Improving climatic signal representation in tropical ice cores: A case study from the Quelccaya Ice Cap, Peru

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[1] The published ice core records for Quelccaya, Peru are shown to contain numerous errors in annual layer determination, introduced by the subjective methodology of the original analysis. A new methodology is presented that aligns and then merges \(^{18}O\) sample measurement profiles from the two Quelccaya cores. Absolute dating of the stratigraphy is established by comparison of prominent dust anomalies with documented earthquake reference-marker events. The results demonstrate that the original sample measurements can register a comprehensive millenial climate history at sub-annual resolution, thus also offering great potential for clearer interpretations of ENSO signals in tropical Andean ice cores. INDEX TERMS: 3344 Meteorology and Atmospheric Dynamics: Paleoclimatology; 1827 Hydrology: Glaciology (1863); 1863 Hydrology: Snow and ice (1827); 3394 Meteorology and Atmospheric Dynamics: Instruments and techniques. Citation: Seimon, A., Improving climatic signal representation in tropical ice cores: A case study from the Quelccaya Ice Cap, Peru, Geophys. Res. Lett., 30(14), 1772, doi:10.1029/2003GL017191, 2003.

1. Introduction

[2] Two deep ice cores from the Quelccaya Ice Cap, Peru (14°S, 71° W; ~5,670 m) in 1983 were the first obtained in tropical latitudes and have yielded a 1500-year annually-resolved climate record [Thompson et al., 1985]. Climatic interpretations of the Quelccaya ice stratigraphy continue to receive widespread application, yet statistical correlation between the two Quelccaya ice cores has never been presented to evaluate the internal consistency of the climate signals between the two records (~150 m apart). The original isotopic analyses were based on water samples as the ice could not be retrieved frozen at that time. The subjectively determined annual-layer parameter averages from both cores are available to the research community, but the individual sample measurements used to create these averages have never been released, eliminating opportunities for independent assessment and validation of results. Although several other long ice core records have since been obtained from the tropical Andes, the Quelccaya cores remain highly relevant in presenting annually-resolvable stratigraphy, much further back in time than any of their counterparts.

[3] The reconstruction of annual climate and diagnosis of climatic variability is dependent upon properly establishing the representation of climate in measured parameters in well-dated ice stratigraphy. Despite the clear seasonality in precipitation, oxygen isotope (\(^{18}O\)) and dust horizon patterns found at Quelccaya, snow pit studies suggest that annual layer discrimination can still be difficult [Thompson et al., 1984]. Accordingly, a subjective methodology was utilized by the original investigators prioritizing visible stratigraphy to determine the separation of annual layering, with other parameters used for supporting reference, [Thompson et al., 1986]. Simple layer counting and a single reference marker event, strong anomalies in large particulates ascribed to the A.D. 1600 eruption of Huaynaputina [Thompson and Mosley-Thompson, 1989], were used to date the ice core strata.

[4] This study presents new results obtained by careful re-analysis of selected segments of the two cores and offers a new approach to their dating. Climatic representation is brought into sharper focus by merging the \(^{18}O\) data series from the cores and establishing the precise time line of their strata.

2. Methodology

2.1. Data

[5] Annual layer data are from WDC-Glaciology files at the NOAA National Geophysical Data Center [Thompson, 1992]. Individual \(^{18}O\) sample values are extracted from figures in publications by the original analysis team as specified in the text, since access to the original sample measurements could not be obtained.

2.2. Procedures

[6] The present investigation aims to improve the resolution of annual climatic signals registered in stratigraphy of the Quelccaya cores by reanalyzing original sample measurements with a new methodological approach that is guided by the following logic. Since the ice cores were drilled only ~150 m apart atop a broad, low-relief plateau, they must have sampled nearly identical stratigraphic profiles. It follows that the individual sample measurements of \(^{18}O\), obtained at 5-cm intervals along each core must therefore represent independent data points of that stratigraphy; they are considered to be reliable in accuracy since analysis was performed independently on each series by different laboratories [Thompson et al., 1989], and the two data series exhibit excellent correspondence. Any differences in published annual layer sample averages between the two ice cores must therefore result from the combination of subjective errors in the assignment of annual layers [Thompson et al., 1985], and the limitations of objective interval sampling.

2.3. Reanalysis Strategy

[7] This study focuses on \(^{18}O\) as a key signifier of annual layering since this parameter exhibits both a distinct
annual sinusoid and marked interannual variability in response to climatic processes [Dansgaard, 1964; Vuille et al., 2003]. Annual layer sequences that abruptly decorrelate are studied to identify where subjective errors have resulted in improper chronological alignment of the two cores. After the suggested adjustments are made to reestablish synchronicity, absolute dating is performed on the now-linked strata by matching anomalous dust signatures to major events listed in a multi-centennial history of regional earthquakes. These events are known to trigger major earth movements and cause injection of dust into the atmosphere [e.g. Henderson et al., 1999].

3. Analysis
3.1. Reestablishing Synchronous Profiles

Statistical correlation was first performed on annual layer means of $d^{18}O$ from the two Quelccaya cores for the 500 year period 1483–1983 to establish degrees of correspondence. Correlation patterns as a function of time reveal offsets in alignment in several multiyear sequences, confirming that errors must also exist for these years in the dating of the ice core profiles of at least one of the cores (Figure 1). Numerous significant decorrelation and recorrelation points are apparent, each shift indicative of inconsistent annual layer assignment between the cores. Strongest correlation is found for multidecadal periods of the 17th and 19th centuries, rather than in the more recent strata of the 20th century as might be expected. A particularly significant loss of correlation is evident between the annual layers ascribed to the years 1764–1805. An opportunity to investigate this case further is presented by examining individual $d^{18}O$ sample measurements ascribed to 1775–1825, displayed for both ice cores in Thompson et al. [1986; their Figure 1] to validate their dating methodology, and redrawn here in Figure 2a.

Reanalysis of the $d^{18}O$ sample measurements reveals errors in the original annual layer determination. Correlation between the unadjusted sample series is relatively poor ($R = 0.51$), likely owing to slight differences in ice flow characteristics at each site causing the series to drift in and out of phase, which is to be expected (Figure 2a). The published annual mean $d^{18}O$ values derived from this data similarly correlate at only $R = 0.54$, however, due to a 1-yr offset sustained prior to 1806 (Figure 2b). Strong correspondence between sample profiles can be reestablished once slight adjustments are made to bring the data into alignment by simple pattern matching of the annual sinusoids in $d^{18}O$. Reassignment of samples to create synchronous annual layers of matched $d^{18}O$ sinusoids brings the climatic representation of the data into greatly improved focus (Figure 2c). Correlation improves to $R = 0.96$ once adjustments are applied (Figure 2d). Since the two $d^{18}O$ profiles sustain consistent behavior, despite high degrees of interannual variation throughout this 50 year segment, they affirm the premise that the cores must display strong correlation since they represent the same stratigraphy. This indicates that the variations exhibited are true climatic signals, rather than glaciological noise.

To serve the primary objective, the rendering of clear climate signals, this concept is developed further here by merging the two data series, once alignment has been properly established, to create a combined “best” data series (Figure 3). This profile can be viewed as one that might be found on the Quelccaya Ice Cap in a column midway between the actual boreholes; it utilizes equal
contributions from each core, and thus yields a profile with twice as many sample points as each of its constituent parts. The resulting gains in resolution effectively double the available inference available on climate at annual scales, while disparities and ambiguities are minimized.

3.2. Time Calibration

[11] The second phase of reanalysis concerns fixing the annual layering in time. This is critical for studies comparing ice core data to that of other high temporal resolution climate proxies such as tree-ring studies and coral growth patterns. Poor correspondence has been found between the Quelccay time series and proxies for El Niño events [Ortlieb and Macharé, 1993], though can be improved if the time scale is adjusted for possible missing years [Michaelsen and Thompson, 1992]. In this study new techniques are developed that greatly improve the time-fixing capabilities for the Quelccaya cores, and might also find application in ice core studies elsewhere.

[12] The original Quelccaya analysis utilized the A.D. 1600 eruption alone as reference marker to date the ice cores. In contrast, the present investigation draws upon a multitude of time-reference indicators from a catalog of significant earthquakes in Peru since the Spanish conquest in the 16th century [IGP, 2001]. Large earthquakes represent an occasional source for potentially identifiable stratigraphic markers in ice core data [Henderson et al., 1999]; this is especially so in southern Peru, where one of the most seismically active zones in the world underlies the Atacama Desert and adjacent arid Andean occidental crest. The earthquake signals in ice core data will be detailed elsewhere, but its application to this study can be briefly described.

[13] Major earthquakes occur at roughly decadal intervals in the central Andean region and generate large debris clouds from landslides and other earth movements. Under a favorable wind regime these particulates will drift across the Andes and deposit dust particles upon the surface. The recent origin of disturbance suggests a size separation process, whereby more massive particulates will sediment to the surface relatively quickly while smaller particulates drift away. This scenario raises the possibility that regional glaciers might preserve a history of paleoseismicity by the introduction of distinct dust horizons characterized by an anomalous ratio of large to small particulates relative to that found in dust layers of non-seismic origin. Since sampling in the Quelccay case was performed at 5-cm intervals only, and was thus not continuous, not all potential earthquake-related events are expected to be represented in both ice core data series. In addition, during the austral summer prevailing easterly flow should tend to advect dust plumes from the most active seismic zone along the Pacific coast away from Quelccaya, diminishing the likelihood for anomalous dust deposition.

[14] Despite these limitations, particulate anomalies strongly suggestive of earthquake occurrence are amply evident in all the individual sample profiles presented in publications of Quelccaya ice core data [Figure 1 in Thompson et al., 1986; Figures 3–5 in Thompson and Mosley-Thompson, 1987; Figure 5 in Thompson and Mosley-Thompson, 1989]. These collectively cover 223 of the possible 452 years between the start of historical documentation (beginning with the Spanish conquest in 1532) and ice core drilling in 1983. At least 26 major earthquake events can be identified that appear to fit the stratigraphic signatures of prominent particulate anomalies, and also indicate when time corrections should be applied (Table 1).

[15] Interestingly, the A.D. 1570–1645 sequence shown by Thompson and Mosley-Thompson [1989] in order to highlight the Huaynaputina eruption actually presents a compelling case for shifting their time line forward by 4 years. The years 1604–09 featured three large magnitude earthquakes in southern Peru, beginning with one of the strongest events in the historical record on 24 November 1604 [Dorbath et al., 1990; IGP, 2001]. It follows that the anomalies in large particulates detailed in Thompson et al. [1986] might have been largely comprised of ash from Huaynaputina deposited regionwide [da Silva and Zielinski, 1998], but actually only deposited on the ice cap in association with the intense seismic activity that commenced four years later. Elsewhere in this sample profile prominent anomalies can be tied to major earthquakes in 1582, 1590, 1600 (attending the Huaynaputina eruption) and 1630; this fortifies the argument that the original time calibration of the ice cores is offset by several years, even for its defining event. This would explain inconsistencies noted by other investigators between Quelccaya and other annually resolved paleoclimate proxies, and affirms that reanalyzed sample measurements can be absolutely dated for much of the first 450 years of the ice core strata.

[16] In the data series for 1775–1825, discussed above, major earthquakes can be fitted precisely to particulate anomalies relatively quickly while smaller particulates...
anomalies in the stratigraphic sequence if both time series are shifted back by one year, in which case earthquakes can be tied to 1821 (Core 1), 1813 (both cores), 1812 (Core 1), 1799 (Core 1), 1784 (Summit) and 1777 (Summit). The likelihood that these anomalies can find comparable correspondence with other phenomena seems remote. As a result, confidence is high that the paleoearthquake reference markers can establish that the reanalyzed d18O sample series presented in Figure 3 is also precisely fixed in time for all of the years shown, with inferences on subannual climatic variation now feasible for each of these annual layers.

4. Applications

[17] This investigation indicates that individual sample measurements would more effectively serve as the basis for paleoclimate analysis with this data series, rather than subjectively determined layer averages made widely available by the original investigators. The results of the alignment and absolute dating correction exercises for selected sample series of the Quelccaya ice cores demonstrate considerable gains in accuracy, and therefore in climatic representation too. The annual sinusoids shown in Figure 3 suggest that the reanalyzed data series exhibits strong representation of significant El Niño events attended by regional droughts, with marked positive anomalies in annual mean d18O similar to that reported from Nevados Huascaran at 9°S [Henderson et al., 1999] and Sajama at 18°S [Bradley et al., 2003]. There is undoubtedly much potential for further improvement by systematic application of these methods to the complete set of Quelccaya sample measurements. In particular, since the Quelccaya stratigraphy is annually resolvable for 1500 years, far longer than that of all other low-latitude ice cores, this indicates the potential for a thorough reanalysis to reveal a complete millennial history of ENSO. Such a record would be suitable for inter-comparison with other paleoclimate proxies from within a region that shows strong sensitivity to ENSO-related climatic perturbations.

[18] In summary, this study finds that discrepancies in the two original ice core profiles for Quelccaya were introduced by subjective errors, and that the original data available in individual sample measurements offer great potential to register a comprehensive millennial climate history at sub-annual resolution.

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References


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