Response to the interactive comment on “Changes of the tropical glaciers throughout Peru between 2000 and 2016 – Mass balance and area fluctuations” by Thorsten Seehaus et al.

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First of all we want to thank the reviewer for constructive comments on our manuscript. All comments have been taken into account and a list of answers and undertaken actions is given below. Answers are in blue font color.

This manuscript presents geodetic mass balance calculations and glacier area fluctuations for Peruvian glaciers for the period 2000-2016. The methods are robust, and the key findings are substantial – specifically that area and mass have reduced considerably over this time period, with a notable increase in the rate of loss during the latter years (2013-2016). A particular highlight is the comprehensive discussion of the study findings in the context of previous work. Despite its density, a clear path is navigable throughout and the argument is strong. The analysis is also very honest about where problems in the current work may lie.

The only area where I think the authors need to think again is in the suggestion of the strong El Niño event of 2015 as the primary reason for the rapid change in area and mass loss rates. It may be just about conceivable that changes in temperature/precipitation/humidity could impact mass balance almost immediately, but the magnitude of the change is (too) substantial for this to be the only factor, and the idea that a warm and dry event could also impact on glacier area to such a degree, within a single year, cannot hold. This requires some further investigation/consideration/analysis.

We appreciate this comment and carried out further analysis regarding this issue.

First, we updated and advance the mass balance computation. Instead of using a constant density for volume to mass convestion, we added a 2nd scenario using different densities for regions below and above the ELA (e.g. Kääb et al. 2012). This scenario is more likely for glaciers in the tropics and the regional mass balance discussion is based on it (statement added in section 6.2):

“The 2nd density scenario leads to 8-21% lower country wide mass balances. As pointed out by Kääb et al. (2012), this scenario is suitable for glacier with no dh/dt due to ice dynamics and when dh/dt is clearly driven by melt or increased accumulation. Since, these conditions are typical for the Peruvian glaciers (see Section 1 and further down), we used the results of 2nd density scenario for further discussion and analyses.“

This scenario lead to a less, but still pronounced change in the mass budget for both observation periods (~15-25% less).

Regarding the mass balances: The comparison of the ONI values and glaciological measurements (specific mass balances and ELA) support the suggested link between increased mass loss and El Nino and the direct (immediately) impact on of ENSO on the mass balances. Moreover, the enhanced ablation during El Niño is on the one hand side force by the changes in e.g. temperature and precipitation, but on the other side also enhance through feedback processes. For example leads the higher temperature to liquid precipitation in the ablation region, which further increases the melting. Moreover during El Niño, precipitation is reduced but also the dry season is prolonged (delayed start of the wet season), leading to enhanced melt due to lower glacier albedo, since the fresh snow cover is missing. We added the following statements in section 6.2 and Figure S30 in the supplement.:

“Those climatic variations enhance the ablation and facilitate a positive feedback that further increase the glacier melt. The higher temperature as well as reduced and delayed precipitation, that are typical during El Niño, lead to liquid precipitation in the ablation regions and a reduced glacier albedo, enhancing the short-wave radiation absorption (e.g. Vuille et al. 2018, Maussion et al. 2015). Thus, the climatic variations explain the more negative mass balances in both subregions in the period 2013-2016, which also correlate with the strong El Niño activities in this interval (Figure 8).“

”The correlation of the annual glaciologial measurements with the average ONI of the respective observation periods indicates a trend towards increased mass loss and higher ELA during El Niño conditions (Figure S30). These tendencies fit to the observations by Silvero and Jaquet (2017) and Morizawa et al. (2013) (see Section 6.1) and support our revealed correlation between the increased glacier wastage in the period 2013-2016 and the strong El Niño event during this period. “

We also added a statement (section 3), that the seasonal offset for intervals ending in 2016 (TDX coverage in ~Oct. Nov.) leads to a small bias towards more negative mass budgets.

“Typically negligible accumulation occurs during the dry season and ablation is dominating the glacier mass budget (Favier et al., 2004; Kaser, 2001; Veettil et al., 2017b). Thus, the mass balances for observation periods ending in 2016 are slightly biased towards more negative values due to this seasonal offset in the data.“

Regarding the impact on glacier area: Silvero and Jaquet (2017) as well as Morizawa et al. (2013) showed that ENSO as a clear impact on the glacier area changes. Both studies report clearly increased retreat during El Niño epochs and even area gain during La Niña. E.g. Silvero and Jaquet discovered a very high retreat rate of -23 km/a in Cordillera Blanca between 2014 and 2016 (average ONI 1.1, ~5%/a area loss, we discovered also 5%/a loss at subregion R1 for the period 2013-2016) and area gain of 5.24 km² (average ONI -0.20) between 1997 and 2002. Moreover, they inferred a linear relation between area changes and ONI with an R^2=0.8. Additinally the glacier in the tropical Andes are in average the thinnest worldwide (Farinotti et al. 2019). Thus, increased ablation will cause more pronounced area reduction as compared to other regions. Thus, we conclude that the El Niño conditions and the associated increased ablation in the period 2013-2016 can be attributed as the driver for the observed increased recession. The following statement was added regarding this issue in Section 6.1:

“This pattern fits also to the finding by Morizawa et al. (2013) (at Condoriri Glacier, Bolivia) and Silvero and Jaquet (2017) (at Cordillera Blanca, subregion R1). Both studies reported enhanced recession during El Niño events and even area gains during La Niña epochs. The latter study also discovered a linear relation between glacier retreat and ONI (R^2=0.8) and reports an change rate of -5% a^{-1} for 2014-2016 that is equal to our change rate at subregion R1 for 2013-2016. Moreover, the glaciers in the Tropical Andes are in average the thinnest worldwide (Farinotti et al. 2019). Therefore, the increased melt will lead to more pronounced changes in glacier area as compared to other glacier region. “

Otherwise, I am very much in favour of seeing this manuscript published, and only have the following minor suggestions (by line number) to make.

10: debris-covered extents were also derived by coherence mapping according to the text?

Thank you for this advise, we added a the following statement: “The mapping of debris-covered glacier extents is supported by SAR-coherence information.”

30: ‘already crossed. . .’

Corrected

39: ‘GLOF incidents. . .’ or ‘GLOF threats. . .’?

Corrected

102: ‘continuous. . .’

Corrected

113: here and elsewhere check your cross-referencing to different sections. This one should be Section 4 (I think) – others later in the manuscript refer to sections 8, 9 and 10 that don’t exist

Thank you very much for this advice. The automatic cross-references were somehow mixed up. We corrected this problem.

122-123: more negative because of the lack of accumulation is what I think you mean here. . . but the previous sentence that refers to reduced ablation is contradictory to a more negative mass balance, so this needs clarification

We appreciate the reviewer’s comment. The review is right. We rephrased this paragraph in order to be more clear:

“Typically negligible accumulation occurs during the dry season and ablation is dominating the glacier mass budget (Favier et al., 2004; Kaser, 2001; Veettil et al., 2017b). Thus, the mass balances for observation periods ending in 2016 are slightly biased towards more negative values due to this seasonal offset in the data. “

173: use the correct GLIMS reference that comes with the download. . .

Thank you for this advice. We changed the reference accordingly.

266: ‘example’ not ‘exemplary’

Corrected

275: missing power on first km

Corrected

280: use of exemplary twice (though it should again be ‘example’ I think)

Corrected

315: ‘temporary’ not ‘temporal’

Corrected

349: Coropuna?

Corrected

386-393: though interesting, this paragraph is only partially relevant here and could probably be cut

If the reviewer agrees, we would like to keep this paragraph, since it summarizes and highlights the changes in the GLOF risk due to the observed glacier recession and expresses the urge for further monitoring.

395: ‘The most extreme surface lowering. . .’

Corrected

Figure 3: caption should read ‘example’ not ‘exemplary’,

Corrected

but moreover I’m not sure what the value of the figure is since we can see most of this in Figure 1?

This figure indicates the glacier area recession at some example mountain ranges. In Figure 1 only one set of outlines is shown and no multi temporal area changes. In order to demonstrate the area changes on spatial scales (due to the scales not possible in Figure 1), this figure shows certain subsets (zoomed in) of the study region. We moved this figure to the supplemental material.

Figure 7: this caption needs some work I think. It took an age to work out that the red bars were vs the blue bars. How about ‘Hypsometric distribution of measured glacier area with elevation (red) and total glacier area with elevation (blue), with mean dh/dt values in each elevation interval (blue dots). . .’?

Following the reviewer’s suggestion, we revised the caption (also of the similar graphs in the supplemental material). We hope it is now more clear:

“Hypsometric distribution of measured (red bars) and total (light blue bars) glacier area with elevation in subregion R1 in the interval 2000-2016. Blue dots represent the mean $\Delta h/\Delta t$ value in each elevation interval. Error bars indicate NMAD of $\Delta h/\Delta t$ for each hypsometric bin. Grey areas mark the lower and upper 1% quantile of the total glacier area distribution. Black dashed line: mean glacier elevation; Red dashed line: equilibrium line altitude (ELA), see also Table S3. Area measurements are based on the glacier outlines from 2000, considering only regions with slopes below applied slope threshold (50°, see Section 4.2). Plots for other subregions are provided in the Supplementary material.”