Response to referee comments

High Mountain Asia glacier elevation trends 2003–2008, lake volume changes 1990–2015, and their relation to precipitation changes

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We would like to thank the two reviewers for their constructive feedback and valuable input that certainly helped to improve the article. Detailed responses are provided below, together with a mark-up manuscript version where the changes made in response to the referees' comments are highlighted.

Anonymous Referee #1

General

The authors present an interesting study and they analyze surface elevation changes in High Mountain Asia with ICESat data between 2003 and 2008. They hypothesize that the positive glacier mass balances found in the eastern Pamir, Kunlun Shan and the central TP can be explained by a step-wise increase in precipitation. They approximate the precipitation change by quantifying changes in lake volume of endorheic lakes, station and reanalysis data. I believe the study definitely has scope to be published in the cryosphere, but I find that the conclusions drawn are too strong and are not supported well enough by what the (uncertain) data shows. I have identified the following issues that need to be addressed before the paper is acceptable for publication:

1. Previous work has aggregated surface elevation changes on a 1 degree or 2 degree grid. In the present study the authors have made their own delineation, which they acknowledge to be subjective. The procedure for delineating the spatial units is not clearly described (p6, l17-24). It comes across as if polygons are drawn around region where trends are most clear and obviously the resulting zonal map (Fig. 2A) looks better than the gridded map (Fig. 2B). The use of the zones needs better justification and they have to be objectively defined ideally without prior knowledge about the ICESat trends.

It is unfortunate that our explanation of spatial unit delineation came across subjective or even unsound. In contrary to what the reviewer seems to assume, our zonation did not make our life easier (i.e. we were not tuning the units to make the results look great) but we rather spent a considerable amount of time to ensure the spatial aggregation is as appropriate as possible. Using a gridded approach or the RGI regions would have been straight forward, but unfortunately these spatial zonations to some degree violate the important principle that in a classification, samples within one group should be maximally similar – and maximally dissimilar to other groups. Existing spatial groupings (including the RGI regions, which were drawn to split a lot of glacier vector data into smaller chunks of approximately equal disk space) or regular spatial grids have several issues: they split mountain ridges into several regions without there being any topographic/climatologic/ elevation reason to do so, they merge several orographic mountain ridges into one unit (the eye prefers roundish units) even though climatic/orographic conditions and elevations change very quickly across sequences of mountain ranges, and they may even split individual glaciers into several spatial units.

We tried to make our zonation as objective as possible by analysing topography and glacier statistics (sizes, types, mass balances, elevations, slopes, aspects…) within each unit, and consulted experts as well as literature. The most objective approach would have been to derive a spatial grouping from ICESat samples directly (using the above glacier statistics of the samples), but our efforts to establish such an automated clustering were not successful; we quickly realised that designing a model rule set would become much too complex. We indeed used ICESat trends iteratively, but only to check whether already drawn units yield robust (and reasonable) glacier surface change rates. If not, we merged units, or in some cases also split units if it seemed like we were capturing a mixed signal of glacier mass balance evolution.

We rewrote the methods paragraph and Appendix in question to better justify the zonation process and did our best to emphasise that we aimed for a transparent and objective approach, as far as this was possible.

2. The lake changes are solely attributed to precipitation changes and I have some doubts about this assumption. I think a potential important factor can be the change in permafrost. Much water is stored in frozen form in the soil. An increase in the active layer as a result of rising temperatures may also considerably impact the lake water balance. However this is not at all discussed, and temperature trends are not mentioned either. Therefore I recommend to include references to changes in permafrost hydrology and to quantify spatially also the temperature trends based on the reanalysis datasets.

It was not our intention to attribute lake changes to precipitation changes only (although we believe they are the main driver). We are aware that in particular evaporation might be an important factor, not least due to strong warming trends and other climatic/meteorological changes. For example, Zhang et al. (2018) suggest lake growth may partly be explained by a significant decrease in evaporation during the past 30 years. – However, we did not discuss thawing permafrost, as the reviewer correctly points out.

The question of how much water may have been released due to thawing permafrost is a difficult one, also for other regions of the world that are better studied than the TP. We discussed thawing permafrost as a potential source of water with experts within our research groups. According to S. Westermann (personal communication), this strongly depends on how much ice there was in the ground in the first place (and on what is replacing the melted ice), and this is largely unknown for the TP. In principle, an increase in the active layer will also allow for more water storage (which again prolongs/increases the runoff to rivers or, in our case, lakes). This however requires that there is sufficient water available to fill the (newly) available storage – from precipitation or potentially also possibly snow melt (only where the ground is thawed during snow melt). Thus, the parameters needed to quantify runoff from thawing permafrost (or groundwater storage of previously frozen ground) are largely unknown. The spatial extent of increasing active layer depths and thawing permafrost on the TP is poorly known due to lack of measurements but has been the focus of several older and recent modelling studies. Discontinuous/sporadic permafrost can be found everywhere on the TP, continuous permafrost is found in the northern half (our regions: NW, NE, Central and upper half of E TP; see e.g. Zou et al, 2017; Ran et al, 2018). Recent and ongoing temperature rise lead to an increase in the active layer and degrading permafrost (Ran et al, 2018). There are however also other ongoing processes that protect the TP such as desertification which leads to cooling of the ground (Xie et al, 2015).In general there seems to be agreement that permafrost degradation was greatest in the southern (where we find little lake change / lake growth) and eastern parts of the TP (strong lake growth).

Considering the complexity of the effects of temperature change on the cryosphere (glaciers, permafrost) and atmosphere (e.g. evaporation), we think including also temperature data in the analysis would be too far off topic for this study and would only result in duplication of existing work with an actual focus on temperature trends. Instead, we state the ongoing warming trend both in introduction and discussion by citing relevant references and believe it can be assumed that the ongoing temperature increase is generally known.

In the revised manuscript, we emphasize in the text that the TP is undergoing substantial warming that rather exceeds warming trends elsewhere in the world. We emphasize the potential role of changes in evaporation and added permafrost thawing as another possible contributor to lake volume changes, with references to recent studies.

Furthermore the assumption that most lakes are endorheic is quite strong. The subjective description of how the HydroShed dataset has been manually modified is a bit worrying (p7, l31-34). It would be recommendable to clarify this.

The reviewer is right in that there might be groundwater exchange between some lakes, and we mention this in the first paragraph of section 3.3. The inner TP and thus the catchments we analyse, however, are endorheic. Groundwater exchange between lakes within (or even between) endorheic catchments does thus not affect our estimate of water volume change over larger spatial areas. We added a note regarding this in sect. 5.1.

As the HydroSHEDS dataset was created at 15 arcsec resolution it does not everywhere produce correct endorheic catchments (Lehner et al., 2008). We used better resolved SRTM DEM data (thus mainly using topography as a definition for endorheic basins, as subsurface water flows are unknown) and time series of Landsat imagery (to detect surface water flow and ensure our catchments correctly reflect where lakes split/grew together/emerged since SRTM DEM (and HydroSHEDS) production) to adjust catchment borders where they were incorrect.

We rewrote the paragraph to clarify why and how the HydroSHED dataset has been modified.

3. MERRA-2 is a reanalysis dataset which is known not to perform very well in high mountain Asia,

We wonder why the reviewer suggests MERRA-2 to perform badly in high mountain and would be interested in according references. We agree that all reanalysis products (and other precipitation estimates) have issues in performance, in particular at high elevation (Reichle, 2017; Sun et al. 2018), but MERRA-2 typically shows among best performance, particularly also for our region. Chen et al. (2019) assessed CFSR, ERA-Interim, JRA-55, MERRA-2, NCEP-2 and found for instance that precipitation and drought characteristics are best represented by MERRA-2 across China. And among all the five sub-periods they analysed, monthly drought areas and severity obtained from MERRA-2 in 2001–2007 agree best with that obtained from the observed data in both eastern and western China. Moreover, also Cuo and Zhang (2018) have chosen ERA-Interim and MERRA-2 for their study on spatial patterns of wet season precipitation vertical gradients on the Tibetan plateau and the surroundings.

yet strong conclusions are drawn based on the projected changes in precipitation. The results of ERA-Interim are largely ignored since they not match as well to the observed lake and glacier changes. It is recommended to better justify the use of MERRA-2 and show a comparison with the station data or provide another argumentation why this reanalysis dataset should be used. It may also be worthwhile to use the recently released ERA5 dataset which is the high resolution successor of ERA-Interim.

The reviewer is right in that our discussion mainly focused on MERRA-2 data. We fixed this and now consider ERA Interim data better in results, discussion and conclusions.
We added the above mentioned references to recent studies which justify (and assess) ERA Interim and MERRA-2 data for the TP to section 3.1.
After discussions with experts for reanalysis products on the TP (see Orsolini et al, 2019), we don't think that ERA5 is a useful choice to model precipitation in HMA as this reanalysis does not contain any data assimilations on snow cover for pixels above 1500 m: ERA5 is produced using the data assimilation in CY41R2 of ECMWF's Integrated Forecast System IFS, where the use of satellite data snow extent is switched off for altitudes > 1500m (ECMWF, 2016; see also point T5 of known IFS forecasting issues on the ECMWF wiki: https://confluence.ecmwf.int/pages/viewpage.action?pageId=28328424). This means that satellite-based information on snow cover fraction is not used in our entire area of interest, resulting in a poorer amount of real data forcing for in particular precipitation modelling in ERA5. Over the TP, also no station data is used. Orsolini et al (2019) thus find that despite its lower spatial resolution, the older ERAInterim is more appropriate and accurate in HMA. Additionally, ERA5 data prior to the year 2000 only became available in January 2019, long after this paper was submitted, and the reanalysis data are currently being moved from ECMWF to the Copernicus Climate Data Store – and monthly means of daily means are not (yet) available via the CDS API. Given the circumstances we unfortunately didn't succeed to verify the datasets assumingly poorer performance by creating the same maps as for MERRA-2 and ERA Interim for this response letter, although we also were curious about this.
However, we added a reference to ERA5 for potential future studies in section 5.2.

4. The use of actual evapotranspiration from MERRA-2 to derive a lake basin water balance is questionable and highly uncertain. The uncertainty needs to be discussed and quantified or ideally an ensemble of re-analysis products should be used. The authors may even consider leaving out the whole reanalysis part given its uncertainty. Linking the lake and glacier dynamics is already exciting enough.

We agree that reanalysis products have high uncertainties in data sparse regions such as HMA. We would however like to emphasize that we are not aiming at providing accurate numbers but rather a rough estimate. In that sense this article is a stub that hopefully leads to further integrated studies across the traditional research disciplines. Reanalysis products are an important source of information for investigating the climate in data sparse regions. We therefore think including the reanalysis part is valuable for this paper and prefer not to leave it out. However, we doubt that a full-scale ensemble analysis would yield much different results within the scope of this

paper. Reanalysis comparison studies have been done for this region (e.g. Cuo and Zhang, 2018; see comment above) and justify the two products we have chosen.
In the reviewed version of this manuscript, we better acknowledge and discuss uncertainties associated with reanalysis products (section 5.2) and added uncertainties (propagated error) to the evapotranspiration numbers in sect. 4.4.

5. The authors conclude that the lake changes match the glacier surface elevation change very well. I am not sure if I agree. Table 1 shows positive lake volume changes everywhere, while the glacier mass balance shows contrasting trends across the region. In addition the periods do not match (1990-2000 versus 2003-2008). The same holds for Figure 4. I do not see many similar patterns between Figure 2A and Figure 4. The lake growth very clearly starts in 1995 (Fig 5), but the increase in precipitation occurs about 5 years later (Fig. 6 and 8), so that does not make sense to me.

Even with additional precipitation, glaciers may still melt in a warming climate, but volume changes might be slowed down and glaciers might adjust their geometry due to dynamical changes: Increased precipitation causes more input (at high elevations) while increasing temperatures might enhance melt (mainly on the tongues). Such a change in climatic regime will cause the glacier to shrink but thicken – with some delay (due to ice flowing slowly). We find indications that exactly this is happening on the TP (fig. 3 in the article). Thus, the patterns of glacier and lake changes do not need to have the same sign to match.

The reviewer is right in that the studied time periods don't match exactly. However, this does not affect the outcome of this study. Unfortunately, the lack of data, and uncertainty in the available data, prevents us from studying shorter time periods: ICESat data are only available during 2003-2008, and uncertainties in precipitation/reanalysis data as well as lake data (Landsat imagery) in particular prior to the year 2000 require temporal summaries. We chose decades due to three reasons:

1) the exact date of the precipitation increase is not clear. From visual inspection of precipitation time series (figs. 6 and 8), the increase started/happened somewhere between 1995 and 2000 – ERA Interim rather suggests the former, and MERRA-2 and most stations the latter.
2) the exact date of the lake increase is not sure either due to data scarcity in particular between 1995 and 2000. Note that the data in fig. 5 in the article is filtered with a 7 years window (before computing the median) which contributes to shifting the onset of volume change in the middle of the period of question. Figure 1 below shows regional median time series from unfiltered data – and there, e.g., the lakes in the region northeast seem to start to increase in 1999. Time series of large individual lakes (e.g. Zhang et al, 2017;2018; Song et al, 2015) show different onset times but mostly closer to the year 2000 than 1995.
3) the (shorter) ICESat period lies in the middle of the 00s decade. By comparing the two we assume the 2003-2008 glacier signal is representative for the entire decade. While glacier mass balances vary annually and are an immediate feedback to precipitation input and melt, the glacier's geometry may take some time to adjust (see comment above).

Considering that, decadal averages and differences are useful measures for the scope of this study.

In the revised manuscript, we better link lake/precipitation changes with the glacier signals/glacier geometry adjustment visible in fig. 3 (section 5.3).

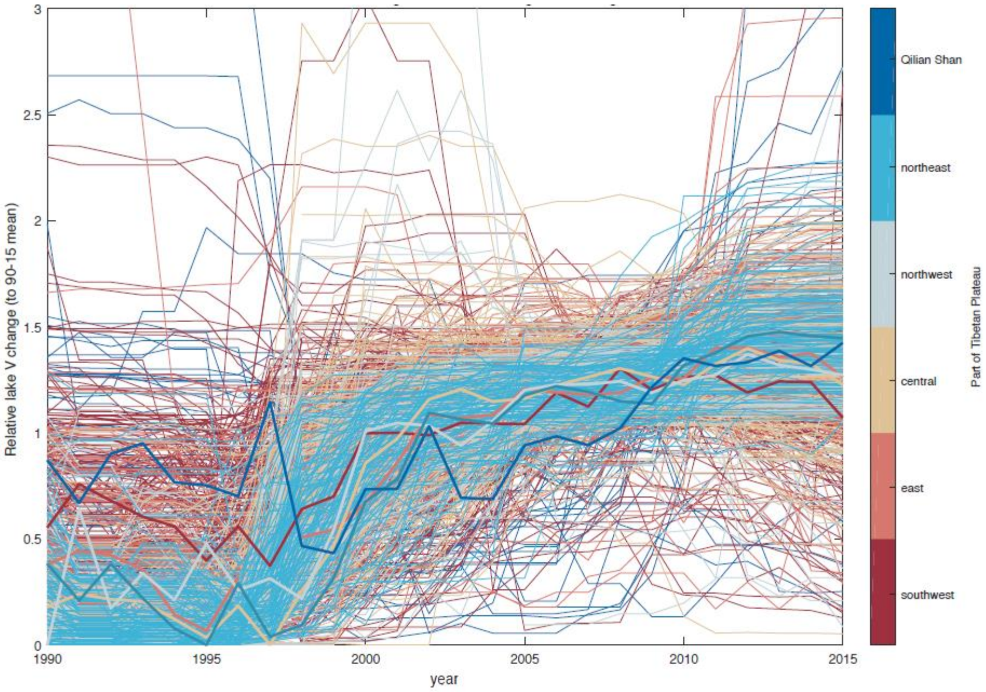

Figure 1: corresponds to Figure 5 in the paper, but regional medians are computed from non-filtered lake time series.

6. Glacier changes are explained only from an accumulation (and precipitation change) perspective. However a glacier mass balance is the results of accumulation and ablation. Total precipitation may increase, but if the temperature increases as well that may still result in less snow. In addition an increase in temperature may also enhance the melt and other energy balance terms may change. Recent work explains the Karakoram anomaly as a result of more summer snow fall and less melt due to less incoming shortwave radiation due to more clouds and a higher albedo (de Kok et al., 2018). An- other important study identified the Karakoram Vortex, which draws cold air into specific part of the region (Forsythe et al., 2017). None of these factors are considered.

We completely agree with the reviewer, glacier mass balance is not governed by precipitation alone. It is unfortunate that this does not come across well enough in the manuscript. As stated above, we are very aware of changes in glacier climatic conditions: changes in both precipitation and temperatures may cause glacier geometry changes. The ICESat results indicate this is happening on the TP (fig. 3).

We added the two suggested references that offer explanations on why precipitation may have increased in parts of the study area. We also state more obviously that temperatures are rising in HMA and discuss the effect of coincident precipitation and temperature changes on glaciers on the TP in more detail (section 5.2, 5.3).

Specific comments

P2, l25: I recommend a more detailed comparison with the Brun et al., (2017) results

This is done in that study already. We added a reference in the text.

P3, l6-7: HMA does not have a typical winter snow fall – summer melt cycle. While this may be true in the west, in the monsoon dominated areas the winters are generally dry and there is synchronous ablation and accumulation. Therefore (high altitude) summer snow events may also cause a bias. In *addition I wonder given the type of trend analysis used, why a single anomalous event in autumn 2018 causes such a bias.*

That's correct; summer snow fall might cause bias in the early summer ICESat campaigns. These are excluded (there are only three years with late spring/early summer campaigns). ICESat autumn campaigns are the only ones where it is dry everywhere. Although there might be some regions where winter campaigns contain useful data (namely the TP, although detailed analyses not included in this paper show evidence of winter snow fall from ICESat data also in this area), we prefer to use a consistent approach throughout the entire study area. Winter campaigns may though be used for local studies focusing on small regions. (See also the reply to comment P6, L12 of reviewer 2.)

The sentence in question is thus a statement that is true in general, not for HMA specifically/only. Precipitation/accumulation patterns for HMA glaciers are described in section 2.

We agree that it might seem strange that the December 2018 snow fall has such a large influence on the fitted trend. That's however not a peculiarity of our study; data points in each end of a trend analysis have a considerably larger influence on trend slopes than other data points. For a discussion/explanation see Appendix D in the paper and our reply to comment P12, L7 of reviewer 2.

P4, l5: What is meant by precipitation availability? Just precipitation is enough I would suggest.

CHANGED

P5, l13: insert here a paragraph on ablation and radiation regimes across HMA?

The focus of this study lies on (changes in) accumulation. However, to better acknowledge other ongoing changes (temperature rise, changes in circulation patterns and effects thereof), we integrated information about glacier ablation (and changes thereof) in the paragraph.

P5, l20-25: not sure if it adds value to mention what has not been used. It is absolutely fine to use SRTM.

Our concerns with temporal inconsistency and data voids of other DEMs available in the area might be useful for readers not so familiar with the different DEMs. We moved the information to the Appendix.

P5, l29: some validation of MERRA5 is required. Large cold biases in reanalysis datasets are very common and this may have very large effects on the modelled snow- fall for example.

Reanalysis products are expected to be more uncertain in data sparse regions like HMA, but they are also an important source of information (the alternative is no data). Reichle et al (2017, 2017a) did rigorous analyses of the MERRA-2 performance in particular also on snow and show that the product is doing very well there. A separate analysis/validation of MERRA-2 is beyond the scope of this study.

To justify the use of the chosen reanalysis products, we added a short note to section 3.1 and further references to Appendix 3. (We also moved some of the details on reanalysis products in section 3.1 to the appendix, to shorten the rather long paragraph and to better match the primary amount of information given for the other data products.)

P5, l4: add reference to the Global Surface Water dataset DONE

P6, l14-16: why use three different methods and then use the average? This assumes each method performs equally well. Are there no arguments why a certain method is preferred in this case?
P6, l16: Same. Why use four different ways of hypsometry corrections and then take the average?

The three regression methods that we use are supposed to be little affected by outliers. As the reviewer mentions in his comment to P3, l6-7, and we mention in Appendix D in the paper, it is surprising that a small amount of samples (December 2008 campaign) affected by a systematic offset has such a large influence on linear fits. Treichler & Kääb (2016) tested a t-fit as an alternative to the previously used robust regression for ICESat data analyses and found no difference in their performance/accuracy. In this study we additionally added the non-parametric Theil-Sen linear regression that is commonly used e.g. in hydrological analyses and should fit our data situation well. However, despite having 100 spatial units at hand to compare the three fits, we find that none is systematically performing 'better' (i.e. visually less sensitive to outliers, systematically different than the other two etc.). The trend slope differences between the three fits are within 0.1 m/a, which is well within the error estimates. We thus chose to use the average of the three.

The situation is similar for the hypsometry correction methods. All have the same goal, but the approach is somewhat different. When looking at their individual performance for single spatial units, we find that some corrections sometimes perform 'worse' than other due to the nature of the local sample distribution in time and space (i.e. they don't fully correct for bias from hypsometric sampling, that is why we came up with several correction methods in the first place). Mostly, however, at least three out of four corrections result in trend slope differences of within 0.1 m/a. For local studies, it would be possible to choose a single correction method and argue why it is best. For the entire study area, however, this is not possible. By using the average of four methods we ensure a consistent approach that maximises the accuracy of hypsometric correction (i.e. minimises a potential error introduced if one of the methods over- or undercorrects hypsometric bias).

P7, l4: Snow does not fall only in winter in HMA, so how are other campaigns influenced?

Late spring/early summer campaigns have little data due to cloud cover in large parts of HMA. In many of our spatial units, we see a snow signal for winter campaigns (in average less negative / more positive dh compared to autumn campaigns; in some of our units and if larger regions are analysed, the snow on-off signal is even visible annually – this depends on the existence of other vertical biases). We added a small side note to the first paragraph of section 3.2 to explain the choice of using autumn campaigns only more explicit: "*We used only samples from ICESat's 2003--2008 autumn campaigns,* the season with least snow cover in entire HMA*, to avoid bias from temporal variations in snow depths (see introduction)."*

P7, l17-20: Again why multiple methods?

The two datasets used have different strengths and weaknesses: ICESat-derived lake surface elevations are far more accurate but available only for about a tenth of all lakes. SRTM elevations have uncertainties of several metres (see e.g. Treichler and Kääb, 2017) but are available for almost all lakes. Using the two complementary methods gives us the possibility to combine their strengths and to validate them against each other, as we write in the end of the paragraph. We added a sentence earlier in the paragraph to already there show the advantages of using two complementary methods.

P7, l20-24: If most lakes are growing and the reference DEM is SRTM (~2001) or IceSat (2003-2009) then how is the water volume change reconstructed prior to this period as there is no information about the lake bed elevation below the water. A discussion regarding the uncertainty of using an "above the water" volume-area scaling would be useful.

We are aware of uncertainties associated with "above the water" lake level-area scaling (and other uncertainties in our data) and ran several control runs of our analysis with maximally conservative assumptions (not included in the paper. For an example, see Figure 2 - apologies for the complexity, this was used for quality control during analyses and originally not meant for publishing). The vast amount of data and large number of lakes forced us to use the same assumptions and fits for all lakes. For a single lake, this indeed causes great uncertainties – some assumptions will lead to overestimation, some to underestimation of the actual lake volume changes (dV, see below). Summarised over the entire study area, however, errors can be assumed to mostly average out. We believe that the effects of "above the water" lake level-area scaling and other uncertainties are of comparatively little importance for the scope of this study, which aims at reconciling changes of glaciers, lakes and precipitation. In other words, we don't aim at exact estimates for single lakes but rather a summarised approximate estimate of dV and their spatial distribution.

SRTM: data for the SRTM DEM was acquired in February 2000. Lakes on the TP have seasonal cycles in line with precipitation and are usually largest at the end of the summer. We use annual maximal lake extents in our analysis – with a reference DEM from winter 2000 where the lakes were smaller (and likely covered by ice) we can thus go somewhat beyond that date (assuming lake growth started before 2000). It is however true that SRTM lake level elevations prior to 2000 have higher uncertainty: Figure 2 below shows that the SRTM data and data points of the 90s have higher associated uncertainties (the red area-lake level scatter cloud has a higher spread; time series data points <2000 are less linear). The effect of extracting SRTM lake elevations for lake areas smaller than during SRTM data acquisition is that pre-2000 SRTM lake levels may be too high, resulting in too small dV (see orange arrows in Figure 2). Comparing SRTM and ICESat time series in Figure 2, this might be true and could be one of the reasons why dV from SRTM data are smaller than for ICESat data.

ICESat: choosing a linear area-lake level fit essentially assumes a parabolic bathymetry between minimum and maximum lake area. To find the best fit, we analysed area-lake level relationships using all 18 ICESat campaigns (and corresponding maximum lake area of the ICESat acquisition month, plus one month before and after, to minimise data gaps). We found no obvious indications that a different fit would be more appropriate – for above-water data points only, though. Assuming a constant shore slope instead, which is a plausible alternative to our implicit assumption, the fit would have to be done with sqrt(A). The orange arc and arrows in Figure 2 show in a qualitative way how this would affect the computed dV for randomly chosen Ayakkum Lake: computed lake levels for small areas would be lower, causing a greater dV between the 90s (small lake areas) and later dates. In that example, our estimate is thus rather under- than overestimating dV. However, the error from the assumed bathymetry underlying the chosen fit has comparatively little influence on dV: in numbers, the area change is much greater than the change in lake level, thus errors in the assumed lake area would cause more bias than it is the case for lake levels (see our reply to comment P12, l7-8 below). As one control approach (not included in the paper) we thus computed lake volume changes also for potential maximal lake areas – assuming all NaN cells in the global water dataset within our lake masks were water cells, which is very likely overestimating the actual area by far. Propagating this in the analysis leads to smaller dV, shown as cyan/magenta time series in panel 4 in Figure 2.

In the appendix, we now explicitly mention uncertainties associated with “above the water” volume-area scaling and SRTM lake elevations for lake areas that are smaller than during SRTM data acquisition.

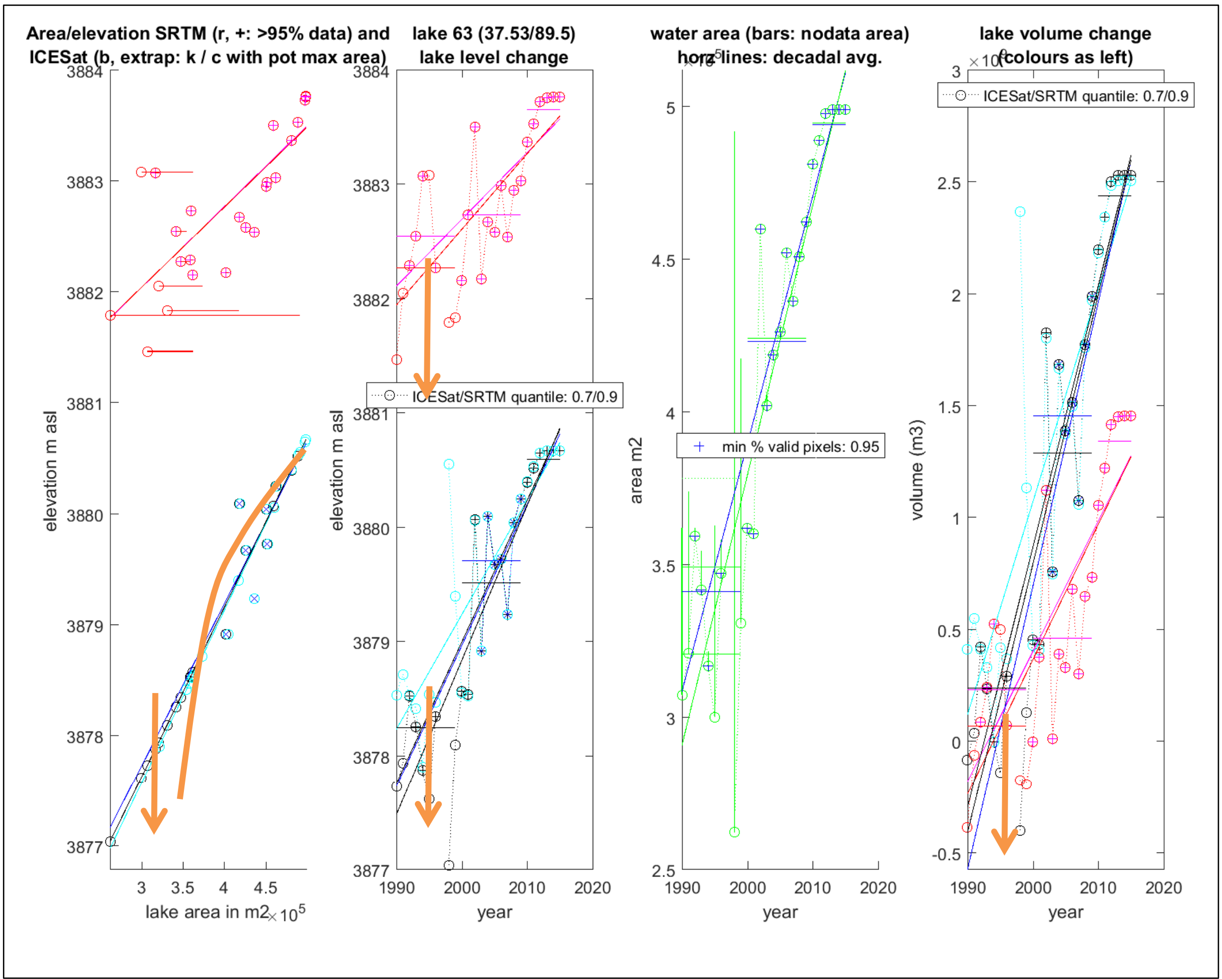

Figure 2: Changes of Ayakkum Lake, East Kunlun Shan. Left: Area-lake level scaling using data points with >95% data. Second panel: lake level vs time, third panel: water area vs. time, right: lake volume change vs. time (using the data from panels 2 and 3). Orange: How a bathymetry with constant slope would change fitted lake levels and computed volumes. Colours and markers: Circles marked with +/x denote data points with <5% no data cells within maximum lake extent; decadal averages (horizontal bars in panels 2-4) are only computed from these. Red/green bars mark the potential maximal area of data points if all no data cells were counted as lake area. Blue – ICESat data; black – ICESat data extrapolated for area data points (years) without lake level data, using the linear fit through blue x; red – SRTM, green – area (Landsat). Cyan/magenta: most conservative alternative that uses the potential maximal lake area instead (for ICESat, this also changes the extrapolated lake levels: circles in cyan).

Ayakkum Lake, width ~20km. Screenshot from Google maps

P8, l5-10: the authors indicate that the reanalysis data is not accurate, but still it is used to draw strong conclusions.

In the revised manuscript, we better consider the uncertainty associated with reanalysis data in the discussion and conclusions. We removed that paragraph and rather added some information on the representativeness and uncertainties of the data to sections 4.4 and 5.2, where they better fit the text flow.

P12, l7-8: Why is the ICESAT based lake level change 1.55 times as large? Does that point towards a systematic difference between SRTM and ICESat in off-glacier areas?

Potential systematic vertical offsets between the two datasets don't influence the analysis, as we look at changes in lake level elevations (for each dataset separately) rather than absolute surface elevations. However, SRTM elevation accuracy is at least a magnitude lower than ICESat elevation accuracy over (flat) lake surfaces (see Treichler & Kääb, 2017, for a discussion of elevation accuracy of the two datasets in mountainous terrain). A potential explanation for the DEM elevation uncertainties and variability of extracted DEM elevations at the lake shores (appendix C1) is penetration of C-band radar into sandy ground (Williams and Greeley, 2004) that varies spatially depending on moisture content (data acquisition was in February 2000, and local conditions/temperatures during acquisitions are unknown). Additionally, the processing steps to mask/interpolate water-covered areas (below lake ice) without radar backscatter during DEM production are not known, resulting in greater uncertainties for DEM cells that correspond to the February 2000 lake shore.
As the reviewer pointed out above, pre-2000 SRTM lake surface elevations are more uncertain, they may be too high for years when the lakes were smaller than during February 2000. As mentioned in our reply above, this might explain why results using SRTM data yield smaller numbers than for ICESat data. Note, however, that the difference between the two estimates is considerably smaller for dV (1.09 times), as the influence of areal changes (up to many km^2) is much greater than the one of different lake level estimates (centimeter-meter).

We added a short explanation and reference to appendix C1 to the text.

P12, l8: lake growth = water level increase? CHANGED

P13: Fig. 4: What is meant by median lake area? Express 4b as mm/year to make it comparable to precipitation rates?

We mean the median lake areas from the 1990--2015 annual lake extents. We changed the text in the figure caption to plural to make it clearer and added an explanation to appendix C on what we mean with median lake areas.

We understand the reviewer's suggestion, but prefer to keep the plot units as is (the same is true for the numbers in table 1). Precipitation is expressed in mm/a, thus a precipitation increase (between decadal averages) also has the unit mm/a. The precipitation data used in this study suggests that the nature of this increase was rather step-wise than gradual. Lake volume changes (dV) are computed as a volume change between decadal means and may either be expressed in total volume change or possibly, as the author suggests, in mm/a to have comparable units. However, spreading the lake increase evenly across ten years might not be correct (fig. 5 in the article), as it looks like most of the extra lake volume appeared within a rather short time (between ca. 1997 and 2001). Thereafter, lakes continue to grow, but more slowly. Considering a step-increase in precipitation, the story would then be: lake volumes increased quickly within only few years, and that rate of growth is directly scalable to the extra precipitation. After the initial increase, with ongoing higher precipitation rates, lake growth quickly decreases as the lakes approach a new equilibrium. Thus, it might thus be equally correct to distribute dV between e.g. five years. We prefer to leave it up to the reader to decide what is most appropriate (as we write on page 14 in the manuscript).

P14, Figure 5: Very interesting to see the abrupt increase from 1995 except for the Qilian Shan region.

Note that lake time series are median-filtered due to data scarcity for the years 1995--1999. There is thus some uncertainty on the exact timing of the onset of lake growth: For lakes with large data gaps, the filter has a tendency to place the onset of lake growth in the middle between 1995 and 2000. See also our reply to the reviewer's comment 5) above.

We added a note of caution in the text (section 4.3) explaining the above.

P15: Instead of the data in table 1 I suggest to sync the periods and show the 2003- 2008 glacier mass balance, lake volume change, re-analysis precipitation change and re-analysis precipitation minus evapotranspiration change.

See our reply to the reviewer's comments 5) and P13: Fig. 4. above.

P16. Fig6: Add the reanalysis data for the same pixel as the stations to assess its validity? Stepwise increase (if significant) occurs around 2000 which is 5 years later than the lake increase. Same for Fig. 8. One solution could be to look at trends and test their significance rather than focusing on the "step-wise" increase.

We acknowledge the reviewer's concerns but don't think a comparison between station data and the corresponding reanalysis grid cell will be useful within the scope of this study. Kääb et al (2018) did extensive tests of various meteorological data to model the Aru glacier collapse on the western TP. They assessed both the Shiquanhe station data (closest) and the NCEP-NCAR, MERRA-2, ERA-Interim and HAR reanalyses (supplement). They found that the different data sets differ substantially especially in terms of precipitation amounts (fig. 7a), and that "Shiquanhe meteorological data gives unreasonably warm temperatures (…) either (due to) a particularly 'warm' setting of the meteorological station, or an applied lapse rate that is not representative for the region". They used ERA-Interim data where especially precipitation had to be heavily corrected to receive required input amounts for glacier modelling. The corrected precipitation shows a step-like increase around 1997, rather than a trend.

Concerning the timing of the postulated step-wise increase, we refer to our reply to the reviewer's comment 5.

It is thus on purpose that we chose decadal means rather than trends, even though trends are very popular within climate analysis and their use is rarely questioned. However, especially for short periods (e.g. a decade), trends are extremely sensitive to the "end years" (same as for our ICESat glacier time series – as the reviewer pointed out above; see Appendix D and our reply to comment P12, L7 of reviewer 2 for an explanation). Naturally, precipitation values vary greatly from year to year. We are confident that decadal means are more robust and better suited for the purpose of, and data used in this study.

A side note – it might well be that the precipitation increase did not occur at the same time everywhere on the TP. After all, this is a pretty large area and circulation patterns (and changes thereof) are not the same everywhere – and both the literature cited by the reviewer and in our response letter suggests that various changes are happening on the TP. Looking at this in more detail would be very interesting for a follow-up study focusing on precipitation and circulation data rather than glaciers and lakes.

P19 l30-31: very thin basis for this conclusion.

We rephrased the sentence and included also a reference to fig. 3a which shows thickening of the upper 50% of glacier area in the regions of question.

P22, paragraph 5.3: very interesting finding that the southern slopes have less negative mass balances. It seems to be related to a higher mass turnover and a reduced sensitivity of the mass balance to temperature changes.

Note that the first orographic ridge, and thus our spatial units, also include the northern slopes on that ridge (very few glaciers face south). We now better stress that information in the appendix.

P25, conclusions:

Conclusion 1: I think it is a bit of an open door. If units are delineated around areas which show most change it is logical that the patterns are more distinct than when you use a gridded approach.

We refer to our reply to the reviewer's first comment.

However, "…units are delineated around areas which show most change…" – this is essentially what we want to achieve! As long as the data points within the spatial unit are representative for the glaciers within that unit (which we assessed carefully), these units will emphasize local differences (and thus, eventually, help to understand why these glaciers behaved differently) rather than blurring that signal.

Conclusion 2: A large part of the variability is probably caused by differences in the energy balance and ablation regime, rather than precipitation alone.

We find that the spatial distribution of precipitation changes and glacier elevation match the spatial variability of glacier changes well. This does of course not exclude that other factors are affected, too. Energy balance and ablation are influenced by both precipitation changes and underlying temperature trends. We hope that the readers will understand this from our revised manuscript, where we better stressed other changes happening in the region (especially the temperature rise).

Conclusion 3: See my earlier points. The stepwise increase seems to come after the lakes start to grow.

We refer to the replies to the reviewer's earlier points, it is difficult to pinpoint an exact date of when the changes happened.

Conclusion 4: ET depends not only on wind, but on humidity and radiation as well. Instead of the wind hypothesis an reduction of ET due to increased humidity is more plausible and this matches the increased in precipitation hypothesis.

We agree and added increased humidity as a potential cause for reduced evapotranspiration (also in the discussion).

References

Forsythe, N., Fowler, H. J., Li, X.-F., Blenkinsop, S. and Pritchard, D. (2017) 'Karakoram temperature and glacial melt driven by regional atmospheric circulation variability',Nature Climate Change, 7(August). doi: 10.1038/nclimate3361.

de Kok, R. J., Tuinenburg, O. A., Bonekamp, P. N. J. and Immerzeel, W. W. (2018)'Irrigation as a potential driver for anomalous glacier behaviour in High Mountain Asia',Geophysical Research Letters, pp. 1–8. doi: 10.1002/2017GL076158.

Anonymous Referee #2

This paper presents an extensive study of glacier elevation changes and lake volume changes in High Mountain Asia (HMA) based on ICESat altimetry, and attempts to link the observed changes with climatic drivers, in particular precipitation. It builds on a number of related studies in the past, but takes a clear step forward by expanding the study region to the entire HMA and introducing a finer spatial zoning that accounts for orographic barriers and other known (and unknown!) reasons for regional patterns in glacier change. This provides some new insights to how HMA glaciers changed in the period 2003-2009, and makes it easier to link the findings with meteorological drivers and the observed lake growth within the endorheic basins of the Tibetan Plateau.

The authors employ a rather complex calculation and correction scheme that is some-times hard to follow. I wish I had read the methodological appendices before trying to make sense of the shortened main text. This needs to be improved for readability. I do not even think it is needed to split up the text, because the appendices read well by themselves and have the same structure as the main text, without being overly detailed. There are also many repeated sentences between the two parts, which is annoying if you spend the effort to read both. The order of calculations and corrections is sometimes confusing, so I think that a few equations or a schematic would be helpful. A few of the corrections need to be better justified, especially since they also have the potential to introduce other types of errors (see the more detailed comments further down).

The methods section and appendices have been rewritten for better readability and clarification.

The authors claim (abstract and conclusion) to make a "spatially resolved estimate ... of glacier volume changes for entire HMA", which would have been very useful since past ICESat studies have been spatially limited or based on older and less accurate versions of the Randolph Glacier Inventory (RGI). However, in the end, there is not a single glacier volume (or mass) change presented here, only figures of spatially averaged elevation trends for regions/zones that do not comply with past publications and RGI, making it impossible for the reader to make out the total numbers. Some aggregated numbers based on upscaling with RGI areas would be highly useful both for comparison with past studies (including GRACE) and as reference for glacier/climate assessments.

We completely agree with the reviewer. In the revised version, our new zonation, surface elevation changes and corresponding glacier volume changes (using RGI glacier areas) will be available in the supplement.

Despite these critical points, I do think that this study is highly valuable and should be considered for publication in the Cryosphere after careful revisions. I have listed a number of more specific comments, edits and suggestions in chronological order below. They refer to printed page and line numbers in the discussion manuscript which unfortunately often differ from true page-by-page line numbers.

P1, L2: A "diverse pattern" of volume change would be highly dependent on regional glacier area. I think you actually mean elevation changes in this context, so that should be mentioned here or in the previous sentence.

Changed to "surface elevation changes"

P1, L3: I find it awkward to say "driven by ... glacier sensitivity". The main physical driver is precipitation changes, but different glaciers can indeed have different sensitivities to that. I suggest to rewrite this sentence.

Changed to "caused by"

P1, L6: I think this statement is based on the reanalysis data which are discussed further down in the abstract. It is better to discuss topic-by-topic in a coherent manner. DONE

P1, L13: "Considering evaporation loss, ... ". What do you mean? It sounds like you are not considering it here since you talk about "average annual precipitation". Please clarify.

Changed to "taking into account"

P1, L16: Unclear what is meant by "geometry changes". Remove or explain. DONE

P1, L18: Should be past tense, like the rest of the abstract, since it refers to a distinct period (2003-2008). Please check this elsewhere too although it is not a big issue. DONE

P2, L2: Or the "Pamir-Karakoram anomaly" as suggested by Gardelle et al. (2013) CHANGED

P2, L8: reduced/decreased evaporation (for consistency) DONE

P2, L15-19: Some of these studies are not region-wide for HMA, but rather HKKH or Tibet only. That makes this study even more relevant (which could be highlighted). DONE

P2, L29: Any reference(s) for the last two issues?

Brun et al (2017) themselves mention problems due to too much noise for time periods shorter than a decade as well as the issue of varying studied time periods throughout the area. We added references to all issues.

P2, L35: You concluded here or Kääb et al. concluded in 2015? Kääb et al (2012) – CHANGED

P3, L3-4: It is not intuitive what "hypsometries of individual years of ICESat samples" and "elevation trend in ... sampling elevations" actually means. I think you should explain what hypsometry is and why it is important in this context, or use different wording to explain what you want to say. DONE

P3, L7: 2018 -> 2008. And either you should explain what was special for this campaign or you should not mention it here. DONE

P3, L15: Write out and reference RGI. And plural - regions of TP and Kunlun Shan? DONE

P3, L20: I don't understand this sentence, and it doesn't seem needed either. REMOVED

P3, L21: "The HMA glacier region is covered by ... " DONE

P4, L2: The fact that extensive parts of HMA has predominant spring/summer accumulation seems to contradict your reasoning to exclude all ICESat winter data (~March) because of variable winter snow, at least for some of your zones.

This is correct, but we don't see this as a contradiction. In areas with spring/summer accumulation, accumulation and ablation happen at the same time, and some of these regions may still receive a share of their accumulation in winter. Thus, autumn still marks the end of the hydrological year in all areas, and it is the season with least snow cover (and cloud cover) in entire HMA. For a consistent approach we thus only use autumn campaigns. We agree with the reviewer that winter campaigns may be useful in some areas for studies with local character. See also comments for P6, L12 below considering including winter campaign data.

P5, L9: This is also nicely shown by Kraaijenbrink et al. [2017], but unfortunately hidden in the Supplementary information of the paper. ADDED

P5, L28: Reference for these data? ADDED

P6, L6: 1990s CHANGED

P6, L12: See comment P4-L2. Considering that the ICESat data sampling is very limited, don't you miss out on a lot of potentially good data in TP and southeasterly regions where winters are relatively dry? I agree that the early summer data should be excluded though.

As explained above, we think a spatially consistent approach is preferable for this HMA-wide study. Even in very dry areas, we find evidence of winter snow from processing/analysing the data (detailed below). Note that if winter data should be used in other/future studies focusing on e.g. only the driest areas within HMA, autumn and winter trends have to be computed separately to avoid a bias from consistently higher elevations (snow cover) at the end of the studied period. Data points in each end of a trend analysis have a considerably larger influence on trend slopes than other data points.

Figure 3 shows the modelled snow fall between the first (October) and second (December) half of the autumn 2008 campaign, and it can be seen that only some areas of the TP receive very little precipitation during the first half of the winter. However, the modelled precipitation is highly unsure and underestimates precipitation at higher elevations severely (e.g. by a factor of 4 at Aru glacier in western TP, Kääb et al. 2017, suppl.). We visually analysed optical satellite imagery of the entire region to classify ICESat laser footprints and for lake areas, and found clear evidence of winter snow fall on the entire TP. While processing and analysing the data, we always also plotted campaign medians for winter and early spring campaigns and found in most cases indications of higher surface elevations during winter also for our zones on the TP, either from snow fall or possibly also ice emergence at the tongues (due to glacier dynamics). Analysing the difference between summer/winter data more closely is thus not feasible within this already extensive project but might be interesting for a future study.

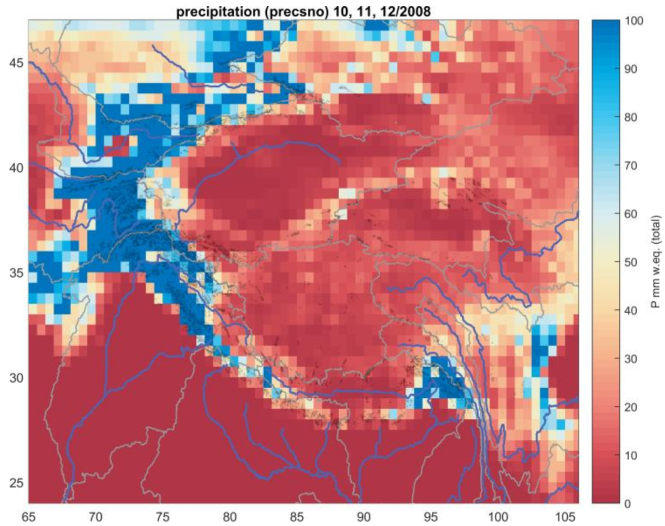

Figure 3: MERRA-2 snow precipitation for October, November and December 2008. (We chose snow precipitation rather than total precipitation to better highlight the mountain areas – otherwise rain fall in the lowlands dominate the plot. At the elevations of question, temperatures during the cold season are low enough that all precipitation falls as snow).

P6, L8: glacier samples

We are not sure we understand what the reviewer means here, but guess (s)he wants to make sure readers not familiar with ICESat glacier analyses understand what data we use. We thus rewrote the sentence.

P6, L17: Any name(s)/reference(s) for the clustering methods you tested?

Unfortunately not – we researched common clustering methods and realised quickly that applying these to our problem would require building a new and very complex iterative setup that 1) groups our data, then 2) runs all kind of analyses to check how similar the data point attributes are not only in spatial space, but in terms of topographic parameters (elevation, aspect…), glacier attributes (glacier type, collecting all points from one glacier within one group) and setting (climate, orography…) and possibly also the resulting elevation trend and uncertainty. Setting up this model would have been extremely challenging as many of the attributes above are not hard facts and would require some kind of categorising process themselves, and the iterative approach would be much too costly computationally. We thus got stuck very early in implementing (inventing) such an automated clustering, and rather did the same thing manually. Which spatial clustering algorithm we would have chosen in the above setup would have been rather irrelevant compared to a lot of other choices and definitions needed, so we prefer not to refer to any methods.

However, we still think it is useful to mention that we thought of this possibility and had to abandon it, as other researchers might have the same idea. We changed the wording from “tested” to “considered” and better explain how the zonation was made in the corresponding appendix.

P6, L21. I think this is a good way to do it.

We appreciate the reviewer’s approval.

P6, L26: Reference or explanation for the four methods?

We moved the reference to the appendix further up in the text. The methods are described there.

P6, L32: This paragraph is confusing and the correction needs to be better warranted. What is actually meant by “local reference elevation bias”? If a bias is truly local, then it is rather a local error (not systematic). In this case, would it not be better termed a “glacier-by-glacier bias”? But then comes the question of what causes such biases and why a correction is needed. Different DEM source date between glaciers within the same region is an obvious explanation in Treichler and Kääb (2016), but that is less of an issue here since the SRTM DEM stems from a single year. Instead, a glacier-median dh correction might erroneously mute some of the real elevation change signal because the glacier-median time of ICESat samples will also vary from glacier to glacier.

See answer to the next comment

P6, L33: Why just from “snow fall in the second part of the autumn 2008 campaign”? If I understand your correction right, the “glacier-by-glacier bias” is impacted by any type of elevation change between the time of SRTM and the respective ICESat measurements? I see the variation in glacier-median dh as a result of variable temporal and altitudinal sampling of ICESat between glaciers, as well as various errors in the SRTM DEM. If the latter is the main issue, why not use nearby land-samples to determine this correction?

As the reviewer writes below, most of the confusion seems to have been solved by the text in the appendix. With local reference bias, we mean any elevation error in the reference DEM that is not systematic (i.e. cannot be removed in a systematic way such as processing per DEM tile). In case of the SRTM DEM this may be horizontal/vertical shifts of single InSAR scenes of penetration into snow, ice or sand. The per-glacier correction was introduced in Treichler and Kääb (2016) to correct for sub-tile misregistration and DEM age. In the case of the SRTM, local shifts/misregistration effects were clearly visible, too – but on glaciers, we found penetration to be the dominating effect; in particular in dry accumulation areas e.g. on the TP. This is also visible in the very steep dh-elevation gradients in this area (fig. 3 d). The reviewer is correct in that such a correction may remove some of the elevation change signal. In the study of Treichler and Kääb (2016), the benefits of the correction outweighed the “flattened” trend by far, as only corrected ICESat data followed the annual cumulative mass balance curve of southern Norway’s glaciers. This is also the case for many of our HMA spatial units, but the large scope of the study doesn’t allow for discussion of each single spatial unit to justify individually applied corrections. We thus only apply the correction where it made the trends steeper (see appendix), i.e. the correction clearly outweighed its side effects of “flattening” the elevation change signal.

The correction for December 2008 snow fall is independent of the per-glacier correction. It is computed using nearby land samples, as the author suggests. We use the elevation difference (i.e.

snow layer) between the 2008 October and December campaigns and compute a snow depth/elevation relationship, assuming a linear increase of snow depth with elevation.

We rewrote the paragraph to make it clearer. In particular, we point to the appendix earlier in the text, and better separate the two different corrections (per-glacier correction and December 2008 snow fall).

P6, L35: What is the correction applied to? I understand it as a normalization of dh on a glacier-by-glacier basis by subtracting the median dh for each glacier, but this is not clear.

This is exactly how the correction works. We hope that the changes made to the paragraph (reply above) and the explanations in the appendix explain this well enough.

P7, L13: Do you actually mean non-glacier mass changes? Hence, removing the gravity signal from changing lakes to derive glacier mass changes from GRACE. Please clarify.

Yes. Resolving the gravimetry signal for a specific component (e.g. glacier mass changes) requires that all other contributing factors are known (changes in surface water, ground water, permafrost, biomass…). We rewrote the sentence so that it becomes clearer that we don't include gravimetry in this study but rather see this as a potential application.

P7, L24: references? ADDED

P8, L5-7: Long and complicated sentence.
P8, L5-10: This section doesn't really describe a clear method beyond looking at the data and taking decadal averages. Is it needed? More confusing than clarifying.

True. We removed the paragraph.

P8, L13: 100 units? It doesn't look like so many.

The number is correct, there are 100 units.

P8, l17: What is done with those 34 units and why?

For these units, we applied the cG correction to dh and/or used only hypsometry methods C and D due to systematic hypsometry missampling (consistently too high/low elevations sampled). The methods and appendices have been rewritten to clarify which corrections were applied where, and why.

P8, L21: This correction appears out of nowhere. Remove or reference appendix B3.

We hope that the correction now is better explained in the method section. We added a reference to the appendix.

P8, L24: Delete last sentence (already explained) DONE

P8, L28: Interesting point, but since the grid cells are already overlapping by 50% and will be naturally smoothed by that, the conclusion is weak.

That is in principle true, but the pattern is smoothed even if grid cells are not overlapping – this is visible Brun et al. 2017 (1x1 degree grid cells there, and not overlapping due to spatially denser results with ASTER DEM stacks). We thus think our conclusion is correct and left it as is, but added a reference to Brun et al. 2017.

P10, L1: Nice!

P10, L35: I do not fully agree. See comments P6-L33 and P30-L20.

See answers to the above comments.

P12, L7: Any idea why?

This is the case for all types of linear fits, and the reason why we used three different fitting methods that are supposedly least sensitive to "outliers" or extreme values in either end of the time axis. We don't have a statistical proof at hand, but rather try to explain this with an example: Given a linear trend with samples that fit the line relatively well. Take one (or even a whole bunch of samples) a) from the middle of the time axis or b) from the very beginning or end of the time axis, and offset it substantially. Fitting a linear trend through a) will not change the trend but only increase the trend error. For b), however, the trend line slope will be increased/decreased to better incorporate the sample(s). That's how the statistical models work, and what they were designed for. Thus, bias from snow fall in the very end of the timeline affects the trends much more than any bias in the middle of the time axis (see also Appendix D in the paper). With this example, we want to illustrate how unexpectedly big such an effect can be – something scientist maybe should be more aware of since linear fits are commonly used (and little questioned) for time series, in particular in relation to climate change.

Fig. 3: Interesting figure, but I suggest to use other colors for panel c to avoid confusion with the thickening-thinning colors in a-b.

We will adapt the figure accordingly for resubmission.

P12, L10: Also mentioned in the caption. Once is enough. REMOVED

P12, L15. I don't think this specification is needed.

We prefer to keep this specification, as the y-axis measure is somewhat non-intuitive. We are afraid readers might easily mistake the graph and assume it shows volume changes (i.e. lake volumes are doubled, halved…), but our graph rather shows what share of the (total) volume change happened when. We shortened and reworded the sentence to make this clearer.

Fig. 4b: Label regions according to Table 1.

We will adapt the figure accordingly for resubmission.

Table 1: The caption is rather confusing, listing three time spans next to each other (belonging to different columns of the table) and giving volume change in unit mm without describing if it is per lake area or basin area.

We rewrote the caption to clarify timespans and volume change units (per basin area).

Fig 6: The combination of two stations in the upper panel makes this figure unnecessarily hard to read. I suggest to split them in each their panel.

We will adapt the figure accordingly for resubmission.

Fig. 7: Why does panel-a show ERA-Interim summer and panel-b MERRA-2 annual, and not either the same period for both products or both periods for one product. Also, the figure is only discussed very briefly, and well after Fig. 8 in the text. I think the figure is interesting, but to be included, it should be properly referenced and discussed in the text.

The reviewer is right – we accidentally added the wrong figure in the manuscript. Fig 7b has now been replaced with difference in summer P, i.e. same periods as for ERA Interim. The spatial pattern of the replaced figure is however nearly the same, in particular for the regions with increased precipitation – which indicates that the precipitation increase happened during summer months. We changed the order of the figures and refer to them earlier and more thoroughly in the text.

Fig. 8: The P-E curves appear are faded and hard to see, despite being most relevant in theory. I suggest you use a thicker line or sharper color/tone to improve visibility.

We will adapt the figure accordingly for resubmission.

P16, L6. Specify these regions (NE, NW, C) DONE

P16, L8: considering the high uncertainty; "results in" -> "suggests"
P16, L9: Fig. 8b?

The paragraph has been rewritten.

P19, L20: ... between the periods DONE

P20, L23: "over 1988-2007" or "between 1988 and 2007" DONE

P21, L18: This sentence is difficult to understand. REWRITTEN

P21, L16-29: I would expect this paragraph to be closer linked with the interesting Fig. 3, as well as independent studies of velocity changes, of which the recently published study of Dehecq et al. [2019] seems particularly relevant.

We agree with the reviewer that the interesting dynamical aspects rather got too little room in our discussion. We thus rewrote the paragraph to discuss Fig. 3 and its implications in more detail, and related our findings to the velocity changes published by Dehecq et al. (2019) while this paper was in review. Unfortunately, the time period (2000-2016) and spatial aggregation doesn't allow a very detailed comparison with our results.

P22, L13: Move authors out of the parentheses. DONE

P22, L22: I think you really want to talk about elevation changes (or thinning) here since actual volume changes are so dependent on regional glacier area. REPHRASED

P22, L31. Uncelar sentence. REWRITTEN

P22, L12: use abbreviated m w.e. a-1, as elsewhere DONE

P22, L22: Is "glacier sensitivity to precipitation" an appropriate heading for this section? I feel it is more a discussion of orographic effects that cause different precipitation regimes on either side of a ridge, not really whether glaciers are more or less sensitive to precipitation in general. Or you need to better explain what you mean by "sensitivity".

We changed the section heading to "Glacier mass balance and precipitation…".

P23, L30: ... both surging glaciers and glaciers recovering ... DONE

P23, L32: Combine references with same authors. DONE

P23, L8: This paragraph is very detailed compared to the others and could be shortened.

The paragraph has been shortened.

P25, L20: The Conclusions section provides a good summary, but would benefit from a shortening to better highlight the main findings and outlook.

We rewrote the conclusions to better highlight the main findings.

P25, L21: This study has many new and interesting aspects, but it is not the first one and does not actually present any volume changes. I would rather highlight the improved zoning and joint analysis of lake changes as the most unique part of this paper.

The reviewer is right in that our study is not the first one, but the region indeed lacked a complete, consistent analysis of ICESat data so far – all other studies only looked at parts of the region and/or used methods that are affected by biases. We rewrote the paragraph to rather highlight the consistent approach and the aspects the reviewer proposes.

P25, L11: The selective mention of MERRA-2 (which fits with your observations) and not ERA-Interim (which doesn't fit) is peculiar as long as you cannot identify reasons why one product should be better than the other. Mention both products or none.

We agree with the reviewer and added a statement about ERA Interim.

P26, L15: Is this significant? If not, no need to mention as a conclusion.

Many studies that assess lake changes claim that this is due to increased lake influx from glacier melt. Our study shows that this is likely a very small contributing factor. We thus think it is important to mention this in the conclusions.

P26, L10: Since Cryosphere has easy support for auxiliary data, it would be very nice for the community if the zoning (including glacier area and averaged dh/dt) is provided with the paper, not only on personal request.

We'll include the zoning and glacier surface change rates as auxiliary data supplement.

P28, L18: ICESat period DONE

P30, L18: Method A is not clear.

We added more explanations for method A and a reference to Kääb et al. (2012), where the method was first described.

P30, L20: Doesn't the B correction also introduce an error due to ICESat's variable temporal sampling? I.e., if a glacier is thinning, then ICESat observations in the later years of the mission would naturally have lower dh values than expected from the general dh-elevation trend. This is the same issue as pointed out for the cG correction (see comment P6-L32). Are both corrections applied in the case of method B?

This is a good observation but not true, as the two methods are different in that aspect. In contrary to the cG correction, method B uses a dh—elevation gradient that is computed from all samples within a spatial unit and applied to all samples, no matter which glacier or campaign. The gradient will be the same for all campaigns, and be in the order of 0-3 m per 100 m elevation (fig. 3d in the paper). Assuming glacier thinning (predominantly on the tongues), the real slope of the dh—elevation gradient would be less (more) in the beginning (end) of the studied time period, resulting in residuals – which correspond to the signal: We use that gradient to remove the expected elevation dependency so that only the temporal aspect remains. In other words, after correction using method B, the regression is done on dh anomalies – which are the (local) thinning/thickening signal (plus other local biases). For method B, the dh—elevation gradient thus has to be the same for the entire time period and the method does thus not introduce an error, but instead removes noise to better show the thinning signal in the example e reviewer states.
Elevation correction (methods A-D) is done everywhere. cG is applied only in some cases (see answers to the other reviewer comments concerning vertical bias correction).

P30, L21: What is meant by "filtering"? If you mean removing/culling data, then useful observations would also be removed and I see no reason for that as long as you can rather introduce a weighting scheme like Method D.

Yes, we mean removing of data. All methods (A-D) have the same goal, to remove elevation-induced bias and false trends due to changing sampling elevations with time. It might seem a bad idea to remove data, but statistically seen, the weighting does essentially the same as it removes equally much influence of "good" samples. Depending on local sampling (timing, location, elevations, also for/within each individual glacier…) in each spatial unit, some of the methods are more appropriate than others, and some would even fail (i.e. introduce errors) for some spatial units. For the vast majority, the differences in final trend estimates lie within 0.1 m/a between methods A-D, if only one method is applied. Using the average of all four methods is thus an appropriate choice to ensure consistency for our study while minimising errors potentially introduced by one of the methods. For more local applications (one spatial unit), however, we recommend to assess all methods carefully.
In fact, we analysed all four methods and how they differ thoroughly for all spatial units – but these technical details and comparisons don't fit this paper (and the journal) well, have negligible influence on the results and are of little importance for the focus of the study, so we prefer to not add more details here. The interested reader will find an extended discussion of all methods, corrections and their implications on the results in the PhD thesis of Treichler (2017).

P30, L10: Thanks, this shows that you are aware of my issue with the cG correction and method B. Since it is in the end only applied to 6 units – is it really needed? And what about the same issue for Method B?

The cG correction was first proposed by Treichler & Kääb (2016), where also its potential side effect of flattening the elevation change trend slope is discussed. In that study, the benefits clearly outweighed the side effect, as campaign medians followed southern Norway's cumulative mass balance evolution only after correction. For many spatial units in this study, the same is the case. However, the correction might not seem equally important since we don't assess campaign medians but only trend slopes. Nevertheless, the fact that some of the elevation change rates become steeper after cG correction (while the contrary is expected) makes it clear that the correction should be applied for these units. Besides, we would like to keep the correction also in this study to encourage its use in other studies, in particular studies of more local character. However, the number 6 stated in the appendix was wrong – assumingly, this was a crippled 16, as we applied cG to 16 units, only hypsometry correction methods C and D to 13 units, and both of the above to 5 units. This was not sufficiently explained in the manuscript, and it also seems errors were not for all 34 cases completely propagated (i.e. the total error should include trend slope differences for with/without applied correction). We double-checked for consistency and updated the corresponding trend errors.

In the revised paper, the methods and appendices are rewritten.

P32, L24: Standard error of the mean? yes – CHANGED

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High Mountain Asia glacier elevation ~~trends~~ changes 2003–2008, lake volume changes 1990–2015, and their relation to precipitation changes

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Abstract. We present an updated, spatially resolved estimate of 2003–2008 glacier ~~volume~~ surface elevation changes for entire High Mountain Asia (HMA) from ICESat laser altimetry data. The results reveal a diverse pattern that is ~~driven~~ caused by spatially greatly varying glacier sensitivity, in particular to precipitation availability and changes. We introduce a spatially resolved zonation where ICESat samples are grouped into units of similar glacier behaviour, glacier type, and topographic settings. In several regions, our new zonation reveals local differences and anomalies that have not been described previously. ~~A step-increase in precipitation around 1997–2000 on the Tibetan Plateau (TP) caused thickening of glaciers in the~~ Glaciers in the Eastern Pamirs, Kunlun Shan and central TP were thickening by 0.1–0.7 m a^{-1}~~. The~~ , and the thickening anomaly has a crisp boundary in the Eastern Pamir that continues just north of the central Karakoram. Glaciers in the south and east of the TP were thinning, with increasing rates towards southeast. ~~The precipitation increase~~ We attribute the glacier thickening signal to a step-increase in precipitation around 1997–2000 on the Tibetan Plateau (TP). The precipitation change is reflected by growth of endorheic lakes in particular in the northern and eastern TP. We estimate lake volume changes through a combination of repeat lake extents from Landsat data and shoreline elevations from ICESat and the SRTM DEM for over 1300 lakes. The rise in water volume contained in the lakes corresponds to 4–25 mm a^{-1}, when distributed over entire catchments, for the areas where we see glacier thickening. The precipitation increase is also visible in sparse in-situ measurements and MERRA-2 climate reanalysis data, but less well in ERA Interim reanalysis data. ~~Considering~~ Taking into account evaporation loss, the difference between average annual precipitation during the 1990s and 2000s suggested by these datasets is 34–100 mm a^{-1}, depending on region, which can fully explain both lake growth, and glacier thickening (Kunlun Shan) or glacier geometry changes such as thinning tongues while upper glacier areas were thickening or stable (eastern TP). The precipitation increase reflected in these glacier changes possibly extended to the northern slopes of the Tarim Basin, where glaciers were nearly in balance in 2003–2008. Along the entire Himalaya, glaciers on the first orographic ridge, which are exposed to abundant precipitation, ~~are~~ were thinning less than glaciers in the dryer climate of the inner ranges. Thinning rates in the Tien Shan vary spatially but are rather stronger than in other parts of HMA.

1 Introduction

High Mountain Asia (HMA) is a large and remote region hosting a range of topographic and meteoclimatic climatic regimes (Palazzi et al., 2013). Some areas, like the Himalaya or Karakoram, are characterized by steep orographic gradients (Bolch et al., 2012). Glacier landscape and shapes, climate, elevation, and consequently glacier behaviour and response to climate change, vary strongly throughout the region (e.g. Scherler et al., 2011; Fujita and Nuimura, 2011; Bolch et al., 2012; Brun et al., 2017; Sakai and Fujita, 2017). Throughout the recent decades, most glaciers in the region seem to have lost mass and retreated (e.g. Bolch et al., 2012; Kääb et al., 2012; Brun et al., 2017). But there are some exceptions, most prominent the so-called Karakoram or Pamir-Karakoram anomaly (e.g. Hewitt, 2005; Quincey et al., 2011; Kääb et al., 2012; Gardelle et al., 2013; Kapnick et al., 2014), and positive mass balances are also reported for reported for some glaciers on the Tibetan Plateau (TP) and Kunlun Shan (Yao et al., 2012; Kääb et al., 2015; Brun et al., 2017).

At the same time, a number of studies report expansion of endorheic lakes on the TP from since around the beginning of this century (e.g. Zhang et al., 2017). For these lake systems, additional lake water masses should either stem from increased lake inflow, i.e. mainly increased precipitation or enhanced glacier melt, or from reduced water loss, i.e. mainly changes in decreased evaporation. However, in-situ meteorological datathat , which could shed light on precipitation and evaporation changes and their spatial patternsis , are barely available for the HMA (Kang et al., 2010) and lacking in particular for the remote areas on the TP and Kunlun Shan with suggested recent positive glacier mass balances. In addition, in-situ measurements at high altitude, in particular for precipitation, are in general subject to challenges (Salzmann et al., 2014). These scarceness and problems associated with in-situ measurements likely also affect the accuracy and reliability of reanalysis data over some zones of HMA, leaving thus an overall limited understanding of glacier changes and associated climate changes over significant areas of HMA.

HMA region-wide assessments of glacier changes have been derived either from (i) interpolating the sparse in-situ measurements (Cogley, 2011; Bolch et al., 2012; Yao et al., 2012), (ii) from digital elevation model (DEM) differencing (Gardelle et al., 2013; Brun et al., 2017), (iii) GRACE (Gravity Recovery and Climate Experiment) gravimetry data (Matsuo and Heki, 2010; Jacob et al., 2012; Gardner et al., 2013), or (iv) ICESat satellite laser altimetry (Kääb et al., 2012; Gardner et al., 2013; Neckel et al., 2014; Kääb et al., 2015; Phan et al., 2017). Of these, only Brun et al. (2017) and the coarse-resolution GRACE studies cover the entire HMA, including also Tien Shan, TP and Qilian Shan. For some regions, the differences between the studies are considerable, even if they address the same time period (Cogley, 2012; Kääb et al., 2015). All four method principles listed above have their specific advantages and disadvantages. A challenge with GRACE data, for instance, is the separation of mass changes due to glacier mass loss and other influences, such as changes in lake and ground water storage (e.g. Baumann, 2012; Yi and Sun, 2014). For some DEM differencing studies in the region, a major source of uncertainties is the Shuttle Radar Topography Mission (SRTM) DEM. The SRTM DEM is based on C-band radar that can penetrate up to several metres into snow and ice, depending on the local snow and ice conditions during the SRTM data acquisition in February 2000 (Gardelle et al., 2012b; Kääb et al., 2015). The recent study of Brun et al. (2017) is not affected by radar penetration as it is exclusively based on time series from ASTER optical stereo DEMs. While their new data set of time-averaged geodetic glacier mass balances is spatially of unprecedented extent and detail, ASTER DEMs can suffer from limitations such as sensor shaking (jitter) (Girod et al., 2017), biased errors/voids in particular in featureless accumulation areas (Wang and Kääb, 2015; McNabb et al., 2018), and spatio-temporal variations in image acquisitions causing (Berthier et al., 2016; Brun et al., 2017) that cause the studied time periods to vary throughout the area. The study of Brun et al. (2017) includes a comparison to ICESat surface elevation changes, although using large spatial regions and ASTER DEMs from 2000–2008 as ASTER DEM stacks were too noisy for shorter time spans. With in-situ measurements and ICESat laser data, the uncertainty lies in the representativeness of the spatial sampling. Both are not spatially continuous but sample only some glaciers, although ICESat with higher density of footprints than in-situ measurements. Direct mass balance measurements are only available for few glaciers (WGMS, 2016, Fig. 1), and the overall mass balance signal they suggest is possibly biased towards glaciers at low elevations because these are easier to access (Wagnon et al., 2013).

From recent glacier studies involving ICESat data over HMAwe conclude , Kääb et al. (2015) suggest that results are sensitive to zone delineation, in particular in areas with strong spatial variability of glacier thickness changes(Kääb et al., 2015). Studies stress the importance of sampling the glacier hypsometry correctly., i.e. that the number of data points per elevation reflects the glacierised area at each elevation. Kääb et al. (2012, 2015) and Treichler and Kääb (2016) found that hypsometries of individual years of ICESat samples may not fit the glacier hypsometry, even if the total of all 2003–2008 samples reflect the glacier elevation distribution accurately. This can alter the results in cases where there is a consistent elevation trend in 2003–2008 sampling elevations., i.e. the average sampling elevation increases or decreases over time. Correct and up-to-date glacier outlines turn out to be very important for deriving ICESat elevation trendschanges. Inclusion of non-glacier elevation measurements, where surface elevation is stable, reduces the glacier elevation change retrieved from ICESat. The effect of snow cover, and thus the choice of whether including ICESat winter campaigns or not, plays a role , not least — also for the autumn 2018 ICESat campaign that was completed in December 2018 only due to technical problems (Kääb et al., 2012; Gardner et al., 2013; Treichler and Kääb, 2016). Spatially varying vertical biases from DEMs used as reference can considerably increase trend uncertainty(Treichler and Kääb, 2016). All ICESat studies in HMA so far rely on the SRTM DEM, where spatially varying penetration could be a source of such biases.

The present study has two objectives. First, we aim to extend the ICESat-based work of Kääb et al. (2012, 2015) to entire HMA, including the Tibetan Plateau, Qilian Shan and Tian Tien Shan, and under special consideration of the issues addressed above and the recent method improvements by Treichler and Kääb (2016). In particular, we present a new elevation change zonation into spatial units that consider glacier topo-climatic setting, behaviour and type rather than relying on a regular grid or RGI Randolph Glacier Inventory (RGI, Arendt et al., 2015) regions. Second, we investigate the possible cause of the positive glacier volume changes in the TP and Kunlun Shan region, regions with the hypothesis of a precipitation increase in this area. For the latter purpose, we quantify the water volume changes in endorheic lakes on the TP, their timing and spatial pattern, and set them in relation to the independent ICESat-derived glacier volume surface elevation changes as well as precipitation estimates from climate reanalyses and sparse in-situ measurements from meteorological stations. In order to avoid compiling spatially, temporally and methodologically inhomogeneous existing studies we prefer to derive integrated and consistent results, mainly based on ICESat data and satellite imagery.

2 Study region

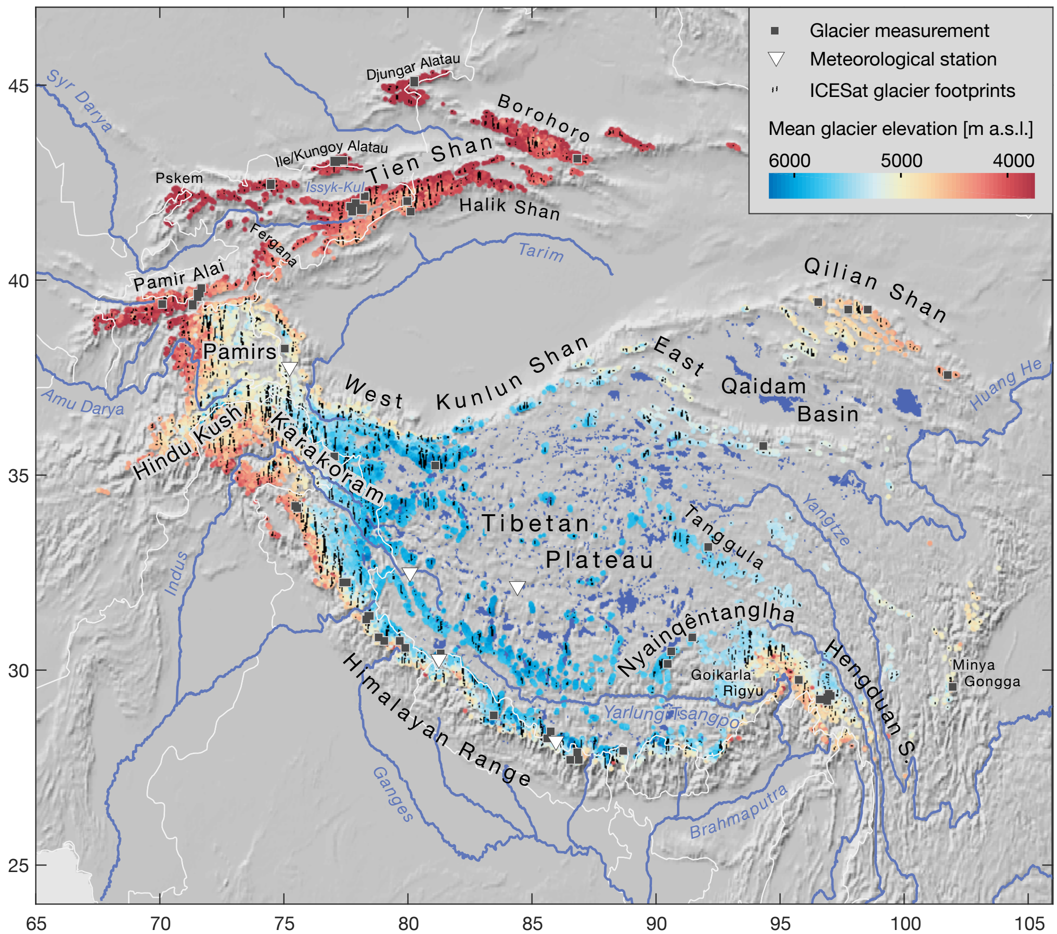


Figure 1. Mountain ranges and major rivers in High Mountain Asia, with meteorological stations used in this study (triangles) and in-situ glacier mass balance measurements done at some point during the last decades (black squares, WGMS, 2016). Lakes on the TP and in the Qaidam Basin are shown in dark blue, and glaciers are coloured according to their mean elevation. ICESat glacier samples are shown as small black dots. Glaciers taken from RGI.

~~HMA~~ The HMA glacier region is covered by about 100’000 km^2 of glacier area ~~(RGI, Arendt et al., 2015).~~ (Arendt et al., 2015). Temperature rise due to global climate change is especially pronounced on the TP and increasing with elevation (Liu and Chen, 2000; Qin et Glaciers are found on all large mountain ranges around the TP at >4000 m a.s.l. but mostly to the south and west, where the steep elevation gradient from the Indian planes acts as a barrier for moisture that is advected by the Indian monsoon (Himalaya, Karakoram, Eastern Nyainqêntanglha Shan) and Westerlies (Hindu Kush, Karakoram, Pamir), respectively (Yao et al., 2012; Bolch et al., 2012; Mukhopadhyay and Khan, 2014). On the very dry TP, glaciers occur only on the sparsely spread small mountain ranges.

In interplay with the Siberian High further north (Narama et al., 2010; Böhner, 2006), the Westerlies are the dominant source of moisture for the mountains surrounding the dry Tarim basin (at ca. 1000 m a.s.l.) — the ~~Tian~~ Tien Shan to the north, and Kunlun Shan to the south (Ke et al., 2015; Yao et al., 2012). The mountain ranges at the eastern margins of the TP (Qilian Shan, Hengduan Shan, Minya Gongga) are also influenced by the East Asian Monsoon (Yao et al., 2012; Li et al., 2015).

In both the monsoonal and westerly regimes, precipitation decreases northward (Bolch et al., 2012). Depending on the regionally dominant source of moisture, glacier accumulation happens at different times of the year (Bolch et al., 2012; Maussion et al., 2014; Yao et al., 2012; Sakai et al., 2015). From the eastern Himalaya and southern/eastern TP to the northwest of HMA, there is a transition from predominant spring/summer accumulation to winter accumulation in the Hindu Kush and the western parts of Tien Shan (Palazzi et al., 2013; Bookhagen and Burbank, 2010; Rasmussen, 2013). Mountains in between, such as the Karakoram and western Himalaya, receive moisture from both sources (Kuhle, 1990; Bolch et al., 2012). The Kunlun Mountains, on the other hand, receive most precipitation around May (Maussion et al., 2014).

For the HMA glaciers with predominant spring/summer accumulation, glacier accumulation and ablation happen at the same time. Besides rising temperatures, recent studies suggest that climate change and altered circulation patterns affect radiation regimes and thus also glacier ablation in HMA through, e.g., changes in evapotranspiration or cloud cover (Forsythe et al., 2017; de Kok et a
The seasonal timing of ~~glacier accumulation~~ snow accumulation on glaciers thus likely plays an important role for glacier sensitivity to a warming climate (Fujita, 2008; Mölg et al., 2012; Sakai and Fujita, 2017). Another important factor is total precipitation~~availability~~, which depends on continentality (Shi and Liu, 2000; Kuhle, 1990) and, on smaller spatial scale, on glacier location on or behind a mountain range that acts as a primary orographic barrier or causes orographic convection. Wagnon et al. (2013) and Sherpa et al. (2016) found indications of steep horizontal precipitation gradients within only a few kilometres on the outermost ridge of the Great Himalaya in the Khumbu region in Nepal. Vertical precipitation gradients at high altitude are still poorly understood. It is suggested that precipitation increases from dry mountain valley bottoms to an elevation of 4000–6000 m a.s.l. and subsequently decreases again at even higher elevations (e.g. Immerzeel et al., 2014, 2015).

Many glaciers in HMA are debris-covered in their ablation areas, and the percentage of debris-covered ice varies greatly between different regions ~~(Scherler et al., 2011; Gardelle et al., 2013).~~(Scherler et al. 2011; Gardelle et al. 2013, Kraaijenbrink et al. 2017, suppl.). Recent studies have found that although debris-covered glaciers in HMA have stable front positions (Scherler et al., 2011), they melt on average just as fast as clean ice glaciers (Kääb et al., 2012; Gardelle et al., 2012b; Pellicciotti et al., 2015). In this study, we distinguish thus not explicitly between debris-covered and debris-free glacier tongues.

3 Data and Methods

In this section we give a short overview of the data and methods used. Details can be found in the Appendix.

3.1 Data

For deriving repeat elevations on glaciers and lakes, we use data from the NASA Geoscience Laser Altimeter System (GLAS) aboard the Ice, Cloud and land Elevation Satellite (ICESat) that measured the Earth's surface elevations in two to three campaigns per year from 2003 to 2009. 2009 (Zwally et al., 2012, GLAH14). The campaigns were flown in northern autumn (∼ October–November), winter (∼ March), and early summer (∼ June). (Appendix A1).

As reference DEM for our ICESat processing and to derive lake shoreline elevations we use the DEM from the Shuttle Radar Topography Mission (SRTM, Farr et al., 2007; Farr and Kobrick, 2000). We used the C-band, non-void-filled SRTM DEM version at 3 arc-seconds resolution (SRTM3). As an alternative elevation reference, we used also the SRTM DEM at 1-arc-second resolution (SRTM1). We did not explore or use the recently published TanDEM-X global DEM as it was not yet available during our processing. Due to temporal inconsistency and substantial voids, we did also not use the ALOS PRISM World DEM (AW3D) or the WorldView satellite optical stereo HMA DEM. ((Appendix A2) .

As an estimate for regional and temporal precipitation patterns for the years 1980–2015 we use data from the Modern-Era Retrospective analysis for Research and Applications, version 2 (reanalysis products MERRA-2), available from the NASA Goddard Earth Sciences Data and Information Services Center, and ERA Interim at T255 spectral resolution(Gelaro et al., 2017) and ERA Interim (Dee et al., 2011). We use monthly summarised values of the variables total precipitation(PRECTOT / tp), snowfall (PRECSNO / sf) and evaporation(EVAP / e) from MERRA-2's surface flux diagnostics dataset tavg1_2d_flx_Nx and ERA Interim's Monthly Means of Daily Forecast Accumulations, respectively. The High Asia Reanalysis (HAR), a product optimised for the TP region and with much finer spatial resolution, is unfortunately only available for the time period 2001–2011 which is too short for our study with respect to the lake volume changes investigated. , snowfall and evaporation. The two chosen reanalysis products have previously been found to model precipitation comparatively well in our study area (Chen et al., 2019; Cuo and Zhang, 2017; Sun et al., 2018). (Appendix A3). Further, we use in-situ data from the five westernmost meteorological stations on the TP and Kunlun Shan (Fig. 1), provided by the China Meteorological Science Data Sharing Service Network. The data includes include daily measurements of precipitation, mean air temperature, and for the four stations on the southwestern TP also evaporation. (Appendix A3).

We extract repeat lake coverage from the Global Surface Water dataset (Pekel et al., 2016) that is a classification of the entire Landsat archive into monthly and annual maps of surface water. The data is are available within Google Earth Engine. Coverage Spatial coverage is nearly complete (>98%) starting from 2000 but considerably worse for some years of the 90s1990s. (Appendix A4).

3.2 Methods for glacier volume change

We use surface elevation measurements from ICESat data points on glaciers and surrounding stable terrain and follow the double-differencing method explained in further detail in Kääb et al. (2012) and Treichler and Kääb (2016), with special consideration of issues mentioned in the above introduction (Appendix B). The difference between ICESat and SRTM elevations is further referred to as dh. Double differencing, i.e. fitting a linear trend through dh from several years, reveals how much the surface elevation has changed on average over the time period studied. We used only samples from ICESat's 2003–2008 autumn campaigns, the season with least snow cover in entire HMA, to avoid bias from temporal variations in snow depths (see introduction). After filtering, 74'938 ice samples and about ten times as many land samples remain. Per spatial unit, we estimate glacier surface elevation change by fitting a robust linear regression through individual dh and also compute a t-fit

~~(Treichler and Kääb, 2016) and a non-parametric Theil-Sen linear regression (Theil, 1950; Sen, 1968). Our final estimate per spatial unit corresponds to the average of the three trend methods. (Appendix B)~~

~~ICESat data needs to be grouped into spatial units to fit surface elevation trends. We tested~~ ICESat data need to be grouped into spatial units to receive surface elevation changes. The samples within each spatial unit need to reflect the glaciers in a representative way — which means that the spatial units need to be chosen such that they group glaciers that are similar to each other in terms of climatic and topographical attributes, including their 2003–2008 mass balances and variations thereof. Previous studies have used regular grids, the RGI regions or their own arbitrary zonation. These do not necessarily fulfil the above requirements. We considered automated clustering methods to receive spatial units from ICESat dh directly, but were not successful. We therefore preferred to delineate spatial units manually, considering topographic and climatic setting, elevation, visual glacier appearance, and input from literature and discussions with experts (Appendix B1). In particular, we paid attention to orographic barriers. The zonation we present here is thus the result of an iterative manual process of re-defining spatial units until they satisfied these criteria. After computing linear regressions on glacier dh, we split or merged some of the previously drawn units such that the final zonation yielded statistically stable and robust glacier surface change estimates. While the procedure is based on carefully applied expert knowledge, we are fully aware that our zonation is eventually a subjective one and certainly open to discussion. As a control approach, we applied the same gridding method as Kääb et al. (2012, 2015) to the entire HMA. ~~(Appendix B1)~~

It is very important to ensure ICESat's elevation sampling is consistent through time and representative for glacier hypsometry (see introduction). We apply four different ways of correcting hypsometry mismatches of ICESat sampling ~~.~~ (Appendix B2). Per spatial unit, we estimate glacier surface elevation change by fitting a robust linear regression through individual dh (which minimises an iteratively weighted sum of squares) and also compute a t-fit (Treichler and Kääb, 2016) and a non-parametric Theil-Sen linear regression (Theil, 1950; Sen, 1968). Our 'standard method' for the final glacier elevation change estimates corresponds to the average of all hypsometry-correcting methods and ~~trend methods(robust, t- and Theil-Sen trends)~~linear regression methods. Additionally, we also compute ~~trends~~ elevation change for only the upper/lower 50% glacier elevations as from RGI hypsometries (samples above/below the median RGI glacier elevation ~~in each unit)~~ of each individual glacier) for each spatial unit. The latter analysis violates mass conservation and should thus not be interpreted in terms of mass balance, but rather, for instance, for changes in glacier elevation gradients (e.g. Brun et al., 2017; Kääb et al., 2018). ~~(Appendix B2)~~ To allow comparison with other studies, we use RGI glacier areas to convert our surface elevation change rates to volume changes.

Glacier ~~elevation difference~~ dh may be subject of vertical bias ~~originating from~~ from elevation differences that are caused by other reasons than glacier surface elevation change, i.e. from bias in the local reference elevation ~~bias~~ (the SRTM DEM) or snow fall~~during the second part of the autumn 2008 campaign.~~. We compute corrections for these biases (Appendix B3). Local vertical bias may result from inconsistent reference DEM age or production, tiling and tile/scene misregistration, or locally varying radar penetration (in case of the SRTM DEM). To remove this bias, we compute a per-glacier elevation correction cG, corresponding to the median dh for each glacier, according to the method described in Treichler and Kääb (2016). Treichler and Kääb (2016, 2017) found that ICESat clearly records the onset of winter snowfall in Norway during the split autumn

2008 campaign (stopped half way in mid-October and completed only in December). Analogue to Treichler and Kääb (2016), we estimate December 2008 snow bias from a linear regression of October/December 2008 land dh on elevation and time. ~~(Appendix B3)~~

3.3 Methods for lake volume change

~~In~~ We derive the volume changes of lakes on the endorheic TP in order to relate glacier changes and precipitation changes on the Tibetan Plateau to each other~~, and in particularto investigate if~~. In particular, we want to investigate whether precipitation increases could be a reason for the positive glacier mass balances found in parts of the region~~, we also derive the volume changes of endorheic lakes on the TP. On first order, and by neglecting changes in subsurface water transport,~~. For endorheic lake systems, additional lake water masses ~~should for endorheic lake systems~~ either stem from increased lake inflow (mainly increased precipitation ~~or~~ and enhanced glacier melt, possibly also thawing permafrost and changes in groundwater storage) or from reduced water loss (mainly changes in evaporation). ~~Lake volume changes on the TP serve thus as potential proxies for precipitation changes, but help also to correct satellite gravimetric signals of glacier mass changes (see introduction; Appendix C)~~This section provides a summary of the methods, details can be found in Appendix C.

We compute annual water volume change of the Tibetan lakes by multiplying annual lake areas with water level changes from repeat water surface elevations for each year over the period 1990–2015. Maximum annual lake extents are obtained directly from the Global Surface Water data set. We retrieve the corresponding lake surface elevations in two ways: a) from SRTM DEM elevations of the lake shore by computing the median of interpolated DEM elevations for lake shore cells for each areal extent, and b) directly from ICESat footprint elevations on the lake areas for those lakes where ICESat data ~~is available.~~ are available. The two datasets used have different strengths: ICESat-derived lake surface elevations are far more accurate but available only for about a tenth of all lakes. To extend the lake elevation time series from method b) beyond the ICESat period of 2003–2009, we compute the area–surface-elevation relationship for each lake by robust linear regression and apply this function to the areal extends of the years before and after the ICESat period, both for annual timeseries and individual ICESat campaigns. The so-extrapolated surface elevation values generate complete 1990–2015 time series for both areal extent and lake levels from SRTM and ICESat data, respectively. Our method is in parts similar to the methods used by previous studies (e.g. Zhang et al., 2017) but the inclusion of a DEM for deriving shoreline elevations, and thus lake water levels, in addition to altimetry data, enabled us to produce volume change time series for one order of magnitude more lakes (>1300) than derived previously. ~~(Appendix C).~~

To minimise the effect of uncertainties in or erroneous estimates for individual years, we analyse time series in a summarised way through regression over time and as decadal averages, and apply a range of filters. (Appendix ~~C1~~C1).

To estimate the lake water volume change in a way that can be related to glacier mass balances and precipitation changes (i.e. mm w.e. per m^2), we summarise and spatially distribute the water volume changes of all lakes within spatially confined basins ~~. These basins are based on endorheic catchments, but because many catchments only contain a single lake and exact catchment areas are not well defined on the TP (e.g., in very flat areas), we manually controlled, adjusted and aggregated~~ aggregated from the endorheic catchments of the USGS HydroSHEDS dataset ~~at 15 arcsec spatial resolution to larger basins of comparable size and consisting of in average 5 catchments~~(Lehner and Döll, 2004). (Appendix ~~C2~~C2).

3.4 ~~Methods for precipitation change~~

~~A change in precipitation, minus the part that is lost through evaporation and when neglecting changes in subsurface water transport, should yield numbers that are directly scalable in relation to endorheic catchment water volume change or glacier mass balance, especially where the latter is governed by precipitation rather than temperature/melt. However, reanalysis data may not be very accurate in HMA due to a lack of ground measurements, and the few meteorological stations are not necessarily representative for a larger area. We therefore use raw precipitation data mainly to detect/confirm temporal and large-scale spatial patterns, and in a summarised way through decadal averages, rather than relying on annual numbers.~~

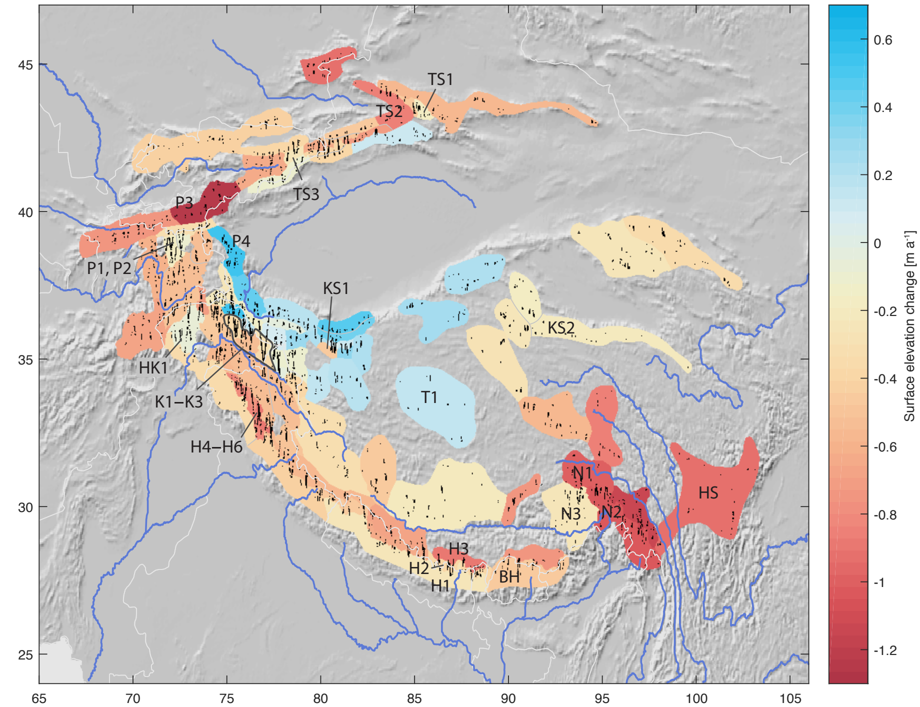
4 Results

4.1 Glacier thinning and thickening

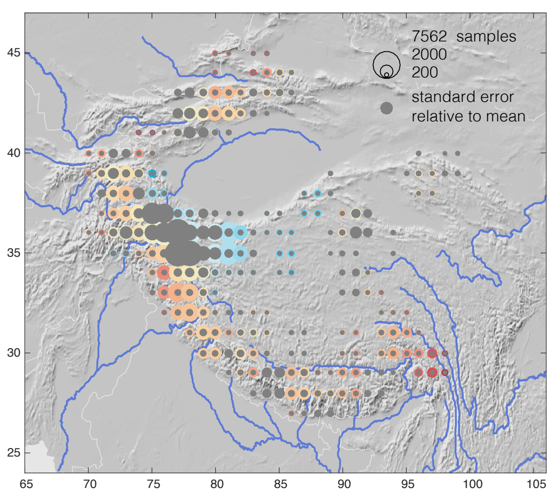
Figure 2a shows the 100 spatial units of glacier surface elevation change that result from the iterative manual zone delineation process. Spatial units needed to be large on the TP where glacier density is low, and could be rather small in the Karakoram which is intensely glacierised. Along major ridges such as the Himalaya, the units were designed narrow and along ridge orientation in order to group glaciers under similar temperature and precipitation regimes rather than across orographic barriers.

Surface elevation change for the new spatial units and the $2^\circ \times 2^\circ$ grid in Fig. 2b are derived using the ‘standard method’ ~~(Appendix B)~~ except for 34 units with hypsometry missampling or elevation bias (Appendix B). The error values given in Fig. 2c and in the text conservatively include, where applicable, uncertainties from off-glacier elevation trends, the deviation from the standard method (greatly increased errors, units showing up in yellow in Fig. 2c), and ~~the difference to the surface elevation change rate corrected for the effect of~~ December 2008 snow fall correction (Appendix B3. In areas with snow-rich winters, the latter may contribute up to 40% of the error budget. In Fig. 2b, the size of the circles corresponds to the number of samples (minimum 200) while the overlaid, grey circles show the trend error (at 1σ) in relation to the trend slope; i.e. ~~trends~~ elevation changes are not statistically ~~significant~~ significantly different from zero where the grey circles fully cover the underlying coloured circle. ~~Errors for 2a are given in Fig. 2c.~~

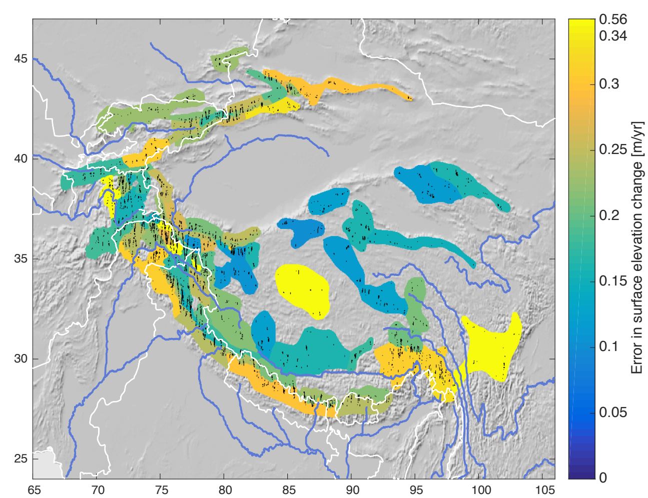
The overall pattern of elevation change is the same for both spatial zonation approaches; positive glacier elevation change in the Kunlun Shan an the inner TP, and spatially varying but modest glacier surface lowering in most areas except for very negative values in Nyainqêntanglha Shan/Hengduan Shan and parts of the Tien Shan. Most of HMA’s glaciers seem to experience thinning both in their ablation and accumulation areas, as shown in Figs. 3a and 3b (upper and lower 50% of glacier area, respectively). Exceptions to these are the areas with positive glacier changes plus parts of the Himalayas and the mountains surrounding the Tarim basin, where upper glacier elevations seem relatively stable.



(a) Zonal glacier elevation change.



(b) Gridded glacier elevation change



(c) Errors for zonal elevation change

Figure 2. 2003–2008 glacier elevation change rates for (a) manually delineated zones and (b) overlapping $2° \times 2°$ degree grid cells with 1° spacing. Colour bar (b) as in (a). Circles in (b) are scaled according to sample numbers. The overlaid grey circles show the standard error in relation to the slope of the linear fit, i.e. elevation change is not significantly different from zero (at 1σ) where the coloured circles are fully covered. (c) ~~,~~Error for (a) at 1σ, including uncertainties from deviations from the standard method, December 2008 snow fall correction, and trends in off-glacier samples. The four bright yellow units have uncertainties between ~~0.42~~0.43–0~~.56~~.50 m a^{-1}.

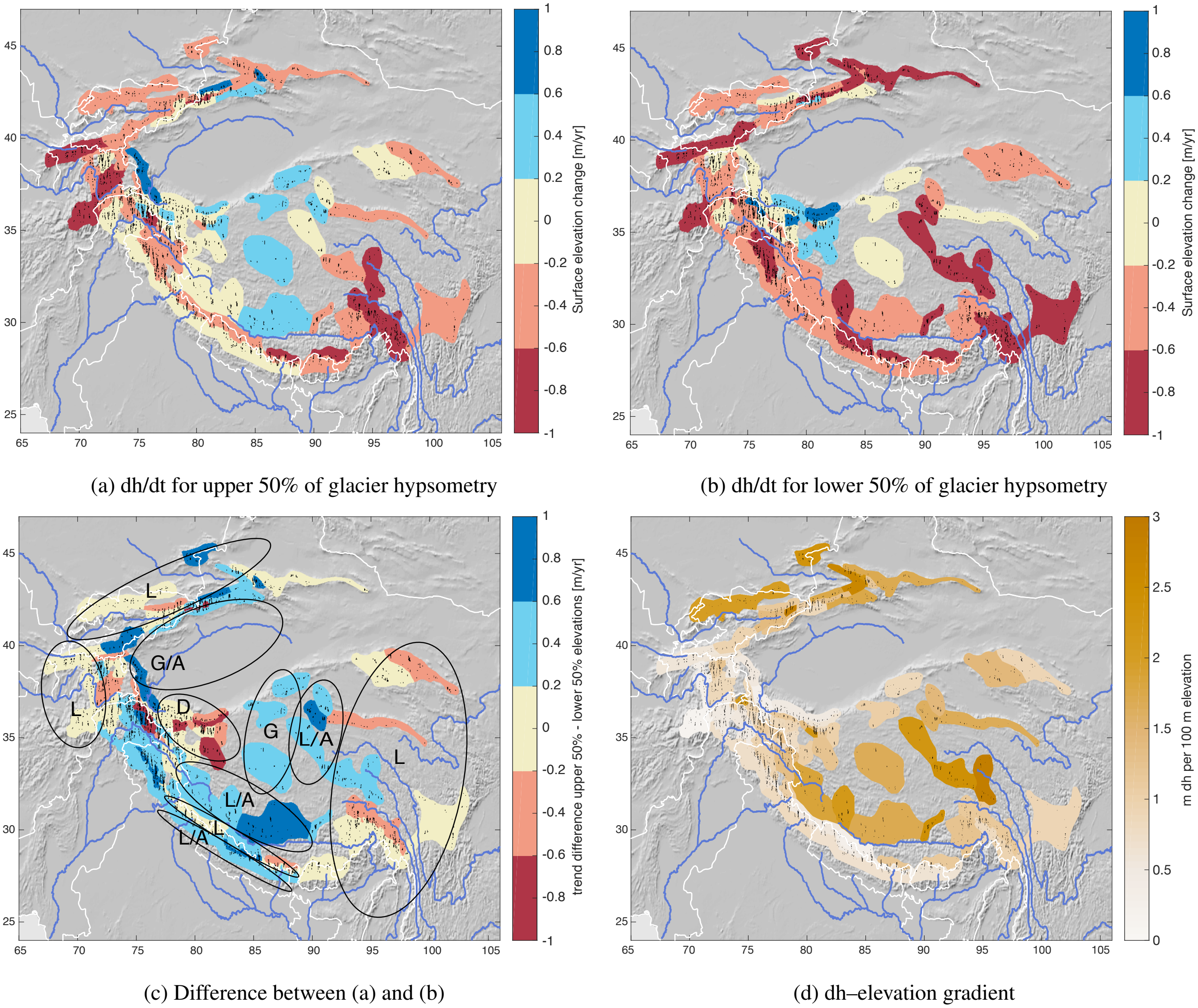
While the grid zonation (and also the smaller grid cells of Brun et al. 2017) shows smooth transitions between areas of positive or negative glacier evolution, our zoned map suggests rather greater spatial variability and sharper boundaries of clusters of similar elevation change. The regular grid size is too small to reach minimum sample numbers in areas with sparse glacier coverage (TP, outer Hengduan Shan, parts of Tien Shan), and the signal from grid cells with few samples is spatially less consistent than what the manually delinated, larger units suggest. The small units in the Karakoram and Kunlun Shan, on the other hand, reveal locally varying signals that are averaged out or not significant in the coarser grid zonation (e.g. units K1–K3 and KS1 in Fig. 2a). Our new zonation, surface elevation changes and corresponding glacier volume changes (using RGI glacier areas) are available in the supplement.

In the Himalaya, the manual zone delineation shows a clear transition from moderately negative elevation change on the first, southern orographic ridge (-0.15 to $-0.34\,\mathrm{m\,a^{-1}}$, maximum trend error: $0.31\,\mathrm{m\,a^{-1}}$) compared to glaciers located further back to the north and on the edge of the TP ($-0.33 \pm 0.22\,\mathrm{m\,a^{-1}}$ to $-0.85 \pm 0.14\,\mathrm{m\,a^{-1}}$). This pattern (e.g. units H1, H2, H3) is consistent along the entire range except for the Bhutanese Himalaya, where ICESat's sampling pattern required grouping of several orographic ridges which together show stronger surface lowering (unit BH, -0.40 ± 0.25 $-0.40 \pm 0.24\,\mathrm{m\,a^{-1}}$). This pattern becomes smoothed out and is thus not visible in the gridded zonation.

Glaciers in the inner Hindu Kush (HK1, $0.03 \pm 0.24\,\mathrm{m\,a^{-1}}$) and the highest regions of the Pamir (P1 -0.07 ± 0.23, P2 $-0.03 \pm 0.16\,\mathrm{m\,a^{-1}}$) were close to balance over 2003–2008 while all surrounding units in the area show stronger glacier surface lowering. Similarly, the glaciers around Lhasa (Goikarla Rigyu, unit N3) lowered their surface by only $-0.18 \pm 0.31\,\mathrm{m\,a^{-1}}$ which is considerably less than the surrounding units and in particular the very negative values in East Nyainqêntanglha Shan/Hengduan Shan (-0.96 to $-1.14 \pm 0.33\,\mathrm{m\,a^{-1}}$).

Further towards the inner TP and in the Qilian Shan, surface lowering decreases to -0.1 to $-0.3 \pm 0.16\,\mathrm{m\,a^{-1}}$. In the central and northern parts of the TP and the Kunlun Shan it turns positive — for nearly all units $> 0.25\,\mathrm{m\,a^{-1}}$, to as much as $0.79 \pm 0.26\,\mathrm{m\,a^{-1}}$ in the Eastern Pamirs/Kongur Shan (P4). The boundary between positive and negative surface elevation change seems to be formed by the Muji Basin, upper Gez river and Tashkurgan Valley. All units to the north of the central Karakoram range were in balance or thickening. The glaciers of the central Karakoram range and southwest of it showed moderate thinning (-0.22 to -0.51 ± 0.43 $-0.47 \pm 0.43\,\mathrm{m\,a^{-1}}$). In the Western Kunlun Shan region, surface elevation trends changes of the lower 50% elevations are more positive than those of the upper 50% elevations (not shownFigs. 3a and 3b). This behaviour is visible for 13 units centred around KS1.

Interestingly, also glaciers on the northern edge of the Tarim basin seem to be closer to balance (-0.3 ± 0.26 to $+0.21 \pm 0.33\,\mathrm{m\,a^{-1}}$) than those in more central or northern ridges of the Tien Shan. In the Tien Shan, most spatial units indicate glacier surface lowering between -0.35 and $-0.8 \pm 0.25\,\mathrm{m\,a^{-1}}$, but two units stick out due to their more moderate surface lowering; TS1: $-0.1 \pm 0.21\,\mathrm{m\,a^{-1}}$, and TS3: $-0.18 \pm 0.18\,\mathrm{m\,a^{-1}}$. Several other units right next to these have considerably more negative values. At the transition between Pamir and Tien Shan (P3), glacier surface elevation decreased by as much as $-1.23 \pm 0.31\,\mathrm{m\,a^{-1}}$ — despite the thickening signal just south and east of this unit.



(a) dh/dt for upper 50% of glacier hypsometry

(b) dh/dt for lower 50% of glacier hypsometry

(c) Difference between (a) and (b)

(d) dh–elevation gradient

Figure 3. Glacier accumulation and ablation areas indicate regionally different, distinct glacier evolution: glacier surface elevation change for (a) upper 50% and (b) lower 50% of glacier hypsometry, and (c) the difference of the two (upper minus lower). The letters indicate: L – thickness loss on entire glacier, G – thickness gain, A – adjusting glacier geometry with thinning ablation areas, D – dynamic adjusting of glacier geometry with thickening ablation areas. (d) Gradients of dh (ICESat–SRTM surface elevation) with elevation. Steep dh–elevation gradients may be caused by high SRTM penetration depths in dry, cold accumulation areas and/or from glaciers adjusting their geometry.

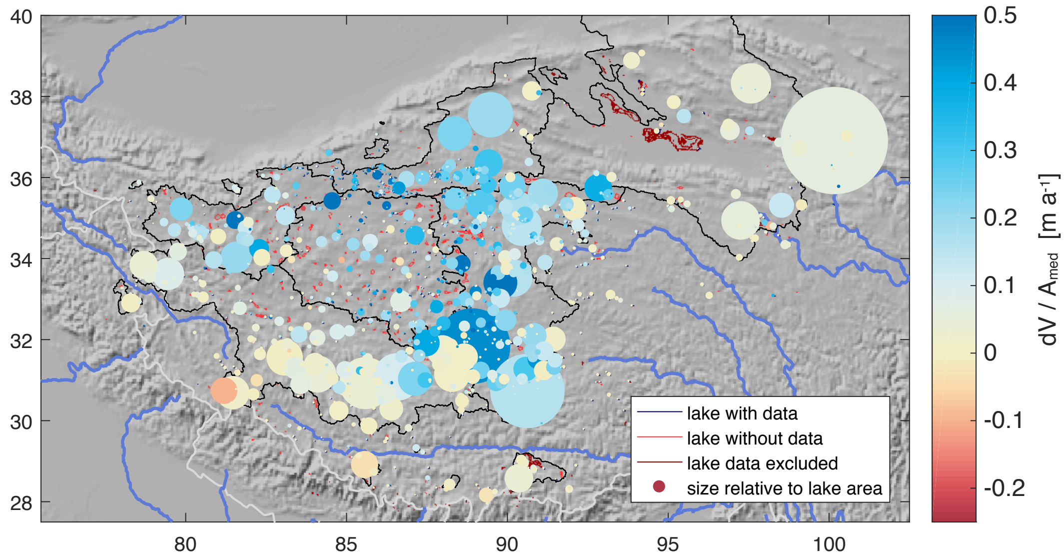
4.2 Influence of dh–elevation gradient and December 2008 snow fall

The dh–elevation gradients ~~between ICESat and the SRTM DEM~~ are in some units very steep (Fig. 3d). This means that the surface elevation differences between ICESat and the SRTM DEM are very negative on glacier tongues but very small or even strongly positive in the upper accumulation areas. Steep dh–elevation gradients can result from altitudinal ~~trends in~~ dependency of radar penetration or glacier geometry changes between SRTM and ICESat surface elevation acquisitions. The steeper the dh–elevation gradients are, the stronger is the biasing influence from glacier hypsometry missampling. On the TP and in the northern and eastern ranges of the Tien Shan, the gradients range between 1.5–2.5 m per 100 m elevation. Glaciers in these areas typically occur within an elevation range of ca. 1000 m. In the Nyainqêntanglha Shan/Hengduan Shan, West Kunlun Shan, Karakoram, southwestern Tien Shan and the highest Pamir mountains, dh–elevation gradient values are 1–1.5 m per 100 m elevation. The gradients are moderate (< 1 m per 100 m elevation) in the Himalaya, East Kunlun Shan, lower in Pamir, and lowest in the Hindu Kush (0.14 m per 100 m). Our method ensures that any bias from inconsistent sampling of glacier elevations for individual ICESat campaigns is corrected. Neglecting the effect of glacier hypsometry missampling or a trend in sampled glacier elevations would result in considerable bias: on average $\pm 0.13\,\mathrm{m\,a^{-1}}$, but exceeding $0.1\,\mathrm{m\,a^{-1}}$ in 51 of 100 units. The most extreme cases ($> \pm 0.3\,\mathrm{m\,a^{-1}}$) are three units each in Tien Shan and Karakoram.

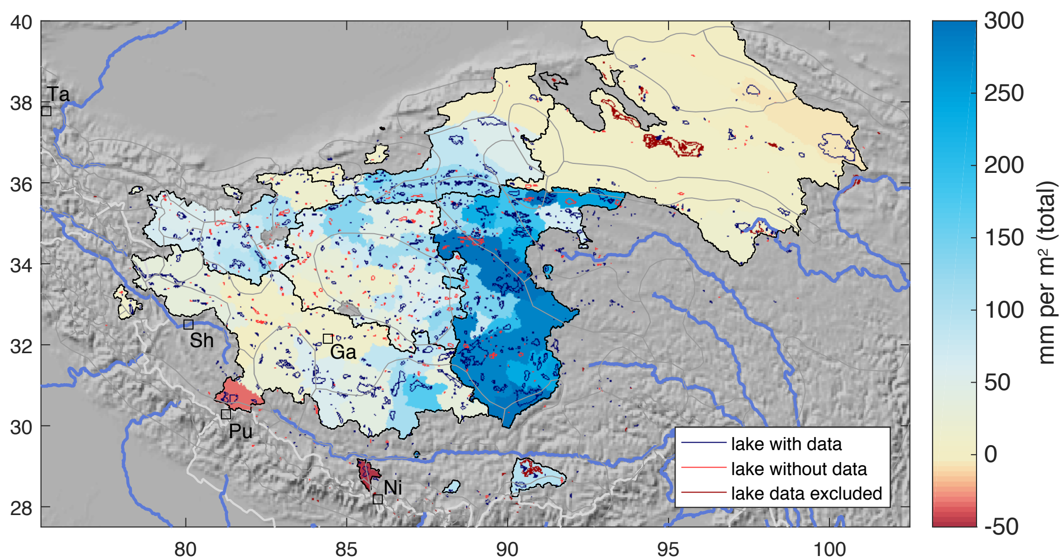
Correcting dh retrieved from the December 2008 campaign for the effect of increasing snow cover has an unexpectedly large influence on glacier surface elevation change rates. Elevation ~~trends~~ changes from corrected dh are on average $0.088\,\mathrm{m\,a^{-1}}$ more negative/less positive. The maximum effect of the December 2008 correction is as much as $-0.25\,\mathrm{m\,a^{-1}}$ (in unit N2; for off-glacier samples: $-0.11\,\mathrm{m\,a^{-1}}$ in unit H2), which is of considerable size given that it is caused by only ca. 10% of all samples (half of one of five campaigns). The potential biasing effect is in fact greatest in areas where MERRA-2 data suggests snow fall during October/November/December 2008 and where off-glacier samples suggest a positive surface change trend ~~.~~ (suppl.). However, in 20 out of 100 units we were not able to compute the potential biasing effect of December 2008 snow cover (e.g., due to lack of off-glacier samples). To ensure a consistent approach, we did therefore not apply this correction to the results presented above but instead added the difference due to bias correction to the error budget ~~.~~ (Fig. 2c). A discussion of biasing influences and corrections is provided in Appendix D.

4.3 Lake changes on the TP

We receive valid (according to our filter procedures) water volume change time series for 89% of the median lake area (74% of all endorheic lakes) on the TP: 1009 lakes with SRTM-based lake surface elevations, thereof 103 also having ICESat-based lake surface elevations (59% of the lake area). Extrapolated lake levels based on annual or campaign ICESat data (Appendix C) yield the same results, but ICESat-based lake level change is on average 1.55 times larger than SRTM-based values. Likely, the reason for this difference is the greater uncertainty of SRTM DEM elevations and pre-2000 SRTM lake levels (Appendix C1). Multiplied with areal changes to receive volume changes, the relative difference is reduced to 1.09 times. Average 1990–2015 ~~lake growth~~ water level increase corresponds to $0.14\ \mathrm{m\ a^{-1}}$ (SRTM) and $0.18\ \mathrm{m\ a^{-1}}$ (ICESat) in lake-level change per year (Fig. 4a, robust linear regression of dV~~sealed with median lake area for easier comparison of values between lakes of very different size~~). All, except a handful of lakes predominantly in the very south of the TP, grew during the studied time period, and growth of individual lakes is largest in the northern and eastern part of the TP. Figure 5 shows relative lake volume growth (based on SRTM lake levels) for individual lakes and regional medians over time for six regions: southwestern, eastern, central, northeastern, northwestern TP and Qilian Shan, indicated in Fig. 4a. (Note that the y-axis in Fig. ~~4a is relative to the~~



(a) Normalised 1990–2015 lake volume change for individual lakes



(b) Annual specific water change per endorheic catchment between 1990–1999 and 2000–2009

Figure 4. Lake volume changes on the Tibetan Plateau. (a) Normalised lake volume change for individual lakes. Colours show the average annual 1990–2015 lake level change in metres (volume ~~change~~ changes dV divided by median lake ~~area~~ areas to receive comparable values for lakes of different sizes). Circles are scaled relative to lake area. (b) Annual specific water change per endorheic catchment for the decadal difference between 1990–1999 and 2000–2009 lake volumes. Values correspond to the sum of individual lake water volume changes (average changes assumed for lakes with missing data) divided by catchment area to make their units comparable to precipitation sums. Red lake outlines: lacking plausible data; purple lake outlines: lakes excluded due to human influence on lake levels/extent. Squares: meteorological stations. Regions with black outlines referred to in the text.

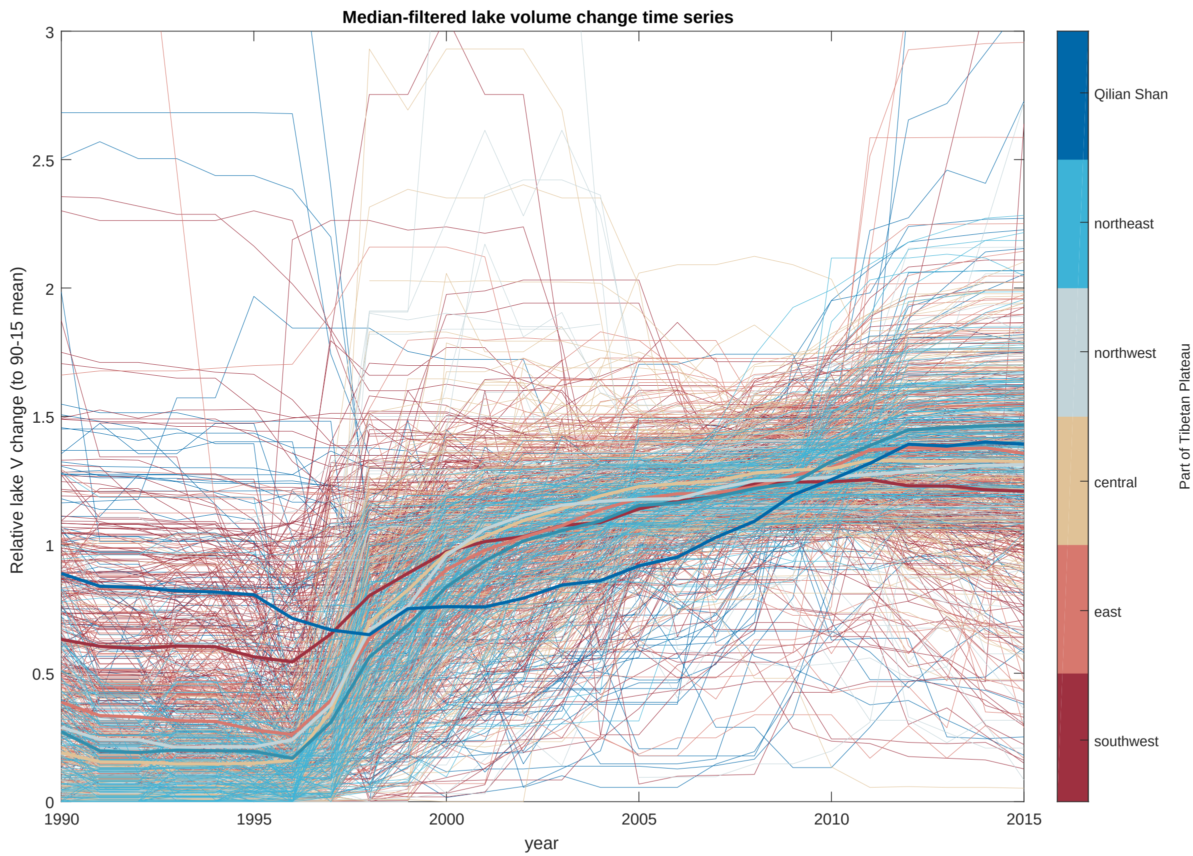


Figure 5. Relative lake volume change for individual lakes on the Tibetan Plateau, coloured by region. Volume changes dV are normalised by the 1990–2015 mean dV for comparability, annual values are median-filtered (7 years window size). Thick lines indicate the median for each region. The regions northeast, northwest and central correspond to areas with observed 2003–2008 glacier thickening.

~~total volume change dV over the time period observed and does not show~~ 5 shows the timing of the volume change and not changes in absolute lake volumes~~; ~~, these are unknown~~as our method only detects lake level changes and not lake depths~~). Rather than growing steadily, most lakes seem to have undergone a phase of sudden and rapid growth starting ~~in ∼1997 and~~ between 1995 and 2000, and gradually slowing down until ∼2009, with rather stable conditions before and after this period. (Note that lake time series are median-filtered due to data scarcity for the years 1995–1999. There is thus some uncertainty on the exact timing of the onset of lake growth.) Relative lake volume change was most sudden and rapid for the northeastern, northwestern, central and eastern TP (the former three corresponding to areas with 2003–2008 glacier thickening). Lakes in the southern and southwestern part of the TP showed more varying and overall less growth, with a tendency to decrease after 2010. Endorheic lakes in the Qaidam basin/Qilian Shan region further northeast also show a different and more varying evolution

Table 1. Water volume changes between decadal averages of the 1990s and the 2000s (dP and dV), and 2003–2008 annual glacier mass balance of adjacent glacierised areas for 2003–2008 (last column). dV: total decadal lake water volume difference per basin region in mm m^{-2}, dP: annual precipitation difference in mm m^{-2}a^{-1}, station order in southwest TP: Shiquanhe, Gaize, Pulan, Nielaer. Glacier surface elevation changes are converted to mm w.eq. a^{-1} assuming a density of 850 kg m^{-3}.

Region	dV SRTM	dV ICESat	dP MERRA-2	dP ERA Interim	dP stations	Glacier mass balance
Southwest TP	39±11	59±16	81±33	15 ± 31	-1 ± 14, 42±17, 19 ± 16, 60±50	-33 ± 11 to -10 ± 14
East TP	252±33	275±37	100±18	30 ± 14		-17 ± 10 to -8 ± 14
Central TP	69±10	71±11	56±5	25 ± 8		21 ± 38
Northwest TP	62±14	70±15	34±11	-33 ± 11	16 ± 72	29 ± 10 to 31 ± 9
Northeast TP	60±12	54±9	85±13	-2 ± 22		13 ± 11 to 50 ± 21
Qaidam / Qilian	1±5	1±4	87±14	24 ± 17		-25 ± 14 to -13 ± 10

with slower growth that started only around 2004, but continued until ~2012. The latter effect is also visible for the adjacent lakes on the northeastern TP (east Kunlun Shan).

Figure 4b shows the corresponding specific annual water volume change per endorheic catchment as the decadal difference between 1990–1999 and 2000–2009 average lake volumes (based on SRTM lake levels). The pattern of predominant water volume increase especially in the northern and eastern TP compares well to the results in Fig. 4abut with a stronger accentuation of the lake . Lake volume growth on the eastern TP is accentuated due to considerably larger lake areas and lake density compared to the mostly small lakes further north/west. Table 1 shows additional water volumes accumulated between the two decades for the same regions as above. To yield values comparable to precipitation changes, the reader has to divide the total decadal differences dV given in the table by the number of years during which the additional water was accumulated. Assuming the change happened rather gradual during the entire decade, the specific annual water change would correspond to 1/10 of the values in Table 1. For instance, for water volumes using SRTM-based lake levels: 25±3 mm a^{-1} for the eastern TP, 4±1 mm a^{-1} for the southwestern TP, 6–7±1 mm a^{-1} for the central and northern TP, and 0.1±0.5 mm a^{-1} for the Qaidam basin/Qilian Shan region. Notably, there are considerable differences between catchments within each region (range for SRTM-based estimates: –5±1 to +35±6 mm a^{-1}, excluding one outlier of 163±7 mm a^{-1} for the catchment centred at 34.3° N / 88.8° E). The estimates based on SRTM- and ICESat lake levels aggregated for the six regions nevertheless agree very closely. The above annual values have to be doubled, or the dV values given in the table multiplied by 1/5, for instance, if one prefers to assume that the water volume increase happened during 5 years only, with stable conditions before and after — an assumption which seems also well also is plausible from Fig. 5.

4.4 Precipitation increase on the TP

A change in precipitation could explain both lake growth and glacier mass balance (if dominated by precipitation rather than temperature/melt). When subtracting the part that is lost through evaporation, precipitation change should yield numbers that are directly scalable in relation to glacier mass balance and endorheic catchment water volume (when neglecting changes in subsurface water transport).

Annual precipitation sums on the TP from meteorological stations range from as little as 50–100 mm a^{-1} (~~Shiqanhe and Thashkurgan~~ Shiquanhe and Tashkurgan stations, southwest TP and West Kunlun Shan) to 500–900 mm a^{-1} (Nielaer station, southern TP). Reanalysis values of both products used, MERRA-2 and ERA Interim, lie in between. All datasets record the majority of precipitation (>70%) during the monsoon-influenced summer months (May–September), except for Pulan and Nielaer, the two southernmost stations close to the Himalaya (only ca. 50% precipitation in summer). On the data-sparse TP, both station data and reanalysis products may contain bias due to the stations not being representative for a larger area and the lack of observational forcing data for reanalysis products, respectively. We thus use the data in a summarised way and focus on relative changes rather than relying on absolute numbers to detect/confirm temporal changes and large-scale spatial patterns.

Of the five meteorological stations available, especially Shiquanhe and Pulan show little change in precipitation and pan evaporation (Fig. 6). The Gaize station, located most central on the TP but still more south than our corresponding glacier unit, indicates a step-like precipitation increase around the year 2000, but data from only one station need of course to be interpreted with care due to potential local effects and changes to the station. A more gradual increase is visible in the Tashkurgan data. Differences in decadal average precipitation range from −1 (Shiqanhe) to 60 mm (Nielaer) within 10 years, notably with greatest relative change for the Gaize station (+42 mm per decade, a 25% increase) and Tashkurgan station (+16 mm or +22% per decade). Decadal differences are mostly (Nielaer, Tashkurgan) or exclusively (other stations) caused by an increase of precipitation during summer months. Pan evaporation reaches twice to tenfold of precipitation sums.

The two reanalyses used here differ considerably both in precipitation evolution and in estimated evaporation ~~.~~ (Fig. 7), and also the spatial patterns of precipitation changes differ (Fig. 8). Figures 7a (ERA Interim) and 7b (MERRA-2) show regional averaged annual sums for total precipitation, evaporation, and the difference of the two, for grid points within the TP lake catchment regions defined above. Notably, ERA Interim suggests considerably higher evaporation values than MERRA-2, in particular for the southwestern TP (SW) and the three northern regions ~~,~~ (NE, NW, QQ) resulting in much lower suggested net water availability in the areas where we see glacier thickening than it is the case for MERRA-2. Both reanalyses show an increase in precipitation starting from ca. 1995, but for ERA Interim, the evolution only lasts until ca. 2000 after which precipitation sums decrease. Also, the short-term precipitation increase is not visible for the northern parts of the TP~~, and it does not result in a noticeable~~. Fig. 8a shows the spatial distribution of the decadal difference between average ~~annual~~ summer precipitation in 1990–1999 vs. 2000–2009. ERA Interim data suggests only a marginal precipitation increase on the TP and a considerable decrease in decadal average precipitation for the Kunlun Shan area (−33±11 mm for northwestern TP, table 1).

MERRA-2, on the other hand, rather suggests a step-wise ~~increase~~ precipitation increase (Fig. 7b) with continuously higher precipitation sums until ca. 2010 for the entire TP, and even a continuous increase through 2015 for the northern part of the TP. For all six regions, this results in a total increase in precipitation of 34±11 mm (northwestern TP, table 1) to 100±18 mm (eastern TP) mm within 10 years. Except for the Qilian Shan region, the change is exclusively driven by increasing summer precipitation(Fig. 8b). Winter precipitaion . Winter precipitation did not change noticeably (−9 to −2 mm decadal change for the five TP regions, +8 mm for Qilian Shan). Fig. 8b shows the spatial distribution of summer precipitation change (difference between decadal averages). Compared to the same map with ERA Interim data, MERRA-2 suggests a considerably stronger precipitation increase on the TP and increasing precipitation also in the Kunlun Shan area. For both reanalyses, the spatial patterns are the same for annual precipitation rather than summer precipitation only (not shown).

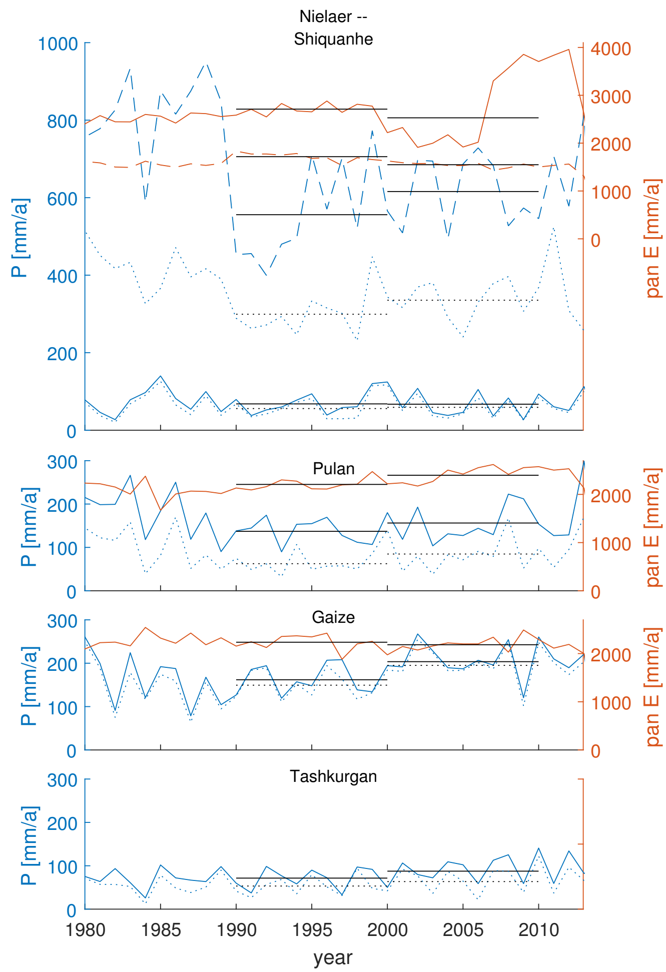
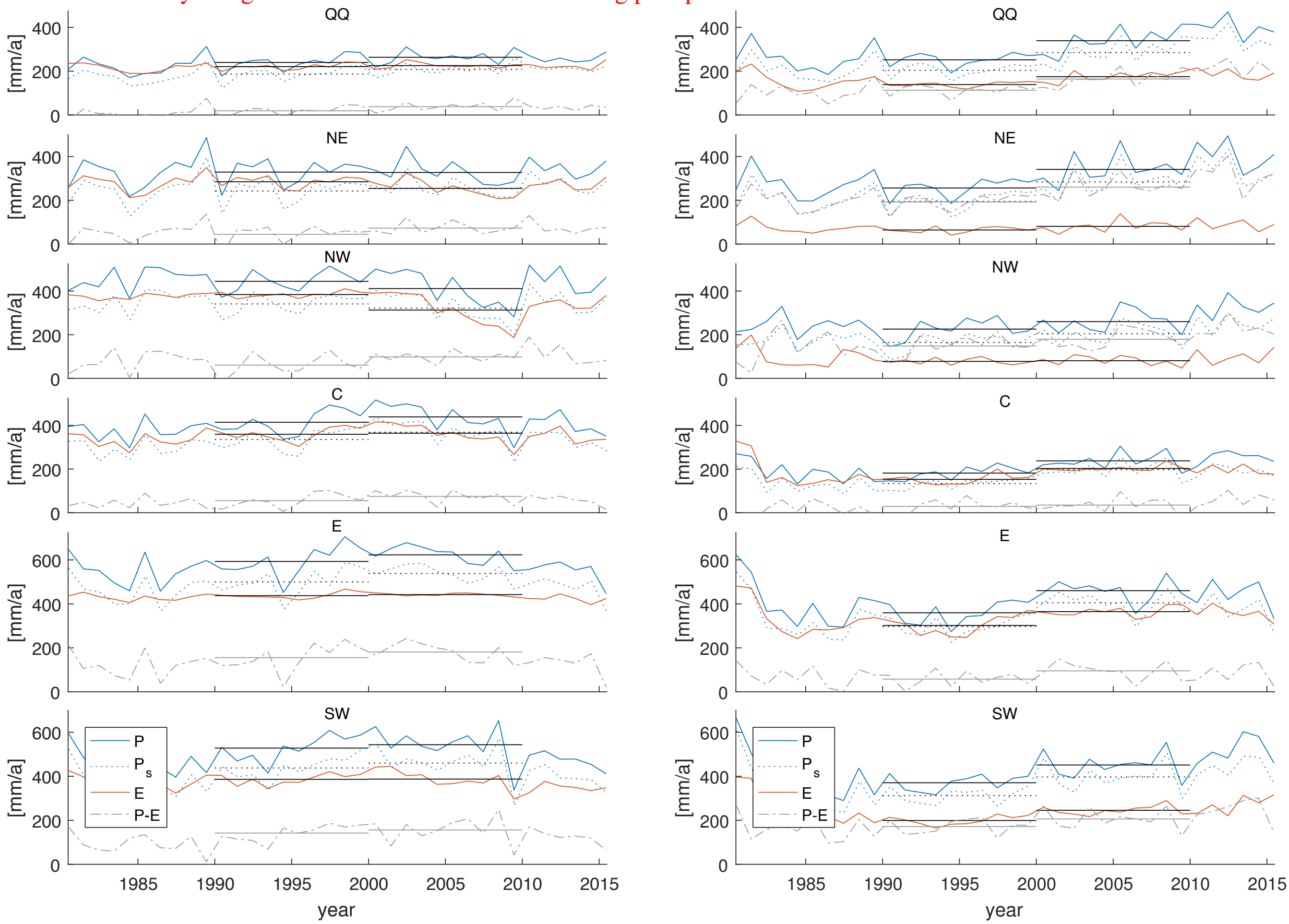


Figure 6. Annual precipitation (P, blue line), pan evaporation (pan E, red line), and summer precipitation (dotted lines) for five stations on the southern and western TP (Fig. 4b). The uppermost panel combines two stations (Nielaer: dashed lines; Shiquanhe: solid lines).

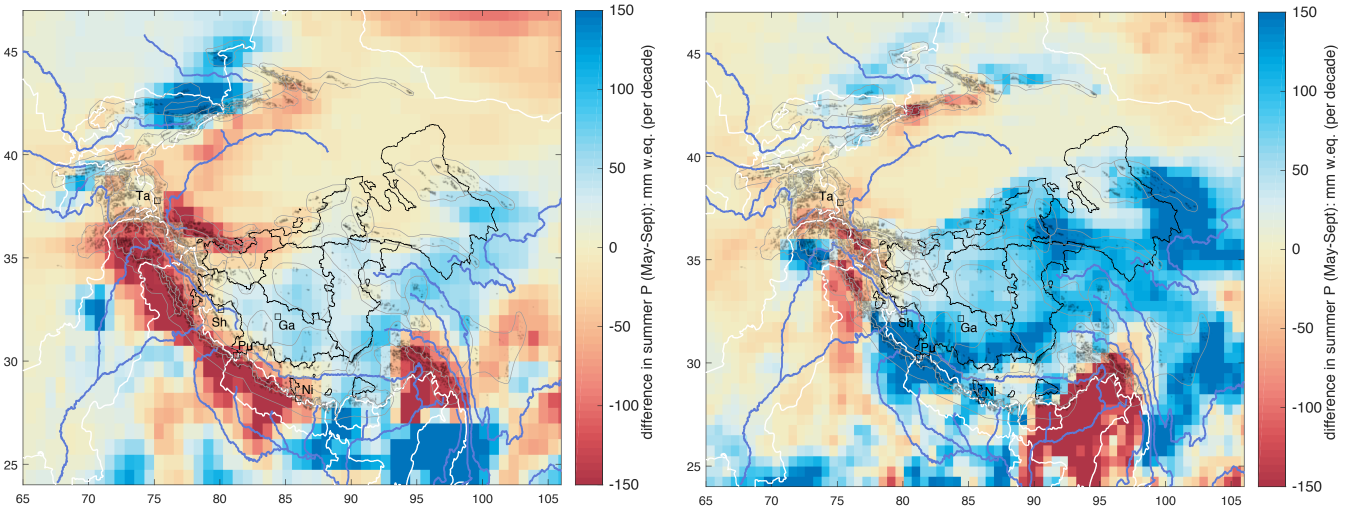
ERA Interim MERRA-2 Difference between decadal averages of summer precipitation (May–September) in 2000–2009 and 1990–1999. MERRA-2 suggests an increase of up to 100 mm within 10 years on the TP and in the Kunlun Shan, compared to only a slight increase on the TP and decreasing precipitation in the Kunlun Shan for ERA Interim.



(a) ERA Interim (b) MERRA-2

Figure 7. Timeseries of annual total precipitation (P), evaporation (E), the difference of the two (P-E), summer precipitation (Ps, May–Sept), and their respective decadal averages, for reanalysis grid points within the six lake change regions on the TP: southwestern (SW), eastern (E), central (C), northwestern (NW), northeastern (NE) TP and Qaidam Basin / Qilian Shan (QQ).

When correcting these values with



(a) ERA Interim (b) MERRA-2

Figure 8. Difference between decadal averages of summer precipitation (May–September) in 2000–2009 and 1990–1999. MERRA-2 suggests a considerable increase on the TP and in the Kunlun Shan, compared to a negligible increase on the TP and decreasing precipitation in the Kunlun Shan for ERA Interim.

The two reanalysis products agree somewhat better when precipitation numbers are corrected with estimates of actual evaporation ~~,~~ to assess the total decadal increase in water availability~~ranges from~~ . For MERRA-2, the decadal difference is then reduced to 6±11 mm (central TP) to 68±13 mm (northeastern TP). ~~The~~ However, the evaporation-corrected increase is ~~even~~ greater when looking at summer months only (~~31–77 mm~~ 31±7 mm to 77±11 mm per decade, compared to a decrease in water availability during winter months of ~~−27 to −6~~ −27±4 mm to −6±3 mm, not shown). ~~MERRA-2 suggests~~ Corresponding ERA Interim increase in annual water availability is 14±32 to 38±12 mm (summer: −19±11 mm in the Kunlun area to 38±13 mm, winter −16±6 to 5±4 mm). Both datasets suggest that 30–60% (MERRA-2) or 13–50% (ERA Interim) of precipitation on the TP falls as snow during the summer months and that the proportion of snow fall did not change noticeably between the decades (not shown).

The regions where MERRA-2 indicates increased summer precipitation correspond well with those areas on the TP and in Eastern Kunlun Shan with moderately negative to positive surface elevation change and/or endorheic lake growth. ERA Interim data indicates a similar pattern but ~~with much~~ the lower (TP) precipitation increase ~~, or even decrease in case of~~ and, particularly, the decrease for the Kunlun Shan region (Fig. 8a) does not fit well with the results from our lake and glacier data.

Our above results on precipitation changes relate to decadal means in order to enable systematic comparison to other data. It is however important to note that these results vary if other time periods are chosen for aggregation. Kääb et al. (2018), for instance, summarize total annual precipitation amounts estimated from ERA-interim reanalysis over the Aru region, nortwestern TP, over 1979–1995 and 1995–2008 to suggest a 33% increase between the ~~latter both~~ periods.

5 Discussion

The 2003–2008 ICESat surface elevation changes paint a spatially diverse picture of glacier changes in HMA. The general pattern — glacier volume gain in the Kunlun Shan and the inner TP and glacier volume loss elsewhere — appears robust, no matter whether we aggregate the samples in a regular grid or manually delineated units. The more distinct spatial pattern agrees with the ICESat studies of Kääb et al. (2015, 2012), the ASTER-based geodetic mass balances of Brun et al. (2017) and with the overall picture drawn by the previous regional studies of Neckel et al. (2014), Gardner et al. (2013) and Farinotti et al. (2015) based on data from ICESat, GRACE and modelling. The pattern found is also robust against small changes in reference elevations (such as from using the 1 arc-second SRTM DEM) or sample composition, and can also be reproduced using the most recent RGI glacier outlines — which have clearly become much more accurate since the study of Gardner et al. (2013).

On a local scale, and in contrast to the above regional view, there are considerable differences to previous findings in glacier changes, including the ones based on the same ICESat data. Compared to a visualisation of our results in a regular grid, we find that spatial aggregation matters: even within our study, only the manual zonation brings forward finer spatial differences e.g. from topographic-orographic setting. Our results also suggest that inconsistent sampling hypsometry, snow cover, and local vertical biases and elevation inconsistencies can have a severe biasing effect on ICESat-based glacier changes when not accounted for properly — in particular where they vary for different ICESat campaigns. A method discussion, in particular on biasing influences on ICESat glacier surface elevation change rates, is provided in Appendix D.

5.1 Coincident lake growth and glacier thickening

The regions with ~~increasing glacier volume~~ glacier thickening, or thickening of upper glacier areas (fig. 3a), spatially match the areas with growing endorheic lakes on the TP and where MERRA-2 data suggests a step-like increase of summer precipitation around the year 2000. The change in available precipitation amounts, lake water volume, and glacier mass balances are of the same magnitude and match well in terms of timing. ~~The~~ Studies analysing individual lake time series suggest the increase started closer to the year 2000 (Lei et al., 2013; Zhang et al., 2017, 2018; Song et al., 2015) than our fig. 5 suggests. This could be due to the application of a median filter which contributes to shifting the onset of volume change in the middle of a period with large Landsat data gaps (1996, 1997, see App. A4). The recent growth of TP's lakes is established by numerous recent studies (e.g., Zhang et al., 2011, 2013; Song et al., 2015; Zhang et al., 2017). In this study, lake volume changes on the TP serve as proxies for precipitation changes, but they may also help resolving satellite gravimetric signals to compute glacier mass changes (see introduction). The fact that glacier volumes are ~~predominantly~~ increasing in regions where also lake volumes increase, and the fact that lake volumes are also increasing in little or not ~~glacierized~~ glacierised basins, both suggest that the increases in lake volumes over the study region are not mainly driven by increased water influx from glacier mass loss (see e.g. Song et al., 2015).

Though, glacier mass loss can certainly play an additional role for lakes with declining glaciers in their catchment. This is in line with, and ~~extents~~ extends geographically, water balance modelling by Lei et al. (2013) for six selected lakes in our East TP zone (Fig. 4b) that suggests mainly precipitation increases to be behind the increases of lake volumes, accompanied by decreases in potential evaporation due to decreasing wind speed, and to a lesser extent increase in glacier runoff (Song et al., 2015). For the Evaporation may also have decreased due to increased humidity from higher precipitation amounts. For 1981–2013, Zhang et al. (2018) find a significant decrease of pan evaporation from meteorological stations on the Eastern TP (these are however further east than the endorheic lakes). For the Siling Co lake in our East TP region, potential evaporation , though decreasing overall over 1961–2010, showed actually showed stable conditions or a slight increase between the mid/end 1990s to 2010 although it was decreasing overall over 1961–2010 (Guo et al., 2019), underlining even more the key role of precipitation increases for the observed lake volume increase.

On a local scale, and in contrast to the above regional view, there are considerable differences to previous findings in glacier changes, including the ones based on the same ICESat data. Compared to a visualisation of our results in a regular grid, we find that spatial aggregation matters: even within our study, only the manual zonation brings forward finer spatial differences e. g. from topographic-orographic setting. Our results also suggest that inconsistent sampling hypsometry, snow cover, and local vertical biases and elevation inconsistencies can have a severe biasing effect on ICESat-based glacier changes when not accounted for properly — in particular where they vary for different ICESat campaigns. Lei et al. (2013) suggest that groundwater exchange between different basins has very limited influence on the water balance of each lake due to the impermeability of surrounding permafrost. Such groundwater exchange does not affect the basin-wide water volume changes of this study, but thawing permafrost could be another potential source of water. An increase of active layer depth also causes an increase in groundwater storage capacity in ice-free ground an may change the amount of precipitation or water from snow melt that is retained or released (S. Westermann, pers. comm.). However, we are not aware of studies that quantify the amount of water available from these processes. Modelling studies (Ran et al., 2018; Zou et al., 2017) find continuous permafrost in the northern part of the TP (our regions NW, NE, C and most of E) and discontinuous permafrost including larger areas of non-frozen ground in the southern/eastern parts of the TP (our regions SW and most of QQ). Recent and ongoing temperature rise led to an increase in the active layer and degrading permafrost that seems to have been greatest during the 60s and 00s and in the southern and eastern parts of the TP (Ran et al., 2018), where we find little lake change / lake growth (SW) and strong lake growth (E), respectively.

5.2 Precipitation increase on the TP

5.2 Precipitation increase on the TP and glacier sensitivity to these changes

In particular the MERRA-2 reanalysis, and to a lesser degree also ERA Interim and station data, suggest precipitation on the TP has increased around 1995–2000. The spatial patterns of MERRA-2 decadal precipitation increases and the glacier growth on the TP and in the Kunlun Shan suggest a causal relationship. Increased precipitation in the region has been noted before: Yao et al. (2012) attributed a pattern of precipitation/glacier changes to a strengthening of the Westerlies while the Indian monsoon is weakening. Also a A rise in extreme precipitation events at stations in the study region was attributed to a weakening East Asian monsoon (Sun and Zhang, 2017). Fujita and Nuimura (2011) and Sakai and Fujita (2017) model a decrease in theoretical equilibrium line altitudes (ELA) in western Tibet over between 1988 and 2007, and attribute these trends to increasing precipitation in western Tibet (but decreasing precipitation in western Pamir and the western Himalaya). Several studies report that lake levels recently were increasing on the TP (e.g., Zhang et al., 2011, 2013; Song et al., 2015; Zhang et al., 2017). Glaciers in West Kunlun were in general shrinking between 1970 and 2001, only those on the south slope were already growing between 1991 and 2001 (Shangguan et al., 2007).

While the MERRA-2 reanalysis data does not suggest an increase in summer precipitation in Eastern Pamir and on the western and northern boundary of the Tarim Basin, Tao et al. (2011, 2014) found indications for a wetter climate and increasing streamflow in the entire basin. Shi et al. (2007) suggest that a shift from a warm-dry to a warm-wet climate in the entire northwest of China happened already around 1987. Our results suggest indicate that glaciers on the southernmost orographic barrier in the Tien Shan are closer to balance than glaciers further north/west. We thus speculate that the change in circulation patterns behind the positive precipitation change, centred further south, extends across the entire Tarim basin, and with it more favourable conditions for glaciers on the edge of the entire basin.

Lack of meteorological observations on large parts of HMA result in substantial uncertainties with recent precipitation changes on the TP (Kang et al., 2010) and available gridded precipitation datasets (Sun et al., 2018; Smith and Bookhagen, 2018). While they are also affected by the lack of direct observations, reanalysis products are an important source of physically based model data in such data-sparse regions (Cuo and Zhang, 2017). Orsolini et al. (2019) find that MERRA-2 does not model snow depth or snow cover fraction well on the TP, but still best matches total precipitation amounts on the TP compared to ERA Interim and other reanalysis products which overestimate precipitation compared to reference data. Assimilation of snow observations and a better parametrisation of snow-related physical processes are thus needed to improve model performance for the often thin and short-lived snow cover should improve future reanalysis products on the TP (Orsolini et al., 2019). Also improved spatial resolution should contribute to better model high-altitude precipitation due to the importance of spatial resolution to capture orographic processes. Examples are the High Asia Reanalysis HAR (Maussion et al., 2014, available for most of HMA the upcoming ERA5 Land reanalysis.

Maussion et al. (2014) proposed a new classification for HMA glaciers based on their main accumulation season from 2000–2011 HAR precipitation data. Our pattern of positive glacier changes matches very well with their classification of the predominant glacier accumulation season as spring or early summer. On the TP, Maussion et al. (2014) find a gradual transition towards later accumulation (monsoon-dominated) whereas there is a crisp boundary to winter accumulation in the Karakoram/Pamir. Both patterns correspond to the zonal boundary of 'extreme continental (polar) glaciers' suggested by Shi and Liu (2000), which encompasses the northwestern half of the TP, glaciers north of central Karakoram, the easternmost Pamir, and the entire Kunlun Shan. On a coarser spatial and longer temporal scale, Kapnick et al. (2014) suggest that glacier accumulation in the Karakoram is least sensitive to atmospheric warming due to dominating non-monsoonal winter precipitation in this region.

Forsythe et al. (2017) attribute recent summer cooling in the Karakoram to a southerly shift of a circulation system that they named Karakoram vortex. In the Karakoram area the southerly shift leads to increased passage of westerly depressions and corresponding cooler temperatures due to increased cloud cover and decreased insolation. The effect of this may extend to the areas to the north, namely the Kunlun Shan, Pamir, Tien Shan and Tarim basin (see their fig. 2b). de Kok et al. (2018) model the effect of increased irrigation intensity in the lowlands of HMA and find that they may cause increased summer snow fall and a decrease in net radiance in the Kunlun Shan and parts of Pamir and northern Tibet.

Fujita (2008) finds that HMA's glaciers are more affected by precipitation seasonality and concentration than by changes in annual precipitation. Where accumulation and warming happen at the same time (i.e. summer), rising temperatures increase both melt and the share of precipitation that falls as rain instead of snow. While temperatures are rising in entire HMA, the glacier sensitivity study of Fujita and Nuimura (2011) suggests that temperature was not the limiting factor for glacier existence everywhere. In the extremely dry and cold TP and Kunlun Shan, with glaciers and in particular their accumulation areas at high elevations (Fig. 1), glacier growth due to increased precipitation is thus entirely plausible — despite a warming trend. This also stresses that the ~~altitude~~ elevation of HMA glaciers (Fig. 1) is an important factor in their respective responses to temperature and precipitation changes (Sakai and Fujita, 2017), and thus in the here-observed glacier volume changes.

5.3 Glacier geometry changes on the TP

In light of continued climatic changes and rising temperatures in the study region, ICESat only provides a short snapshot of ongoing glacier reactions. This snapshot falls exactly into the decade where an increase in precipitation on the TP around the year 2000 would cause the largest effects on glacier volume changes~~due to dynamic adjustment of the geometry in ablation areas as a delayed signal towards a~~: with some delay, glaciers dynamically change the geometry of their ablation areas (they are thickening) to adjust to a new glacier equilibrium state (Kääb et al., 2018; Gilbert et al., 2018). Ke et al. (2015) and Bao et al. (2015) report such stronger surface elevation gain for ablation areas compared to elevation gains in accumulation areas in what they refer to as West Kunlun Shan (our unit KS1, plus four to the North and East of it). ~~We~~ As visible in Fig. 3c, we find the same signal for a larger area of an additional eight adjacent units, including those to the South (area marked "D"). Care has to be taken when analysing elevation changes over only parts of a glacier as this violates the condition of mass continuity. ~~A thickening~~ Thickening of the ablation parts of a glacier can ~~thus~~ be caused by either positive surface mass balance or dynamical changes (i.e. increased ice flux). In the case of West Kunlun Shan, a stronger thickening of the tongues compared to ~~higher elevations could indicate~~ upper glacier areas could indicate that both were happening: a general glacier thickening from ongoing positive mass balances, plus a delayed dynamical thickening from earlier mass gain in the accumulation areas.

~~Southeast~~

The rate of warming on the TP is greatest for the elevations where glaciers have their ablation areas (Yao et al., 2012; Ran et al., 2018). In the southeastern part of the TP, dh–elevation gradients are largest (darker units in Fig. 3d), which could indicate that dynamical changes are happening also there: an overall thinning signal could be composed of increased melt at lower elevations, causing strongly negative dh, while the accumulation areas are ~~growing~~ thickening or stable due to increased precipitation/accumulation, causing ~~strongly positive dh(Fig. 3d)~~stable surface elevations or positive dh. This interpretation is supported by the gradual transition visible in Fig. 3c: in East Kunlun Shan and central TP, we see a thickening of accumulation areas and no change on the tongues (area marked "G"), and further east/south accumulation areas experienced little change but tongues were thinning (marked "L/A").

Dynamic glacier geometry adjustments might also be reflected in glacier flow. Dehecq et al. (2019) found that, for the 2000–2016 period, the flow speed of HMA glacier tongues decreased everywhere but in the Kunlun Shan and Karakoram and only slightly decreased on the TP. While the different time periods and spatial aggregation don't allow a more detailed comparison, their results confirm that these regions were not or less affected from rapid glacier mass loss with thinning and increasingly inactive tongues.

5.4 Glacier thinning on the Eastern Tibetan Plateau

The negative ~~trends~~ elevation change rates on the eastern border of the TP agree with reported glacier mass loss in this area, although varying annually and in space (Kang et al., 2009; Yao et al., 2012). For this part of the southeastern TP, Mölg et al. (2014) found that the competition between the monsoon and large-scale westerly waves of the mid-latitude circulation in spring/early summer determines annual mass balance. The south–north transition of the jet stream across the TP in spring varies in timing and efficiency, and its re-intensification in summer on the northern edge of the TP is related to the onset of the summer monsoon (Schiemann et al., 2009). This interplay affects both precipitation and summer air temperature. All glaciers in the region are of summer accumulation type, except for East Nyainqêntanglha Shan and Hengduan Shan (Maussion et al., 2014). The area where the atmospheric flow strength over the TP correlates strongly with summer temperatures (Mölg et al., 2014) forms an arc-shaped band from the above mentioned mountain ranges along the northern slopes of the East Nyainqêntanglha Shan to the easternmost glacierised mountains in the area. The correlation of Monsoon/Westerlies competition with temperature is decreasing rapidly north towards the easternmost Kunlun Shan and south to the Goikarla Rigyu range just north of the Yarlung Tsangpo Valley. This pattern corresponds well with our findings of only slight glacier thinning in Goikarla Rigyu/East Kunlun Shan (units N3 and KS2) but more negative volume changes in the easternmost HMA glaciers (our unit HS). Reconstructed mass balances from six glaciers on the eastern slope of Minya Gongga (in the very east of unit HS) were $-0.79\,\mathrm{m\,w.e.\,a^{-1}}$ in 2001–2009, a notable further decrease from an already negative average of $-0.35\,\mathrm{m\,w.e.\,a^{-1}}$ in 1952–2000 (Zhang et al., 2012). Converted to mass loss, our results in this area are $-0.77 \pm 0.42\,\mathrm{m\,w.e.\,a^{-1}}$ — the large uncertainty reflects the sparse glacier coverage and low sample numbers in this unit. ~~(Zhang et al., 2012)~~ Zhang et al. (2012) report that both the ELA and temperatures in the beginning and end of the melt season were strongly rising during the ICESat decade.

Glaciers in the Qilian Shan in the very northeast of the TP have been shrinking less than those further south in the last decades (Tian et al., 2014). In-situ mass balances on Qiyi glacier were strongly negative in 2005–2006 ($-0.95\,\mathrm{m\,w.e.\,a^{-1}}$) but less so in 2006–2007 ($-0.3\,\mathrm{m\,w.e.\,a^{-1}}$). The 2006 negative mass balance is indeed visible as a marked decrease between ICESat's 2005 and 2006 autumn campaign median dh in all our units north of Nyainqêntanglha Shan (not shown). We find only moderate thinning in the eastern part of Qilian Shan (converted to mass changes: $-0.26 \pm 0.14\,\mathrm{m\,w.e.\,a^{-1}}$), where Qiyi Glacier lies, and even less negative values further west ($-0.14 \pm 0.10\,\mathrm{m\,w.e.\,a^{-1}}$), in line with Tian et al. (2014). Towards east, glaciers become smaller and elevations lower, and the influence of the East Asian Monsoon becomes stronger.

5.5 Glacier ~~sensitivity to~~ mass balance and precipitation in the ~~Himalaya~~Himalayas

We find consistently less ~~negative glacier volume changes~~ severe glacier thinning on the first orographic ridge across the entire Himalayan Range. Misclassifications of e.g. perennial snow patches with stable surface elevations classified as glaciers would cause a mixed glacier/land trend with a weaker surface lowering signal. To achieve this effect, the misclassification would have to be severe (ca. half of the samples) and be present in both our manual classification and the RGI, as the pattern is visible with both glacier classifications. We carefully classify our samples manually to avoid precisely such mixed signals, thus we consider this bias unlikely. Another cause could be reduced melt due to insulation from debris cover. It has previously been shown that stagnant (debris-covered) tongues lose mass at a similar rate as clean ice glaciers (Kääb et al., 2012; Gardelle et al., 2012b; Pellicciotti et al., 2015; Ragettli et al., 2016). We thus assume that debris-cover is not the cause of the observed differences.

~~Locally varying sensitivity to precipitation might also explain~~ A potential explanation for the less negative mass balances on the first, and thus wettest, orographic ridge in the Himalaya is a locally lower sensitivity of glacier mass balances to precipitation (and changes thereof). Precipitation from summer monsoon influx decreases sharply after large changes in relief (Bookhagen and Burbank, 2006). Maussion et al. (2014) find that precipitation regimes are strongly varying over short distances in the Himalaya, not least due to glacier orientation on the windward or lee side of the a mountain range. Wagnon et al. (2013) and Sherpa et al. (2016) mention the meteorologically exposed location of Mera glacier (4949–6420 m a.s.l.) in the Khumbu region, Nepal, as a possible explanation of its roughly stable mass balance since 2007 when in-situ measurements began. This stands in stark contrast to the considerable mass loss seen in Pokalde and Changri Nup glaciers only 30 km further north (the latter are also smaller and located at lower and thus warmer elevations, which likely contributes to these differences). In our ICESat zonation, these glaciers are located in units H1 ($-0.12 \pm 0.25\,\mathrm{m\,a^{-1}}$) and H2 ($-0.50 \pm 0.32\,\mathrm{m\,a^{-1}}$). Wagnon et al. (2013) note that in the DEM differencing study of Gardelle et al. (2013), larger glaciers in the same range as Pokalde/Changri Nup also seem to experience more surface lowering than Mera glacier further south.

Our consistently less negative glacier volume changes of the first orographic ridge across the entire Himalayan Range supports the interpretation of Wagnon et al. (2013) and Sherpa et al. (2016), and suggests the effect is visible along the entire Himalayan Range. However, the 2004–2008 average annual mass balances of the well-studied Chorabari and Chhota Shigri glaciers in western Himalaya do not follow this pattern. South-facing Chorobari lies on the outermost orographic ridge and lost mass at a rate of -0.73 ~~metres water equivalent per year (m w.e. a^{-1}, Dobhal et al., 2013)~~m w.e. a^{-1} (Dobhal et al., 2013), which is comparable to north-facing Chhota Shigri's balance of -0.9 m w.e. a^{-1} (Ramanathan, 2011). Both glaciers lie at comparable elevations (ca. 4000–6400 m a.s.l.).

The ELA sensitivity study of Fujita and Nuimura (2011) is too coarse to confirm orography-related spatial differences across the Himalaya, but along the mountain ridge their findings correlate well with both Yao et al. (2012) and our pattern of glacier changes in the inner Himalayan ranges ~~(Sakai and Fujita, 2017, see also)~~(see also Sakai and Fujita, 2017). In particular the stable glacier elevations in our unit HK1 — between areas of glacier loss in the Hindu Kush and the particularly negative western Himalaya (units H4–H6) — are backed up by their modelled stable ELAs. According to MERRA-2 data (but not ERA Interim), the area experienced an increase in summer precipitation between the 90s and 00s (Figs 8a, 8b). The particularly negative surface elevation change in the western Himalaya has previously been attributed to rapidly shrinking accumulation areas, seen in rising firn lines in Landsat images (Kääb et al., 2015, area called Spiti Lahaul). Kääb et al. (2015) see the same pattern for the strongly negative glacier evolution in Nyainqêntanglha Shan/Hengduan, which has low-lying accumulation areas. Thus, once the accumulation area becomes too small or disappears entirely, also abundant or increasing precipitation cannot compensate for melt due to increased temperatures (Sakai and Fujita, 2017).

5.6 Dissimilar glacier behaviour in the Karakoram/Kunlun Shan

The zonation we present here is the result of an compromise between within-unit glacier similarity, representative sampling, and stable glacier surface change ~~trends~~rates. In the Karakoram/Kunlun Shan area, this approach is clearly more appropriate than sample grouping into a regular grid. The latter results in large ~~trend uncertainties~~ uncertainties in the glacier elevation change signal (Fig. 2b), since grid cells include both the thinning signal south of the central Karakoram and thickening signal in the Kunlun Shan.

In the Karakoram, we see indications of ~~surging~~ both surging glaciers and glaciers ~~/glaciers~~ recovering from a surge. In most units, such as K1–K3, the surface elevation change signal is different in the upper 50% elevations compared to the ablation areas. This is in line with e.g. ~~Gardelle et al. (2013) or Gardelle et al. (2012a)~~Gardelle et al. (2012a, 2013), who find that most of the glaciers in this area were in some stage of a surging cycle in the ICESat decade. Our units are just large enough not to be dominated entirely by a retreating or rapidly growing tongue of one single large glacier, but rather provide an average of these locally different signals. After ensuring correct hypsometry sampling, the surface elevation changes of the different units in the area agree well. We find evidence of surging glaciers also in other areas, such as the Zhongfeng glacier in the Western Kunlun Shan (unit KS1) (Ke et al., 2015). ICESat does not sample the tongue of Zhongfeng glacier (whose surface might be rising) and the negative elevation ~~trend dominates~~ changes dominate the signal in the unit — which does not fit the otherwise positive elevation change of the surrounding units. Aggregated in larger spatial units such as a regular grid, this local peculiarity is not visible. Whether such signal is representative for all glaciers in a unit or not would require complete geodetic analysis of all glaciers and also a longer time span.

5.7 Varied pattern in Tien Shan

Glacier evolution in the Tien Shan has shown a spatially diverse pattern already in the last decades of the 20th century (Narama et al., 2010; Farinotti et al., 2015). Together with contributions from northerly areas, the Westerlies are the source of precipitation for the entire region (Bothe et al., 2012), but there are different climatic sub-regions: glaciers in the Western Tien Shan (and Pamir Alai) receive precipitation mainly in winter, the northern and northeastern ranges both in winter and summer, whereas the inner ranges are of the spring/summer accumulation type (Sorg et al., 2012). In the (north)western Tien Shan, our zonation does not consider this transition from winter-only to summer/winter precipitation ~~. The thinning rate in this unit is dominated by glaciers in the eastern part (two thirds of all samples are in Ile and Kungoy Alatau). Between 1961 and 2012, Farinotti et al. (2015, modelled balances) found that glaciers in the very west (Pskem) lost more mass than those further east (Ile and Kungoy Alatau). Farinotti et al. (2015) also used ICESat, but their 2003–2008 results for Ile and Kungoy Alatau are~~

more negative (-0.68 ± 0.44 m w.e. a $^{-1}$, at 2σ) than both their modelled mass balances for the same area(-0.33 ± 0.16 m w. e. due to too low sample numbers for a $^{-1}$) and our result for the entire western Tien Shan. Splitting the unit, our ICESat data indeed shows stronger glacier thinning west of Issyk-Kul but only with high uncertainty, caused by spatially strongly varying vertical offsets (or very varied glacier behaviour) which clearly add temporal variability to campaign median dh. finer zonation in this area.

Narama et al. (2010) suggest that glaciers of the outer ranges , — which receive more precipitation — are melting faster since they have a higher mass turnover and their tongues are at lower elevations. They see such a pattern in 2000–2007 glacier shrinkage, which was more pronounced in the Western/northern Tien Shan than in interior areas such as the southeastern Fergana Range or At-Bashy Range at the transition to the Pamir. Our thinning rates do not confirm this — precisely in this latter area (unit P3), we find the most negative glacier surface elevation changes in the entire region (converted to mass change: -1.04 ± 0.23 m w.e.). However, the The modelling study of Farinotti et al. (2015) suggests spatially highly varying glacier reactions in the last few decades in that area (their coarser zonation in the Central Tien Shan does not allow direct numerical comparison with our results).

ICESat suggests moderate thinning for the north-eastern Borohoro range, in particular the central part at higher elevations (TS1, converted: -0.09 ± 0.18 m w.e. a^{-1}, upper 50% glacier elevations thickening in Fig. 3a). Farinotti et al. (2015) found that the central parts of the range receive 50% more summer precipitation compared to the rest of the range, and modelled -0.17 ± 0.24 m w.e. a^{-1} for 2003–2009 for a slightly larger area than our most central unit.

In the inner Tien Shan, our elevation change rates vary on a small spatial scale. To some degree, the pattern resembles the land trends which indicate an influence of spatially varying elevation bias or snow cover in December 2008. Subtracting the negative land trends from the glacier trends greatly reduces the local differences. Reconstructed annual mass balances of Batysh Sook glacier and glacier No. 354 were -0.37 and -0.47 m w.e. a^{-1} respectively (average 2003–2008; Kenzhebaev et al., 2017; Kronenberg et al and also (Kenzhebaev et al., 2017; Kronenberg et al., 2016) and DEM differencing/modelling studies in the area found similar values (Fujita and Nuimura, 2011; Shangguan et al., 2015; Barandun et al., 2018) match the range of our thinning signal. Our zonation does not consider glacier aspects, which seem to play an important role in explaining glacier melt over this region (Farinotti et al., 2015).

For the glaciers in the Aksu-Tarim catchment in central Tien Shan, Pieczonka et al. (2013) found a decelerated mass loss between 1999 and 2009 (-0.23 ± 0.19 m w.e. a^{-1}) compared to earlier decades, which supports our only slight thinning on the northern slopes of the Tarim basin. Our units with less thinning resemble the pattern of glaciers with little long-term changes by Farinotti et al. (2015, modelled) — except for our balanced glacier signal in the southern Halik Shan on the northeastern edge of the Tarim basin. The few glaciers in this unit are small and lie at lower elevations, which would make them prone to fast melting in a warming climate. This is what Farinotti et al. (2015) found for the entire Halik Shan (2003–2009: -0.69 ± 0.28 m w.e. a^{-1} modelled, -0.68 ± 0.43 ICESat) and corresponds to our thinning rates in the northern parts of the Halik Shan.

ICESat suggests more moderate thinning for the north-eastern Borohoro range (converted: -0.44 ± 0.22 m w.e. a^{-1}), and even less negative values for the glaciers in the central Borohoro range (TS1, converted: -0.09 ± 0.18 m w.e. a^{-1}) that are at higher elevations. Farinotti et al. (2015) found that the central parts of the range receive 50% more summer precipitation

~~compared to the rest of the range, and modelled -0.17 ± 0.24 m w.e. a^{-1} for 2003–2009 for a slightly larger area than our most central unit. There, our thinning rates fit better to their modelled glacier balances than their ICESat-based mass loss estimates. The opposite is the case for the northernmost range (Djungar Alatau), where both our (converted: -0.81 ± 0.16 m w.e. a^{-1}) and their ICESat-based results (-0.75 ± 0.52 m w.e. a^{-1}) are nearly twice as negative as their modelled average 2003–2009 mass balances.~~

~~A method discussion, in particular on biasing influences on ICESat glacier surface elevation change rates is provided in Appendix D.~~

6 Conclusions

We present ~~the first complete , spatially resolved~~ a complete and consistent estimate of glacier ~~volume changes in~~ surface elevation changes for entire High Mountain Asia (HMA) ~~for 2003–2008~~ based on ICESat data ~~. The study confirms existing knowledge about glacier change in the region, but also~~ for 2003–2008 and relate the spatial pattern to lake volume and precipitation changes on the Tibetan Plateau (TP). For the ICESat analysis, our new spatial zoning better reflects different glacier setting in particular in relation to orographic effects, and updated methods ensure that biases present in earlier ICESat studies are removed. The study addresses several new aspects of the spatial pattern of glacier changes and stresses in particular the role of precipitation and elevation sensitivity of glaciers in different parts of HMA. To confirm underlying precipitation changes on the ~~Tibetan Plateau (TP)~~ TP with an independent approach, we estimate the 1990–2015 change in total water volume from all endorheic lakes on the TP, based on variations in both areal extent and water surface levels. The latter work results in volume change time series of >1300 lakes, much more than available so far. In more detail, we conclude:

- Only carefully delineated spatial units show local patterns of glacier change that are diluted or hidden if samples are gridded. On a larger scale, the pattern we find in this study agrees with previous regional estimates based on ICESat — but provides finer detail. The new zonation and improved bias control in this work stretches the applicability and precision of ICESat-derived elevation changes in rough and glacierised terrain further than was the case for previous studies.

- The pattern of glacier changes is spatially ~~very varied because glacier elevations , and their sensitivity to temperature and precipitation changes vary spatially~~ varied because of differences in the glaciers' elevations and sensitivity to climate changes (Sakai and Fujita, 2017; Kapnick et al., 2014). Together with glacier elevations, precipitation distribution and changes are able to explain large parts of the ~~general~~ spatial variability of the glacier change pattern observed for 2003–2008.

- An almost step-like precipitation increase on the TP, Kunlun Shan and possibly also the Tarim Basin between 1995 and 2000 is clearly visible from changes in lake water volume as well as MERRA-2 reanalysis data. The precipitation increase is able to fully explain 2003–2008 glacier thickening in an area centred over the Kunlun Shan. The boundary between positive and negative glacier changes is sharp in the Kunlun Shan and formed by the Muji Basin, upper Gez river and Tashkurgan Valley. It is more gradual on the TP. Also glaciers on the northern slopes of the Tarim Basin were close to balance.

– Lake volume changes on the TP reflect a clear and comparably sudden increase of water availability from ca. 1997 through ∼2010 for the northern and eastern TP, but only minor changes in the southwestern TP and Qilian Shan. The observed lake changes correspond to a precipitation-equivalent 6–7 mm a^{-1} for the northern TP and 25 mm a^{-1} for the eastern TP, from decadal averages between the 1990s and 2000s. ~~According to~~ MERRA-2 reanalysis data ~~, the change can~~ suggests the change is exclusively be driven by increased summer precipitation of 34–100 mm decadal difference between the 1990s and 2000s. ~~Decreasing potential evaporation from reduced wind speeds is also suggested to have in general contributed to lake growth (with uncertain timing though). Only in some areas increased~~ ERA Interim reanalysis data suggests a smaller precipitation increase for a smaller spatial area that does not explain lake growth and glacier thickening equally well.

– The magnitude of lake volume change, glacier mass balance and precipitation changes agree within each other, considering also evaporation. Increased influx from glacier mass loss ~~should~~ may in some areas have contributed to lake growth but cannot explain it, as the zone of lake growths roughly coincides with the zone of positive glacier mass balances ~~. The magnitude of lake volume change, glacier mass balance and precipitation changes agree within each other, considering also evaporation.~~ or dynamical glacier geometry change.

– Glaciers on the TP changed their geometry during 2003–2008. In the northeastern TP/western Kunlun Shan, upper glacier surface elevations were stable while tongues were growing. Further south/east, upper elevations were thickening while the tongues were thinning due to both increased accumulation and melt. The further southeast on the TP, the stronger the glacier thinning rates. Glaciers in the Qilian Shan were only moderatly losing mass.

– Along the entire Himalayan Range, glaciers on the first orographic ridge were thinning less than those further back in a drier climate, likely due to abundant precipitation on the first ridge, which causes ~~ELAs~~ equilibrium line altitudes (ELAs) to be at lower elevations. Precipitation and ELA gradients might be very steep in the outermost ridges of the Himalaya. ~~Glaciers in the Tien Shan were thinning rather more than in other parts of HMA, in particular those in the transition between the Tien Shan and Pamir mountains. There are exceptions to this general trend: glaciers in the central Borohoro range (at higher elevations) and on the northern slopes of the Tarim Basin were close to balance, possibly due to precipitation increase. From a methodological point of view, this work stretches the applicability and precision of ICESat-derived elevation changes in rough and glacierised terrain further than was the case for previous studies. We carefully examined the influence of how spatial units are delineated to derive ICESat-based glacier change over HMA as well as a range of potential biases and error influences on the analyses.~~

While the glacier change pattern presented in this study is robust and well explained by glacier sensitivities to climate change, our unit boundaries might not match areas of consistent glacier changes everywhere, despite best efforts. Low ICESat sample density prohibits a further refinement in areas with sparse glacier coverage. Other remote sensing data with finer spatial resolution could improve the pattern — for example DEM differencing from ASTER stereo-imagery (Brun et al., 2017) and other spatially extensive data available for the last decades, or also ICESat-2, once this data becomes available. Combinations of remote sensing products for precipitation, snow and atmospheric parameters as well as improved reanalysis data could help to determine precipitation numbers with more certainty in Asia's water tower.

Code and data availability. ICESat data are freely available from NSIDC and NASA, the SRTM DEM and Landsat data from USGS, the MERRA-2 reanalysis data from NASA Goddard Earth Sciences Data and Information Services Center, ERA Interim from the European Centre for Medium-Range Weather Forecasts, the Global Surface Water dataset within Google Earth Engine. The derived ICESat zonation is available as a data supplement to this publication.

Appendix A: Data

A1 ICESat elevation data

The NASA Ice, Cloud and land Elevation Satellite (ICESat) measured the Earth's surface elevations in two to three campaigns per year from 2003 to 2009. The campaigns were flown in northern autumn (∼ October–November), winter (∼ March), and early summer (∼ June). Autumn is overall the driest season in HMA, and ICESat's autumn elevation samples on glaciers thus fall to a large extent on ice and firn rather than fresh snow. By contrast, snow falls in March/June in parts of HMA. ICESat's Geoscience Laser Altimeter System (GLAS) sampled surface elevations within ground footprints of ∼ 70 m in diameter (Schutz et al., 2005). Elevation samples are separated by ∼ 170 m along ground tracks/orbits but up to 75 km between orbit paths in HMA. The ground track pattern was not repeated exactly during each overpass, as the near-repeat orbit mode was not activated at lower latitudes (Schutz et al., 2005). Rather, individual ground tracks lie as far as 2–3 km from the reference ground track in HMA. A direct comparison between ICESat elevations is thus difficult in the region. Instead, double-differencing techniques are applied, i.e. comparing ICESat elevations with a reference DEM to receive elevation differences and analysing their subsequent evolution over time (Kääb et al., 2012; Gardner et al., 2013; Neckel et al., 2014; Kääb et al., 2015; Ke et al., 2015).

Here, we use GLAS/ICESat L2 Global Land Surface Altimetry HDF5 data (GLAH14, release 34) which is optimised for land surfaces (Zwally et al., 2012). From comparison with reference DEMs, elevation uncertainty of GLAH14 data was found to be on the order of decimetres to metres in mountainous terrain in Norway (Treichler and Kääb, 2016). Elevation biases and inconsistencies throughout ICESat's lifetime are of centimetre to decimetre magnitude and thus negligible compared to uncertainties from the underlying terrain and biases in the reference DEM (Kääb et al., 2012; Treichler and Kääb, 2016).

A2 SRTM DEM

The DEM from the Shuttle Radar Topography Mission (SRTM, Farr et al., 2007; Farr and Kobrick, 2000) is a consistent DEM in the HMA region. We used the C-band, non-void-filled SRTM DEM version at 3 arc-seconds resolution (SRTM3, corresponding to 92 m in y, and 66–82 m in x-direction at 45/28° N) which is accessible from the U.S. Geological Survey at https://dds.cr.usgs.gov/srtm. The SRTM DEM used here is a product of single-pass C-band SAR interferometry from images acquired on 11–22 February 2000 (Farr and Kobrick, 2000). SRTM DEM nominal vertical accuracy is of the order of metres (Rodriguez et al., 2006). Treichler and Kääb (2016) found spatially varying vertical offsets on the order of metres to decimetres in mountainous terrain in Norway. They attributed the vertical biases to the fact that the SRTM DEM is a composite from several individual images and overpasses, and likely processed in (unknown) spatial sub-units. Offsets caused by shifts of sub-units were not removed by global DEM co-registration, but the bias/uncertainties caused by them are within the nominally stated accuracy. On glaciers, larger elevation uncertainties are to be expected due to penetration of the C-band signal into ice and, even more so, into snow. Also dry sedimentary soils may be subject to radar penetration. The penetration is estimated to be in the range of several metres for glaciers in HMA (Gardelle et al., 2012a; Kääb et al., 2012, 2015).

The vertical offsets from DEM shifts or penetration increase the uncertainty of surface elevation changes — possibly also for ICESat-based studies, if the spatial pattern of SRTM DEM offsets interferes with ICESat's spatial sampling pattern (Treichler and Kääb, 2016, 2017). As an alternative elevation reference, we used the SRTM DEM at 1-arc-second resolution (SRTM1) from https://earthexplorer.usgs.gov. The 1-arc-second DEM has undergone fewer revisions than the 3-arc-second DEM, making the data not necessarily superior, and most data voids are filled in with other elevation data that have different time stamps. We therefore excluded the data void areas contained in the 3-arc-second DEM version also in the SRTM1 DEM to ensure that we only use original elevation data from February 2000.

Further, we did not explore or use the recently published TanDEM-X global DEM as it was not available during our processing. It remains to be investigated how potential advantages of this DEM (larger coverage, less penetration than C-band) balance potential disadvantages (longer time difference to ~~ICEat~~ ICESat period, temporal inconsistency from stacking). Also due to temporal inconsistency and substantial voids, we did not use the ALOS PRISM World DEM (AW3D) or the WorldView satellite optical stereo HMA DEM.

A3 Precipitation data

As an estimate for regional and temporal precipitation patterns for the years 1980–2015 we use data from the Modern-Era Retrospective analysis for Research and Applications, version 2 ~~(MERRA-2 Bosilovich et al., 2016)~~ (MERRA-2 Gelaro et al., 2017) at resolution of 0.625° x 0.5° in lat/lon and available from the NASA Goddard Earth Sciences Data and Information Services Center at https://disc.sci.gsfc.nasa.gov/mdisc~~, and ERA Interim (Berrisford et al., 2011)~~. We also use the ERA Interim reanalysis (Dee et al., 2011) at T255 spectral resolution (0.7° lat/lon), available from the European Centre for Medium-Range Weather Forecasts at http://apps.ecmwf.int/datasets/. We use monthly summarised values of the variables total precipitation (PRECTOT / tp), snowfall (PRECSNO / sf) and evaporation (EVAP / e) from MERRA-2's surface flux diagnostics dataset tavg1_2d_flx_Nx (GMAO, 2016) and ERA Interim's Monthly Means of Daily Forecast Accumulations, respectively. ~~The~~ Due to the scarcity of observations in HMA, reanalysis products are less constraint and have higher uncertainties in our study area than in more densely populated areas of the Earth. The two chosen reanalysis products have been found to model precipitation and snowfall comparatively well (Reichle et al., 2017a, b). The High Asia Reanalysis (HAR, Maussion et al., 2014), a product optimised for the TP region and with much finer spatial resolution, is unfortunately only available for the time period 2001–2011 which is too short for our study with respect to the lake volume changes investigated.

~~Further, we use in-situ data from the five westernmost meteorological stations on the TP and Kunlun Shan (Fig. 1), provided by the China Meteorological Science Data Sharing Service Network. The stations are located relatively close~~ The meteorological stations included in this study were chosen because they are closest to the area with reported glacier mass gain~~(we~~ . We are not aware of any meteorological measurements on the ~~northeastern TP). The data includes daily measurements of precipitation, mean air temperature, and for the four stations on the southwestern TP also evaporation.~~ northwestern TP.

A4 Global Surface Water Dataset

The Global Surface Water dataset (Pekel et al., 2016) is a classification of the entire Landsat archive into monthly and annual maps of surface water (https://global-surface-water.appspot.com). The data is available within Google Earth Engine (Gorelick et al., 2017). To map the changing extents of Tibetan lakes, we used the variable occurrence which provides the classes no data, no water, water (for both monthly/annual data), and seasonal water (for annual maps only). ~~Coverage is nearly complete (>98%) starting from 2000 but considerably worse for some years of the 90s (Pekel et al., 2016, for our areas of interest: 20–75% no data p~~ coverage is poor for years with little Landsat data, for our areas of interest: 20–75% no data pixels in 1990, 1991, 1995, 1997 and 1998 (Pekel et al., 2016).

Appendix B: Methods for glacier volume change

We follow the double-differencing method explained in ~~further detail in~~ Kääb et al. (2012) and Treichler and Kääb (2016)~~, with special consideration of issues mentioned in the above introduction~~. ICESat data and individual SRTM DEM tiles were converted into the same geographical reference system, co-registered (Nuth and Kääb, 2011), and reference elevations for ICESat footprint centres retrieved by bilinear interpolation. The difference between ICESat and SRTM elevations is further referred to as dh. Double differencing, i.e. fitting a linear trend through dh from several years, reveals how much the surface elevation has changed on average over the time period studied.

ICESat samples were reduced to those within a 20 km buffer around RGI glacier outlines. To avoid inclusion of off-glacier elevation samples in our glacier surface change analyses (see introduction), we classified all ICESat footprints manually into *ice* and *land* samples, using the most snow-free Landsat images from ca. 2000–2013. Samples on water and clouds ($|\mathrm{dh}| > 100$ m) were excluded. Samples on glacier borders were also excluded, to avoid inclusion of 70 m footprints that only partially fall on ice and because glacier areas could have changed in the course of 2003–2008 (Treichler and Kääb, 2016). ~~We used only samples from ICESat's 2003–2008 autumn campaigns to avoid bias from temporal variations in snow depths (see introduction). After filtering, 74'938 ice samples and about ten times as many land samples remain.~~ To compute statistics per glacier, we also classified the samples based on glacier outlines of the newest version of the RGI (version 5, Arendt et al., 2015).

~~Per spatial unit, we estimate glacier surface elevation change by fitting a robust linear regression (which minimizes an iteratively weighted sum of squares) through individual dh (Kääb et al., 2012).~~ To test the sensitivity of biased dh at either end of the studied time period, we also compute a do not only compute a robust linear regression, which is commonly used for ICESat glacier applications (Kääb et al., 2012), but also a t-fit (Treichler and Kääb, 2016) and a non-parametric Theil-Sen linear regression (Theil, 1950; Sen, 1968). Both alternative robust fitting algorithms better fit our dh distribution and are commonly used for datasets with large natural variability and measurement errors.

We find little difference between robust and t-fits, and slightly larger (but no systematic) differences when using Theil-Sen linear regression. The trend slopes from the three methods agree on average within 0.1 m/a and differences always lie well within trend error estimates. Our final estimate per spatial unit thus corresponds to the average of the three trend methods.

B1 Zonation

ICESat data needs to be grouped into spatial units to fit surface elevation trends. The samples within each spatial unit need to reflect the glaciers in a representative way. This condition is easier to fulfil if the glaciers are similar to each other, including their 2003–2008 mass balances and their variations. We tested automated clusteringmethods from ICESat dh directly, but were not successful. We therefore preferred to delineate As seen in Kääb et al. (2015), grouping of ICESat samples into a regular grid without a-priori knowledge results in a blurring of local glacier change signals. Since such local signals consist of a specific dh magnitude and evolution over time which should be governed by climatic or topographic drivers, we tried to derive a more realistic spatial division from the ICESat samples directly, using glacier statistics, dh and iterative clustering. This approach was not successful: the number of (semi-quantitative) statistical parameters turned out to be too large and dh vary too much spatially, not least due to bias. We thus carefully delineated spatial units manually, considering topographic and climatic setting, elevation, visual glacier appearance, and input from literature and discussions with experts. Zones were drawn by hand to avoid splitting any glacier between several zones. In particular, we paid special attention to orographic barriers. The zonation we present here is thus the result of an iterative manual process of re-defining spatial units until they yielded statistically stable and robust glacier surface change estimates. While the procedure is based on carefully applied expert knowledge, we are fully Rather than roundish zones across the entire Himalayan range, we chose elongated zones around mountain ridges. Size, length and width of spatial units (i.e. how many parallel ridges) were largely determined by ICESat sample numbers and the condition of representativeness. For example, we included both the windward and leeward side of a Himalayan range as there are very few glacier facing south (i.e. windward), and we suspected that leeward accumulation areas close to a mountain peak might still receive more precipitation from turbulences than the dry, leeward valley bottoms (Immerzeel et al., 2014). We are very aware that our zonation is eventually a subjective one and certainly open to discussion. As a control approach, we applied the same gridding method as Kääb et al. (2012, 2015) to the entire HMA In some parts, other operators will likely come up with modified zones. However, our zonation is based on carefully-applied expert knowledge, and we are convinced it displays the 2003–2008 HMA glacier elevation changes with a spatial resolution and precision that reflects the optimum that is feasible from ICESat over such a mountainous and heterogeneous region.

B2 Glacier hypsometry

We compute the relationship between glacier dh and elevation (hereafter called dh–elevation gradient) by fitting a robust linear regression through individual glacier samples' dh vs. elevation. Greater radar penetration in the accumulation areas and more prominent melting of tongues steepen dh–elevation gradients (e.g. Vijay and Braun, 2016; Ragettli et al., 2016). ~~It is therefore very important to ensure ICESat's elevation sampling is consistent~~ Representative elevation sampling through time and ~~representative for glacier hypsometry (see introduction)~~in relation to local glacier hypsometry is thus very important. Our primary approach to improve sampling hypsometry is to enlarge spatial units, but in some areas this would have ~~in turn~~ led to considerably reduced glacier similarity within the unit. To account for these conflicting cases, we computed four different corrections and compared the such-adjusted results: (A) correcting the slope of the glacier elevation-change trend for the effect of a positive/negative elevation trend in time, i.e. correct for the case where ICESat consistently samples higher/lower elevations (smaller/larger dh) with time (Kääb et al., 2012, suppl.); (B) correcting individual dh for the effect of elevation, i.e. computing the expected dh from the dh–elevation gradient and the individual elevations sampled, and removing the expected dh values from the measured dh values; (C) filtering of the samples of each ICESat campaign to match the hypsometry of the glaciers within each spatial analysis unit; (D) assigning weights to samples depending on their elevation so that they match the glacier hypsometry, i.e. analogue to C but without removing any samples.

All four corrections are here applied to all units, and both for ice and land samples separately. Methods A and B are based on the method used in Kääb et al. (2012, 2015). If ICESat consistently samples lower (or higher) elevations than the reference hypsometry, methods A and B will not correct for this — they only correct elevation-induced bias relative to the mean sampled elevations of all campaigns. Methods C and D, however, adjust the hypsometry so that it should become representative for the glacier elevations in the unit. ~~All four corrections are here applied to all units, and both for ice and land samples separately. Our 'standard method' for the final glacier elevation change estimates corresponds to the~~ For 18 units, the difference in derived surface elevation change between the 'standard method' (average of all ~~hypsometry-correcting methods (A–D) and trend methods (robust, t- and Theil-Sen trends) . Additionally, we also compute trends for only the upper/lower~~ methods A-D) and only applying the latter methods (average of methods C and D) exceeds 0.05 m a^{-1}, and at the same time, average glacier elevations sampled in these units is also > 50 ~~% glacier elevations as from RGI hypsometries (samples above/below the median RGI glacier elevation in each unit). The latter analysis violates mass conservation and should thus not be interpreted in terms of mass balance, but rather, for instance, for changes in glacier elevation gradients (e.g. Brun et al., 2017; Kääb et al., 2018).~~ higher or lower than average glacier elevations for this unit (SRTM elevations within RGI glacier outlines). For these units with systematic elevation missampling, we used the average of methods C and D only. To 5 of the affected units we also applied the cG correction (see below).

B3 Correction of vertical bias

~~Glacier elevation difference dh may be subject of vertical bias originating from local reference elevation bias or snow fall during the second part of the autumn 2008 campaign. Local vertical bias may result from inconsistent reference DEM age or~~

~~production, tiling and tile/scene misregistration, or locally varying radar penetration (in case of the SRTM DEM). To remove this~~ To remove local systematic elevation bias, we compute a per-glacier elevation correction cG corresponding to the median dh for each glacier ~~, according to the method described in Treichler and Kääb (2016). In that study~~ (i.e. subtracting the median dh for each glacier from each corresponding dh). In the study of Treichler and Kääb (2016), the correction successfully reconciled annual ICESat-based glacier elevation changes with mass balance time series from in-situ measurements. Also in the present study, cG-corrected dh (in combination with above hypsometry methods A–D) remove the effect of a varying spatial composition of elevation offsets. However, as the correction results in lower sample numbers and removes parts of the signal where some glaciers are only sampled in the beginning and some other glaciers only in the end of the ICESat acquisition period, the correction shows a tendency to erroneously flatten out linear trends. We thus ~~only apply cG to 6 units,~~ apply cG only where the opposite is the case and trends from become considerably ($> 0.05\,\mathrm{m\,a^{-1}}$) steeper after cG correction. This is the case for 21 units. To limit the effect of potential bias from lower sample numbers, our final trend estimate for these units is the average of the 'standard method' with and without application of cG, respectively. The final thinning/thickening rates of the in total 21 affected units differ from the 'standard method' by on average $0.08\,\mathrm{m\,a^{-1}}$ and range from -0.37 (unit HS) to $+0.15\,\mathrm{m\,a^{-1}}$ (a unit in the central Karakoram range). ~~This correction changed the thinning/thickening rates for the 18 affected units by on average $0.09\,\mathrm{m\,a^{-1}}$.~~

~~Treichler and Kääb (2016, 2017) found that ICESat clearly records the~~ The onset of winter snowfall ~~in Norway during the~~ might cause erroneously positive dh in the December part of the split autumn 2008 campaign ~~(stopped half way in mid-October and completed only in December). This could be the case~~ for parts of HMA~~, too — in particular in areas~~ : Areas under influence by the Westerlies (Tien Shan, Pamir, Karakoram, western Himalaya) or winter precipitation in Nyainqêntanglha Shan/Hengduan Shan (Maussion et al., 2014). ~~Analogue to Treichler and Kääb (2016), we estimate December 2008 snow bias from a linear regression of October/December 2008 land dh on elevation and time. The correction is computed individually for each spatial unit.~~ We estimate the influence of this according to the method of Treichler and Kääb (2016).

Appendix C: Methods for lake volume change

We compute annual water volume change of the Tibetan lakes by multiplying annual lake areas with water level changes from repeat water surface elevations for each year over the period 1990–2015. Maximum annual lake extents are obtained directly from the Global Surface Water data set by exporting bitmaps of annual water occurrence over the entire TP, using the web API of Google Earth Engine. The data is exported at a resolution of $50\,\mathrm{m} \times 38$–$44\,\mathrm{m}$ in lat/lon (corresponding to 0.00045 degrees). Subsequently, we retrieve the corresponding lake surface elevations in two ways: a) from SRTM DEM elevations of the lake shore by computing the median of interpolated DEM elevations for lake shore cells for each areal extent, and b) directly from ICESat footprint elevations on the lake areas for those lakes where ICESat data is available. To extend the lake elevation time series from method b) beyond the ICESat period of 2003–2009, we compute the area–surface-elevation relationship for each lake by robust linear regression and apply this function to the areal extends of the years before and after the ICESat period. We extract the relationship both for annual time series and individual ICESat campaigns (2–3 campaigns each year, using the monthly water classifications). The so-extrapolated surface elevation values generate complete 1990–2015 time series for both areal extent and lake levels from SRTM and ICESat data, respectively. Our method is in parts similar to the methods used by previous studies investigating lake volume changes on the TP from satellite data (Zhang et al., 2011; Kropáček et al., 2012; Song et al., 2013; Zhang et al., 2013; Song et al., 2015; Zhang et al., 2017, e.g.,) but the inclusion of a DEM for deriving shoreline elevations, and thus lake water levels, in addition to altimetry data enabled us to produce volume change time series for one order of magnitude more lakes than derived previously.

We apply our procedure to the 1364 endorheic lakes on the TP and in the Qaidam Basin (Fig. 1) with a maximum lake extent of $> 1\,km^2$. We generated here our own lake database since we found that existing collections, such as the Global Lakes and Wetlands Database (Lehner and Döll, 2004), are lacking numerous lakes that likely only emerged during the last two decades. Consulting satellite imagery like Landsat data, we manually adjusted our lake database to remove delta-like seasonal wetlands from water inflow on sloping terrain from the lake masks, we excluded non-endorheic lakes (visible outflow), and we excluded inundated areas affected by human interventions (e.g. for salt production) (133 wetlands not included in the above number). For spatial aggregations, computation of relative numbers per lake and for plotting, we use the median lake areas from the 1990–2015 annual lake extents.

C1 Uncertainties and filtering

To minimise the effect of uncertainties in or erroneous estimates for individual years, we analyse time series in a summarised way through regression over time and as decadal averages. Uncertainties associated with the lake data used include misclassification of water area in the Global Surface Water dataset (Pekel et al., 2016), lake surface elevation errors and local bias in the SRTM DEM, and bias in ICESat surface elevation measurements. For each lake and year, we compute the percentage of missing data (e.g. from cloud cover or classification voids), and years with $< 95\%$ of data coverage within the lake masks are excluded from further analyses. Lake time series that, after removing these years of insufficient coverage, do not contain any data from the 1990s are excluded entirely. For ICESat-derived lake levels, only lakes with measurements from at least three laser footprints each from at least five years are considered. Data from the 90s have higher uncertainties in extracted/extrapolated lake levels due to a) the implicitly assumed bathymetric profile using area–lake level scaling for years without ICESat data; and b) because the SRTM DEM was acquired in February 2000: While lake areas vary seasonally and we use annual maximum areas, the effect of extracting SRTM lake elevations for lake areas smaller than during SRTM data acquisition is that some pre-2000 SRTM lake levels may be too high, resulting in too small dV. Despite the lake areas and surroundings being extremely flat, SRTM DEM cells indicate up to 10 m elevation differences between neighbouring cells in a seemingly random way, and the SRTM DEM turns out to be the dataset within our lake change analysis with the greatest uncertainties. Potential explanations for the DEM elevation uncertainties are penetration of C-band radar into sandy ground and unknown processing steps during DEM production to mask/interpolate water-covered areas without radar backscatter. For some lakes, SRTM DEM errors result even in negative area–lake-surface elevation relationships, i.e. lake shore elevations seemingly decrease for expanding lake areas which is physically not plausible. We therefore excluded all lakes with either a negative area–lake-elevation relationship or where the 26-year linear trends for lake area and lake surface level do not have the same sign. This is done both for ICESat-and SRTM-derived lake level estimates. The overall error for a decadal average lake volume stage is estimated as the standard error of the mean, and for decadal differences propagated as the root of the sum of squares of the two errors (RSS).

C2 Endorheic basins

~~To estimate the lake water volume change in a way that can be related to glacier mass balances and precipitation changes (i.e. mm w.e. per m^2), we~~ We summarise and spatially distribute the water volume changes ~~of all lakes within spatially confined basins. These basins are~~ based on endorheic catchments ~~, but because~~ of the USGS HydroSHEDS dataset at 15 arcsec spatial resolution (Lehner and Döll, 2004, https://hydrosheds.cr.usgs.gov) . However, many catchments only contain a single lake and exact catchment areas are not well defined on the TP ~~(e. g., in very flat areas),~~ (e.g., in very flat areas, Lehner et al., 2008) and the spatial resolution of the HydroSHEDS dataset is in parts too coarse to correctly attribute the lakes of our lake dataset to the correct catchment. Therefore, we manually controlled ~~, adjusted and aggregated the endorheic catchments of the USGS HydroSHEDS dataset at 15 arcsec spatial resolution (Lehner and Döll, 2004, https://hydrosheds.cr.usgs.gov) to~~ and adjusted the endorheic catchment borders using the finer topography of the SRTM DEM at 3 arcsec resolution as well as Landsat imagery to detect surface water exchange between lakes/catchments, and aggregated the catchments to larger basins of comparable size~~and~~ , consisting of in average 5 catchments.

We define the total lake area per catchment (and basins) as the sum of the 1990–2015 median lake area of all lakes within the spatial unit, also including the endorheic inundated areas confined by human infrastructure mentioned above, which are otherwise excluded from analyses. To compute total water volume change per catchment, we assume that lakes excluded from the analysis (see previous subsections) behaved the same way as the average of the lakes we have sufficient data for, and subsequently scale the total volume change accordingly. For total water volume change from decadal averages, we compute the error as the sum of the errors of all individual lakes' volume change (see above), again scaled according to the share of total lake area we have sufficient data for. This conservative approach of adding errors (instead of root-sum-of-squares, RSS, for instance) includes as a worst case the full correlation of the behaviour of all contributing lakes.

Appendix D: Discussion of biasing influences on ICESat glacier surface elevation change

Representativeness of samples within spatial units is the key requirement for robust glacier thickening/thinning estimates. However, we found that enlarging spatial units was not always the best remedy to ensure sample representativeness: In some areas this would have considerably reduced glacier similarity within the unit. Applying a regular grid can have ~~this~~ the same effect. Consequently, only carefully adapted zones can show local peculiarities that are otherwise diluted.

Especially for small units with few samples, careful consideration of how potentially biasing factors interplay is important. Our use of four different methods to ensure correct hypsometry sampling makes the results very robust. The overall pattern is not affected by zonation, small changes in sample composition (RGI outlines), or reference DEM (here: SRTM1). Of all corrections, the most essential requirement is therefore that the regional glacier hypsometry is sampled appropriately, also over time. Locally, however, the different methods and corrections can result in considerable differences between glacier thickening/thinning rates. Especially where ICESat data is used on a local scale or as input for modelling studies, we strongly recommend to carefully assess the difference between hypsometry corrections, the effect of our per-glacier correction cG, and the influence of snow cover, in order to ensure a representative estimate and appropriate uncertainty.

Our snow correction affects trends significantly. In southern Norway, the study region for which the correction was developed, it removed a positive land trend but did not affect the glacier trend (Treichler and Kääb, 2016). Our results in HMA show that trend fitting methods are surprisingly sensitive to a lowering of the last (half) campaign, no matter which trend fitting algorithm is used, and for both land and glacier dh. In contrast, if the same correction is applied to a campaign between 2004 and 2007, trends only change marginally. Due to too few land samples in either of the autumn 2008 campaigns, we did not succeed to compute a correction for all units which makes the approach inconsistent, and we therefore decided not to include the correction in our final trend estimate. However, the exercise shows that November/December 2008 snow fall has the potential to erroneously decrease ICESat-derived glacier thinning rates, in particular in Tien Shan, Pamir, Hindu Kush, Nyainqêntanglha Shan/Hengduan Shan and maybe also the outer Himalayan ridges . (suppl.). We therefore recommend to assess the bias potential of December 2008/October snow fall for ICESat studies on a smaller spatial scale. Also, we advise not to rely on ICESat's March campaigns for glacier studies wherever snow is falling in winter in the northern hemisphere.

ICESat elevations have previously been used to estimate SRTM penetration (Kääb et al., 2012, 2015; Shangguan et al., 2015). On glaciers where no ICESat data is available, dh–elevation gradients of larger spatial units — such as in this study — could improve the estimated elevation dependency of penetration.

Author contributions. D. Treichler jointly designed the study with A. Kääb, performed all data analyses and prepared the manuscript. A. Kääb contributed to data interpretation and edited the manuscript. N. Salzmann and Ch.-Y. Chu contributed to analyses and interpretation of the climate/precipitation signals and lake water volumes, and the joint interpretation of the data.

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