

## Response to referee comments and short comments

Brief Communication:

### Contending estimates of early 21<sup>st</sup> century glacier mass balance over the Pamir-Karakoram-Himalaya

Andreas Kääh, Christopher Nuth, Désirée Treichler, Etienne Berthier  
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We would like to thank the authors of all reviews and comments for their valuable and helpful feedback that certainly helped to improve our contribution. Detail responses are provided below together with a mark-up manuscript version showing the changes made in response to the referees.

#### M. Pelto:

1) *There should be a mention of the difference between the dominantly summer accumulation type glaciers and the glaciers that receive considerable winter accumulation.*

2) *There are nine regions listed in Table 1, most do not get mentioned, but should be to provide a balanced comprehensive assessment at the start of section 2. Seven of the nine regions have substantial negative balances, one a slight negative balance and one a positive balance. From the eastern end of the study area the ENS range through the main Himalaya of Bhutan, Nepal, India and Tibet, China to the Split-Lahaul Region the mass balance losses are consistently significantly negative. This area is dominated by summer accumulation type glaciers with the majority of the snowfall occurring during the summer monsoon. There is then a sector of less negative mass balance in the Western Kunlun Shun and Karakoram and Eastern Pamir. The mass balance is again negative in the Hindu Kush and Western Pamir range. This western end of the study area features glaciers less influenced by the summer monsoon. This paper does not need to fully explore the issue just comment on it in the review of data in Section 2. Might be worth referencing the recent paper by Li (2014), which discusses some of these regional variations in Tibet. LI Z.. Glacier and Lake Changes across the Tibetan Plateau during the Past 50 Years of Climate Change. Journal of Resources and Ecology, 5(2): 123-131, 2014.*

We agree that summer- and winter-accumulation types of glaciers along the Himalaya arc should be mentioned. We added a paragraph at the end of section 2.2 with references to several key recent papers that suggest a possible relationship between diverse climate influences (monsoon, westerlies) and the contrasted rates of glacier mass change.

#### Anonymous Referee #1 :

— SUMMARY —

*In this brief communication, Kääh and coauthors present a well written, extremely condensed series of results concerning the glacier mass changes in the Pamir-Karakoram- Himalaya region. The results are based upon analyses of ICESat data, and thus refer to the period 2003-2008. Important insights are gained in the spatial pattern of the glacier mass changes, differences with respect to earlier estimates are discussed, and some simple quantification of the glacier*

41 *contribution to regional runoff is performed. Whilst there is no question about the scientific merit of*  
42 *the publication, I wonder whether the format of the contribution complies with “The Cryosphere”:*  
43 *The main text contains minimal methodological explanation, and the reader has basically to*  
44 *“discover” himself that some additional, still not exhaustive information can be found in an online*  
45 *supplement.*

46 *In my opinion, deciding whether this kind of format wants to be promoted by "The Cryosphere" is a*  
47 *task of the editorial board.*

48  
49 To our best knowledge, the format of our contribution fits to the character of a 'Brief  
50 Communication' ([http://www.the-cryosphere.net/submission/manuscript\\_types.html](http://www.the-cryosphere.net/submission/manuscript_types.html)) and has been  
51 approved as such by an editor before appearing in The Cryosphere Discussion. In the revised  
52 manuscript, we now make sure the online supplement is well referenced (see our response below).  
53 Also, the choice of this short format is justified by the fact that the methodology and part of the  
54 results are published in extensive detail elsewhere (Kääb et al., 2012 and the supplement) and  
55 thus there is no need to repeat this already peer-reviewed and published information.

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58 — GENERAL COMMENTS —

59 *The only general comment I have concerns the way methodological information is given. Basically,*  
60 *the main article contains only brief “hints” on the methodology, mostly concentrated in the current*  
61 *“introduction” section and the first lines of section 3. The problem is somehow “aggravated” by*  
62 *the fact that the information about some additional information being available in an online*  
63 *supplementary is not well communicated either: The reader has to “discover” it either through the*  
64 *standard sentence appended to the manuscript (“The Supplement related to this article is available*  
65 *online at: : :”) or through the caption of Figure 2 (“For details on the gauging stations used and*  
66 *the uncertainty of the contributions see Supplement.”). Having this information mentioned earlier*  
67 *would already help. I’m not sure whether the decision of not including more detailed*  
68 *methodological information was guided by space restrictions due to the “Brief communication”-*  
69 *format or because the manuscript was originally intended for another journal. As a reader,*  
70 *however, I would appreciate if the most important information about the methodology could be*  
71 *included in the main manuscript. By “most important” I mean, for example, the information*  
72 *necessary to understand why the authors conclude that the magnitude and variability of the SRTM*  
73 *C-band penetration is “of larger magnitude than previously assumed” (Abstract and conclusions).*  
74 *This is an important statement, but from the main text it is unclear what analyses have led to this*  
75 *conclusion. As said in the “summary” of this review: The question is not about the scientific merit*  
76 *of the publication, but rather about the format with which it is presented.*

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78 Our contribution is an original submission to TC, and was in no form submitted before to any other  
79 journal.

80 We included in the text several more clear references to the Supplement related to river discharges.

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82 More information on the method of estimating SRTM radar penetration was added in section 2.3.

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84 We prefer not to repeat the ICESat-related methods, as they are described in detail within Kääb et  
85 al. (2012), and we note that also other authors (Gardner et al. 2013) refer to Kääb et al. (2012) for  
86 method details. See also referee's #2 vote to not repeat method details from another paper. The  
87 decision not to include ICESat method details in the main text is guided by the aim that the reader  
88 is not distracted by it from the results (the main aim of this short contribution) and the tight length  
89 constraints for a TC 'Brief Communication'. We also prefer not to include these method details in a  
90 Supplement as this would result largely in a duplication of an already existing Supplement to  
91 another paper (Kääb et al. 2012).

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— SPECIFIC COMMENTS —

*P. 5859 L.14-16: The comparison as such still does not ensure the absence of a sampling bias, does it? Some information about the histogram-matching step that (I believe) was performed would be useful.*

We found that no adjustments were necessary as ICESat sampled **glacier** hypsometry in a representative way. In the text we replaced 'ensure' with 'confirm'. Adjustments were indeed done for **stable ground**, as described in Kääb et al. (2012).

*P. 5861, L. 22-25: I have difficulties in understanding the sentence. From what I understood from P.5862 L 5-6, the basic statement is that by repeating the analysis using the Randolph Glacier Inventory instead of the outlines actually used in the analyses, one would get more negative elevation changes, correct? I suggest rewording the sentence.*

Done

*P. 5862, L 5-6: Do you actually mean “too negative”? According to the numbers given in Table 1, the results by Gardner et al. are less negative than the one presented here. Why would they be “too negative” then?*

The referee is right. As explained above, the Gardner et al. rates of elevation changes on glacier tends to be too high (i.e., not as negative as they should) due to the inclusion in their glacier sample of mis-classified land footprints for which rate of elevation difference are close to 0. Thanks for spotting this mistake, this is now fixed.

*P. 5862, L. 19-20: The references are all right, but here is definitively a point where some more information on how the penetration depth was estimated would be of great benefit.*

More information on the penetration estimate was included in section 2.3.

*P. 5863, L. 24-26: Again, I don't understand the sentence. Can it be splitted in two separate statements? I would think that for clarity, even an equation would be helpful.*

The sentence was split and the scaling was explained in more detail (in addition to the description in Kääb et al. 2012). We believe that a relation of the form

$$\text{Area}_{\text{glaciers}}/\text{Number}_{\text{glacier\_footprints}} = \text{Area}_{\text{entire\_zone}}/\text{Number}_{\text{all\_footprints}}$$

is too trivial to include as a formula in a compressed 'Brief Communication.

*P. 5864, L. 5-9: The description is “minimalistic” again. Taking the text literally, one could even arise the doubt whether the units have been treated adequately...*

The text was modified to reflect that the list of uncertainties included should not strictly be read as formula.

*P. 5865, L. 22-23: In the text, the description of what data led to Fig. 2 is insufficient. Either include more information or (at least) point directly at the supplementary material.*

A reference to the Supplement was included.

*P. 5866, L. 15-19: Where is this result coming from exactly? There were no sampling problems mentioned in the text, were there? Has it to do with the procedure mentioned at P. 5863, L. 24-26?*

End of section 2.3. the insufficient ICESat sampling with respect to glacier surges was explained in a more detail in the revised manuscript.

*P. 5866, L. 20-22: Again: It is not clear what exactly led to this conclusion. In particular:*

145 *Why is the penetration depth now estimated to be higher than what estimated in Kääb*  
146 *et al. (2012)?*

147 We modified slightly to clarify that this is not in contrast to Kääb et al. 2012. In fact maximum  
148 penetration (average per zone) found by Kääb et al. 2012 is around 2.5 m, but much higher values  
149 were found for the new areas in the west and east that were not part of Kääb et al. 2012.

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151 *P. 5867, L. 11: Mentioning the actual stream gauges the given numbers refer to would*  
152 *facilitate comparability to other studies. The generic information “where they [the mentioned*  
153 *rivers] leave the mountains” is too vague for being useful.*

154 More details are now provided and all necessary information included in Table S1.

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156 *P. 5867, L.18-19: Maybe repeat what could explain the discrepancy found for the Himalaya*  
157 *and the East Nyainqentanglha Shan.*

158 We provide some potential explanations in section 3.1, but prefer to not highlight these in the  
159 conclusions beyond stating the disagreement, as we think it would be more up to gravimetry  
160 experts to discuss the potential influence of ground water depletion and endorheic basins on  
161 satellite gravity.

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164 — *MINOR COMMENTS, AND SUGGESTIONS FOR TEXT RE-ARRANGEMENTS*  
165 *AND FORMULATIONS* —

166 *Title: The study addresses the period 2003-2008 only. I would therefore replace the*  
167 *rather vague “early 21st century” with the more specific information “2003-2008”. DONE*

168 *P. 5858 L.10-12: Since these sentences are more a methodological aspect than a*  
169 *proper result, I would suggest moving them directly at L.2 (i.e. after the first sentence). DONE*

170 *P. 5858 L.13: As now, the section should probably be called “introduction and methods”. DONE*

171 *P. 5858 L.14-18: It would be good having some references backing up this claims. DONE*

172 *P. 5858 L.19: A detail, but since ICESat was operative until 2009, you may want to*  
173 *include a hint already here for why your period of analysis spans to 2008 only. DONE*

174 *P. 5858 L.14: “by” should be moved before “(i)” DONE*

175 *P. 5859 L.5-6: Since geographic names are mentioned, it would be good being pointed*  
176 *at Fig. 1 here already. DONE*

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178 *P. 5859 L.18-20: More a question than an analysis I would*  
179 *suggest to actually include in the manuscript: Wouldn't the High Asia Reanalysis (HAR)*  
180 *dataset be suitable for gaining some additional insights in these processes?*

181 We are not sure what the referee means as L18-20 are section titles. In general we prefer to not  
182 investigate trends based on HAR. According to the HAR user guide ([http://www.klima-ds.tu-](http://www.klima-ds.tu-berlin.de/har/har_user_guide_V1.4.pdf)  
183 [berlin.de/har/har\\_user\\_guide\\_V1.4.pdf](http://www.klima-ds.tu-berlin.de/har/har_user_guide_V1.4.pdf)): "Due to the use of final analysis data as input and the  
184 short period of time where HAR data is available, trend calculations are not robust and should not  
185 be conducted with HAR. The focus of HAR based analyses should be hold on decadal averages,  
186 inter-annual to intra-seasonal variability, and physical process understanding". But we added the  
187 HAR key publication as further reference related to the different climatic regimes along the  
188 Himalayas. HAR is certainly very helpful (and meant) for that purpose. A detailed meteorological  
189 interpretation of potential processes behind the observed spatio-temporal patterns of glacier  
190 volume change is beyond the focus of the present contribution.

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192 *P. 5860 L.2: I suggest replacing “is” with “seems” since there is no proper evidence for*  
193 *the claim (is there?). DONE*

194 *P. 5860 L. 5-7: I do not understand this sentence. My guess is that you mean something*  
195 *like “Combined, the results by Gardner et al. (2013), Neckel et al. (2014), and the glacier elevation*  
196 *change pattern of Fig. 1 suggest...”. Please reformulate the sentence. DONE*

197 *P. 5864, L. 27: I suggest reformulating the sentence into something like “Note that*  
198 *Gardner et al. (2013) offer a second, more negative...” (the many commas in the*  
199 *current formulation are distracting). DONE*  
200 *P. 5865, L. 10: Is the number “0.06 +/- 0.01 mm/yr” a results of this study or from the*  
201 *study by Gardner et al.? The sentence is not clear in this respect . DONE*  
202 *P. 5865, L. 15: I suggest adding “(positive discharge equivalent, DE)” after “2003-2008” (as far as*  
203 *I understand, you don’t want to mention the value given in Tab. 2 here, correct?). DONE*  
204 *P. 5865, L. 18: What does “at the glaciers” actually mean? DONE*

205

206 **P. Reggiani and T.H.M. Rientjes**

207 A general response to Reggiani and Rientjes is given in a separate Author Comment:

208 <http://www.the-cryosphere-discuss.net/8/C2809/2015/tcd-8-C2809-2015.pdf>

209 Here we list the changes made to section 3.2 of the revised manuscript in response to the  
210 comment:

211 Added: "Note that computation of our discharge equivalents is a pure unit conversion from Gt yr<sup>-1</sup>  
212 to m<sup>3</sup> s<sup>-1</sup>, neglecting any hydrological processes and with the sole aim to roughly evaluate the  
213 relative importance of glacier mass changes in the catchments for river flow."

214 Added: "For instance for the Upper Indus basin, the hydrological balance is under ongoing  
215 discussion (Reggiani and Rientjes, 2014) and we hope that our glacier mass change estimates can  
216 contribute towards balance closure and better understanding of spatial-temporal patterns of run-off  
217 or high-elevation precipitation amounts in the region (e.g. Immerzeel et al., 2012)."

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219 **D.J. Quincey (Referee # 2)**

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221 *General comments:*

222 *This contribution is a valuable extension to the study of Kaab et al., 2012 to include*  
223 *several poorly studied parts of the Himalaya and neighbouring ranges. Given that*  
224 *the methods are largely detailed in this previous study, it makes sense that they are*  
225 *not repeated here. The results are clearly presented and discussed and will make*  
226 *a further excellent contribution to the literature. The additional discussion relating to*  
227 *SRTM penetration is interesting and of value to many other related studies.*

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229 *Specific comments:*

230 *I have two specific comments. The first relates to the conclusions of the study. Several of them were*  
231 *a bit surprising, in that they weren’t an obvious outcome of the study (until I read them). I therefore*  
232 *suggest the authors revisit the stated conclusions and ensure they properly reflect the preceding text.*  
233 *My last four comments in the ‘technical’ section below reflect this. The second relates to the*  
234 *consideration of climate in the study. Of course it is difficult to give full consideration to everything*

235 *in such a short manuscript, but since you devote the second half of a long paragraph to specifically*  
236 *discussing the Karakoram climate, it should be mentioned somewhere that the climate in the west is*  
237 *very different to that in the east. It is after all the primary control on the spatial variability in mass*  
238 *change that you present. A few lines should sort it.*

239 We added a paragraph on glacier-climate variability at the end of section 2.2.

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241 *Technical comments:*

242 *P5858*

243 *Lines 18-23: these aims neglect a major point of the study - to evaluate the contribution*  
244 *of glacier mass loss to river discharge. ADDED*

245 *Line 24: 'by' should be before the (i). DONE*

246 *P5860*

247 *Lines 2-5: as far as I'm aware there hasn't really been much support for the topographic*  
248 *or glaciological characteristics being the cause of the anomaly in the literature. On the*  
249 *other hand there have been rather more studies showing/citing climate as being the*  
250 *driving force, most of which you then go on to discuss. I'm thus not sure this statement*  
251 *reflects the debate very well. AGREED, AND MODIFIED ACCORDINGLY*

252 *Lines 5-7: This doesn't read very well - can you rephrase? REPHRASED*

253 *Line 7: You could (should?) split the paragraph starting at 'Direct', since this is now*  
254 *discussion related to your data, rather than your own results. DONE*

255 *Line 8: missing 'are' between 'trends' and 'uncertain'. DONE*

256 *Line 9: suggest, not suggests. DONE*

257 *P5861*

258 *Lines 5-6: Not sure I follow. How have the accumulation areas been lost? And how is*  
259 *this evidenced in the Landsat data? MODIFIED*

260 *P5862*

261 *Lines 10-11: should read 'As a consequence, SRTM glacier elevations do not, in general,*  
262 *reflect real mid-February 2000 glacier surface elevations...' DONE*

263 *P5863*

264 *Line 5: 'is able to reconcile' can simply be 'reconciles' Line 15: 'is again able to completely*  
265 *reconcile' can just be 'again reconciles' DONE*

266 *P5866*

267 *Lines 6-7: did you show this here (that firn lines have risen towards or above max*  
268 *glacier elevations?). You're probably right, but I'm not sure it's a conclusion of this*  
269 *study? REMOVED*

270 *Lines 15-19: again, I'm sure you're right but did you show this here?*

271 We modified, but prefer to leave this important disclaimer with respect to our Pamir and Hindu  
272 Kush glacier volume changes. In fact, when superimposing the ICESat tracks over Landsat data  
273 and the elevation change maps from Gardelle et al. (2013), as we did, the problem becomes  
274 obvious.

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276 *P5867*

277 *Lines 2-4: It's good that you're open about this, but are you suggesting your inference*  
278 *is not believable? In which case it rather undermines your previous discussion about it*  
279 *(in which there is no hint that you think it could be wrong). REMOVED*

280 *Lines 9-16: Given this is a key conclusion, I see no obvious mention/discussion of it in*  
281 *the preceding text? I think you should at least mention it in Section 3.2. In fact, these*  
282 *lines read like a part of the discussion, rather than a conclusion.*

283 Explained now in more detail in section 3.2.

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2 **Brief Communication:**

3 **Contending estimates of ~~early 21<sup>st</sup> century~~2003-2008**  
4 **glacier mass balance over the Pamir-Karakoram-Himalaya**  
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10 Correspondence to: Andreas Kääb (kaeab@geo.uio.no)

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12 **Abstract**

13 We present glacier thickness changes over the entire Pamir-Karakoram-Himalaya arc based  
14 on ICESat satellite altimetry data for 2003-2008. **We highlight the importance of C-band**  
15 **penetration for studies based on the SRTM elevation model. To the very east and west of our**  
16 **study area, this penetration seems to be of larger magnitude and variability than previously**  
17 **assumed. The most negative rate of region-wide glacier elevation change ( $< -1 \text{ m yr}^{-1}$ ) is**  
18 **observed for the East Nyainqêntanglha Shan. Conversely, glaciers of the West Kunlun Shan**  
19 **are slightly gaining volume, and Pamir and Karakoram seem to be on the western edge of this**  
20 **mass gain anomaly rather than its centre. For the Ganges, Indus and Brahmaputra basins, the**  
21 **glacier mass change reaches  $-22 \pm 3 \text{ Gt yr}^{-1}$ , about 10% of the current glacier contribution to**  
22 **sea-level rise. For selected catchments, we estimate glacier imbalance contributions to river**  
23 **runoff from a few percent to greater than 10%. ~~We highlight the importance of C-band~~**  
24 **~~penetration for studies based on the SRTM elevation model. To the very east and west of our~~**  
25 **~~study area, this penetration seems to be of larger magnitude and variability than previously~~**  
26 **~~assumed.~~**

## 1 Introduction and Methods

Region-wide measurements of glacier volume or mass change are limited for the Pamir-Karakoram-Himalaya region, leaving room for speculation about the glacier response to climate change and its hydrological significance. ~~Between a handful of studies that narrow down the range of uncertainties for core parts of this remote mountain region, significant inconsistencies exist.~~ Glacier mass change in high mountain Asia (or some part of it) have been obtained by (i) extrapolating the few existing in-situ mass balance series (Cogley, 2011; Bolch et al., 2012; Yao et al., 2012), (ii) using space gravimetry (Jacob et al., 2012; Gardner et al., 2013), (iii) laser altimetry (Kääb et al., 2012; Gardner et al., 2013; Neckel et al., 2014), and (iv) the differencing of digital elevation models (Gardelle et al., 2013). Between this handful of studies that narrow down the range of uncertainties for core parts of this remote mountain region, significant inconsistencies remain.

The aims of this study are to provide (i) a new consistent regional-scale data set from the ICESat autumn laser campaigns (2003-2008) by extending Kääb et al. (2012) to completely cover the study region by Gardelle et al. (2013) and several major river basins, (ii) to compare the results to other previous estimates of the Pamir-Karakoram-Himalaya glacier volume change, and (iii) to evaluate the contribution of glacier mass change to river runoff.

We follow the methods explained in Kääb et al. (2012) with a considerable extension towards the East Nyainqêntanglha Shan, the Pamir and part of the Tibetan Plateau (Fig. 1). In short, ICESat footprints are intersected with the February 2000 SRTM DEM and overlaid on the most snow-free multispectral Landsat images over ~2000-2013 to manually classify footprints into three classes; glaciers, non-glaciers and water. Glacier elevation difference trends are then estimated regionally and at a  $1^{\circ} \times 1^{\circ}$  geographic grid by fitting a robust linear temporal trend to the time series of elevation differences between the SRTM DEM and individual ICESat footprint elevations. Trends are derived from autumn ICESat campaigns only (2009 ICESat winter campaigns excluded), because combined autumn and winter trends are sensitive to temporal variations in accumulation amount and timing, potentially introducing bias (see Supplement of Kääb et al., 2012). We ~~ensure-confirm~~ that our trends are not due to sampling bias of ICESat elevations by comparing ICESat elevation histograms with glacier hypsometry. The resulting elevation difference trends for all our zones are given in Tab. 1.



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## 2 Glacier thickness changes

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### 2.1 Thickening in the Karakoram and West Kunlun Shan

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A first striking feature in the regional map of elevation difference trends (Fig. 1) is glacier thickness gain in the West Kunlun Shan ( $\sim +0.1 \text{ m yr}^{-1}$ ), agreeing with in-situ mass balance and length change measurements (Yao et al., 2012). There is a southwest to northeast gradient from considerably negative glacier mass balances in Hindu Kush and Spiti Lahaul to positive values in the Pamir-Karakoram-West Kunlun Shan region (Fig. 1). This suggests the so-called Karakoram glacier mass-balance anomaly (Hewitt, 2011; Gardelle et al., 2012), or Pamir-Karakoram anomaly (Gardelle et al., 2013), is rather the edge or southwest limit of an anomaly centred more to the northeast over the West Kunlun Shan, or Tarim Basin. The anomaly ~~seems~~ **is thus indeed the result of a larger-scale meteorological or climatic feature, not necessarily due to** peculiarities of the Karakoram topography or glaciers (e.g., surge type, hypsometry, avalanche contribution; Hewitt, 2011) do not necessarily play **a decisive role, but a result of a larger-scale meteorological or climatic feature.** Combined, ~~the~~ **Using** results ~~from~~ **by** Gardner et al. (2013), ~~and~~ Neckel et al. (2014), ~~and combined with~~ the glacier elevation change pattern of Fig. 1 suggest the centre of the anomaly could be located over the Tibetan Plateau.

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Direct precipitation measurements in this region are scarce thus trends are uncertain. Satellite-retrieved precipitation and gauge data (Global Precipitation Climatology Project) suggest an increase of precipitation over the study region north of Karakoram and east of Pamir (Yao et al., 2012). Chinese measurements show increased precipitation over the Tibetan Plateau (personal communication Chong-Yu Xu), and Tao et al. (2014) suggest wetter conditions over the Tarim Basin since the mid 1980s. A number of abnormally wet years occurred during the early 21<sup>st</sup> century over the Tarim Basin and the Tibetan Plateau (Becker et al., 2013), in particular for the hydrological years 2003/4 and 2005/6. A recent climate modelling study proposes that stable or increasing snowfalls characterise the Karakoram anomaly on a background of increasing air temperatures (Kapnick et al., 2014). Despite the available studies and data, further research seems necessary to consolidate the precipitation and temperature trends and the reason behind the slight glacier volume gains.

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### 2.2 Massive thinning in East Nyainqêntanglha Shan and Jammu-Kashmir

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The other striking feature in Fig. 1 is the massive glacier thickness loss in the East Nyainqêntanglha Shan to the very east (between  $-1 \text{ m yr}^{-1}$  and  $-1.7 \text{ m yr}^{-1}$ ), also consistent

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90 with the large negative mass balances and frontal retreats in this zone (Yao et al., 2012). The  
91 glaciers of East Nyainqêntanglha Shan have the smallest total elevational range in our study  
92 region, indicating a large sensitivity to fluctuations in the equilibrium line altitude (Pelto,  
93 2010; Loibl et al., 2014). The few available in-situ mass balance measurements in the area  
94 suggest that the equilibrium line was over the vertical limits of the monitored glaciers in the  
95 late 2000s, and precipitation in this zone shows the strongest long-term decrease over the  
96 entire Pamir-Karakoram-Himalaya region (Yao et al., 2012; Becker et al. 2013). A similar  
97 pattern of glacier shrinkage, though less distinct, is found in Jammu Kashmir within our Spiti  
98 Lahaul zone and forms the cluster of second-largest thickness loss rates in this study (-0.5 to -  
99 0.7 m yr<sup>-1</sup>). Also here, Landsat data indicate that firn lines have risen towards high glacier  
100 elevations ~~widespread loss of large parts of~~ resulting in very small accumulation areas or even  
101 their complete loss.

102 The 2003-2008 glacier thickness changes in the other study zones are all similar, on the order  
103 of ~ -0.4 to -0.5 m yr<sup>-1</sup> (Tab.1), with more negative values in the Bhutan zone at the transition  
104 between the East Nyaiqêntanglha and Everest zones. We note that glaciers dominated by the  
105 summer monsoon (i.e. east of the Spiti Lahaul) all show thickness losses (summer-  
106 accumulation type glaciers; Fujita, 2008; Kapnick et al., 2014; Maussion et al., 2014). East  
107 Nyaiqêntanglha Shan, the zone with strongest glacier thickness loss, receives most  
108 accumulation during March-May (spring-accumulation type; Maussion et al., 2014). The  
109 glaciers with considerable winter accumulation under influence of the Westerlies show a more  
110 mixed picture with stable or growing thicknesses in the Karakoram and West Kunlun Shan,  
111 but thickness losses for instance in the Hindu Kush.

### 112 **2.3 Comparison to previous thickness change studies**

113 The following comparison to other studies uses average glacier thickness changes rather than  
114 total mass changes in order to minimize effects from different delineations of study zones,  
115 glacier cover areas, and density assumptions. From Hindu Kush and Karakoram in the west to  
116 Nepal in the east, results of all studies agree within their errors (Tab.1). Results are most  
117 sensitive to zone delineation in the Hindu Kush, reflecting the strong spatial variability of  
118 glacier thickness change rates in this area (Fig. 1) and presumably also locally heterogeneous  
119 glacier behaviour (Sarikaya et al., 2012; see also below for Pamir).

120 Significant differences between the results of all studies are found over East Nyainqêntanglha  
121 Shan. Our results and those from Neckel et al. (2014) agree within the errors, but not with  
122 Gardner et al. (2013) although all three studies are based on ICESat. While our study and

123 Neckel et al. use ICESat footprint classifications from contemporary satellite images, Gardner  
124 et al. use Randolph Glacier Inventory outlines (RGI version 2.0; Pfeffer et al., 2014), which  
125 contain considerable errors of commission and omission in this zone (see Table 1 in Gardelle  
126 et al., 2013). Repeating our analysis with footprint classifications based on the Randolph  
127 Glacier Inventory results in roughly 20% less negative elevation difference trends on glaciers  
128 (~ 20% less negative) due to inclusion of non-glacier footprints. Vice versa, the elevation  
129 difference trends on land, very close to 0 when using our own footprint classification, become  
130 negative if ICESat footprints are classified using RGI, due to inclusion of glacier footprints.  
131 The remaining discrepancy is presumably due to the fact that the ICESat-based results of  
132 Gardner et al. are averaged from three different methods. Their results based on autumn  
133 footprints only (method B, Gardner et. al., 2013) suggest a thickness change rate of  $-0.86 \text{ m yr}^{-1}$ ,  
134 which is in closer agreement with our results.

135 At a first glance, East Nyainqêntanglha Shan results from Gardelle et al. (2013; zone called  
136 there Hengduan Shan) and Gardner et al. (2013) seem to agree, but we believe this might be a  
137 coincidence. First, above we argue why the Gardner et al. results might be less negative.  
138 Second, the results in Gardelle et al. (2013) rely crucially on an estimate of SRTM C-band  
139 penetration. Over any glacier globally, the SRTM radar waves will typically have penetrated  
140 into the snow and ice, with potential largest penetration depths through snow and firn, and  
141 smallest through ice (Kääb et al, 2012; Dall et al., 2001; Rignot et al. 2001). As a  
142 consequence, SRTM glacier elevations do not, in general, reflect real mid-February 2000  
143 glacier surface elevations but some lower horizon, the elevation of which depends among  
144 others on the dielectric properties and structure of the penetrated glacier volume during the  
145 SRTM campaign. For elevation difference studies where one of the elevation data sets is the  
146 SRTM, its penetration depth needs to be estimated for correction, and biases in this estimate  
147 translate directly into offsets in thickness change. ~~While~~ Gardelle et al. (2013) used an  
148 average C-band penetration of 1.7 m for East Nyainqêntanglha Shan estimated from the  
149 difference of SRTM C-band and X-band DEMs (Gardelle et al., 2012). Here, we extrapolate  
150 our ICESat elevation trends over 2003-2008 and their uncertainty back in time to the SRTM  
151 acquisition period in February 2000. Under the coarse assumption that the 2000-2003 trends  
152 equal the 2003-2008 ones, the extrapolation should at February 2000 result in a zero elevation  
153 difference to ICESat since the SRTM DEM was used as elevation reference. Offsets in this  
154 elevation difference for February 2000 are mainly attributed to SRTM radar penetration into  
155 ice and snow (for method and discussion see Kääb et al., 2012). For East Nyainqêntanglha  
156 Shan this analysis indicates an ~~much higher~~ average penetration of 8-10 m (7-9 m if based on

157 the winter trends that might alternatively be assumed to reflect February conditions), **much**  
158 **more than the 1.7 m assumed in Gardelle et al. (2013)**, while the corresponding off-glacier  
159 penetration is not discernible from zero. Clearly, our penetration depth lies at the high end,  
160 but remains within the range of possible C-band phase-centre penetrations (Kääb et al, 2012,  
161 Dall et al., 2001, Rignot et al. 2001). Sakai et al. (2014) suggest the highest accumulation  
162 rates of the entire study region occur in East Nyainqêntanglha Shan, together with Hindu  
163 Kush. Correction of the Gardelle et al. (2013) results by our present C-band penetration  
164 estimate completely reconciles their results with ours. Note, however, that extrapolation of  
165 our 2003-2008 elevation difference trend back to 2000 is based on the **strong-risky**  
166 assumption that the 2000-2003 trend equals the 2003-2008 trend.

167 For the Bhutan zone, Gardelle et al. (2013) estimated a C-band penetration for February 2000  
168 of 2.4 m whereas our extrapolation of ICESat trends suggests around 6 m, which again **is-able**  
169 **to-reconciles** the results of both studies for this zone.

170 In the Pamir, our results are more negative than Gardner et al. (2013) and in particular  
171 Gardelle et al. (2013). As above, we suggest that our manual classification of ICESat  
172 footprints versus the Randolph Glacier Inventory contributed to the difference with Gardner et  
173 al. (Gardelle et al. used their own inventory). Also, the difference between our study and  
174 Gardner et al. is reduced if only the results from their Method B (similar to ours) is  
175 considered. Gardelle et al. (2013) find glacier thickness changes of  $+0.16 \pm 0.15 \text{ m yr}^{-1}$  over  
176 the Pamir whereas the present study suggests  $-0.48 \pm 0.08 \text{ m yr}^{-1}$ . Again, we find larger  
177 SRTM C-band penetration of 5-6 m compared to 1.8 m (Gardelle et al., 2013). Applying the  
178 average C-band penetration from the present study **is-again able-to-completely-reconciles** the  
179 results of both studies. However, comparison of both studies in Pamir is complicated by a  
180 number of glacier surges (Gardelle et al., 2013) in connection with particularly sparse ICESat  
181 glacier coverage. **Visual-inspection-shows-some** Superimposing ICESat tracks **over Landsat**  
182 **images and the elevation change map of Gardelle et al. (2013) reveals that they** cross areas of  
183 **either** strongly positive or negative elevation change zones from surge waves. **The ICESat**  
184 **trends thus become biased depending on where they sample surges, and the total ICESat**  
185 **sample size over Pamir is not large enough to compensate for these effects.** The different  
186 observation periods for both studies (2000-2011 versus 2003-2008) may also have  
187 considerable impact due to surge activities and climate inter-annual variability (Yi and Sun,  
188 2014).

### 3 Glacier mass changes and water resources

We assume an average density of  $850 \text{ kg m}^{-3}$  for all 2003-2008 volume changes to convert the thickness changes to water equivalent quantities (Huss, 2013; see Kääb et al. for different density scenarios). The total glacier area is estimated using a simple cross-product: we multiply the number of ICESat glacier footprints in each zone with the ratio between the total zone area and total number of ICESat footprints. ~~Toe to the complete glacier cover to the complete glacier cover and used area estimates for the complete glacier cover based on scaling the density of ICESat footprints on glaciers with the areas and footprint densities of entire zones (Kääb et al., 2012), to convert the thickness changes to water equivalent quantities (Tab. 2).~~ Our method to estimate the total glacier areas is certainly open to discussion, but we prefer the above procedure over using areas from the Randolph Glacier Inventory because of the large deviations to our estimates, mainly for East Nyainqêntanglha and Pamir, from the obviously outdated glacier outlines and voids in the Randolph inventory (Nuimura et al., 2014). The uncertainty of water equivalent quantities ~~is estimated as root sum square of~~ includes the standard error of the elevation difference trend fit, the off-glacier trends, an error due to temporal offset of the ICESat autumn campaigns from maximum cumulative ablation conditions, an uncertainty of  $\pm 20\%$  for the glacier cover areas, and an uncertainty of  $\pm 60 \text{ kg m}^{-3}$  for density (Kääb et al. 2012; Huss, 2013). ~~The effects of these individual sources of uncertainty, all converted to error in mass change, are combined through the root sum of squares to arrive at the total uncertainty.~~ Note that water equivalent results from this study are not identical to Kääb et al. (2012), even if elevation difference trends agree, due to the simplified density assumption and the different glacier area estimates used.

#### 3.1 Comparison to gravimetric mass loss

For the Pamir, Kunlun Shan and Karakoram (zone 8b of Jacob et al., 2012; note that the Karakoram is part of their zone 8b, not 8c as suggested by their zone names) we estimate a glacier mass change of  $-6 \pm 2 \text{ Gt yr}^{-1}$  for 2003-2008 that agrees well within the error with Jacob et al. results from satellite gravimetry of  $-5 \pm 10 \text{ Gt yr}^{-1}$  (Jan 03-Dec 07) and  $-8 \pm 9 \text{ Gt yr}^{-1}$  (Jan 04-Dec 08). For the Himalayas and East Nyainqêntanglha Shan (zone 8c of Jacob et al. 2012) we estimate a 2003-2008 glacier mass change of  $-19 \pm 3 \text{ Gt yr}^{-1}$  that compares to  $-3 \pm 12 \text{ Gt yr}^{-1}$  (Jan 03-Dec 07) and  $-2 \pm 10 \text{ Gt yr}^{-1}$  (Jan 04-Dec 08) from satellite gravimetry. Given their fundamentally different approaches, it is challenging to discuss potential sources of disagreement between the two studies in the Himalayas and East Nyainqêntanglha.

221 Groundwater depletion (Rodell et al., 2009), glacier imbalance runoff into endorheic basins  
222 (Zhang et al., 2013), and errors and biases in the ICESat-derived trends as discussed above  
223 and in Kääb et al. (2012) are all likely explanations. Note that Gardner et al., 2013, offer a  
224 second, more negative gravimetric estimate for the entire combined High Mountain Asia that  
225 is, though, not spatially resolved enough to compare to our results. The uncertainties of our  
226 results in this entire paragraph are given at  $2\sigma$  confidence level to better agree with the  
227 uncertainty level in Jacob et al. (2012), whereas elsewhere in this contribution uncertainty is  
228 provided at  $1\sigma$  confidence level.

### 229 **3.2 River runoff**

230 The glaciers of the Tarim Basin (only 40% of total glacier area is covered here, with notably  
231 Tien Shan missing) and the Amu Darya basin (all glacier areas covered) drain into endorheic  
232 basins and thus their mass changes do not contribute to sea-level (Tab. 2). The glacier mass  
233 changes in the Indus, Ganges and Brahmaputra basins from the present study contributed  
234 together  $\sim 0.06 \pm 0.01 \text{ mm yr}^{-1}$  to eustatic sea-level rise, that is  $\sim 10\%$  of the current sea level  
235 contribution of  $0.71 \pm 0.08 \text{ mm yr}^{-1}$  from glaciers outside the ice sheets (Gardner et al., 2013).

236 The discharge equivalent of these mass changes, that is the annual average glacier imbalance  
237 contribution to river runoff, is given in Tab. 2 for the major river basins covered. Note that  
238 computation of our discharge equivalents is a pure unit conversion from  $\text{Gt yr}^{-1}$  to  $\text{m}^3 \text{ s}^{-1}$ ,  
239 neglecting any hydrological processes and with the sole aim to roughly evaluate the relative  
240 importance of glacier mass changes for river flow in the catchments.

241 The Tarim Basin glaciers most likely stored water over 2003-2008 ( $+24 \pm 33 \text{ m}^3 \text{ s}^{-1}$  discharge  
242 equivalent, DE). The glacier imbalance contribution to runoff is largest for Brahmaputra ( $-400$   
243  $\pm 60 \text{ m}^3 \text{ s}^{-1}$  DE), followed by the Indus ( $-220 \text{ m}^3 \text{ s}^{-1}$  DE), and Ganges and Amu Darya ( $-130$   
244  $\text{m}^3 \text{ s}^{-1}$  DE). ~~The imbalance DEs calculated here relate to runoff at the glaciers.~~ Comparison of  
245 the discharge equivalent of glacier imbalance to measured river runoff is biased the further  
246 downstream the gauging stations are situated from the glaciers due to ~~upstream-cumulative~~  
247 natural and man-made losses. It is important to note that the available runoff data from  
248 literature and databases refer to various time periods, in parts considerably older than the  
249 ICESat period. Figure 2 illustrates thus only roughly the hydrological significance of the  
250 2003-2008 glacier mass change in selected gauged catchments. (For details on the gauging  
251 stations used and the uncertainty of the contributions see Supplement). As an example, the  
252 2003-2008 glacier imbalance within the Upper Indus basin at Besham Qila contributes  $\sim 6\%$  to

253 annual average river discharge (Fig. 2; Supplement), and we roughly estimate a very similar  
254 number for the Amu Darya (Supplement). For the Upper Indus basin, the hydrological  
255 balance is under ongoing discussion (cf. Reggiani and Rientjes, 2014) and we hope that our  
256 glacier mass change estimates can contribute towards balance closure and better  
257 understanding of spatial-temporal patterns of run-off or high-elevation precipitation amounts  
258 in the region (e.g. Immerzeel et al., 2012).

259 The modelling results for “non-renewable glacier runoff” of Savoskul and Smakhtin (2013)  
260 agree well with ours for Amu Darya, less for Indus (they obtain  $-0.55 \text{ m w.e. yr}^{-1}$  specific  
261 mass loss rate over 2001-2010, we  $-0.28 \text{ m w.e. yr}^{-1}$ ) and Ganges (they obtain  $-0.77 \text{ m w.e. yr}^{-1}$ ,  
262 we  $-0.37 \text{ m w.e. yr}^{-1}$ ), and not very well for Brahmaputra (they obtain  $-0.36 \text{ m w.e. yr}^{-1}$ , we  
263  $-0.90 \text{ m w.e. yr}^{-1}$ ).

## 264 4 Conclusions

265 From 2003-2008 ICESat-derived elevation difference trends over Pamir-Karakoram-  
266 Himalaya and from comparison to geographically overlapping studies we draw the following  
267 conclusions:

- 268 • ~~Glacier thickness loss over the study region is most pronounced for the East  
269 Nyainqêntanglha Shan, followed by Jammu-Kashmir. In these regions, the firm lines seem  
270 to have risen towards or above the maximum glacier elevations.~~
- 271 • Glaciers in and around the West Kunlun Shan are in balance or even gaining volume, and  
272 Pamir and Karakoram seem to be on the western limit of this mass balance anomaly  
273 rather than its centre. This suggests it is a meteorological or climatic anomaly (rise in  
274 precipitation) ~~rather than caused directly by glaciological and topographic peculiarities in  
275 the Karakoram, even if these certainly influence the glaciological expression of the  
276 anomaly.~~ But the cause and duration of this regional glacier anomaly is not fully  
277 understood yet.
- 278 • Our glacier volume changes ~~are seem~~ especially ~~sensitive to spatial and temporal  
279 distribution of sampling~~ uncertain in Pamir and, to a lesser extent Hindu Kush. The  
280 heterogeneous ~~glacier~~ behaviour of individual glaciers in these two zones, for instance  
281 from glacier surges, ~~enhances~~ may lead to ~~uncertainty~~ biases when extrapolating  
282 elevation difference trends from particularly sparse ICESat tracks, or areas covered by  
283 differential DEMs, to the entire zones.

- 284 • Extrapolation of ICESat trends **back in time** to the SRTM acquisition date suggests a

285 much larger **potential** magnitude and variability of SRTM C-band phase-centre

286 penetration than ~~previously~~-often assumed. Given the crucial importance of radar

287 penetration for glacier thickness change studies based on radar DEMs, such as the SRTM

288 or the upcoming TanDEM-X, we recommend to be critical against penetration

289 assumptions used in previous studies and to investigate the issue more extensively and

290 systematically (Langley et al., 2007; chapter 7 in Müller, 2011). The problem is

291 complicated by the fact that radar penetration has to be known specifically for certain

292 dates from the past. ~~In fact, we are still puzzled about the seemingly large SRTM~~

293 ~~penetration we inferred in the East Nyainqêntanglha Shan (8–10 m) and Pamir (5–6 m).~~
- 294 • The glacier mass changes in the Tarim and Amu Darya Basins of  $+0.7 \pm 1.0 \text{ Gt yr}^{-1}$  and -

295  $4.0 \pm 0.8 \text{ Gt yr}^{-1}$  do not contribute to sea level rise. The combined Ganges, Indus and

296 Brahmaputra basin glacier mass change is  $-23.7 \pm 2.1 \text{ Gt yr}^{-1}$ , almost 10% of the glacier

297 contribution to sea-level rise during 2003-2009.
- 298 • Neglecting water losses ~~between-downstream of~~ the glaciers ~~and gauging stations~~, the

299 2003-2008 glacier imbalances amount to  $\sim 6\%$  of the annual discharge of Amu Darya and

300 Upper Indus where they leave the mountains. This is a considerable amount given the

301 significance of the rivers for the Aral Sea (Amu Darya), and massive irrigation schemes

302 and household use in these dry climate regions. Maximum glacier imbalance

303 contributions to annual average river runoff ~~are-of~~ up to  $\sim 17\%$  are found for the Shyok

304 (Indus) and  $\sim 10\%$  Vaksh (Amu Darya), minimum contributions are only  $\sim 1\text{-}3\%$  for the

305 monsoon-type catchments in Nepal.
- 306 • Our results on glacier mass loss agree with those from satellite gravimetry (Jacob et al.

307 2012) over Pamir, West Kunlun Shan and Karakoram, but significantly diverge over the

308 Himalaya and East Nyainqêntanglha Shan.

309 It is important to note that our results only cover 5 yr, 2003-2008, and it remains open to what

310 extent those years are representative for longer periods, such as the 10 yr covered by Gardelle

311 et al. (2013). For short mass balance series, single anomalous years may have large impacts

312 on trends. Our water equivalent results are also sensitive to density and glacier area

313 assumptions. We find that glacier outlines and areas in the study region are still quite

314 uncertain and invite the reader to use improved glacier area estimates for upscaling our

315 results, and their own assumptions for the conversion of volume changes to mass changes.



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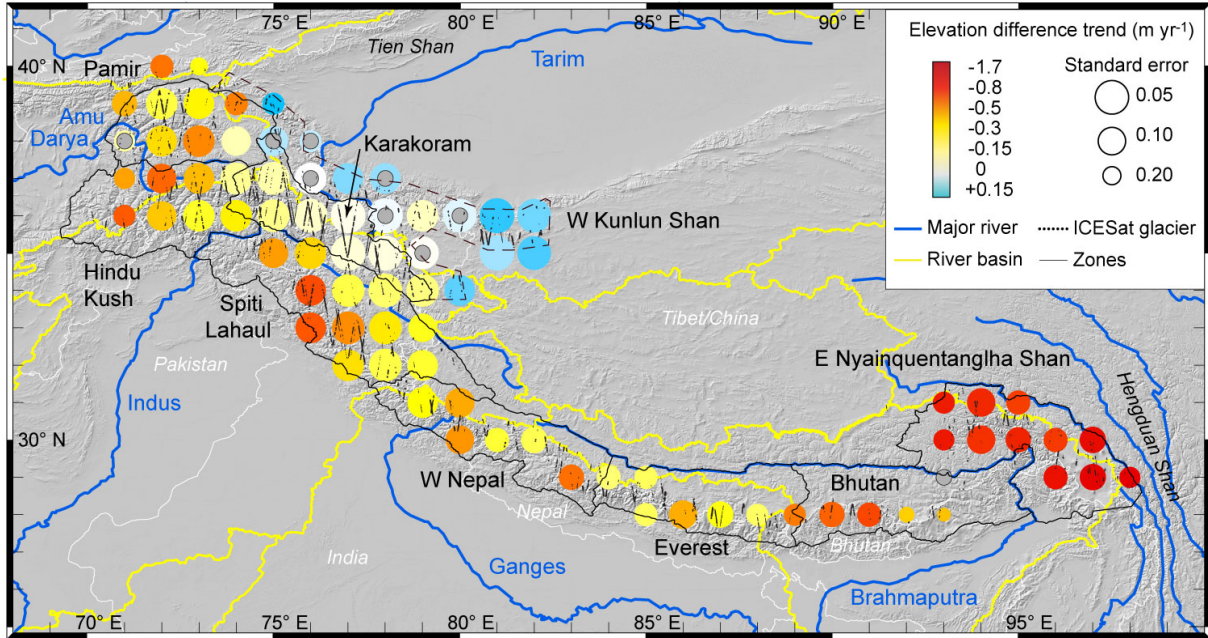
## **Author contributions**

A.K. designed the study, performed the data analysis and wrote the paper. C.N., D.T. and E.B. contributed to data analysis, performed supporting analyses and edited the paper.

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## Figures and Tables



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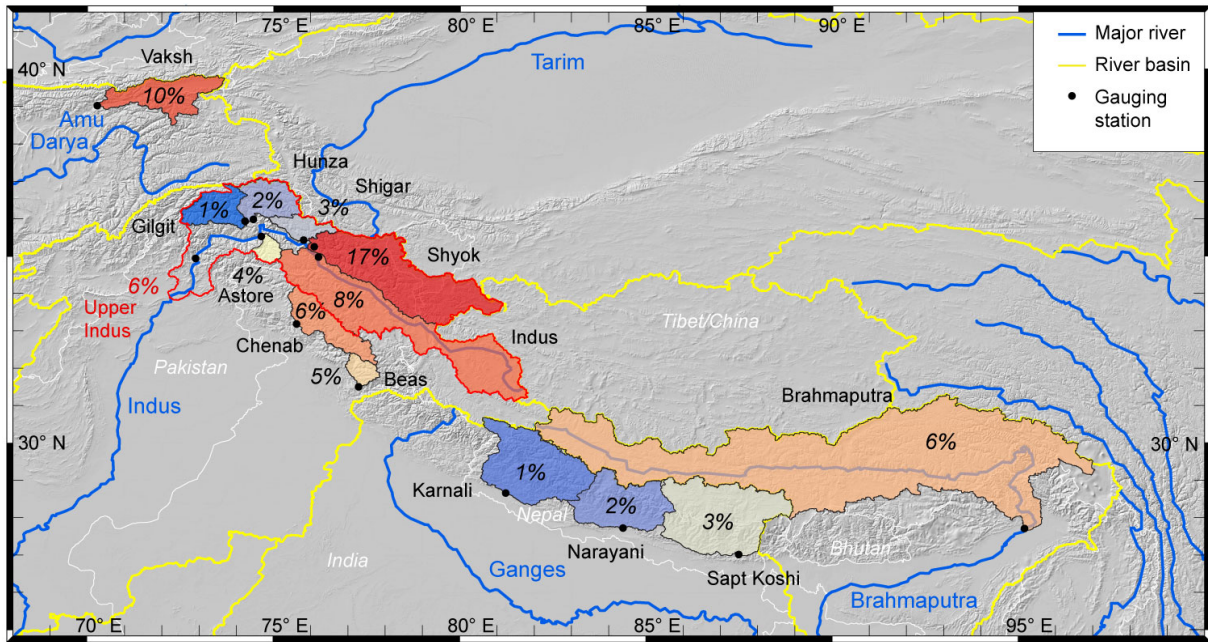
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Fig. 1 Study region and trends of elevation differences during 2003–08. Data are shown on a 1° grid with overlapping rectangular geographic averaging cells of 2° × 2°. Trends are based on autumn ICESat acquisitions. Only ICESat footprints over glaciers are indicated. The zones indicated by black outlines are equivalent to the ones of Gardelle et al. (2013) with the W Kunlun Shan-Tarim zone (dashed outline) being the only additional one. Trends for all cells (coloured data circles) are statistically significant except for the cells that are marked with grey centres. The uncertainty of the temporal trends per cell is indicated through circle sizes indirectly proportional to the standard error of trends at 68% level.

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Fig. 2 The percentage of discharge equivalent from annual glacier imbalance to measured average river runoff for selected catchments. Note that the actual numbers will be somewhat lower due to unaccounted water losses such as from evaporation or to groundwater. For details on the gauging stations used and the uncertainty of the contributions see Supplement.

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**Table 1:** Glacier elevation difference trends over the Pamir-Karakoram-Himalaya from this and other studies. Note that Gardelle et al. (2013) cover the period 2000 to ~2010, while the other studies cover 2003 to 2008/9. Note also that the zones of this study and Gardelle et al. coincide, whereas the zones of the other do so only roughly, which can potentially explain parts of the disagreements. See text in sections 3 and 4 for an explanation of how the glacier areas were estimated. \* named Hengduan Shan in Gardelle et al.; \*\* two zones of Gardner et al. overlap with our zone and both their values are given.

Zone	Glacier area (km <sup>2</sup> )	This study (m yr <sup>-1</sup> , ± at 1σ-level)	Gardner et al. (m yr <sup>-1</sup> , ± at 2σ-level)	Neckel et al. (m yr <sup>-1</sup> , ± at 1σ-level)	Gardelle et al. (m yr <sup>-1</sup> , ± at 1σ-level)
East Nyainqêntanglha *	6000	-1.34 ± 0.29	-0.30 ± 0.13 -0.40 ± 0.41 **	-0.81 ± 0.32	-0.39 ± 0.16
Bhutan	3500	-0.89 ± 0.16	-0.89 ± 0.18	-0.78 ± 0.27	-0.26 ± 0.15
Everest	8500	-0.37 ± 0.10	-0.44 ± 0.20		-0.30 ± 0.16
West Nepal	7500	-0.43 ± 0.09		-0.44 ± 0.26	-0.38 ± 0.16
Spiti Lahaul	9500	-0.49 ± 0.12	-0.53 ± 0.13		-0.53 ± 0.16
Karakoram	21000	-0.10 ± 0.06	-0.12 ± 0.15		+0.12 ± 0.19
Hindu Kush	5500	-0.49 ± 0.10			-0.14 ± 0.19
Pamir	6500	-0.48 ± 0.14	-0.13 ± 0.22		+0.16 ± 0.15
West Kunlun Shan - Tarim	12500	+0.05 ± 0.07	+0.17 ± 0.15	+0.04 ± 0.29	

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**Table 2:** Glacier thickness and mass changes over the major river basins of the study area. The discharge equivalent is a unit conversion from mass change and neglects any losses such as by evaporation or to groundwater. (i) The Tarim Basin is endorheic. Only parts of the glacier area (~40%) within the Tarim Basin are covered in this study. (ii) Endorheic basin.

Major river basin	Glacier area (km <sup>2</sup> )	Elevation difference trend (m yr <sup>-1</sup> )	Mass change (Gt yr <sup>-1</sup> )	Discharge equivalent DE (m <sup>3</sup> s <sup>-1</sup> )
Tarim <sup>(i)</sup>	15000	+0.06 ± 0.08	+0.7 ± 1.0	+24 ± 33
Amu Darya <sup>(ii)</sup>	11000	-0.43 ± 0.08	-4.0 ± 0.8	-128 ± 25
Indus	25000	-0.33 ± 0.04	-7.0 ± 0.8	-220 ± 26
Ganges	11000	-0.44 ± 0.07	-4.1 ± 0.6	-130 ± 20
Brahmaputra	14000	-1.06 ± 0.15	-12.6 ± 1.9	-400 ± 60

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## Supplement

The gauging stations used for the results shown in Fig. 2 are listed in Tab. S1. Reliable river runoff data are notoriously difficult to obtain over and around the Himalayas. Even if available, their use and distribution are sometimes restricted. As example catchments we select therefore only the ones where discharge data stem from peer-reviewed studies, or where the data were used in peer-reviewed studies, and where the data cover sufficiently long time periods. It is outside the focus of the present brief communication to compile a geographically complete set of catchment discharge data. The uncertainty of the glacier imbalance contribution to river runoff (Fig. 2) is estimated in the same way as the uncertainty of glacier mass changes, but uncertainties in the river runoff data used are neglected.

**Table S1.** Gauging stations indicated in Fig. 2 and uncertainty of our percentage discharge contributions of glacier imbalance to river runoff at  $1\sigma$ -level.

River	Gauging station	Annual discharge ( $\text{m}^3 \text{s}^{-1}$ )	Period of measurements	Source	Uncertainty of percentage discharge contributions
Vaksh	Garm	320	1933-1990	Global Runoff Data Centre (GRDC)	$\pm 5\%$
Gilgit	Gilgit	287	1980-2010	Mukhopadhyay and Khan (2014)	$\pm 2\%$
Hunza	Dainyor Bridge	332	1966-2010	"	$\pm 2\%$
Shigar	Shigar	203	1985-1998	"	$\pm 2\%$
Astore	Doyian	136	1974-2009	"	$\pm 2\%$
Upper Indus	Kharmong	452	1982-2010	"	$\pm 3\%$
Shyok	Yogo	362	1973-2010	"	$\pm 6\%$
Upper Indus	Besham Qila	2431	1969-2010	"	$\pm 2\%$
Chenab	Prem Nagar	626	1968-1986	Hofer (1993)	$\pm 3\%$
Beas	Thalout	190	1997-2001	Liu et al. (2013)	$\pm 2\%$
Karnali	Chisapani	1350	1962-1993	GRDC	$\pm 1\%$
Narayani	Narayangh	1590	1963-2006	Collins et al. (2013)	$\pm 1\%$
Sapt Koshi	Chatara	1537	1977-	GRDC	$\pm 1\%$
Brahmaputra	Pasighat	5870	1949-1962, 1976-1978	Sarma (2005)	$\pm 2\%$
Amu Darya	ungauged	$\sim 2300$	"long-term mean"	<a href="http://www.cawater-info.net">http://www.cawater-info.net</a> ; Agal'tseva et al. 2011	$\pm 1\%$

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