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Supporting Information for

Drivers of $\delta^{18}O$ Variability Preserved in Ice Cores from Earth's Highest Tropical Mountain

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Table S1. Huascarán ice core sampling details.

ID	Full Name	Elevation (masl)	Length (m)	Number of Samples
CCA	Col Core A	6050	165.0	4795
CCB	Col Core B	6050	168.6	5138
SCA	Summit Core A	6768	69.3	2055
SCB	Summit Core B	6768	68.7	2122

Text S1. Reproducibility of the Huascarán $\delta^{18}O$ records in the 1993 cores

Thompson et al. (1995) produced a ~19 ka record of oxygen isotope data from two ice cores drilled on the Huascarán Col in 1993. The first core was melted and bottled in the field while the second core was kept frozen during transport back to the ice core facilities at Ohio State University. The annual isotope reconstruction from Core 2 is shown in Figure S1 (blue line) and compared to the same period as reconstructed from the composite record of the new Col cores (red line). Although drilled 26-yr apart (with the 1960-1993 layers in the original cores consisting primarily of firn and the same layers in the new cores consisting entirely of glacial ice) the isotopic signals are highly reproducible.

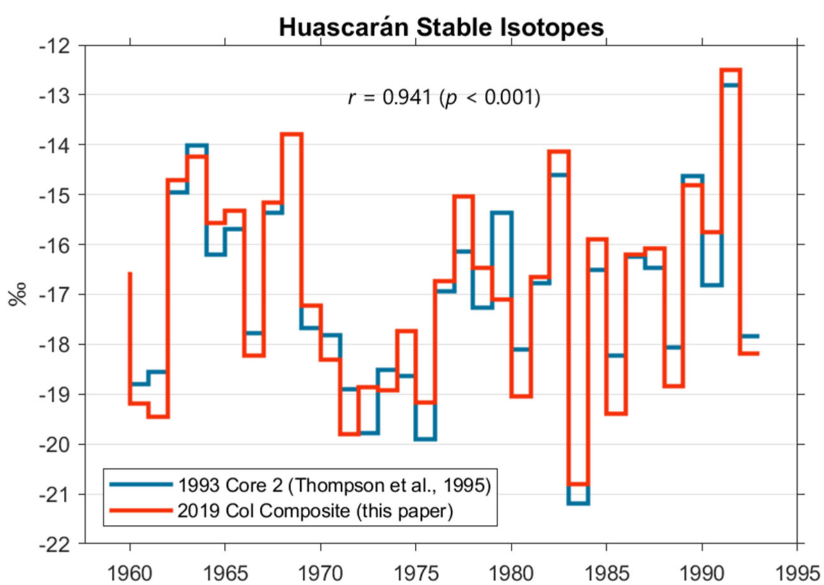

Figure S1. Reproducibility of the annual $\delta^{18}O$ record on the HS Col. Data for the 1993 cores were obtained through the National Centers for Environmental Information Paleo Data Search Tool (https://www.ncei.noaa.gov/access/paleo-search/study/2447).

Text S2. Reconstruction of net annual accumulation in the Huascarán ice cores

The reconstruction of an annual accumulation record (which provides insight into precipitation but does not account for losses due to sublimation or wind scour) for the Col and Summit sites is complicated by the effects of densification and ice flow which decrease the original annual layer thicknesses of the firn and ice with depth in a nonlinear fashion. To correct for layer densification in the upper firn layers, the density of each ~1 m (± 10 cm) core section was determined by measuring the mass of each section using an analytical balance and by calculating the cylindrical volume using measurements of the diameter at the top and bottom of each core section as well as the length of the section. A polynomial function was then fit to the measured density values of each core section as a function of depth (Fig. S2). The polynomial expressions were modified by user manipulation by adding non-measured "dummy values" equivalent to 0.917 g cm^{-3}. This was done to force the polynomial curve to approach the value typically used for the theoretical maximum density of glacial ice described by Cuffey & Paterson (2010), although the true density of ice can vary with the inclusion of bubbles, particles, and other additional materials. Likewise, some density values were selectively rejected if they caused anomalous dips in the polynomial curve (indicated in Fig. S2). The anomalous nature of these measured densities can arise due to core breaks, irregularly shaped core breaks, and other physical damage in the respective firn cores. Any core sections containing missing ice (due to damage or partial melting during transport) will have erroneously low masses or imperfectly cylindrical shapes (and therefore, anomalous densities). The density of each annual layer was determined by modeling the density at the top and bottom of the layer and then taking the mean. For example, if the depth at the top of an annual layer in Col Core A (CCA) is 10 m and the depth at the bottom is 12 m, then the polynomial expression for CCA would be used to evaluate the modeled density at 10 m and 12 m. The mean of these two densities would be used to represent the entire annual layer, and any such value exceeding the theoretical maximum would be programmatically assigned a value of 0.917 g cm^{-3}. Next, this value is divided by 0.917 to obtain a normalized density. Multiplying the original layer thickness (in m) by the normalized density therefore gives an ice-adjusted annual layer thickness in m of ice equivalent (m i.e.).

A second model was employed to account for the thinning of ice with depth due to ice motion. Since the ice was drilled at the approximate ice divide at both the Col and Summit, it is assumed that layer thinning is entirely due to vertical compression and that the role of horizontal flow is negligible. The model, derived by Bolzan (1985), was adapted for the 1993 Huascarán ice cores and is described by Henderson (1996) as follows:

$$A_n \text{ (m i.e.)} = T' \, (1 - (z'/h'))^{-(p+1)}$$

where A_n is the annual net accumulation rate for a year centered at depth z'. The value T' represents the ice-adjusted annual layer thickness for that year, and h' is the ice-adjusted thickness for the entire core. The value p represents a thinning parameter. For the 1993 Huascarán cores, the value of p was derived by modeling the relationship between age and depth (Henderson, 1996). This was not done here, however, because the timeline of the cores near the base is still under development. Rather, p was estimated by assuming steady state conditions at Huascarán for the annually resolved portion of the record. That is, based on the 2015-2019 ice-adjusted annual layer thicknesses, we assumed a steady state annual average of 1.4 m i.e. for the Col and 2.1 m i.e. for the Summit. With these assumptions, a function was designed to calculate annual accumulation rates for each of the Huascarán cores by looping through 10,000 different values of p. When the mean value of all the accumulation rates equaled our steady state assumption for each core, the loop was broken and the corresponding value of p was identified. Following these calculations, the two Huascarán Col cores were combined into a single composite record, as were the two Summit cores. The A_n composite records were evaluated by simple element-wise averaging between the annual values in each pair of cores (Fig. S3).

Note that the A_n records derived in this analysis are an update to the preliminary A_n reconstruction reported by Weber (2022). In this case the polynomial fitting of the density-depth relationship for CCB has been improved not only in terms of the R^2 parameter (0.96 vs 0.98) but also now the general shape of the curve more-smoothly reflects the pattern of the observations. Moreover, the analysis here improves upon the A_n reconstruction by Weber (2022) as the value for the thinning parameter p was chosen programmatically rather than by using the same value of p that was modeled for the 1993 Huascarán ice cores.

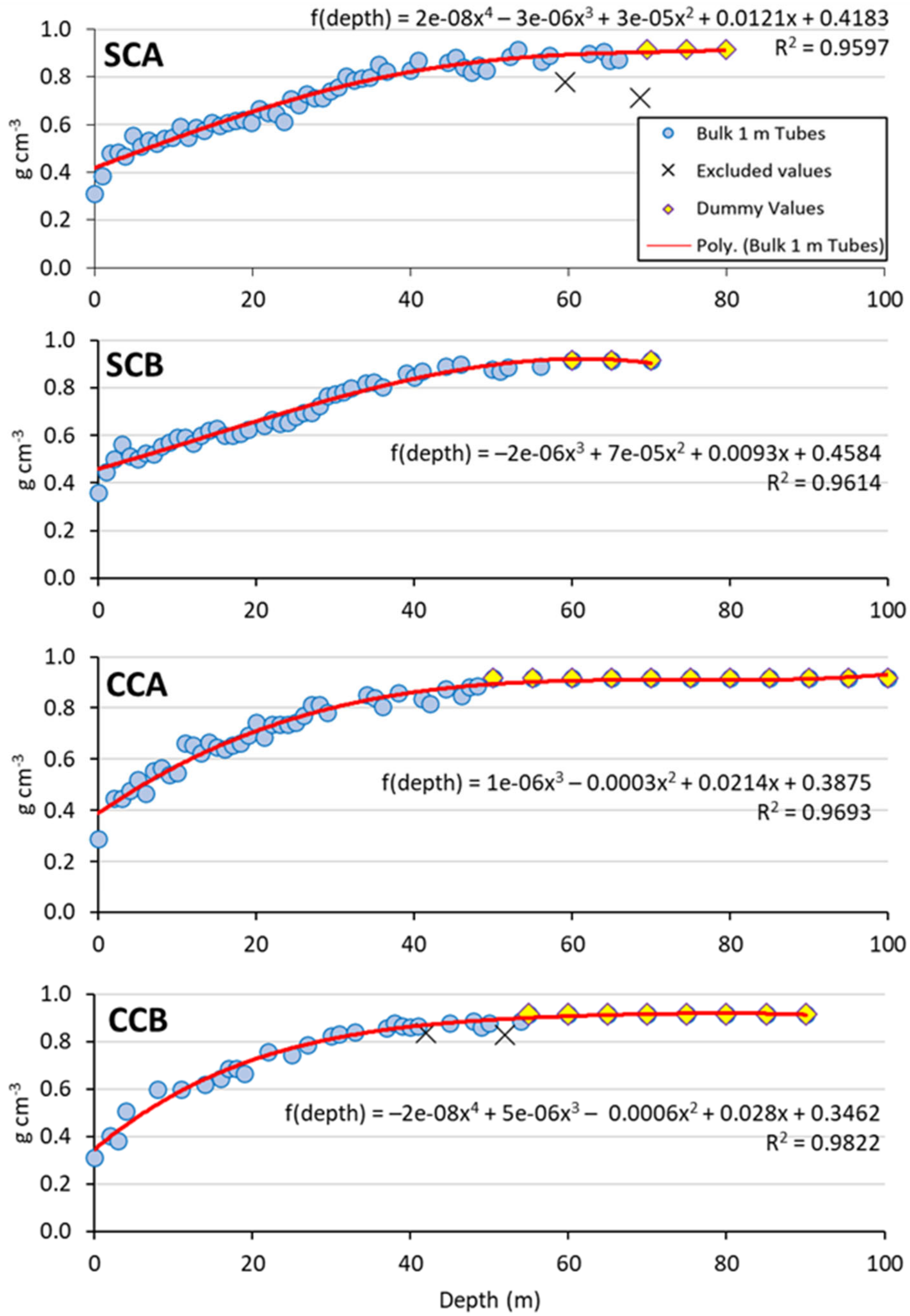

Figure S2. Polynomial fitting of the density-depth relationship in each Huascarán ice core.

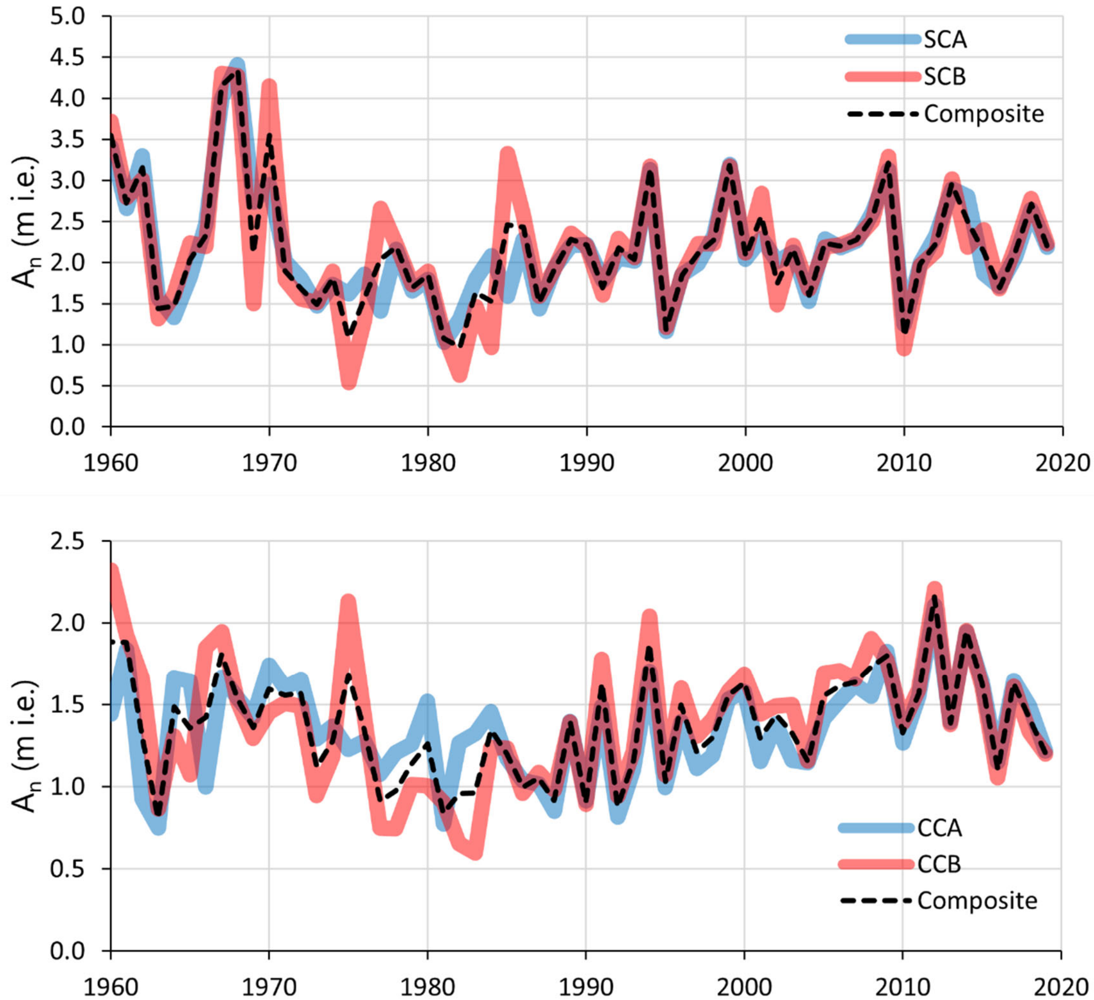

Figure S3. Net annual accumulation (A_n) records for the Huascarán ice cores. The Summit A_n reconstruction is shown in the top plot while the Col A_n reconstruction is shown in the bottom plot.

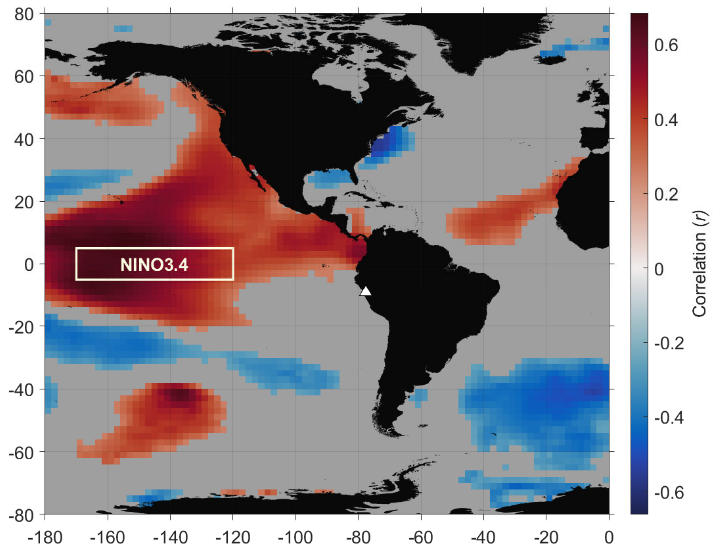

Figure S4. HS $\delta^{18}O_{summit}$/ERSST spatial correlation field for the October through April wet season months over the period 1960-2019. The white triangle denotes the location of the ice core site. Only the grid cells that are statistically significant at the 95% level (*p*-value ≤ 0.05) are plotted.

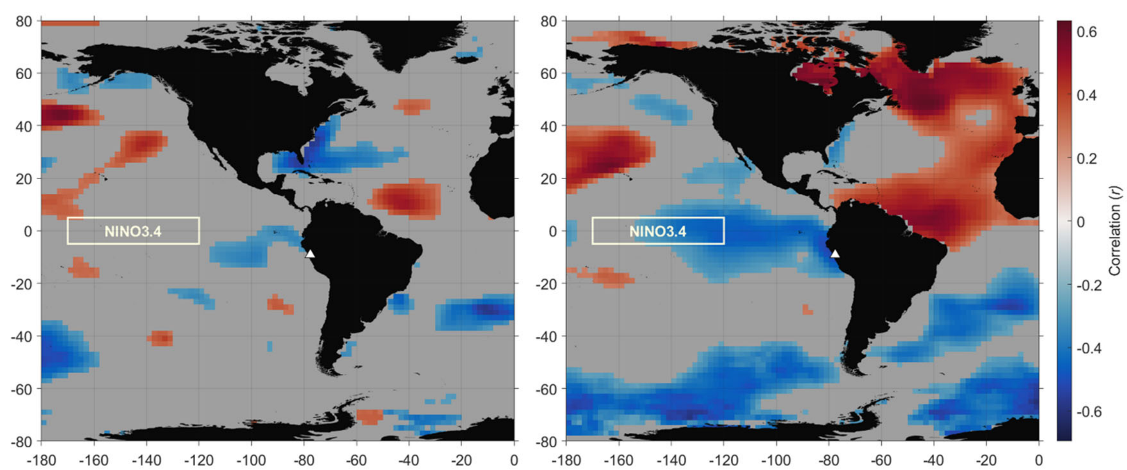

Figure S5. Spatial correlation fields between ERSSTs and deuterium excess in the Col composite record (left) and Summit composite record (right). The larger surface area of positive correlations over the Atlantic in the Summit composite record likely suggests that the Summit may receive more moisture directly of oceanic origin than the Col, and that the Col may receive a greater mixture of recycled continental moisture. The white triangle denotes the location of the ice core site. Only the grid cells that are statistically significant at the 95% level (*p*-value ≤ 0.05) are plotted.

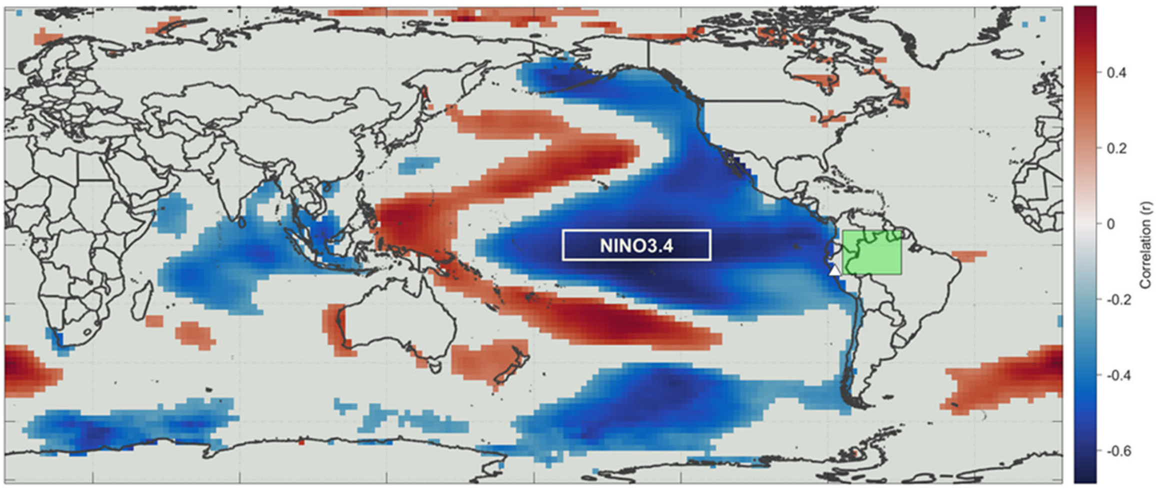

Figure S6. Spatial correlation field between ERSSTs and precipitation over the Amazon Basin (as delimited by the green box; 5°N-10°S, 75°W-55°W). The white triangle denotes the location of the ice core site. Only the grid cells with results that are statistically significant at the 95% level (p-value ≤ 0.05) are plotted.

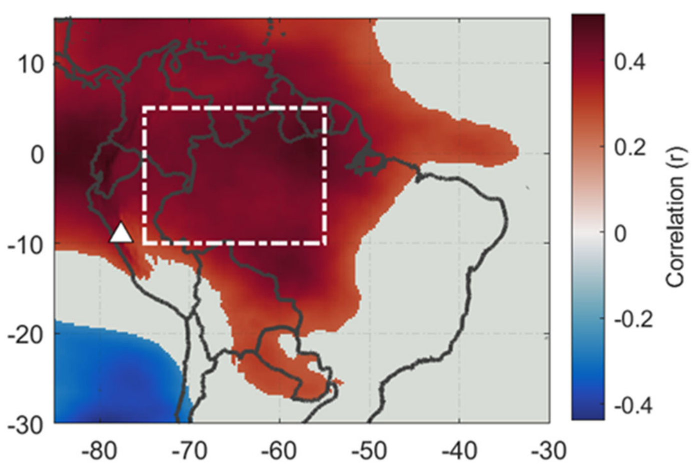

Figure S7. Spatial correlation field between $\delta^{18}O_{summit}$ and 500 hPa temperatures. The white box delimits the Amazon Basin (same as Fig.S4; 5°N-10°S, 75°W-55°W). The white triangle denotes the location of the ice core site. Only the grid cells with results that are statistically significant at the 95% level (p-value ≤ 0.05) are plotted.

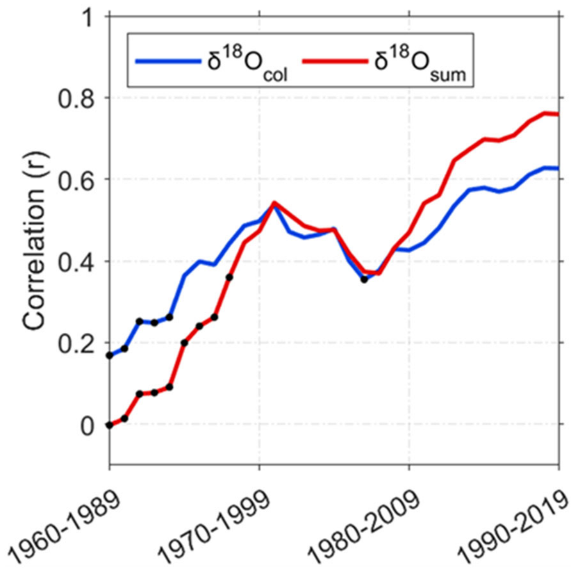

Figure S8. Time series of 30-yr multidecadal rolling correlations between $\delta^{18}O/T_{500}$ in the grid cell from Fig.S5 that contains the ice core site. Black dots indicate that the data point is not statistically significant at the 95% level (p-value ≤ 0.05).

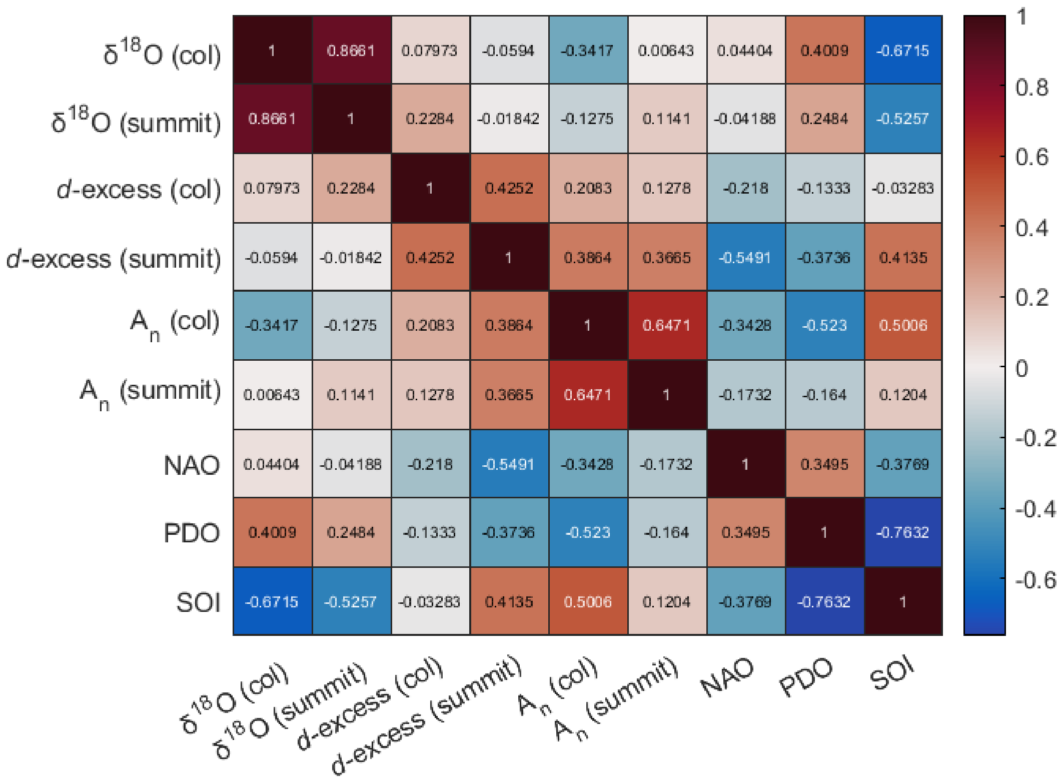

Figure S9. Heat map of correlations (r) for the HS composite cores and the NAO/PDO/SOI indices. Correlations are reflected about the diagonal.

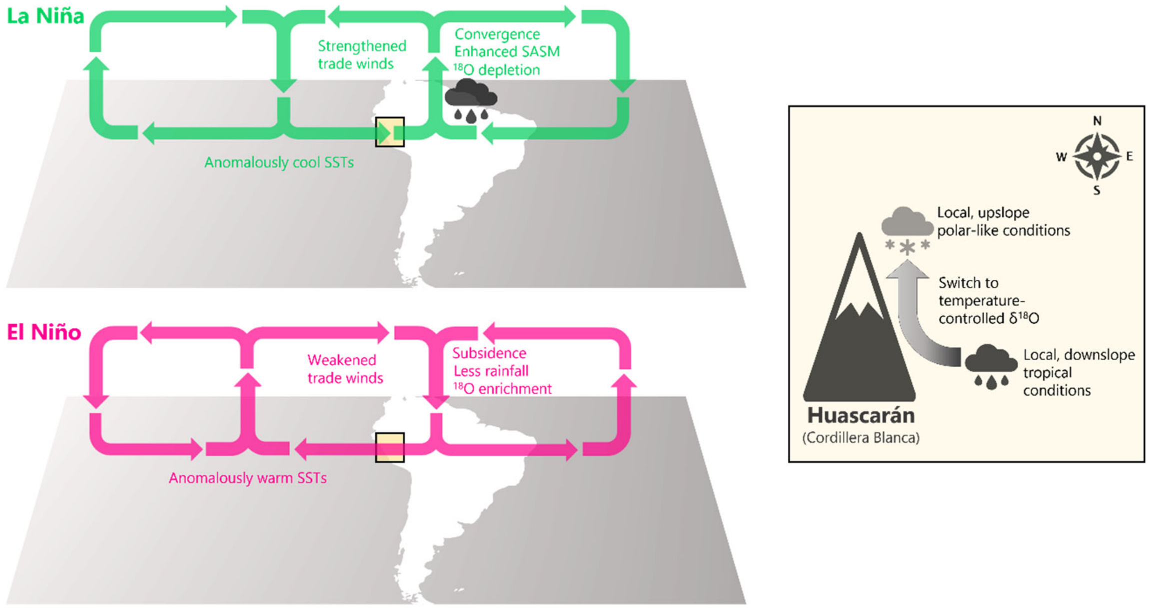

Figure S10. Illustration of the mechanisms that are proposed to be the primary drivers of the $\delta^{18}O$ signal in the Huascarán ice core records.

References

Bolzan, J. F. (1985). Ice flow at the Dome C ice divide based on a deep temperature profile. *Journal of Geophysical Research: Atmospheres*, *90*(D5), 8111–8124. https://doi.org/10.1029/JD090iD05p08111

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