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 #2

This manuscript evaluates the change in the Quelccaya Ice Cap from 1985 to 2023, using satellite imagery. The year-to-year changes are described, and an evaluation is conducted as to the change in strong El Niño years. The analysis is interesting, particularly the discussion of the snow covered area rebound time after El Niño events.

Some clarification is needed before publication, particularly on the definition of El Niño years and some of the statistical analysis. Detailed comments are provided below.

Comments

Full manuscript: Could the authors clarify which El Niño years are chosen for which parts of the analysis in this manuscript, and why? The authors focus on the 1997-1998, 2015-2016 and 2023 events for much of the manuscript, but use more years for figure 5, for example. Some graphs (e.g. S4) are unclear in which ENSO years are used.

Line 215 – We note that the strongest El Niño events are the ones considered for our analysis. For figure 6 (previously 5), we chose to display all Ninos and Ninas with an ONI index that surpasses 1.0 or -1.0. Clarifying language has been added to the discussion section to reflect that decision (Line 311 and Figure 6 caption).

Line 312-315- Figure S4 – We added details to the discussion surrounding Figure S4. It was created as an assessment across the entire observed temporal scale to evaluate how the measured variables change with response to neutral vs ninos vs ninas. These events were used based on the previously mentioned ONI index threshold that we have defined, and has been clarified (Line 311).

Line 86 and Table S1: The authors have picked the closest cloud-free images to September 1st in order to calculate the area of the ice cap accurately, however these images vary from June to October. Can the authors comment on the effect of this difference on their results?

Line 114-122: We have adjusted our window for imagery selection to better target the end of the dry season. The only July imagery is from the first two years as no other options were available, and we clarified our reasoning for how and why we chose and acquired imagery. The section now reads 'To automate the SCA detection and ELA calculation, the following data inputs were required: an annual satellite image, a DEM, and the 1985 outline of the QIC. Using the Google Earth Engine platform (GEE) we selected annual Landsat images as close as possible to September 15th with clear visibility of the QIC from 1985 to 2023 (Table S1). Mid to end September marks the end of the dry season in the CV, which enabled analysis of the ice cap without extraneous snowfall around the perimeter. Imagery from each year was on average ±23 days within the target date and was manually inspected to ensure no

recent snowfall events occurred. If September imagery was not available, October and November images were collected, and if imagery was still not available August and July were collected with the intention to collect the closest to end of dry season conditions at the QIC. No images were used if a recent snowfall event was evident. Sentinel-2 imagery was used in 2021 and 2023, due to a lack of cloudless images from Landsat 8/9.'

Line 96: 1999 was a strong La Niña year, not an El Niño year (as the authors note in line 261). 2017 was a neutral year. Can the authors clarify the dates of the 16 and 18 images collected, and what the ONI index was for the rolling three month period covering those dates?

Line 128-130 – Dates clarified for the 1998 and 2016 El Nino event sampling.

Line 308 – The ONI index during 1999 is now noted in this discussion section regarding the rebound of the SCA.

Line 126: Could the authors expand on the difference between the manual calculation of ELA and the automated calculation? Is the 3 % in this instance 3 % of the elevation above sea level? If so, this would be greater than the change in ELA between 1985 and 2022 that the authors calculate on line 143, and may require further consideration.

Line 157-160 – Our discussion of the error was centered around the manual tracing of the SCA&TA and not the ELA. Apologies for the typo. We have corrected and clarified the language as to the error calculation and included an additional reference. Additionally, we have updated Figures 2, 3, and 6 (previously 5) to include error bars/semi-transparent margins of error on the line graphs.

The new section includes a new reference as well to further assist in explanation and now reads 'Calculated results for the SCA and TA via our automated methods are in good agreement with manual digitizations (within ±3%). Other studies have shown manual and automated detection of snowline produces similar result to manual digitization and low level of error (Hanshaw & Bookhagen, 2014) with automated detection being preferable to manual as repetition is simpler and any error is likely to be more consistent (Paul et al., 2013)

Line 142-146: The authors have calculated the loss of TA and SCA based on the first and last years of data only. Especially for SCA, the year-to-year variation is relatively high. I would suggest the authors calculate the loss through the average loss (which would then match with the loss calculated through linear regression), or take the average of the first few and last few years. This comment also holds for figure 2.

Line 173 – We have now included average loss per year in our results.

Figure 2 – The intention of this figure was to display the shift of the snow cover area (SCA) to higher elevations. We would prefer to leave it as is, since the intent was to display the drastic change over the short time period. Error bars are now included, see above. We added some more information into the results section discussing average shift from the first five to the last five years, as suggested, immediately following the full scale results. Lines 173-175 reads 'Over the observation period (1985 and 2022), the QIC lost ~37% of its TA and ~58% of its SCA (1985: TA=~58.7 km^2, SCA=~46.3 km^2; 2022: TA=~36.7 km^2, SCA=~19.7 km^2 (Table S2).Average loss between first five observed years and the last five recorded an SCA decline of ~38% and the TA by ~29%, respectively.'.

Line 154: Could the authors clarify why they have removed El Niño years to calculate the trend in AAR, but not comparative La Niña years? The analysis shown in figure S4, which clearly shows the

difference between El Niño, La Niña and neutral years, may be more appropriate to determining the effects of El Niño events on the AAR.

Line 184-187 – We have amended the average AAR to only include neutral years instead of neutral and La Nina years, and added La Nina years to read 'The QIC's average AAR (minus El Niño and La Niña years) is 0.74 over the study period. Conversely, during the strongest El Niño years (1998, 2016, and 2023) the QIC's AAR was 0.32, 0.40, and 0.52, respectively and during the strongest La Niña years (1999 and 2011) the QIC's AAR was 0.83, and 0.82.'

Figure 5: The x-axis seems to be misaligned in this plot. For example, the lowest SCA occurred in 1998, along with the El Niño year. Both of these are plotted covering the tick mark for 1999.

Figure 6 (previously 5) – Line 328– The Nino and Nina bars were offset unintentionally. We had adjusted them accordingly to cover the intended year. See figure change above in reviewer #1 comments.

Line 163: I agree with the other reviewer comment that it is necessary to apply a simple bias-correction to the ERA5 temperature, to account for the difference in elevation between the QIC and the ERA5 elevation, in order to determine the percentage of days above the freezing level height. I would also suggest that the authors' findings of an increase of 1.24 degrees in the dry season over 37 years is somewhat greater than the 0.1 degree/decade in the quoted references.

Line 188-190– As mentioned above under reviewer #1s comment, we have assessed and readjusted to the 550 mb ERA5 temperature as it most properly reflects the observed temperature at the QIC (e.g., Bradley et al., 2009). In text changes have been adjusted accordingly 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 187 and figures 2 and 3: These figures might be easier to interpret if they were plotted the total SCA in each elevation bin, rather than the percentage. For example, in figure 3 (lower), thepercentage of SCA in 2015 and 2017 is similar at low elevations, suggesting the SCA may be similar in both years, but they vary considerably at higher elevations. Total SCA would then match better with the text stating the change in SCA is 70% of its 2015 value.

We chose to use the percentage of the SCA in Figure 2 so the comparison between the beginning and end of the temporal scale is normalized and the shift to higher elevations is evident. We have altered Figure 3 as suggested to display the total SCA values since, in this case, we show consecutive groups of three years.

Line 253: Lagos et al., 2008 record higher than average precipitation during El Niño events along the northern coast, but a mixed response in the Amazon and the Andes (including around the QIC).

Line 298-299– Reviewer #1 noted a similar concern with this sentence, we have adjusted accordingly and added their proposed references. 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).'

Line 263: Could the authors explain how they have calculated the drop in correlation from 1998 to 2016? Are these correlations based on the yearly measurements and yearly ONI? If so, how is the correlation calculated for a single year? Similarly, how are the regressions calculated in line 266 (and

what are the multiple variables used?.

Line 220 -222 – We have clarified this process by changing the text to read 'To better determine QIC changes during the El Niño events, high frequency sampling was conducted around the complete El Niño events, consisting of 16 and 18 images collected between 1997–1999 and 2015–2017, respectively.' The results are reported onLine 224-225– The correlation is calculated using the high frequency sampling previously discussed to analyze changes during the El Ninos. We have added clarifying language to discuss that we evaluated those images during when the three month avg ONI recorded Nino conditions. The adjusted sentence reads In addition, correlation between the monthly ELA and monthly ONI index during the two El Niño events (1997-1999 and 2015-2017) are 0.68 and 0.26, respectively The referred to Line 266 has been deleted in effort to clarify the prior comment and we move on to discuss El Nino as a binary predictor in the regression.

Line 265 and 297: the authors state that anthropogenic warming is overwhelming natural climatic signals, but in this manuscript, the most severe El Niño effects seem larger than the overall reduction from anthropogenic warming (e.g. figure 5, 1998/1999)

Line 315-321 – We clarify this statement that while the QIC responds to ENSO fluctuations in the most recent La Nina (2021/2022) the SCA only declines and in all the others it experienced some level of rebound. We added additional commentary about the effects of anthropogenic warming and while this lack of rebound is a single isolated event, we expect this behavior to continue into the future with the next La Nina. The new section reads 'While the SCA is notably briefly impacted by these El Niño events, decline from anthropogenic warming has resulted in the long-term decline of the SCA and TA of the QIC (Bradley et al., 2009; Rounce et al., 2023; Thompson et al., 2021; Vuille et al., 2018; Yarleque et al., 2018). Further, during all previously noted La Niña events (Fig. 6), the SCA experienced some level of temporary expansion, but throughout the 2021-2022 La Niña, the SCA did not rebound, but only declined further. While this is only one incidence, we expect this behavior to continue through the onset of the predicted upcoming 2024/2025 La Niña. The decrease in the percentage of days at or below freezing during the wet season will only exacerbate the decline in SCA.'

Minor suggestions

Line 9: I would suggest rephrasing the first sentence to "Tropical glaciers in the central Andes are vital water resources….". As it stands, water resources are mentioned twice.

Line 9 - We have adjusted this sentence as requested and removed the double mention of resources.

Line 30: Please defined what the modern rate is of (retreat, volume loss etc). and Line 30: 'further evidence of the QIC …' what's this further evidence of, is it retreat?

Line 33-34 – We have adjusted this sentence to clarify ice margin retreat and the QIC's evidence of past fluctuations. It reads 'Further evidence of the QIC's past fluctuations has recently been placed within a longer-term context using radiocarbon-dated plant remains from the ice margin suggesting that the ice cap's present-day margin extent has not occurred in the last 7,000 years (Lamantia et al., 2023).'

Line 32: 'since 7000 years ago' -> 'in the last 7000 years'

Line 34: Adjusted the phrasing as requested. See above comment.

Line 42: 'southern wet outer tropics' 'wet' is perhaps a typo here?

This sentence was removed and replaced by discussion of the SAMS (see reviewer #1 comment)

Line 48: typo ‘recording documenting’.

Line 72 - Removed ‘recording’

Line 114: Please define ‘Ab’

Line 144 – Ab has been defined in the text. Ac = accumulation area (snow). Ab = ablation area (ice). Ac+Ab = Total Area

Line 152: as the AAR is defined based on the SCA and TA, I think the correlation between these variables seems inevitable.

Line 195. This is a great point, we have removed the reference to AAR correlation and the corresponding supplemental table.