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.

Christian Huggel (Referee)
Received and published: 31 March 2019

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.

In my opinion this is a solid study with important new results and there is no doubt that I would like to see this paper published, eventually. While I think that the methods are good state of the art there are a few issues in the results which irritate me and make me wonder whether there are some more basic problems with data collection and analysis which I detail further below. To start I’m impressed by the amount of work done by the authors on a generally high level of data analysis, well presented. It adds new insights on glacier changes (area, surface changes and mass balance) which were previously not known on this level of detail and spatial coverage. I also like the discussion section which is transparent, comprehensive and encompasses the (full) coverage of available literature. In this discussion section the authors critically analyze a number of differences (and similarities) between their results and those of other studies. I can follow this discussion and I think it is mostly appropriate but I’m wondering whether there are underlying errors or uncertainties in terms of data sampling or analysis that may have gone undiscovered. I list here a number of possible problem areas:

The authors did not measure the full extent of the glaciers, and transparently report on it but the effect and possible uncertainties involved are not clear to me. The glacier area changes reported in Figure 9 and Table 2 contain numbers that raise some questions.
An area loss of only about 5% from 1970 to 2000 is in contradiction to what is generally reported, indicating values of 15-20% (Salzmann et al. 2013, Silverio and Jaquet 2004, others, incl. unpublished data). The authors indicate some aspects about incomplete inventories, or sampling issues. I’m not sure whether this large discrepancy can be explained by the mentioned aspects but urgently needs to be clarified.

The reviewer is right. An area change of -7% (Section 6.1) between 1970 and 2000 is too low. Therefore, it was mentioned in the text, that not all Cordilleras were mapped completely by the 1st Peruvian Glacier Inventory. In order to avoid irritations, we computed the changes considering only Cordilleras with full coverage in 1970 and revealed a value of -23% area changes (which fits to the findings by other studies). Consequently, we also adjusted Figure 9 and rephrased the statements in Section 6.1 and the caption of Figure 9.

“The comparison of our area measurement of 1916.6±48.3 km² in 2000 and the 1st Peruvian Glacier Inventory (Hidrandina SA, 1989) in 1970 (2041.85 km²) results in a retreat of -7% (-139.9 km²; 0.2% a^{-1}). However, the area changes amounts to -23%, considering only glaciated Cordilleras, which were completely mapped in the 1st Peruvian Glacier Inventory (UGRH, 2014). “

I’m also irritated by the error indications related to glacier area changes reported in Table 2, of up to 30% which is much higher than what is commonly achieved in remote sensing based mapping studies (ca. up to 5%). This also needs to be clarified.

The error values of the area changes dS in Table 2 result from basic error propagation using the uncertainties of the total glacier areas (Table 1 ~2.5-3.3%). Thus the uncertainty of the individual outlines is within the range of other studies. Area change computations are more sensitive to the uncertainty of individual outlines, explaining the higher relative errors of up to 30%. The following statement was added in section 5.1, in order to clearly explain the error computation.

“It should be noted, that the uncertainty of the area changes (Table 2) result from the uncertainty of the individual inventories (quadratic sum), assuming independence of the individual area measurements.”

I have seen many glacier mapping studies in the tropical Andes (published, or reviewed) which had errors because of inappropriately selected images with snow coverage which then resulted in erroneous glacier change results. I can’t say whether this study is affected by a similar problem. In any case the authors should carefully review the literature they cite and whether some of these studies have such errors (at Coropuna for instance some published studies have such errors).

The reviewer is right, that temporary snow cover, but also clouds, can strongly impact the quality of glacier outlines. By selecting only images towards the end of the dry season, manual editing and inspection as well as cross-checking with high-resolution imagery (Google Earth), we tried to minimize this impact as far as possible. Particularly, the outlines in subregion R3 in 2016 might be affected by snow cover, since significant snow coverage was recently reported at the non-glaciated Cordillera Barroso during dry season 2016 (Léon et al., 2019), explaining the nearly stable glacier area between 2013 and 2016 in this region. A statement (see below) regarding this issue was added in Section 6.1.

“… A significant temporary snow cover at the non-glaciated Cordillera Barroso (subregion R3, close to the boarder to Bolivia) was observed during the dry seasons in 2015 and 2016 (Lèon et al. 2019), which fits to the suggested increased precipitation at high elevations during after 2013. Moreover, snowfall events during try season strongly affect the glacier albedo an thus lead to reduced ablation. However, the temporary snow cover during dry season 2016 in subregion R3 might have also affected the mapping of the glacier outlines. Albeit, only imagery with no or only minimal snow coverage is selected, it is quite likely that some remaining snow cover was located at the glaciated peaks, leading to a slightly larger glacier area in 2016 as compared to 2013. This bias is not quantifiable and certainly within the range of applied uncertainty. Thus, we conclude that the glacier area kept nearly stable after 2013 in subregion R3 and attribute this to the allocation of the remaining ice at higher altitudes and increased precipitation, especially during the dry season, even though a strong El Niño event occurred in this period. “

Regarding the quality of the cited studies: We checked the studies, especially at Coropuna. Some studies provide information potential impact due to snow cover (e.g. Peduzzi et al., 2010; Silverio and Jaquet, 2012), whereas other do not even provide information on the date of the accquisitions. Thus, it is difficult to assess the quality of the data.
Since, in this study comparisons with the general (average) trends of typically an ensembles of studies are discussed, we conclude that the impact of biases due to snow cover in other studies can be neglected.

I’m surprised by the drastic change of glacier and mass balance change of 2000-2013 vs 2013-2016. The authors list a number of plausible reasons, and I think the increased precipitation(accumulation) at high altitudes is a very important finding here. Nevertheless, important open questions remain. Fig. 9 indicates a change in the El Niño Index around the year 2013, changing from slightly negative to strongly positive. Reported mass balance and (high altitude) surface change can certainly be explained with this mechanism to some extent. But it is unclear (and not plausible) how precipitation changes would immediately translate into rather drastic changes in glacier area, even if the response of tropical glaciers through feedback processes including precipitation and albedo changes is more direct than in mid-latitude glaciers. The comparison of their results with ground based mass balance measurements (glaciological method) are very significant.

Regarding the area changes: Other studies also inferred drastic changes in glacier area in correlation with El Niño. Silvero and Jaquet (2017) as well as Morizawa et al. (2013) reported clearly increased retreat during El Niño epochs and even area gain during La Niña. For example 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. 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. A comparison of our area change measurements with field measurements is not meaningful due to the large differences in the basin delinations.
The following statemant was added 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. "
Regarding glaciological mass balance measurements, see answer to next comment.

The authors are right that there are problems with the mass balance measurements which in fact are very challenging on these glaciers. Nevertheless, the authors should investigate this issue in more depth. I would also recommend to look in more detail on locally available field data which co-author Alejo Cochachin disposes of. The measurement interval (2000-2013) could have an effect, and changes towards more negative glacier mass balances could have been started earlier than 2013.

We carried out an extended analysis of the field measurements. The glaciological mass balances and ELA values are correltated with annual ONI values (Sep.-August). A clear trend towards higher mass losses and ELA values is visible for positive ONI values, indicating El Nino conditions (Fig. S30). Moreover, the annual mass balances at Yanamarey and Artesonraju, show strongly negative mass balances for 2015/16 and increase average mass loss trends after 2013. Unfortunatly, the mass balance series do not cover our whole remote sensing observation period, starting in 2000. Since, the mass balance variability of tropical glacier is strongly dominated by the lowest section (Soruco et al., 2009), we analyses the geodetic mass balances at regions below 4900/5000 m a.s.l. (approx. average ELA) separatly. Moreover, these lower sections have the highest density of glaciological point measurements. For both glacier, an onset of the rapid surface lowering at the terminus region is obvious already before 2013 (Fig. S31, 2011/12 for Artesonraju, unfortunatly the data at Yanamarey had some issues in the period 2009-2011). A comparison with the remote sensing data for the period 2013-2016 shows at Yanamarey a good agreement (average glaciological: -3152 kg/(m²a), geodetic: -3164 kg/(m²a)), whereas at Artesonraju the values differ (average glaciological: -4206 kg/(m²a), geodetic: -2696 kg/(m²a)). This difference can be partly attributed to the different glacier basin definitions. To sum it up, we revealed higher mass loss rates after 2013 and for positive ONI values a trend towards more negative mass balances (glaciological data). These, findings fit to our observed geodetic mass balance trends. Moreover, we discovered a strong increase in the mass loss for the lowest glacier section, starting around 2011.

The following text was added to the manuscript in Section 6.2:
"The correlation of the annual glaciological 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.
Since the highest density of glaciological point measurements are collected at the lowest section at both glacier and considering the observation of Soruco et al. (2009) at Zongo Glacier, Bolivia, that the terminus region strongly dominates the mass balance variations of a tropical glacier, we did an analysis of the glaciological mass balance at regions below 4900 m a.s.l. and 5000 m a.s.l. at Yanamarey and Artesonraju glaciers, respectively. A trend toward increased mass losses after 2011 is obvious (Figure S31, unfortunately the data at Yanamarey Glacier for the period 2009-2011 was incomplete), fitting to the revealed more negative geodetic mass balances after 2013. Moreover, the most negative values are derived for the period 2015-2016, which also supports our suggestion, that ENSO force the increased glacier wastage after 2013. The comparison between the geodetic and the average glaciological measurements at the terminus regions in the period 2013-2016 revealed a good agreement of both methods at Yanamarey Glacier (average glaciological: -3152 kg $m^{-2}a^{-1}$, geodetic: -3164 kg $m^{-2}a^{-1}$), whereas at Artesonraju Glacier, the geodetic measurements indicate higher mass loss (average glaciological: -4206 kg $m^{-2}a^{-1}$, geodetic: -2696 kg $m^{-2}a^{-1}$). This difference can be partly attributed to the different glacier basin definitions and slightly different observation intervals, but also to limitations of the individual methods, as discussed above."

Also, just as an additional information, according to mass balance measurements we did in collaboration with the Peruvian colleagues indicate that mass balances (since 2010) are much more negative in the Cordillera Blanca than in the Cordillera Vilcanota.

We appreciate this information. I sent requests regarding mass balance measurements in the Cordillera Vilcanota region to the respective institution. However, I did not receive an answer until now. If this data will become available during the further review process, I will certainly include it in the analysis.

All these points, open questions and uncertainties leave me with considerable doubts whether there are (basic?) problems with data collection, processing and analysis. For me these are the fundamental points that absolutely need to be clarified before this study can be published. I encourage the authors to do a serious investigation about these issues such that we can have reasonable confidence that the reported results reflect the reality and are not distorted by any errors.

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