Supporting Information for

Impacts of recent warming and the 2015/16 El Niño on tropical Peruvian ice fields

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Text S1.

Pit and shallow core δ¹⁸O data from the QIC

Most of the pits excavated on the summit dome of the QIC were 2 to 3 meters deep in order to capture the snowfall of the previous thermal year. Of the 24 field seasons conducted on this ice cap from 1974 to 2016, 6 resulted in the collection of samples from pits alone, 6 resulted in the collection of shallow cores alone (or a deep core, in the case of 2003), and 12 resulted in the collection of both pit samples and shallow (Fig S1). During the first deep drilling expedition in 1983, a shallow core was drilled at the bottom of a 2.6 meter snow pit. The seasonal variations in the δ¹⁸O data are highly reproducible in the 15 profiles for which duplicate sets of samples (shown in red) were collected from pits or a combination of pits and cores.
Dating of 2015/16 shallow cores from QIC and HS

The shallow cores from the QIC summit dome (Fig. S2a), from the QIC north
dome (Fig. S2b), and from the HS col (Fig. S2c), all drilled in July 2016, were dated
using seasonal variations in δ^{18}O and nitrate (NO_3^-) and insoluble dust concentrations.
The annual values are shown in Fig. 5 (main text). The samples from these cores were
cut, bagged, melted and bottled at the field site under less than ideal conditions for
recovering the highest quality dust data. Thus, while the δ^{18}O values would not be
altered by such handling, the seasonal aerosol variations may not be as well-defined as
they would be had the samples been cut directly from the cores in the BPCRC freezer and
prepared for analysis under environmentally controlled laboratory conditions.
Nevertheless, the dust and especially the nitrate concentrations (smoothed with 3-sample
running means) show wet/dry season concentrations that are in phase with low/high δ^{18}O
values at the tops of the cores and thus allow thermal year determinations in the cores,
especially in the QIC cores at depths where the isotopic signal has been smoothed. The
seasonal δ^{18}O variations in the 2016 QIC summit and north dome cores are difficult to
distinguish, particularly in TY1 (shaded) and below 6 meters and thus other seasonally
varying parameters were used to date the cores (Figs. S2a, b).

Criteria for determination of major El Niños

Major El Niño events were selected on the basis of the Oceanic Niño Index for
DJF (http://www.cpc.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml),
as the δ^{18}O values in the QIC and HS originate in snow deposited mainly in the austral
summer and the SSTs, 500mb-Ts and CTTs used for creating Figure 7 (main text) are
average DJF values. A lower ONI boundary of 1.0 was arbitrarily established to
determine major events. As Table S1 shows, only 5 years meet that criterion (1982/83,
1986/87 (barely), 1991/92, 1997/98, and 2015/16). These are emphasized in Table S1;
however, no isotopic data exist from the QIC or HS for the 1997/98 event (as no field
program was conducted on either ice field in 1998). Note that strong El Niños are
indicated by ONI values exceeding +1.0 and very strong El Niños are indicated by ONI
values exceeding +2.0.

Retreat of the QIC ice margin

A western margin of the QIC was photographed from the ground in 2000, 2005,
2015, and 2016 (Fig. S3) and the glacier edges in the 2000, 2005, and 2016 photographs
were superimposed upon the 2015 image (Fig. 6a, main text). In Fig. 6b (main text), the
position of the glacier edge was determined manually based on the in situ 2000 and 2005
photographs, and on high-resolution visible satellite images for 2015 and 2016. As for
the ground images, the glacier edges are superimposed on the 2015 satellite image.
These satellites images were acquired by DigitalGlobe's WorldView-3 satellite on 29
June 2015 and 2 July 2016 and were obtained from TerraServer.com. The area covered
by the glacier within the bounds of the satellite image was estimated using the
georeferenced glacier boundaries in a Peru96/UTM zone 19S projection (EPSG:5389).
All data processing and calculations (Table S2) were performed using the QGIS software.
Figure S1. $\delta^{18}O$ data from pit and shallow core samples from the summit dome of the QIC. Above each column is the year of the sample collection which was always during the austral winter (dry season). The top thermal year (TY1) is marked in each profile. The range of the x-axis is identical for each profile. Where more than one set of samples was collected during a field season, the additional data are shown in red.
Figure S2. Data from shallow cores drilled in July 2016 from (a) Quelccaya summit dome, (b) Quelccaya north dome, and (c) Huascarán col demonstrate time scale development based on seasonal variations in $\delta^{18}O$ and concentrations of nitrate and insoluble dust with diameters between 0.63 and 20 μm. Austral winters are indicated by the prefix “W”. The nitrate and dust concentrations are smoothed with 3-sample running means to minimize noise, while the $\delta^{18}O$ profiles have not been smoothed. All the samples in these cores were melted and bottled in the field. TY1 layers are shaded.
**Figure S3.** Individual photos of the Quelccaya ice cap margin from which the ice margin composite in Fig. 6a and the 2000 and 2005 composite in Fig. 6b are created.
<table>
<thead>
<tr>
<th>Years</th>
<th>Area (m²)</th>
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<tbody>
<tr>
<td>2000</td>
<td>230,550</td>
</tr>
<tr>
<td>2005</td>
<td>181,518</td>
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<tr>
<td>2015</td>
<td>86,705</td>
</tr>
<tr>
<td>2016</td>
<td>74,471</td>
</tr>
</tbody>
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**Table S1.** Oceanic Niño Indices (ONI) for December to February (DJF) from 1973/74 to 2015/16. Notable El Niños (ONI > 1.0) are emphasized in bold italics; the major 1997/98 event for which no δ¹⁸O data exist is merely italicized.

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**Table S2.** Area of ice cover for a region along the western margin on the QIC at time intervals outlined in Fig. 6 (main text).