Supplement to: Modeling the impacts of climate trends and lake formation on the retreat of a tropical Andean glacier (1962-2020)

1.1 DEM Coregistration

The 1962 DEM was coregistered to that of 2008 using ESRI ArcPro georeferencing tools. Six control points were identified through visual comparison of stable features in the DEMs and used to calculate a first-order transformation of the 1962 DEM, aligning it with the later epoch. Stable terrain was then selected by masking out pixels covered by ice in the 1962 imagery and those above 5000m altitude (Fig. S1). The latter adjustment accounts for systematic error along ice-free ridge lines due to DEM resolution differences. Stable terrain residuals were then calculated by subtracting the elevation values of the masked DEMs. To identify further biases between the elevation datasets, residuals were compared against topographic variables including aspect, slope, altitude, length (the distance across the long axis of the DEMs), and width (the distance across the short axis of the DEMs) (Fig. S2). Linear regressions showed that the length variable had the most significant impact on residuals, explaining 15% of the variability in residuals ($p<0.0001$). This indicates a systematic tilt over the short axis of the 1962 DEM with respect to that of 2008. We therefore apply a Z-dimension correction to the 1962 DEM using the parameters of the linear regression, then recalculate elevation model residuals over stable terrain. After the second adjustment, R-squared values for all explanatory variables is reduced below 0.10 ($p<0.0001$), indicating that any systematic bias in glacier volume change would be negligible (Fig. S2). After coregistering the 1962 DEM to that of 2008, residual error between stable ground pixels of the two DEMs is significantly reduced. The original mean error with a one standard deviation window falls from 33±29 m to 0±12 m (Fig. S3).

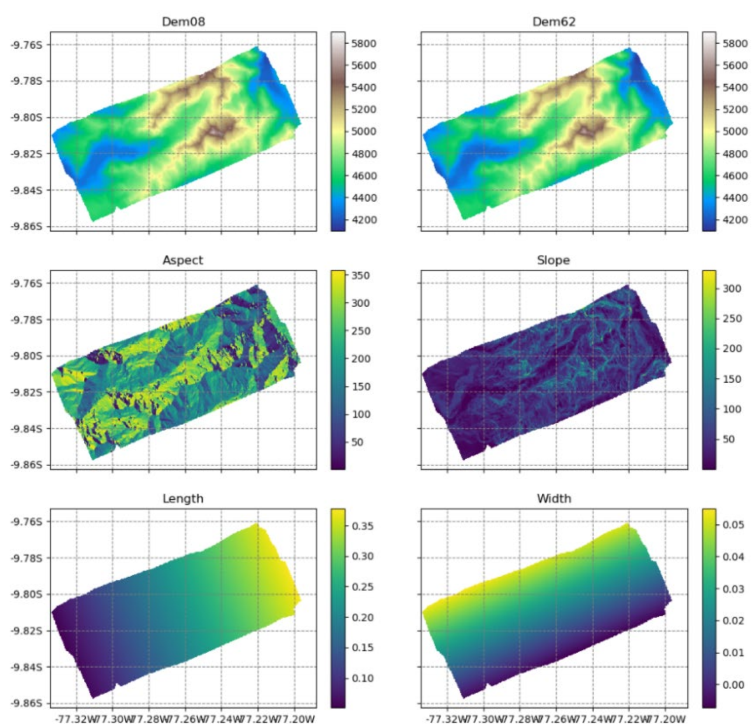

Figure S1: Input variables for DEM coregistration. Note than length and width area calculated using indices and have no units.

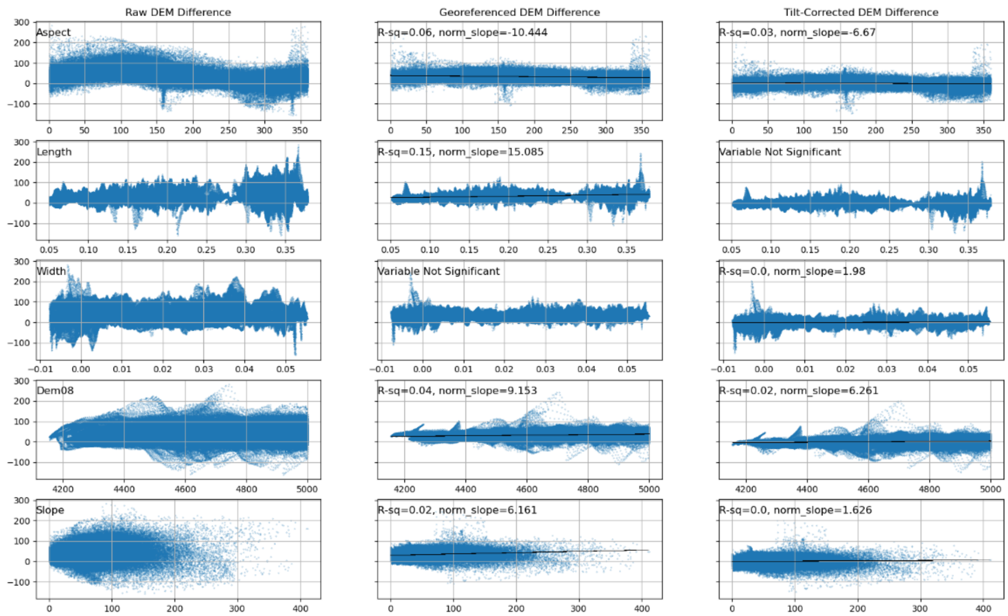

Figure S2: Matrix plot of coregistration variables (rows) and coregistration stages (columns). Variable names are listed in the first column. Each point on a given subplot corresponds to a single stable-ground pixel pair. The x-axes indicate the magnitude of a given variable (e.g. 0-360˚ for aspect) and the y-axes indicate the residual error in meters. For variables with significant R-squared values relating the magnitude and residual error, the R-squared and normalized slope (norm_slope) are included on the subplot. The normalized slope considers the change in residual error predicted for a unit change in the coregistration variable.

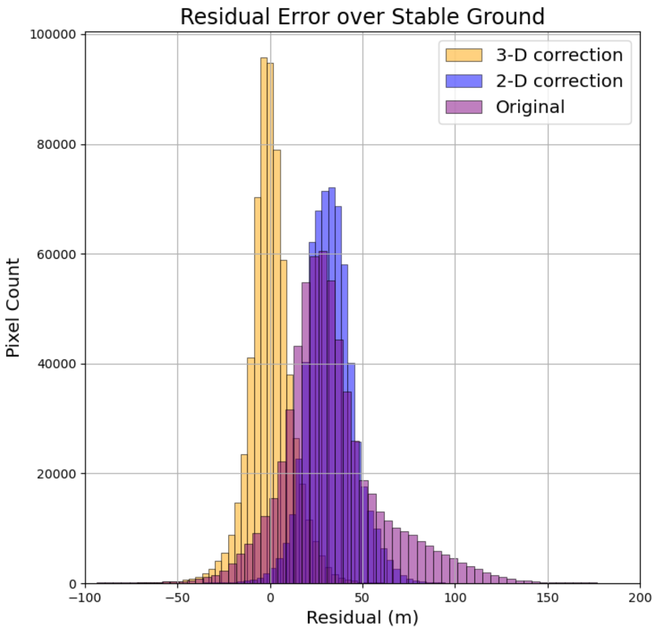

Figure S3: DEM coregistration stable ground residuals. The three stages are shown: original DEM difference prior to georeferencing, the DEM difference after georeferencing (2-D), and the DEM difference after applying a linear correction to the elevation values along the length of the georeferenced DEM (3-D).

1.2 Climatological Trend Analysis

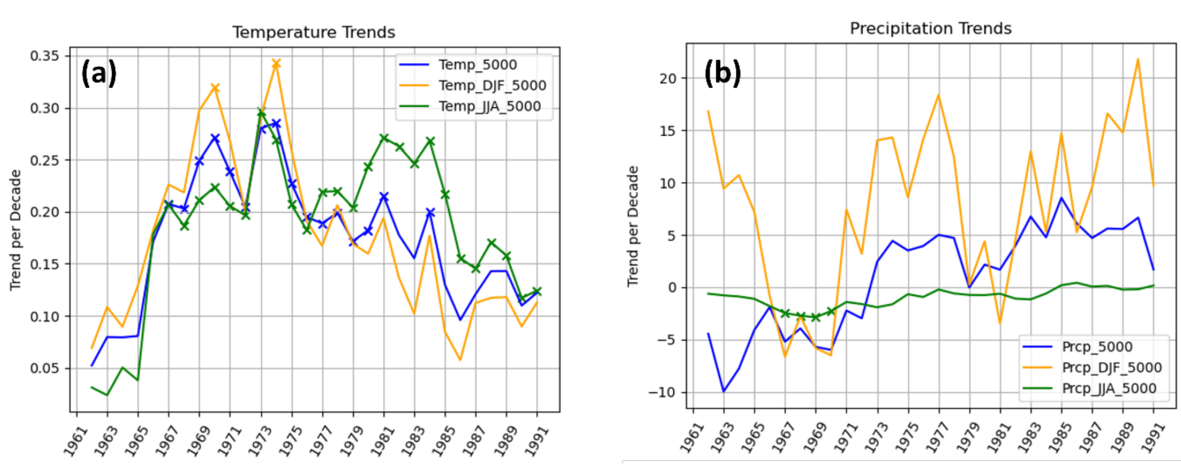

Figure S4: Trends per decade in the extended PISCO dataset for temperature (a) and precipitation (b) at the assumed altitude of 5000 meters within the gridcell containing the Queshque Glacier centroid. Trends are calculated in running 30-year periods for annual values, wet season (DJF) and dry season (JJA). Significant trends are marked with crosses and correspond to the 30-year period beginning at the given year.

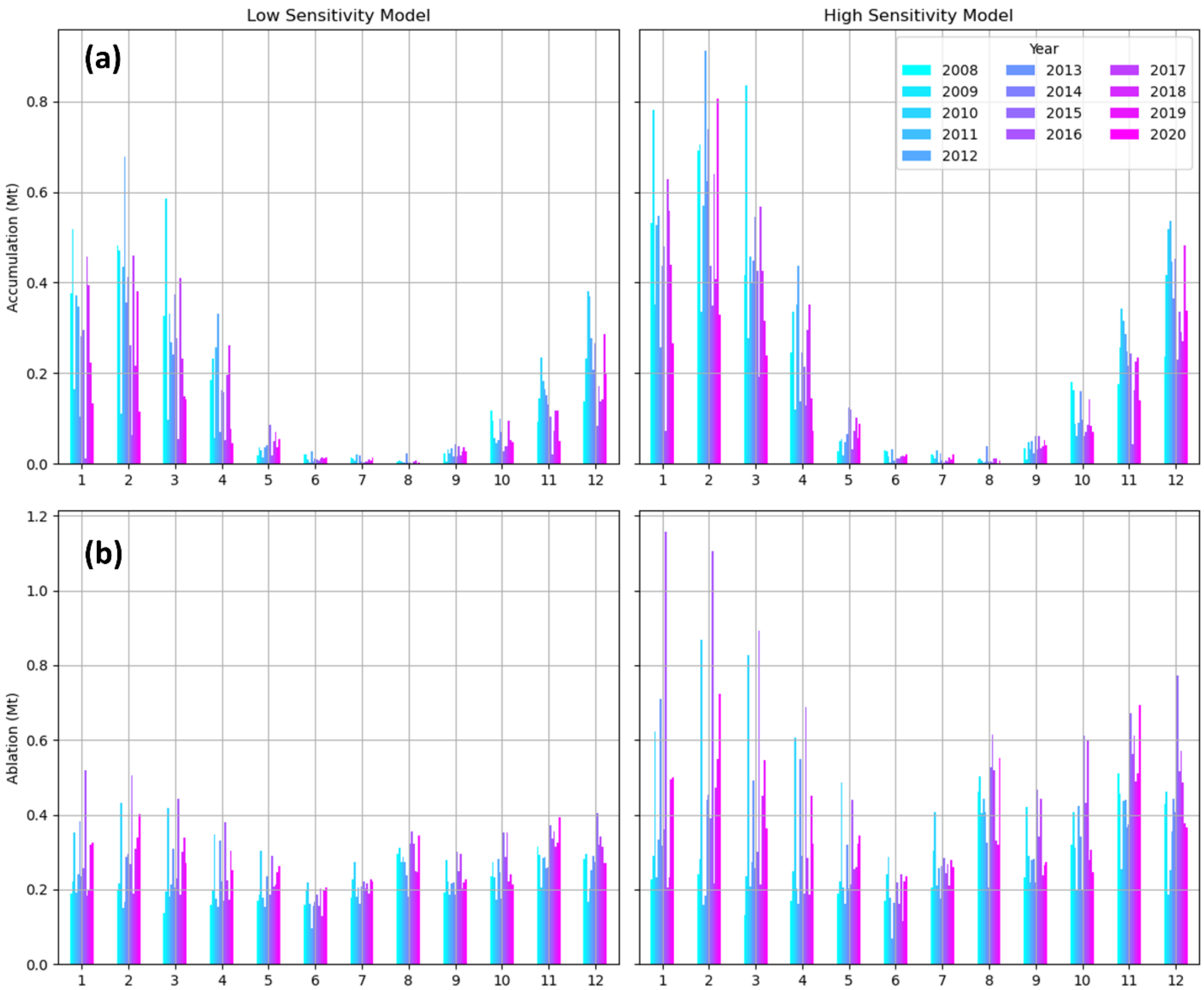

Figure S5: Model accumulation (a) and ablation (b) for each month of each year (2008-2020). The low (left) and high (right) sensitivity models correspond to model numbers 2 and 5, respectively.