separating surging and non-surging glaciers for interpolation (e.g. Morris et al., 2020), or hypsometric averaging for individual glaciers (e.g. Larsen et al., 2015). In this study we do not achieve the spatial resolution to address this, and we therefore do not distinguish between surging and non-surging glaciers when applying hypsometric averaging. However, it has to be noted that the affected area is relatively small; In this study we only interpolate 4% of glacierised area for the Gulf of Alaska and 12% of

glacierised area for High Mountain Asia. Assuming that we statistically sample dynamic processes with Swath measurements, the impact on our overall elevation change measurements is therefore minimal.

4. The authors exclude the endorheic basis when considering the contribution to sea level rise. Here, the authors need to be more specific: Basins where part of the glacier melt as led to lake level rise (e.g. Neckel et al., 2014) this is suitable, but for the others the water (if not sored in the ground) would end up in the hydrological cycle and ultimately in the oceans.

Answer: In the same manner as Brun et al. (2017) we provide estimates including all glaciers and estimates excluding the major endorheic basins. We have clarified this in the following sections:

In the data methodology section (2.3):
To generate the contribution to sea level rise (SLR) we assume an area of the ocean of 361.8 · 106 km^2 and **consider total contributions from all glaciers and then only those glaciers within exorheic basins in High Mountain Asia, based on the HydroSHEDS dataset (Lehner et al., 2006)**.

In the result section (3.2):
"The total HMA mass balance between 2010 and 2019 was –28.0 ± 2.4 Gt yr^{-1} (–0.29 ± 0.03 m w.e. yr^{-1}), **or –18.3 ± 1.6 Gt yr^{-1} when including only exorheic basins. This mass loss corresponds to 0.078 ± 0.007 mm yr^{-1} SLE, or 0.051 ± 0.005 mm yr^{-1} when including only exorheic basins.**"

In the conclusion:
"We find that between 2010 and 2019, HMA has lost mass at rates of 28.0 ± 2.4 Gt yr^{-1} (0.29 ± 0.03 m w.e. yr^{-1}), and the GoA region has lost mass at rates of 76.3 ± 5.6 Gt yr^{-1} (0.89 ± 0.07 m w.e. yr^{-1}), **for a sea-level contribution of 0.078 ± 0.007 mm yr-1 (0.051 ± 0.005 mm yr^{-1} from exorheic basins)** and 0.211 ± 0.016 mm yr^{-1} respectively for HMA and the GoA."

5. Climatic consideration: The authors explain some of the variation by accumulation type and changes in weather and climate. While I agree that this is in principle true the relation to the weather and climate is too simplified. E.g. there are regions in the Tien Shan which receive more accumulation during summer and winter snowfall is also of high importance for parts central Himalaya. Please be here more specific. I suggest to consider more references (e.g. Maussion et al. 2014) and consider Sakai and Fujita (2017) more in detail.

Answer: Thanks for this valuable input. We agree with the reviewer and have rewritten the discussion section on temporal variability in High Mountain Asia:

"The seasonal and annual time series variability reflects the influence of atmospheric circulations and precipitation seasonality in High Mountain Asia on ice thickness change. Sub-regions dominated by winter accumulation (generally westerly regimes), such as the Hindu Kush, Western Himalaya and the Pamir region (see Pohl et al.,

2015; Yao et al., 2012), show the typical seasonal pattern with mass accumulation during winter/early spring and mass losses in the summer/autumn months (Figure 5).

Contrarily, sub-regions such as Central Himalaya, Eastern Himalaya and Hengduan Shan show a more heterogeneous seasonal pattern. The elevation change time series of these three sub-regions display that the annual cycle has two peaks, with a first peak in winter and a second and smaller peak in summer (Figure 5, S1). Receiving summer-accumulation through the Indian monsoon these sub-regions generally have a precipitation maximum in July/August, however they are also defined by a high variability of precipitation regimes (Maussion et al., 2014) and a high temperature range (Sakai and Fujita, 2017) resulting in glaciers with varying types over very short distances (Maussion et al., 2014). The impact of this variability becomes evident when compared to the more periodic seasonal patterns of the Hindu Kush, Western Himalayas and Pamir time series. This also stands in contrast with the inner Tibetan Plateau, dominated by a more continental climate, which displays almost no intra-annual cycle.

In general, the heterogeneity of the time series reflects the sensitivity of mountain glaciers to meteorological patterns and changes and emphasises that glaciers in High Mountain Asia cannot be considered as one entity with uniform temporal variability and sensitivity to changes."

6. Sections on main results: Sections 3.2 and 3.3: are important sections as the main results are shown. However, these are really short and lack details. You have much more to show. Highlight here all the important results including the shorter term trends and seasonal variability

Answer: We have extended both result sections (3.2 and 3.3) with paragraphs on seasonal / annual changes and altitudinal distribution of elevation changes and specific sub-regional for both regions. Please refer to answers of the specific comments on L210ff and L213ff for details.

7. Discussion sections: Put more emphasis on possible reasons of mismatches to other studies (also see specific comments).

Answer: We have put emphasis on this in the discussion section in 4.1.3., 4.2.2 and 4.2.3 (for more details see answers in the specific questions). We have extended the discussion on the uncertainties and variability of our own results in sections 2.2, 2.4 and 3.2, which is outlined in detail in the specific comments below and the responses to reviewer #1.

8. HIMAP-regions: In order to be able to better compare the regional results to other studies, I suggest to include also a comparison the subregions presented by the cryosphere chapter of the HIMAP report (Bolch et al. 2019) at least in a figure and table in the supplement. These regions were defined by an international team including local scientists and are often used (e.g. Shean et al. 2020, Rounce et al., 2020). Moreover, these regions capture better the regional variability (e.g. mass balances in East Pamir which are more positive and those

in central and west Pamir which are more negative). However, I do not want to force you as I am one of the lead authors of this HIMAP chapter and leave this decision to you/the editor.

Answer: Thank you for this valuable input. We have included the HiMAP regions in our analysis (see Figure and Table below).

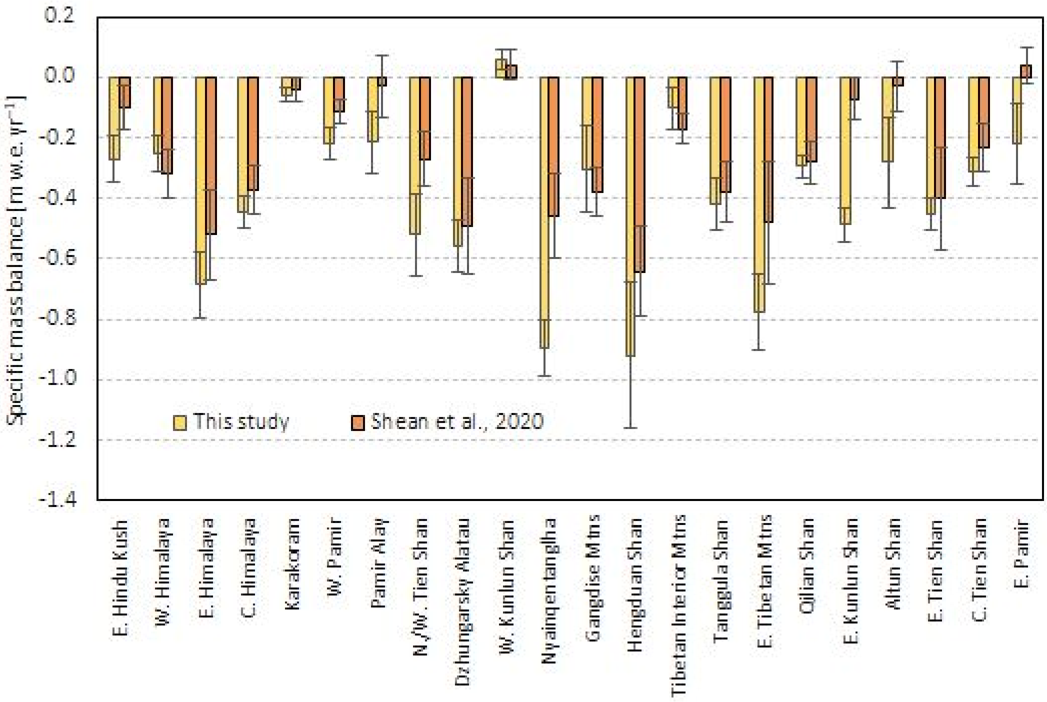

Figure S9: High Mountain Asia (HMA) specific mass balance trends on a sub-regional level (using the HiMAP sub-regions) in comparison with Shean et al. (2020). This study covers the time period of 2010 to 2019, whilst Shean et al. (2020) cover the time period of 2000 to 2018.

	Glacier area [km^2]	**Specific mass change [m w.e. yr^{-1}]**	**Mass change [Gt yr^{-1}]**
Eastern Hindu Kush	2938	–0.27 ± 0.08	–0.79 ± 0.22
Western Himalaya	7986	–0.25 ± 0.06	–2.00 ± 0.46
Eastern Himalaya	2844	–0.69 ± 0.11	–1.94 ± 0.31
Central Himalaya	8682	–0.44 ± 0.05	–3.84 ± 0.44
Karakoram	21472	–0.06 ± 0.02	–1.25 ± 0.49
Western Pamir	8418	–0.22 ± 0.05	–1.85 ± 0.44
Pamir Alay	1846	–0.21 ± 0.10	–0.39 ± 0.19
Northern/Western Tien Shan	2261	–0.52 ± 0.14	–1.17 ± 0.31
Dzhungarsky Alatau	521	–0.56 ± 0.09	–0.29 ± 0.04
Western Kunlun Shan	8457	+0.06 ± 0.03	+0.51 ± 0.26
Nyainqentanglha	7047	–0.89 ± 0.09	–6.29 ± 0.64
Gangdise Mountains	1271	–0.30 ± 0.14	–0.38 ± 0.18

Hengduan Shan	1282	–0.92 ± 0.24	–1.18 ± 0.31
Tibetan Interior Mountains	3815	–0.10 ± 0.07	–0.39 ± 0.26
Tanggula Shan	1841	–0.42 ± 0.08	–0.77 ± 0.16
Eastern Tibetan Mountains	312	–0.78 ± 0.12	–0.24 ± 0.04
Qilian Shan	1598	–0.30 ± 0.04	–0.47 ± 0.06
Eastern Kunlun Shan	2995	–0.49 ± 0.06	–1.45 ± 0.17
Altun Shan	295	–0.28 ± 0.15	–0.08 ± 0.04
Eastern Tien Shan	2333	–0.45 ± 0.05	–1.05 ± 0.13
Central Tien Shan	7270	–0.31 ± 0.05	–2.25 ± 0.35
Eastern Pamir	2118	–0.22 ± 0.13	–0.46 ± 0.27

Table S2: High Mountain Asia (HMA) mass balance trends from 2010 to 2019, aggregated on the HiMAP sub- regions (Bolch et al., 2019).

Specific comments:

Title: The title does not fully reflect the content. One of the strengths of the study is that is shows not only one period but annual and the seasonal variability.

Answer: Thank you for this valuable input. We have changed the title 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"

Abstract: It is good to keep the abstract short. However, it would benefit if the variations of glacier mass/elevation change found are better highlighted (also in quantitative way).

Answer: We revised this and highlighted the temporal changes in the variations of elevation changes in the abstract:

In the abstract:
"We find that during this period, HMA and GoA have lost an average of –28.0 ± 2.4 Gt yr^{-1} (–0.29 ± 0.03 m w.e. yr^{-1}) and –76.3 ± 5.6 Gt yr^{-1} (–0.89 ± 0.07 m w.e. yr^{-1}) respectively, corresponding to a contribution to sea level rise of 0.078 ± 0.007 mm yr^{-1} (0.051 ± 0.005 mm yr-1 from exorheic basins) and 0.211 ± 0.016 mm yr^{-1}. Glacier thinning is ubiquitous except for the Karakoram-Kunlun region experiencing stable or slightly positive mass balance. **In the GoA region, the intensity of thinning varies spatially and temporally with acceleration of mass loss from –0.03 ± 0.33 m yr^{-1} to –1.1 ± 0.06 m yr^{-1} from 2014 which correlates with the strength of the Pacific Decadal Oscillation. In HMA ice loss is sustained until 2015-6, with a slight decrease in mass loss from 2016, with some evidence of mass gain locally from 2016-17 onwards."**

L23: Write consistently "Glaciers and ice caps" and include also the percentage area of the glaciers as the area matters more when considering ice melt.

Answer: We have changed this to write consistently “glaciers”, which is understood to be land ice outside ice sheets. We have also added the area percentage:

“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 accounts for almost a third of the global sea level rise, the largest sea level rise (SLR) contribution from land-ice (Bamber et al., 2018; Gardner et al., 2013; Slater et al., 2020; Wouters et al., 2019; Zemp et al., 2019).”**

L40: Include here also Shean et al. (2020)

Answer: We have included Shean et al. (2020)

L43-45: I suggest to include lines 25f here as it is a repetition apart from the seasonality. And please include also a suitable reference for food security and GLOFs.

Answer: To avoid repetition we have moved lines 25f down to this paragraph and re-written the section and added more references.

“**Besides representing an icon for climate change (Bojinski et al., 2014) and impacting global sea level rise, the retreat and thinning of mountain glaciers also affects local communities (Immerzeel et al., 2010). Glacier retreat introduces substantial changes in seasonal and annual water availability, which can have major societal impacts downstream, such as endangering water and food security for populations relying on surface water (Huss and Hock, 2018; Pritchard, 2019; Rasul and Molden, 2019), or introducing geohazards such as extreme flooding (Guido et al., 2016; Quincey et al., 2007; Ragettli et al., 2016). Despite substantial advances with geodetic remote sensing methods, enhancing the spatial resolution and coverage of ice loss estimates, there is currently no demonstrated operational system that can routinely and consistently monitor glaciers worldwide, especially in rugged mountainous terrain and with the necessary temporal resolution.**”

L65ff: I suggest to introduce the subheading “Study regions” here.

Answer: We have added the subheading study regions.

L66: write “. . . includes the Himalaya, Tibetan mountain ranges, the Pamir and Tien Shan” (Shan=Mountain).

Answer: We have changed this.

L67: write “about 95,500 (or 96,000 or even “almost 100,000”) glaciers”. Glacier number is a bit arbitrary and depends on the size threshold used and how you split contiguous ice masses.

Answer: We have changed this to “about 95,500 glaciers”.

L79: not only since the satellite records but also before. You may then cite here Bolch et al. (2012) which summarised the info for the Himalaya. Please also consider a reference for the Tien Shan which was not covered by the HIMAP report.

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Answer: We agree with the reviewer that this statement was ambiguous and have rephrased 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; Maurer et al., 2019) which has led to widespread glacier slowdown (Dehecq et al., 2019)."

L83: See my comment on the glacier number above

Answer: We have changed this to "about 26,500 glaciers".

L97: See my comment on L79. This applies also here.

Answer: Same as L79 we have rephrased accordingly:

"As a result of atmospheric and oceanic forcings, glaciers in the GoA region have been **losing mass during the satellite records** (Arendt et al., 2002; Berthier et al., 2010; Wouters et al., 2019; Zemp et al., 2019)."

L167: See my comment above. Be more specific

Answer: As described above, we have clarified this in the following sections:

In the data methodology section (2.3):
To generate the contribution to sea level rise (SLR) we assume an area of the ocean of 361.8 · 106 km^2 and **consider total contributions from all glaciers and then only those glaciers within exorheic basins in High Mountain Asia, based on the HydroSHEDS dataset (Lehner et al., 2006)**.

In the result section (3.2):
"The total HMA mass balance between 2010 and 2019 was –28.0 ± 2.4 Gt yr^{-1} (–0.29 ± 0.03 m w.e. yr^{-1}), **or –18.3 ± 1.6 Gt yr^{-1} when including only exorheic basins. This mass loss corresponds to 0.078 ± 0.007 mm yr^{-1} SLE, or 0.051 ± 0.005 mm yr^{-1} when including only exorheic basins.**"

In the conclusion:
"We find that between 2010 and 2019, HMA has lost mass at rates of 28.0 ± 2.4 Gt yr^{-1} (0.29 ± 0.03 m w.e. yr^{-1}), and the GoA region has lost mass at rates of 76.3 ± 5.6 Gt yr^{-1} (0.89 ± 0.07 m w.e. yr^{-1}), **for a sea-level contribution of 0.078 ± 0.007 mm yr-1 (0.051 ± 0.005 mm yr^{-1} from exorheic basins)** and 0.211 ± 0.016 mm yr^{-1} respectively for HMA and the GoA."

L188: Omit "very". I would not anymore consider ASTER as "very-high resolution".

Answer: We have changed this.

L206: The Karakoram anomaly was first introduced by Hewitt (2005) and then confirmed by geodetic measurements by Gardelle et al. (2012). Please cite these two references here.

Answer: We have changed accordingly:
"This spatial pattern confirms the suggestion of previous studies (Brun et al., 2017; Gardner et al., 2013; Kääb et al., 2015), that the so-called "Karakoram anomaly" **(Gardelle et al., 2012; Hewitt, 2005)** stretches up to West Kunlun Shan, which has now become the centre of the anomaly."

L207: I am surprised to read about the moderate thinning for Lahaul-Spiti. In line with mass balance measurements and modelling of Chhota Shigri glacier (e.g. Azam et al. 2014), Mukherjee et al. (2018), showed significant mass loss in this region using geodetic data. However maybe mass loss was less after 2010? Please be more specific and quantitative and discuss in the discussion section.

Answer:
Our sub-regional results show significant mass loss (–0.26 ± 0.06 m w.e. yr^{-1}) in Spiti-Lahaul, which however are below the average rate for the whole High Mountain Asia region (–0.29 ± 0.03 m w.e. yr^{-1}) and therefore described as moderate. Our estimates are in agreement with the –0.31 ± 0.08 m w.e. yr^{-1} of Shean et al. (2020) and the of –0.37 ± 0.09 m w.e. yr^{-1} Brun et al. (2017).

We clarified what "moderate thinning" implies by quantifying this gradient:
"Another striking feature is the gradient from moderate thinning in Spiti-Lahaul and western Himalaya **(–0.25 ± 0.07 m w.e. yr^{-1})** to increasingly negative surface elevation changes along the central **(–0.43 ± 0.05 m w.e. yr^{-1})** and eastern **(–0.56 ± 0.10 m w.e. yr^{-1})** Himalayan mountain range, with the Nyainqêntanglha mountains and Hengduan Shan **(–0.98 ± 0.11 m w.e. yr^{-1})** showing the highest negative trends."

L210ff: Be more specific about the own results here (and double check your results especially considering the uncertainty) and move the critical comparison to other studies to the discussion.

Answer: We have added specific numbers on the sub-regional elevation change rates.

"Our maps of surface elevation change show a heterogeneous pattern in the Himalayan range, with a cluster of slightly positive/near balance trends in the Kunlun and Karakoram ranges (Figure 2), the so-called "Karakoram anomaly" (Gardelle et al., 2012; Hewitt, 2005). **Another striking feature is the gradient from moderate thinning in Spiti-Lahaul and western Himalaya (–0.25 ± 0.07 m w.e. yr^{-1}) to increasingly negative surface elevation changes along the central (–0.43 ± 0.05 m w.e. yr^{-1}) and eastern (–0.56 ± 0.10 m w.e. yr^{-1}) Himalayan mountain range, with the Nyainqêntanglha mountains and Hengduan Shan (–0.98 ± 0.11 m w.e. yr^{-1}) showing the highest negative trends.**"

In addition we included results on elevation change at different elevations and seasonal / annual changes:

“We display the altitudinal distribution of elevation changes in Figure 6 and a comparison with Brun et al. (2017) in Figure S7. While some variability exists along the profiles, in particular over regions and elevation range containing fewer glaciers that can reflect a less robust solution and or spatial variability in glacier response, trends between elevation and ice thickness change are clearly visible. In general, we observe decreasing negative trends with increasing altitudes, which is an expected pattern (Brun et al., 2017; Gardelle et al., 2013). We find the steepest gradient (Figures 6, S7, Table S4) in the Nyainqêntanglha/Hengduan Shan, which is in line with the findings of Brun et al. (2017). We also observe lower or even inverse gradients in Bhutan/East Himalaya, Spiti-Lahaul/West Himalaya, Karakoram/West-Kunlun and Pamir (Figures 6, S7, Table S4), which have been reported previously and been related to debris thickness (Bisset et al., 2020; Brun et al., 2017).
We show temporal variability of surface elevation change for the whole HMA region (Figure 4), the RGI second order regions (Figures 5, S1) and the regions by Brun et al. (2017) (Figure S2). The monthly time series show sustained multiannual trends across almost all of the subregions until 2015-6, and decreased loss or even mass gain from 2016/2017 onwards (Figure 5, S2), which is also reflected in the full HMA time series (Figure 4). The Karakoram region in particular displays thinning from 2011 to 2014/5 before abating and thickening again from 2016/7. This shift of thinning rates post-2015 is also clearly seen in Bhutan/East Himalaya, Kunlun (West and East), Tien Shan, Pamir Alay/Hissar Alay and Nyainqêntanglha/Hengduan Shan (Figures 5, S1, S2).”

L213ff: Similar in this section: Be more specific about the own results and move the critical comparison to other studies to the discussion.

Answer: Similar to the previous item, we have added specific details on the sub-regional elevation change rates.

“**We present sub-regional estimates aggregated on the RGI 6.0 second order regions in Table 2**. The largest mass loss is seen in the Northern Coast Ranges **(–1.08 ± 0.09 m w.e. yr^{-1}; –24.8 ± 2.1 Gt yr^{-1})** and Saint Elias Mountains **(–1.03 ± 0.10 m w.e. yr^{-1}; –34.1 ± 3.4 Gt yr^{-1})**, especially the Yukutat and Glacier Bay region, which is in line with the spatial patterns of Luthcke et al. (2008) and Luthcke et al. (2013). The lowest thinning rates are observed in the Alaska Range mountains **(–0.41 ± 0.05 m w.e. yr^{-1})**, which is also in agreement with other studies (Berthier et al., 2010; Luthcke et al., 2008).”

In addition we included results on elevation change at different elevations and seasonal / annual changes:

“**We observe a clear correlation between surface elevation changes and altitude (Figure 11, Table S2), with the highest negative trends at low altitudes in the Saint Elias Mountains and Coast Ranges.**
We display temporal variability of surface elevation change for the whole GoA region (Figure 4), the RGI sub-regions (Figures 9, S3) and for different elevation bands within sub-regions (Figure 10). Figure 9 shows negative trends across all the sub-regions.

The four coastal sub-regions – Alaska Pena, Western Chugach Mountains, Saint Elias Mountains and Coast Ranges – display a seasonal oscillation, with an annual surface elevation maximum in spring and annual surface elevation minimum in autumn. In contrast, the seasonal cycle of Alaska Range mountains is shifted, with the thickness maximum in winter, which is also somewhat visible in the time series by Luthcke et al. (2008). A very noticeable feature within the full GoA time series is the steepening (more negative) of inter-annual elevation trends from 2013-4 onwards (Figure 4). We record an acceleration of thinning from –0.03 ± 0.33 m yr^{-1} (before 2014) to –1.1 ± 0.06 m yr^{-1} (2014–2018). We observe this almost consistently across all the five sub-regions, but this is most pronounced in the Saint Elias Mountains, the Western Chugach mountains and Coast Ranges."

L224ff.: This section contains several interesting findings which I suggest presenting in the results section (e.g. the variability in mass changes for the different regions) and keep here, but extend the climatic discussion.

Answer: We agree with the reviewer and have made the following changes:

In the result section (3.2) we added:
"**We show temporal variability of surface elevation change for the whole HMA region (Figure 4), the RGI second order regions (Figures 5, S1) and the regions by Brun et al. (2017) (Figure S2). The monthly time series show sustained multiannual trends across almost all of the subregions until 2015-6, and decreased loss or even mass gain from 2016/2017 onwards (Figure 5, S2), which is also reflected in the full HMA time series (Figure 4). The Karakoram region in particular displays thinning from 2011 to 2014/5 before abating and thickening again from 2016/7. This shift of thinning rates post-2015 is also clearly seen in Bhutan/East Himalaya, Kunlun (West and East), Tien Shan, Pamir Alay/Hissar Alay and Nyainqêntanglha/Hengduan Shan (Figures 5, S1, S2).**"

In the discussion section:
"The seasonal and annual time series variability reflects the influence of atmospheric circulations and precipitation seasonality in High Mountain Asia on ice thickness change. Sub-regions dominated by winter accumulation (generally westerly regimes), such as the Hindu Kush, Western Himalaya and the Pamir region (see Pohl et al., 2015; Yao et al., 2012), show the typical seasonal pattern with mass accumulation during winter/early spring and mass losses in the summer/autumn months (Figure 5). Contrarily, sub-regions such as Central Himalaya, Eastern Himalaya and Hengduan Shan show a more heterogeneous seasonal pattern. The elevation change time series of these three sub-regions display that the annual cycle has two peaks, with a first peak in winter and a second and smaller peak in summer (Figure 5, S1). Receiving summer-accumulation through the Indian monsoon these sub-regions generally have a precipitation maximum in July/August, however they are also defined by a high variability of precipitation regimes (Maussion et al., 2014) and a high temperature range (Sakai and Fujita, 2017) resulting in glaciers with varying types over very short distances (Maussion et al., 2014). The impact of this variability becomes evident when compared to the more periodic seasonal patterns of the Hindu Kush, Western Himalayas and Pamir time series. This also stands in contrast with the inner Tibetan

Plateau, dominated by a more continental climate, which displays almost no intra-annual cycle.
In general, the heterogeneity of the time series reflects the sensitivity of mountain glaciers to meteorological patterns and changes and emphasises that glaciers in High Mountain Asia cannot be considered as one entity with uniform temporal variability and sensitivity to changes."

L249: This is again an important finding and should be move to the results section and the reasoning discussed here

Answer: We have made the following changes.

In the results section:
"We display the altitudinal distribution of elevation changes in Figure 6 and a comparison with Brun et al. (2017) in Figure S7. While some variability exists along the profiles, in particular over regions and elevation range containing fewer glaciers that can reflect a less robust solution and or spatial variability in glacier response, trends between elevation and ice thickness change are clearly visible. In general, we observe decreasing negative trends with increasing altitudes, which is an expected pattern (Brun et al., 2017; Gardelle et al., 2013). We find the steepest gradient (Figures 6, S7, Table S4) in the Nyainqêntanglha/Hengduan Shan, which is in line with the findings of Brun et al. (2017). We also observe lower or even inverse gradients in Bhutan/East Himalaya, Spiti-Lahaul/West Himalaya, Karakoram/West-Kunlun and Pamir (Figures 6, S7, Table S4), which have been reported previously and been related to debris thickness (Bisset et al., 2020; Brun et al., 2017)."

In the discussion section (4.1.3):

"We record less mass gain in Kunlun (+0.01 ± 0.03 m w.e. yr^{-1}; +0.06 ± 0.03 m w.e. yr^{-1} in the Western part of Kunlun) than previous studies – indicating that the Karakoram anomaly might not persist long-term (Farinotti et al., 2020; Rounce et al., 2020). **This observation is also reflected in the elevation change profile of the Kunlun regions, where Brun et al. (2017) find constant thickening at almost all elevation during the survey time period of 2000 to 2016, whilst we record thinning at lower elevations (see Figure S7). These findings suggest a shift towards negative mass balance at lower elevations in the Kunlun region in comparison to the previous decade.**"

L264: Please avoid the term doubling or almost doubling. There is a clear increase of mass loss, but uncertainty ranges in this studies are (realistically calculated) and large. Consider here also the Study by King et al. (2019) who used similar data for the Himalaya but found less increase.

Answer: We have revised 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 an acceleration in mass loss of 10 ± 5 Gt yr^{-1} per decade for the period of 2002 to 2019, 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]."

L296: "Widely discussed and predicted. . ." please provide evidence for that.

Answer: We rephrased accordingly:

"We record less mass gain in Kunlun (+0.01 ± 0.03 m w.e. yr^{-1}; +0.06 ± 0.03 m w.e. yr^{-1} in the Western part of Kunlun) than previous studies – **indicating that the Karakoram anomaly might not persist long-term (Farinotti et al., 2020; Rounce et al., 2020)**."

L385: Avoid citations in the conclusions (especially when too prominently referring to own work). Move this to the discussion for more details but keep the main statement here.

Answer: We have removed the references:

"**This, along with recent work in the Arctic and Patagonia demonstrates the potential of such a system to monitor trends in ice mass on a global scale and with increased temporal resolution.**"

L305ff: I am not too familiar with all the work from Alaska, but I ask you to be more specific regarding the work you are considering. Some have clear different time periods of analysis. As mentioned above discuss in more detail possible reasons to different results.

Answer: We have added specifics about the time periods of the studies and possible reasons for mismatches in the discussion session:

"Our total mass budget of –76.3 ± 5.6 Gt yr^{-1} (–0.89 ± 0.07 m w.e. yr^{-1}) agrees with existing estimates, including those using GRACE (−76 ± 4 Gt yr^{-1} for 2002−2009, −72.5 ± 8 Gt yr^{-1} for 2002−2019 and −69 ± 11 Gt yr^{-1} for 2004−2011 by Sasgen et al., 2012, Ciracì et al., 2020 and Luthcke et al., 2013) and ICESat (−65 ± 12 Gt yr^{-1} for 2003−2010, by Arendt et al., 2013) as well as a study from airborne altimetry (–75 ± 11 Gt yr^{-1} for 1994−2013 by Larsen et al., 2015) and a consensus estimate combining glaciological and geodetic observations (–73 ± 17 Gt yr^{-1} / −0.85 ± 0.19 m w.e. yr^{-1} for 2006−2016 by Zemp et al., 2019) (Figure 8b). Our result is significantly more negative than two GRACE studies, with estimates of −53 ± 14 Gt yr^{-1} for 2002−2016 (Wouters et al., 2019) and −42 ± 6 Gt yr^{-1} for 2003−2010 (Jacob et al., 2012). Besides the variations in methodologies and data between these studies, also differences in study area extents, glacier masks and volume to mass conversion factors contribute to the spread of total mass change results. Our estimates correspond to the RGI 1 region (excluding Northern Alaska) to make the results more comparable for future studies. In general, our total mass balance is more negative than most other studies' findings, reflecting the increased thinning rates we show in the sub-regional time series from 2014."

Some remarks on figure 2: The overall pattern of mass changes makes sense and fits to the current knowledge. There are, however, certain 100x100 grids where the mass balance does not fit. This is especially the case for the central part of Northern Tien Shan in Kazakhstan. There was a positive balance according to your data, but both geodetic data and in-situ measurements of Tuyuksu glacier clearly highlight negative mass balance Kapitsa et al. (2020) and WGMS data. As already mentioned above Lahaul-Spiti has also more negative values in other studies. You may compare to Chhota Shigri glacier which was shown to be representative for the region. In contrast Eastern Pamir and Altun Shan seems more negative than suggested by other studies. This highlights again that a more careful uncertainty analysis and comparison to existing data and studies are needed.

Answer: Thank you very much for this valuable input. Indeed the estimate for this grid cell appears not to be robust as running various regression models generate significant spread of solution. This is also the case for a handful of other grid cells.
We have addressed this issue by adapting a part of the elevation change methodology. In the new approach we use the spread of results from different regression models (using a set of different quality weightings and outlier removal approaches), as a means of identifying grid cells where the results are particularly sensitive to data sampling, data distribution and data weighting. The updated Figure 2 (displayed below) shows negative mass balance in the above-mentioned grid cell, which is now more comparable to other geodetic measurements in this particular grid cell. We retrieve –0.58 ± 0.10 m yr^{-1} in this study between 2010 and 2019, Kapitsa et al. (2020) propose –0.35 ± 0.17 m yr^{-1} for the Tuyuksu glacier between 1998 and 2016, and geodetic measurements by Shean et al. (2020) retrieve an elevation change of –0.40 m yr^{-1} between 2000 and 2018 (no uncertainty given). In addition, the updated results display a more homogeneous pattern on the Tibetan Plateau and in Nyainqêntanglha/Hengduan Shan, which is more comparable to other studies (Brun et al., 2017, Shean et al., 2020). As discussed above, our results in Spiti-Lahaul are within uncertainties with Brun et al. (2017), Shean et al. (2020) and Kääb et al. (2015) (see Figure 7) and the spatial spread is not particularly different here than the results of the named studies.
All other figures, tables and sub-regional estimates have been updated based on the revised elevation change map results. The methodology section has been updated accordingly to include this change in methodology (Section 2.2 and Supplementary Information S1.2).

In the data and methods:
"However, whilst their weights are calculated only according to the power attribute, here we assign each observation a weight based on power and coherence, i.e. measurements with high power and low coherence within the sample will have lower weights assigned (see Supplementary Information S1.1). **We exclude solutions that display extremely large variability across various regression models, considering them as unstable solutions results (see Supplementary Information S1.2)**. When fitting the model, we iteratively exclude measurements that are more than 3σ from the mean distance to the fitted line, until no more outliers are present (e.g. Foresta et al., 2016, 2018). We discard bins that did not fulfil a set of quality criteria based on elevation change uncertainties, temporal completeness, interannual changes and **stability of regression results (see Supplementary Information S1.2). The remaining bins covered more than 96% of the total glacierised area in the GoA region, and 88% in HMA**."

The overall mass change and SLE from the improved dataset is now:

- **HMA:** –28.0 ± 2.4 Gt yr^{-1} (–0.29 ± 0.03 m w.e. yr^{-1}), corresponding to a contribution to sea level rise of 0.078 ± 0.007 mm yr-1 (0.051 ± 0.005 mm yr^{-1} from exorheic basins)
- **GoA:** –76.3 ± 5.6 Gt yr–1 (–0.89 ± 0.07 m w.e. yr^{-1}), corresponding to a contribution to sea level rise of 0.211 ± 0.016 mm yr^{-1}

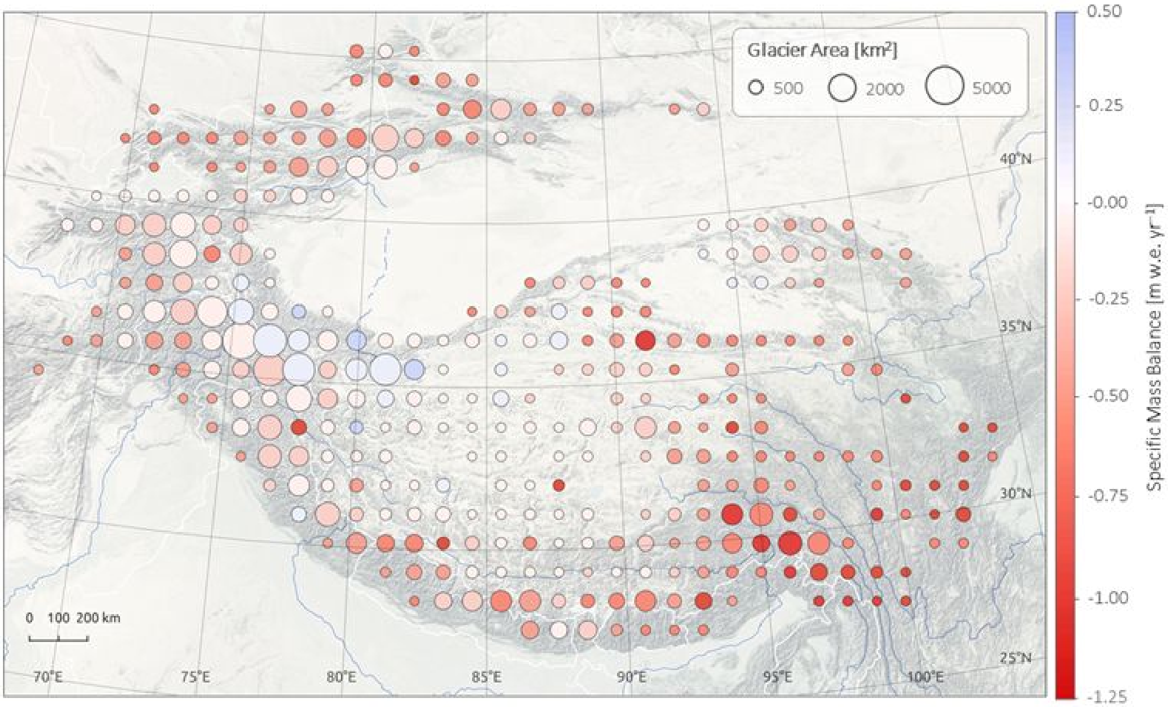

Figure 2: Specific glacier mass balance (m w.e. yr^{-1}) in High Mountain Asia (HMA) for the period of 2010 to 2019 on a 100 x 100 km grid. The size of the circles is scaled by the total glacierised area within a 100 x 100 km bin.