Response to Reviewers

We thank both reviewers for their constructive feedback. We have addressed all major and minor comments below, our responses are in blue text. Specifically, we adjusted the topographic correction within the analysis code and adjusted our target date for imagery based on comments from the reviewers. All results have been updated as well as the corresponding figures both in text and in the supplement. A note that Figure 5 is now Figure 6 in our revisions. We were informed that the colormap on Table 1 would not be possible to do with color shading so we have created a bar chart figure instead, which is now Figure 5.

Reviewer #1

This is an interesting paper analyzing the relationship between ENSO and snow-covered area and ELA on the Quelccaya ice cap in Peru. The paper, however, has a number of weaknesses that need to be improved before it is ready for publication. I have tried to outline some of the main aspects that could benefit from more attention below.

Main comments:

Title: I think the title may have to be changed – as far as I know Quelccaya is no longer the world's largest tropical ice cap (see Kochtitzky et al., 2018). This statement is also repeated several times in the text.

We have eliminated or adjusted mentions to resolve this comment. Our proposed new title – 'El Niño Enhances Snowline Rise and Ice Loss on the Quelccaya Ice Cap, Peru.' Line 12 – changed mention to one of the largest. Line 26 – deleted mention

Line 22-24: Statements such as this one regarding projected future loss of a glacier surface area need to include a date, as the percentage loss quoted is time-dependent. Are you referring to the year 2100?

Line 22-23 – Yes, the reference does refer to the year 2100. We have adjusted the mentioned sentence accordingly to read 'In the low latitudes, glaciers are projected to lose ~69-98% of their 2015 mass by 2100, depending on the emissions scenarios RCP2.6 and RCP 8.5 (Rounce et al., 2023).'

Line 28: Yarleque et al. (2018) did not state that the QIC would disappear by 2050 under a high emission scenario. They only determined that the ELA would move above the summit by that point. Given the ice thickness of the QIC, it would likely still take several decades to fully melt all the ice in the ablation zone. Hence 2050 is a date for a 'point of no return' with the accumulation zone gone, but it is not a date for the complete disappearance of the QIC.

Line 27-30 – Adjusted to reflect that Yarleque et al., (2018) projects the QIC's point of no return and not total disappearance. We added a mention that once the QIC is not receiving accumulation it will cease to be an ice cap with outlet glaciers and simply a wasting ice field like Kilimanjaro. Our new text reads 'The decline of the Quelccaya Ice Cap (QIC; Fig. 1), located in the Cordillera Vilcanota (CV) range in the outer tropical region of the Andes, is one such concern with worst case (RCP8.5) projections suggesting the 'point of no return' (i.e., the rise of the ELA above the summit) as early as 2050 (Yarleque et al., 2018), leading to the QIC's classification as a wasting ice field instead of an ice cap, similar to Kilimanjaro.'

Line 32: I think what you refer to here is the actual size of the ice sheet, not the 'magnitude of retreat', which suggests something different (the loss of ice per unit time). Also the citation for this statement (Lamantia et al., 2023) is not included in the reference list

Line 32 – Adjusted the wording 'magnitude of retreat' to 'margin-extent' to better reflect the conclusions of Lamantia et al., (2023).

Line 426- Lamantia et al., (2023) has been added to the reference list.

Line 42-44. The snowfall on Quelccaya has no dynamical connection to the ITCZ. The ITCZ is a maritime feature located north of the equator. Snowfall on Quelccaya is fueled by the South American summer monsoon, with much of the heavy snowfall associated with convective activity over the western Amazon basin, triggered via cold air incursions (see Hurley et al., 2015).

Line 66-68 – Sentence rewritten to include the Hurley reference and discussion of SAMS and ENSO as dominant factors affecting QIC snowfall and moisture transport. Now reads ' Quelccaya's snowfall is largely controlled by the South American Summer Monsoon (SAMS) with the snowfall peak in December and moisture transport from the Amazon is influenced by ENSO variations (J. V. Hurley et al., 2015).'

Lines 50-51: The change in the FLH is not just worrisome because of direct melt, but also because it leads to a rise of the rain-snow line, thus affecting the albedo in the ablation zone. This likely has a larger impact on the total glacier energy and mass balance than the change in the sensible heat flux alone (e.g. see discussion in Rabatel et al. (2013)).

Line 72-75 –Added the reference to Rabatel et al., (2013) and expanded sentence to read 'Nearby mountain ranges such as the Cordillera Blanca and Real have experienced an increase in the freezing level height (FLH) by 160 m over the last five and a half decades with implications for not only where snow can survive and accumulate (Bradley et al., 2009; Schauwecker et al., 2014; Seehaus et al., 2020) but also increased albedo in the ablation zone influenced by a rise of the rain/snow line (Rabatel et al., 2013).'

Lines 52-53: Your statement here would imply that both La Nina and El Nino events lead to warmer SST in the tropical Pacific. Of course this is the case only for El Nino, while La Nina events are associated with colder SST.

Line 76-77 – Removed mention of La Nina in this sentence to refer to only El Nino, as the ice core signature is smoothed from the warmer SSTs (El Ninos).

Line 60-64: The first study to test this idea regarding end-of-the-dry-season snowline serving as an estimate of the ELA in the Andes was by Rabatel et al. (2012). This should be acknowledged. Their methodology was then applied by Yarleque et al. (2018) to estimate the interannual ELA variability on Quelccaya, equally relying on Landsat data to estimate the ELA via maximum elevation of the dry-season snowline. Hence the ELA approach used here has been applied on QIC before and the results obtained here should thus be compared to those previously published in Yarleque et al. (2018) to the extent that this is possible, especially when discussing the ELA results from your study in section 3.1 or during the discussion of the results in section 4.2.

Line 88-91 – We have added mentions of both the Rabatel and Yarleque studies to read 'Initial studies in the Andes involved a manual assessment of the Artesonraju and Zongo glaciers via Landsat and SPOT imagery compared against field measurements (Rabatel et al., 2012). Yarleque et al., (2018) most *recently analyzed the QIC's response to warming scenarios based on the FLH/ELA relationship and future ELA projections.' Will further discuss Yarleque's results on the QIC in the discussion section 4.2. See below.*

Line 340-344 – We have added a reference to Yarleque's findings of the QIC's average ELA compared to our calculation (within 5m) to read 'Similarly, previous studies of the QIC note a mean ELA between 1992 and 2017 of ~5,436 m a.s.l. (Yarleque et al., 2018) while our automated methods suggest a mean ELA of ~5,351 m a.s.l. for the same temporal scale. Considering the QIC's out of equilibrium state, as well as continued decline of the SCA and rise of the ELA due to ongoing anthropogenic climate change, we suggest the QIC may be completely melted away prior to 2100 (assuming the rate of loss is constant; Fig. S5'.

Line 135: I am not sure you can use surface temperature from ERA5 directly to calculate days with above- or below-freezing on QIC without making some bias adjustments. What is the absolute surface elevation of Quelccaya in ERA5? I assume it is considerably lower than 5670 m, hence the ERA5 surface temperature will have a warm bias, no? Alternatively, you may want to use the free tropospheric temperature interpolated to the QIC elevation as it is less affected by a topographic bias than surface temperature.

Line 162-164 – We have clarified the data usage, it was two-meter temperature from ERA5 which does take elevation into account but is slightly warm biased as the reviewer suggested. Considering most of the QIC is likely between 500-600mb of pressure we instead have used the 550mb temperatures from ERA5 daily temperature on pressure levels. This is comparable to temperature noted in Bradley et al., (2009) and we have added this reference as well on Line 186 to read 'Daily and monthly variations recorded by the QIC summit and bottom margin weather stations from Bradley et al., (2009) are well correlated with the ERA5 550mb temperature dataset, which was analyzed to determine changes in climatic variables through the observation period.'

Line 189-196 – The changes recorded by the 550mb temperature data have been adjusted accordingly in the results section.

Line 185: Snow cover, unlike ice cover, varies interannually. Hence I would not refer to the change in snow cover from one year to the next as a 'loss', which sounds as if it were permanent. Maybe refer to snow cover 'change' or 'reduction' instead, but it is not a permanent 'loss'.

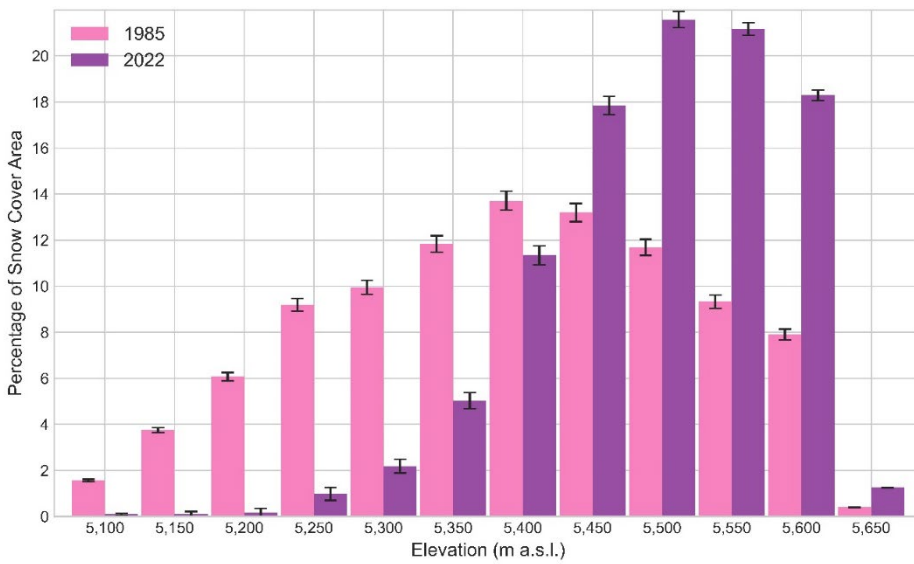
Line 218-219 – Have changed the term for 'SCA loss' to 'SCA reduction' as suggested when discussing year to year change. We've also changed loss to reduction in the Figure 3 (Line 287) caption to reflect this comment. Other changes from "loss" to "reduction" are on Lines 15, 302, & 306. We have kept the term loss when referring to the entire temporal scale or yearly avg loss as it is a downward trend.

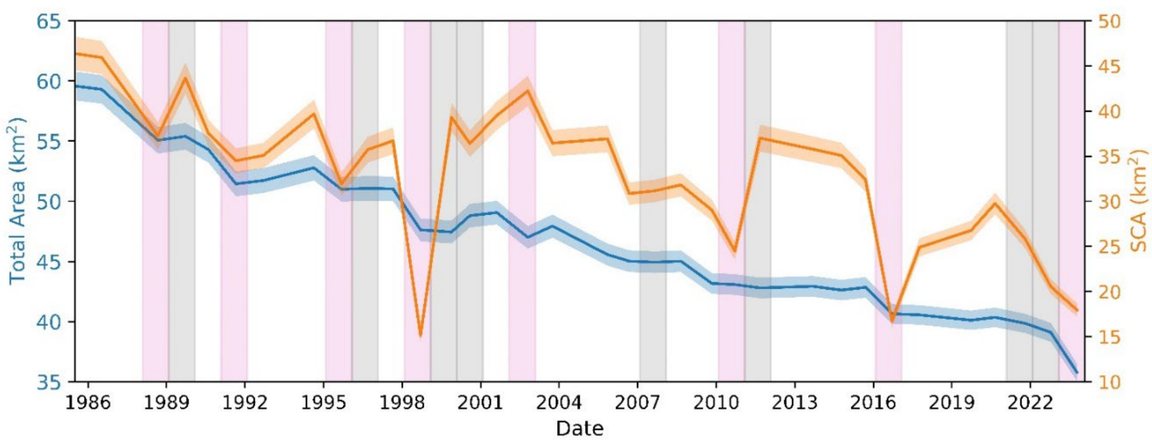
Line 253-254: While the northern Peruvian coast indeed receives more precipitation during El Nino, the Peruvian Andes and the western Amazon are drier than normal. For example, see detailed analysis of precipitation effects of ENSO in Peru by Sulca et al. (2018). Also Hurley et al. (2019) have investigated the ENSO influence on snowfall amount and temperature anomalies on Quelccaya using on-site meteorological measurements, showing that conditions on the QIC are warmer and drier than normal during El Nino events.

Line 297-298 – We have adjusted the introduction to the discussion section to include the above mentioned references and to properly reflect the changing meteorological conditions at Quelccaya during El Ninos. It now reads 'During El Niño events the Peruvian Andes are often drier than average (Sulca et *al., 2018), with on-site measurements at Quelccaya recording warmer and drier conditions (J. Hurley et al., 2019).'*

Figures 2-5: I think all these bar and line graphs require uncertainty estimates. While there is some discussion of error estimates in the text, the Figures do not include any such uncertainties. Figure 5 in particular is strange. While it make sense that the total snow covered area varies from year to year in response to ENSO, why would the total area (ice cover) increase by several km^2 from one year to the next? This would imply a rapid advance of the ice cap increasing the total ice covered area by ~10% over the course of a year, which is highly unlikely. To me this rather suggests that significant uncertainties exist in the yearly estimates of total ice cover. This makes including error bars all the more important, to understand whether interannual variations of the total ice cover reside within these uncertainty estimates.

Figures 2, 3, & 6 (previously 5) have been edited to include error estimates (error bars on the bar charts and a semi-transparent fill behind the line graphs for figure 6). Figure 4 is updated with the most recent results. Figure 6 also displays Nino and Nina events with ONI over 1.0 for clarity. Sample below of updated Figure 2 and Figure 6.





Additionally, we have been working on improving the topographic correction and have since updated that portion of the code. This results in a much more consistent TA calculation and is reflected in new results *calculations and the corresponding figures. Since the end of the dry season is the middle of September to the end of October, we shifted our target date to September 15th instead of the 1st and re assessed which imagery would be best. This results in more imagery in October and less in July/August to enable the assessment of a proper end of dry season state. We also removed the years 1993 and 2018 as the only imagery available of the QIC was after a very obvious snowfall event. Reviewer #2 made a comment about the time of imagery selection, more comments are below and changes are reflected in the text on imagery selection on Lines 114-117. Description of the new topographic correction in the methods section is on Line 133-136.*

Minor suggestions for change:

Line 9: Glaciers are 'vital water resources as vital water resources'? Something went wrong here.

Line 9 - We have adjusted the sentence to remove the double mention and accounted for reviewer 2's phrasing comment as well.

Line 48: delete either 'recording' or 'documenting' (one verb too many).

Line 72 – Removed 'recording'

Line 131: 'European Centre for Medium Weather Range Weather Forecast'. Delete the first 'Weather' as it should say 'European Centre for Medium-Range Weather Forecast'.

Line 95 – Removed the first mention of 'Weather'

Line 198: different => difference

Line 233 – Adjusted to difference as requested

Line 199: complied => compiled

Line 236 – Changed to compiled

Line 282: You refer to a paper by Taylor et al. (2022), yet this paper is not listed in the reference section.

Line 475 – Taylor et al (2022) has been added to the references.

Line 336: Please add the name of the journal where this article was published.

Line 387 – Journal name (Terrestrial Photogrammetry) has been added to the Brecher and Thompson (1993) reference.

Lines 353-354: delete 'an international journal'.

Line 406-407– Deleted ' an international journal' in Hall and Riggs (2007) reference.

Lines 335-339: You repeat the same reference twice. Delete one of them. Also, in the text simply cite Hanshaw & Bookhagen (2014). There is no need for the labels 'a' and 'b' – it's one and the same paper.

Line 408 – We removed the extra reference. All in text citations should now read Hanshaw & Bookhagen (2014) on Lines 20, 108, and 157.

Line 382: delete 'Article 3'

Line 438 – Deleted 'article 3' as requested in Mark et al (2002) reference.

Line 388: This should be Pepin 'et al.' (the paper has many co-authors). Also note that there is an updated newer version of this paper (Pepin et al., 2022).

Line 448 – Adjusted Pepin et al., (2015) reference. Also fixed in text citation (Line 21). Added Pepin et al., (2022) reference as well in both text (Line 21) and in reference list (Line 445).

Line 404: delete 'Article 1-5'.

Line 477 – Deleted 'Article 1-5' as requested in Thompson et al (2000) reference.

Line 433: delete 'Article 9'.

Line 506 - Deleted 'Article 9' as requested in Vuille et al (2015) reference.

References:

Hurley, J.V., et al. 2015. Cold air incursions, d^{18}O variability and monsoon dynamics associated with snow days at Quelccaya Ice Cap, Peru. *J. Geophys. Res*., 120, 7467-7487, doi:10.1002/2015JD023323.

Hurley, J.V., et al. 2019. On the interpretation of the ENSO signal embedded in the stable isotopic composition of Quelccaya Ice Cap, Peru. *J. Geophys. Res.* 124, 131-145, doi: 10.1029/2018JD029064.

Kochtitzky, W.H., et al. 2018. Improved estimates of glacier change rates at Nevado Coropuna Ice Cap, Peru. *J. Glaciol*., 64(244), 175-184, doi: 10.1017/jog.2018.2.

Pepin, N.C., et al. 2022. Climate changes and their elevational patterns in the mountains of the world. *Rev. Geophys*. 60, e2020RG000730, doi:10.1029/2020RG000730.

Rabatel, A., et al., 2012: Can the snowline be used as an indicator of the equilibrium line and mass balance for glaciers in the outer tropics? *J. Glaciol.,* 58(212), 1027-1036. doi:10.3189/2012JoG12J027

Rabatel, A., et al. 2013. Current state of glaciers in the tropical Andes. A multi-century perspective on glacier evolution and climate change. *Cryosphere*, 7, 81-102, doi:10.5194/tc-7-81-2013.

Sulca, J., et al. 2018. Impacts of different ENSO flavors and tropical Pacific convection variability (ITCZ, SPCZ) on austral summer rainfall in South America, with a focus on Peru. *Int. J. Climatol.,* 38, 420-435, doi:10.1002/joc.5185.

Yarleque, C., et al. 2018.. Projections of the future disappearance of the Quelccaya Ice Cap in the Central Andes. *Sci. Rep.* 8, 15564, doi:10.1038/s41598-018-33698-z.