The Challenges, Successes, and Preliminary Status Report on the 2019 Recovery of Ice Cores from Nevado Huascarán, Earth's Highest Tropical Mountain

Los Desafíos, los Éxitos y el Informe Preliminar de la Recuperación de Núcleos de Hielo en 2019 del Nevado Huascarán, la Montaña Tropical Más Alta de la Tierra

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Abstract

Nevado Huascarán in the central Peruvian Andes is Earth's tallest tropical mountain and lies just west of the Amazon rainforest. In 1993, scientists from the Byrd Polar and Climate Research Center (BPCRC) and their Peruvian colleagues drilled ice cores to bedrock through the col of the mountain (6050 m a.s.l.) and reconstructed a ~19 ky history of climatic and environmental variations in this region of the Andes and in the Amazon Basin. The information extracted from the 1993 Huascarán ice cores contributed to a growing body of information on pre-Holocene tropical climate and potential biological activity in the Amazon Rainforest.

In 2019 the BPCRC team returned to Huascarán and with their Peruvian colleagues drilled two cores to bedrock on the col and then drilled the first two ice cores to bedrock from the peak of the South Summit (6768 m a.s.l.). Those drilled on the summit are the highest elevation ice cores from the Southern Hemisphere. Altogether four cores were drilled on the mountain, resulting in a total 471.6 meters of ice. The very low temperatures at the bottom of the boreholes ensured that the ice was frozen to the bed and thus no time was removed from the earliest parts of the records preserved in the cores. While the drilling was underway, extensive geophysical and geodetic surveys of the col and south summit ice fields were conducted to evaluate ice thickness, ice distribution, and deformation patterns. The results of this survey will be the highest elevation ice thickness and surface topography datasets.

Here we provide an overview of the studies that are currently underway on the col and summit ice cores along with preliminary results. While the Huascarán analysis is still underway and much work remains to be done, our first assessment indicates that these new cores have much to tell us about the tropical climatic, environmental, ecological, biological, and anthropologic history of the Andes and of the Amazon Basin over the last ~19 to 20 ky. In addition to the data obtained from the 1993 cores, we anticipate that the new cores will provide valuable data on major cation and black carbon concentrations, microorganisms (viruses and bacteria) and atmospheric gases.

In the Cordillera Blanca and throughout the Peruvian Andes, mid-tropospheric warming is destroying the climate signals preserved in the ice fields and accelerating glacier retreat. Because of its high elevation Huascarán is one of a few tropical sites where a largely unaltered climate history, which extends back to the Last Glacial Stage, is still being preserved. The 2019 field program on Huascarán can be considered to be a salvage mission to try to secure ice cores for current and future research. However, geodetic data from the 2019 field season, together with archived data, indicate that from 1987 to 2020 the total surface area of ice on Huascarán decreased by 20.5%. Given the current rate of warming throughout the tropical Andes, it is only a matter of time before climate records preserved in Huascarán ice will also be lost.

Keywords: *Ice cores, climate signal, Huascarán, col, south peak*

Resumen

El nevado Huascarán en los Andes peruanos centrales es la montaña tropical más alta de la Tierra y se encuentra justo al oeste de la selva amazónica. En 1993, científicos del Centro de Investigación Polar y Climática Byrd (BPCRC por sus siglas en inglés) y sus colegas peruanos extrajeron núcleos de hielo hasta el lecho rocoso a través del collado

de la montaña (6050 m s.n.m.) con los que reconstruyeron una historia de ~19 ka de cambios climáticos y ambientales en esta región de los Andes y de la cuenca del Amazonas. La información extraída de los núcleos de hielo del Huascarán de 1993 contribuyó a un creciente cuerpo de información del clima tropical del preholoceno y la posible actividad biológica en la selva amazónica.

En 2019, el equipo del BPCRC regresó al Huascarán y junto con colegas peruanos extrajeron dos núcleos hasta el lecho rocoso en el collado y los primeros dos núcleos de hielo hasta el lecho rocoso desde el pico de la Cumbre Sur (6768 m s.n.m.). Los núcleos de la cumbre son los núcleos de hielo de mayor elevación del hemisferio sur. En total, se extrajeron cuatro núcleos de la montaña, lo que resultó en un total de 471.6 metros lineales de hielo. Las temperaturas tan bajas en el fondo de los pozos de perforación aseguraron que el hielo se mantuviera congelado en el lecho rocoso y, por lo tanto, no se perdió tiempo de las partes más antiguas de los registros conservados en los núcleos. Mientras se realizaba la perforación, se condujeron extensos estudios geofísicos y geodésicos del collado y de los campos de hielo de la cumbre sur para evaluar el espesor del hielo, la distribución del hielo y los patrones de deformación. Los resultados de este estudio serán la base de datos de topografía de superficie y espesor de hielo de mayor elevación.

En este artículo proporcionamos una descripción general de los estudios que se están realizando actualmente con los núcleos de hielo del collado y de la cumbre, así como resultados preliminares. Si bien el análisis del Huascarán aún está en curso y aún queda mucho trabajo por hacer, nuestros primeros resultados indican que estos nuevos núcleos tienen mucho que decirnos acerca de la historia climática, ambiental, ecológica, biológica y antropológica tropical de los Andes y de la cuenca del Amazonas durante los últimos ~19 a 20 ka. Además de los resultados que se obtuvieron con los núcleos de 1993, los nuevos núcleos proporcionarán datos valiosos de los cationes más importantes y de carbono negro, de microorganismos (virus y bacterias) y gases atmosféricos.

En la Cordillera Blanca y a lo largo de los Andes peruanos, el calentamiento de la tropósfera media está destruyendo las señales climáticas que se conservan en los campos de hielo y acelerando el retroceso de los glaciares. Debido a su gran elevación, el Huascarán es uno de los pocos sitios tropicales donde aún se conserva una historia climática prácticamente intacta, que se remonta a la última etapa glacial. La expedición científica del 2019 en el Huascarán puede considerarse una misión de salvamento para tratar de asegurar núcleos de hielo para investigaciones actuales y futuras. Sin embargo, los datos geodésicos de dicha expedición, junto con datos de archivo, indican que de 1987 a 2020 la superficie total de hielo en el Huascarán disminuyó un 20.5%. Dada la tasa actual de calentamiento en los Andes tropicales, es solo cuestión de tiempo antes de que también se pierdan los registros climáticos que se conservan en el hielo del Huascarán.

Palabras clave: *Núcleos de hielo, señal climática, Huascarán, collado, cumbre sur*

Introduction

Fifty percent of Earth's surface lies between 30°N and 30°S, and it is predicted that by the mid-21st century 50% of its population will reside within the tropics (23.5°N to 23.5°S) (Harding et al., 2014). Information about past climate change in these latitudes is essential to place the current warming climate into perspective. Ice cores drilled through temperate and tropical glaciers and ice caps offer long-term histories of variability in precipitation, temperature, aridity, and atmospheric circulation that are unavailable from other proxy sources. It is of paramount importance that we attain a better understanding of the climatic factors that control the recent low-latitude glacier responses. However, the continued loss of glaciers and ice caps will increasingly compromise and eventually obliterate most of the non-polar, ice core-derived climate histories. This is a particular concern in the Peruvian Andes, where mid-tropospheric warming, enhanced by recent strong El Niño events, is destroying the climate signals preserved in the ice fields and accelerating glacier retreat (Thompson et al., 2017).

More than 99% of the world's tropical glaciers are located in the Andes (Randolph Glacier Inventory). The world's tallest tropical mountain, Nevado Huascarán (9.1°S 77.6°W; 6768 m a.s.l. at its highest point, the South Peak summit), in the Cordillera Blanca of central Peru is located ~200 km from the western edge of the Amazon Basin. In 1993, the Ohio State University's Byrd Polar and Climate Research Center (OSU-BPCRC) drilled two ice cores (160.4 m, 166.1 m) to bedrock through the ice in the col ("La Garganta") at 6050 m a.s.l. Analysis of the cores provided a paleoclimate history that extends back ~19,000 years (Figure 1) and includes the Younger Dryas and the end of the Last Glacial Stage (LGS) (Thompson et al., 1995).

In August 2019, under a cooperative research program with Peru's National Institute for Research on Glaciers and Mountain Ecosystems (INAIGEM), the OSU-BPCRC team returned to Huascarán and recovered four ice cores totaling 471.6 m. As in 1993, two cores were drilled to bedrock in the col: Col core A (CCA) is 165 m in length, and Col core B (CCB) is 168.6 m in length. However, in addition to the cores from the col, two ice cores were drilled to bedrock on the summit of the South Peak. Summit core A (SCA) and Summit core B (SCB) are 69.33 m and 68.73 m long, respectively. SCA and SCB are the highest elevation ice cores to be collected from a Southern Hemisphere glacier.

Here we describe the highlights of the 2019 field program, including the geodetic and geophysical measurements that were conducted, the analysis of the new Huascarán ice cores, and the anticipated information these ice cores are expected to provide about climatic and environmental changes in the central Andes and in the Amazon Basin since the Last Glacial Stage. These cores have the potential to provide a rare methane record from

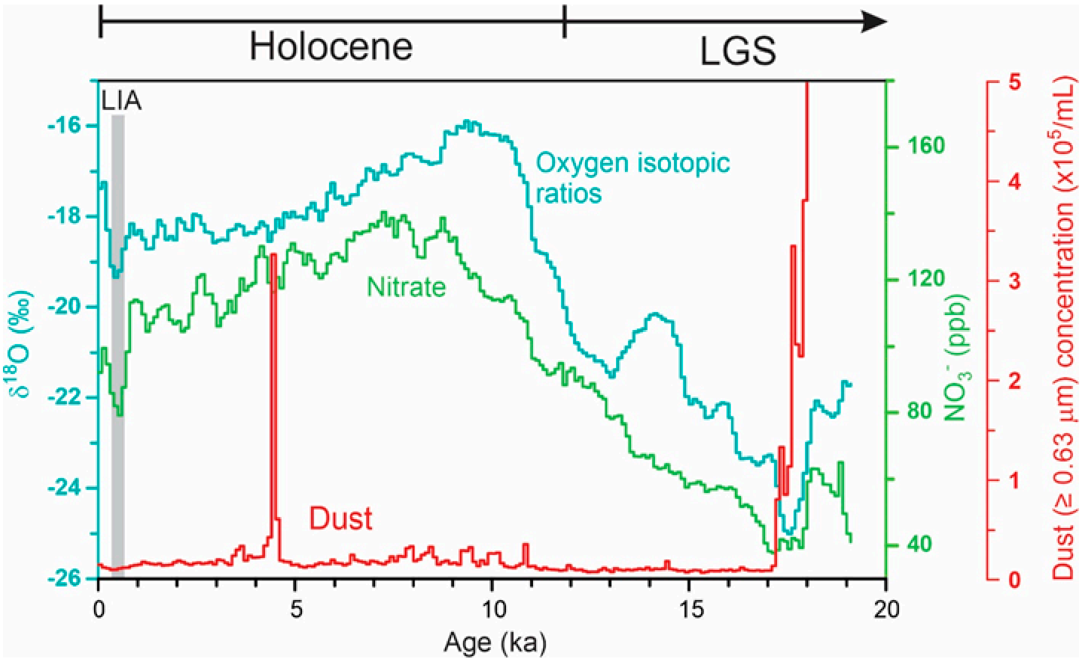

Figure 1. The ~19 ky records (100-year averages) of oxygen isotopic ratios ($\delta^{18}O$) and the nitrate (NO_3-) and dust concentrations from the 1993 Huascarán col core illustrate regional and Amazon Basin climatic and environmental variations. The Holocene and the end of Late Glacial Stage (LGS) are indicated, and the Little Ice Age (LIA) is depicte by the gray shaded bar.

a tropical glacier located in close proximity to one of the world's major emitters, the Amazon Basin rainforest (Wilson et al., 2016).

The 1993 Huascarán Ice Cores as Recorders of Amazon Basin Environmental Variations

During the wet season, the easterly air masses move across the Amazon Basin and up over Andes. The Amazon Rainforest, which presently covers ~80% (5.5 x 106 km^2) of the Amazon Basin, is a reservoir for 10 to 15% of Earth's land biodiversity, ~15% of its freshwater, and 150 to 200 billion tons of carbon (Nobre et al., 2016). The Amazon Rainforest is one of Earth's major centers of tropical deep convection (Olson et al., 2001; Werth and Avissar, 2002), and thus environmental change in this region has major implications for the global water and carbon cycles (Werth and Avissar, 2002; Brienen et al., 2015), as well as for biodiversity (Häggi et al., 2017). Human activities during the Holocene have significantly influenced land cover (e.g., deforestation), creating major disruptions and climate changes that have altered the surface albedo and hence the net radiation budget which controls the energy available for evapotranspiration (de Oliveira et al., 2019; Stark et al., 2016). Large uncertainties are associated with the level of deforestation necessary for collapse of the Amazon Rainforest, with estimated tipping points ranging from deforestation of 20% (Lovejoy and Nobre, 2018) to 40% (Nobre et al., 2016; Salazar and Nobre, 2010) of its currently forested area.

Although there are few long-term paleoclimatic records available from the lowlands, proxy records from the high Andes, such as those from the ice cores drilled on Huascarán in 1993, have provided important data on climate variables during the last glacial to interglacial transition (Thompson et al., 1995 and 2000). In addition to the information on regional climate since the LGS, the records from the Huascarán cores yield important insights into how the environment and ecosystems in the Amazon Rainforest have varied through time. Most prominent in the records are the 6.3‰ $\delta^{18}O$ depletion, a 200-fold increase in insoluble dust, and a two- to three-fold decrease in nitrate (NO_3-) during the LGS compared with the Early Holocene (~10 ka BP) (Figure 1).

A climatic reversal (i.e., an episode of cooling during the deglaciation) equivalent to the Younger Dryas stadial is clearly detected in the $\delta^{18}O$ record of the Huascarán ice core, but its occurrence appears to be asynchronous with that in the Northern Hemisphere. The very low $\delta^{18}O$ values during the LGS, especially between 17 and 18 ka BP (Figure 1), have been interpreted as significant tropical cooling (Thompson et al., 1995; 2000). The amount of cooling indicated by the ice core record contradicts the 2 °C tropical temperature decrease indicated by CLIMAP reconstructions (CLIMAP, 1976; CLIMAP, 1981). However, it has become part of a growing body of evidence (e.g., Guilderson et al., 1994; Stute et al., 1995) that supports the hypothesis of much colder conditions during the LGS in the tropics (perhaps by as much as 8 °C) relative to the Early Holocene. The magnitude of the cooling has been confirmed on six continents using four decades of groundwater noble gas data along with new records from the tropics, which indicate a widespread 6 °C temperature decrease on land during the Last Glacial Maximum (Seltzer et al., 2021).

The nature and forcings of the climate and environment of the Amazon Basin during the end of the Late Pleistocene are controversial. Much of the controversy centers on the “refugia” hypothesis, i.e., the concept that during arid periods in the Pleistocene the Amazon Rainforest consisted of several small forests, which were isolated from each other by non-forest vegetation (Haffer, 1969). Gomes da Rocha and Kaefer (2019) provide a discussion of the history of the refugia controversy. The high insoluble dust and low NO_3- concentrations in the Huascarán record during the LGS (Figure 1) imply increased atmospheric turbidity, which is consistent with climate proxy records from tropical South America that indicate lower humidity and precipitation, as well as a possible reduction of forest and grass cover (Clapperton, 1993). It has been hypothesized by Clapperton (1993) that up to 25% of South America was covered by eolian deposits, such as sand dunes and loess at this time. Although the sources of atmospheric NO_3- are not well defined, the lower concentrations in Huascarán LGS ice imply that nitrogen sources, such as tropical rain forests and forest soils (Robertson and Tiedje, 1988) may have been restricted. Therefore, the Huascarán dust and nitrate records during the LGS appear to lend some support to the refugia hypothesis.

Throughout the most recent 10 ky of the Huascarán record, $\delta^{18}O$ steadily decreased to its lowest values in the Little Ice Age (LIA) before increasing in the 20th century (Figure 1). Nitrate concentrations follow the $\delta^{18}O$ trends, but the Early to Middle Holocene maximum lags by about 2000 years (Thompson et al., 1995). Similar to $\delta^{18}O$, Holocene NO_3- concentrations were lowest during the LIA and have increased in the last two centuries. A higher resolution LIA record from the Quelccaya ice cap in southern Peru reveals that the first half (~1450 to 1700 CE) was cold and wet, while the latter half (~1700 to 1900 CE) was cold and dry, and the 20th century was warm and wet (Thompson et al., 2013).

The 2019 Huascarán Field Program

The organizing and preparation for the Huascarán field program started four years in advance of the actual work on the mountain. This included discussions about the project with our Peruvian colleagues at INAIGEM and development of cooperative agreements in an ever-changing political landscape. In 2016, a small team from BPCRC, including Lonnie Thompson, Emilie Beaudon, Vladimir Mikhalenko, Stanislav Kutuzov, Wilmer Sánchez-Rodríguez, and our long-time guide Félix Benjamin Vicencio Maguiña, visited Huascarán for a week and extracted a short ice core from the col. Analysis of the core showed that the seasonal oscillations in $\delta^{18}O$, NO_3-, and mineral dust are still preserved at this site (Thompson et al., 2017). The year before the start of the fieldwork involved the planning, purchasing, and testing of scientific and drilling equipment. In January 2019 Vladimir Mikhalenko and Stanislav Kutuzov, the chief ice core drillers, traveled from Russia to the OSU-BPCRC in Columbus to become familiar with the drill and undertake the necessary repairs and tests.

The drill, along with six tons of equipment, was shipped to Lima before the field team left the U. S. and cleared customs shortly after the team’s arrival. In Lima, Dr. María Gisella Orjeda Fernández, the former Executive President of INAIGEM, arranged media interviews and meetings with government officials, including Lucía Ruiz Ostoic, Minister of the Environment (Figure 2A), to explain the objectives of the Huascarán research.

In the province of Ancash where Huascarán is located and in Mancos where the expedition was staged, team members had a series of meetings with members of INAIGEM, with biologist Willian Martínez Finquin, the Director of Huascarán National Park, and with local media, community leaders and local residents to explain the project’s objectives and to answer questions about the project (Figure 2B). The plan was presented to employ mountaineers and porters to man-haul the drilling, surveying, and camping equipment up the mountain to the col and summit drill sites, then carry the ice cores and equipment back down to the Refugio “Don Bosco” Huascarán (a.k.a. Alpine Hut, 4650 m a.s.l.) on the flank of the mountain. The ice would be stored there in boxes along with cold packs that were frozen in two commercial freezers powered by a gasoline generator. Once the drilling was completed, the cores were to be transported to freezer trucks in the valley below and from there to freezers in Lima.

The field team, along with the equipment and supplies, moved to the Alpine Hut on July 7. There the science team acclimatized and met with then President Martín Vizcarra Cornejo to explain the objectives of the project (Figure 2C). During the president’s visit, he hiked to the edge of the ice together with the science team, guides and some local residents. After discussing the project and viewing the glacier, President Vizcarra offered to arrange for a helicopter to bring ice cores from the Alpine Hut down to the freezer trucks at the end of the project.

On July 16, Father Alessio Busanto, who manages the Alpine Hut for the Association Don Bosco, gave his blessing to the team and to the mountain (Figure 2D). Because recent avalanches made the normal climbing route to the col too dangerous, Peruvian mountaineers and porters spent several days securing a new and safer route to the col and ultimately to the South Peak summit (Figure 3). This team included guides Jorge Walter Albino Rosales, Agripino Henostroza Vargas, Guido Mollepaza Mollohuanca, and lead mountaineer Félix Benjamín Vicencio Maguiña. During the drilling season, this new and safer route was also used by many recreational mountain climbers.

Figure 2. OSU-BPCRC team members and officials from INAIGEM meet with: (A) Minister of the Environment in Lima, (B) local government officials and citizens of Mancos, and (C) President Martín Vizcarra Cornejo at the Alpine Hut on Huascarán. (D) Members of the field team with Father Alessio Busanto, manager of the Alpine Hut, who blessed the mountain and expedition members before their ascent.

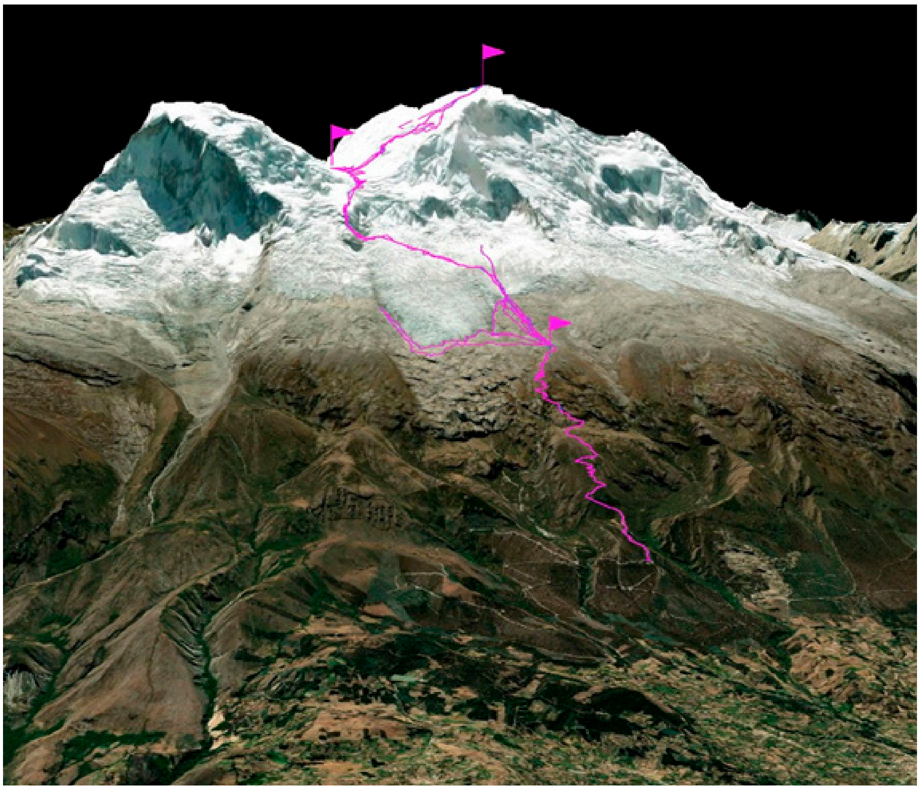

Figure 3. The route from the Alpine Hut to the Col and South Peak drill sites (marked by flags). The tandem routes, which branch from the main route, are ground penetrating radar (GPR) tracks.

Ice Core Drilling

After the new route was secured and the drilling, surveying, and camping equipment was transported up the mountain (Figure 4A), the scientists traveled from the Alpine Hut to the col. Drilling started the following day and two cores (CCA and CCB) were completed to bedrock on July 23 and July 26 (Figure 4C), respectively. Immediately afterward, the team relocated to the summit of the South Peak (Figure 4B), where drilling began on July 31 (Figure 4D). The first core to bedrock (SCA) was completed on August 2 and the second core (SCB) was completed 25 hours later. The drilling operation was conducted quickly and with very little difficulty. Borehole temperatures measured in one of the drill holes at the col ranged from -6.1 °C at 1 m depth to -4.0 °C at the ice-bedrock contact. At the summit site, the borehole temperatures were consistently -9 °C from surface to the ice/bedrock interface.

An ice core processing tent was erected at the drill sites where the freshly recovered cores were logged, cut, and packed in tubes as they emerged from the drill holes (Figures 5A and 5B). Afterward they were stored in a large snow pit (Figure 5C). Eventually, porters and mountaineers under the direction of Félix Vicencio (Figure 5D) man-hauled the ice cores from the drill sites to the Alpine Hut (Figures 6A and 6B), where they were placed in insulated boxes (six cores per box), along with frozen cold packs (Figure 6C) before being flown by helicopter (Figure 6D) to the Río Santa Valley where the freezer trucks were waiting (Figure 7A). By August 17 all the ice cores had been removed from the mountain and loaded onto the trucks (Figure 7B) for immediate transport to Lima.

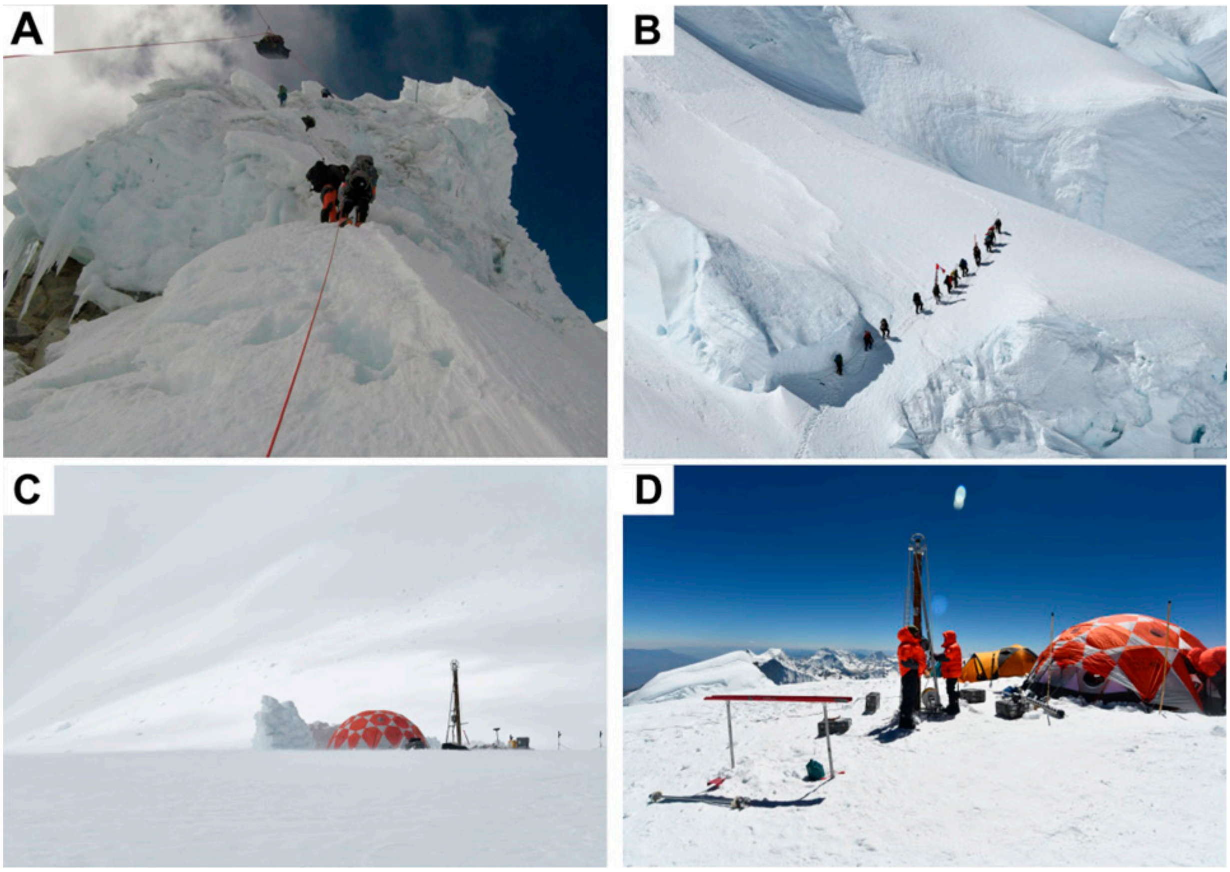

Figure 4. (A) Moving people and equipment up the new route from the Alpine Hut to the col. (B) Members of the field team ascending from the col to the summit drill site on the South Peak. (C) The ice core drill and the ice core processing dome stand in the center of the col on Huascarán. (D) The drill camp at the summit of Huascarán's South Peak.

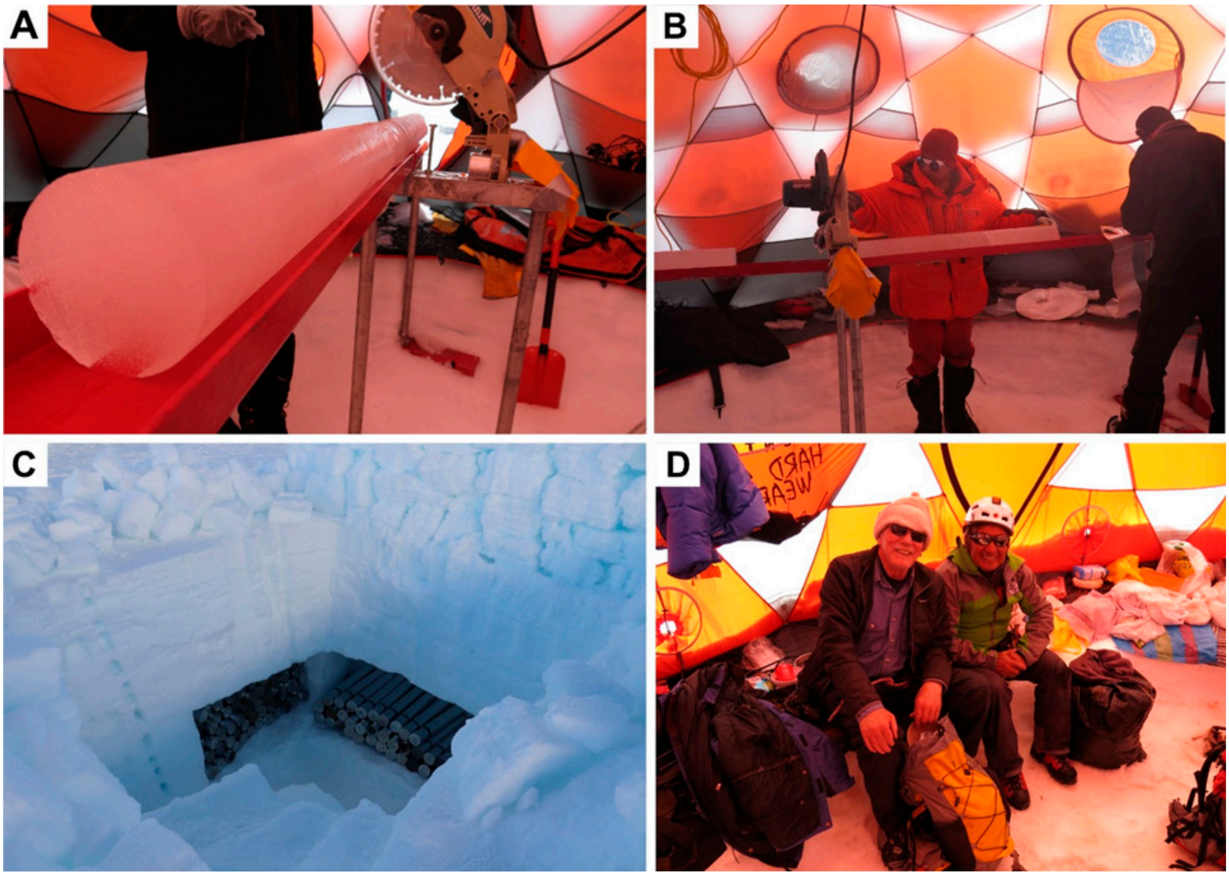

Figure 5. (A) A piece of freshly drilled ice core ready to be cut into 1-meter long sections in the ice core processing dome at the col drill site. (B) Wilmer Sánchez-Rodriquez logging a freshly cut ice core section. (C) After logging, ice cores were placed in tubes and stored in a snow pit. (D) Lead mountaineer Félix Benjamín Vicencio (right) and Lonnie Thompson inside the kitchen dome at the col.

Figure 6. (A) Porters transport the ice cores from the summit down to the Alpine Hut (B). (C) Cryopaks are frozen in two freezers at the hut and placed into the insulated core boxes to keep the cores frozen as they are transported by helicopter (D) to the valley below.

Figure 7. (A) Two freezer trucks wait in Mancos to receive the ice cores and transport them to freezers in Lima. (B) Loading ice core boxes into the freezer trucks. (C) Lonnie Thompson delivering a lecture to students of the Colegio Nuestra Señora del Sagrado Corazón de Jesús in Huaráz before departing for Lima.

Geophysical and Geodetic Field Work

While the drilling was underway, extensive geophysical and geodetic surveys of the col and south summit ice fields were conducted to evaluate ice thickness, ice distribution and deformation patterns. The results of this survey will be the highest ice thickness and surface topography datasets ever recorded in the Southern Hemisphere. In addition, the data will be used to estimate the volume of ice on Earth's highest tropical mountain, and from this, the approximate amount of water that is stored in these ice fields can be calculated.

To accurately construct basal topography maps and measure glacier surface deformation, the surface elevation must be well constrained. A network of stakes was deployed along gridded intervals and used to perform repeated high-precision, static global navigation satellite system (GNSS) measures which were collected throughout the duration of the expedition. A total of 61.8 km of kinematic GNSS measures were made across the glacier surface, yielding 22,592 point-measures of surface elevation. One GNSS receiver was configured as a rover and used by the science team to acquire kinematic and static observations, while the other was anchored at the Alpine Hut to serve as a precision base station. The mean horizontal error of the kinematic GNSS measures was 1.8 cm and the mean vertical error was 7.3 cm. For the static GNSS measures, the mean horizontal error was 0.14 cm and mean vertical error was 2.3 cm. The ellipsoidal height measure recorded on the south summit was 6,784.16 m. It is interesting to note that personal handheld GPS devices consistently underestimated elevation across Huascarán by up to 200 meters (15 m average). Due to the high precision of the GNSS ground control points, these data have enabled us to fuse multi-sensor satellite datasets and measure the fluctuations of the surface area of the ice on Huascarán at much higher spatial resolutions. For example, from these GNSS and archived data we determined that between 1987 and 2020 the total surface area of ice on the mountain decreased by 20.5%

To measure ice thicknesses, ground penetrating radar (GPR) surveys were conducted across the col and summit along 5.8 km and 1.12 km transects, respectively, using precision GPR units manufactured by Geophysical Survey Systems Incorporated (GSSI) and 40 MHz (120 cm wide) antennas. The GPR receiver and transmitter were carried by the science team and one mountaineer in tandem along transect routes (Figure 3). A GNSS receiver was also carried and simultaneously recorded kinematic measures of surface elevation alongside each GPR sounding to enhance accuracy. Data were recorded as continuous profiles and the 40 MHz antennas were oriented perpendicular to the profiling direction, parallel to each other, and spaced by one standard GSSI cable length of 4 m.

This ground-controlled approach to modeling Huascarán's topography and ice hypsometry will also be useful for evaluating the quality of IceSat-2 (Ice, Cloud, and Land Elevation Satellite-2) measurements in the tropics. These data were requested in advance of the field project via NASA's Target of Opportunity Program and were acquired synchronously during the field campaign. These combined in situ and remote measurements will contribute to the empirical knowledge of tropical climate-ice interactions and further develop understanding of how ice volume, water resources, and geohazard risks are evolving in the context of a destabilizing tropical cryosphere.

The End of the Field Season

While the summit drilling was underway, a situation was developing that had the potential for serious consequences for the program and for both the Peruvian and foreign participants. A group of people from local villages expressed their opposition to the Huascarán drilling program, and as the summit drilling was being completed, the foreign members of the field team were told to evacuate from the area immediately. In response, representatives from INAIGEM, Servicio Nacional de Áreas Naturales Protegidas por el Estado (SERNAMP), and the Prefect of Ancash met with representatives of nearby villages. Nevertheless, all field team members, mountaineers and porters left the mountain prematurely. After their evacuation, the field team members held a "town hall" meeting with about 200 people in Musho, in which the local leaders presented their concerns about the activities on Huascarán. An agreement was ultimately reached which allowed our lead guide Félix Vicencio and the 38 mountaineers and porters of the field team to remove all the ice cores and equipment from the mountain by August 18.

Before leaving Huaráz, Lonnie Thompson was invited to deliver a lecture on the impact of climate change on the glaciers of Peru, along with an account of the 2019 Huascaran expedition, to 220 11^{th} and 12^{th} grade students and 25 faculty members at the Colegio Nuestra Señora del Sagrado Corazón de Jesús (Figure 7C). By August 22, all the field team members arrived safely in Columbus, Ohio and were followed two days later by all the ice drilled on Huascarán.

Ice Core Analysis

The analytical and interpretive phases of the Huascarán project have the following objectives: (1) establish tightly constrained timescales for each of the ice cores, (2) document and characterize abrupt climatic and environmental variations with emphasis on mid-Holocene events and the last deglaciation, (3) assess how the climate and environment have changed over the past century in response to anthropogenic forcing, (4) determine tropical atmospheric and climatological dynamics on multi-decadal, decadal, and ENSO time scales, and (5) assess the regional characteristics of climatic and environmental variability during the Holocene and Last Glacial Stage with a focus on changes in the Amazon Basin, and determine how they compare to contemporaneous conditions elsewhere. Records of stable isotopes of oxygen and hydrogen in the ice will provide histories of mid-troposphere temperature and precipitation. By analyzing biological parameters (e.g., microbial populations, pollen, and methane concentrations), we can study environmental changes in the vast Amazon rainforest, which is located in close proximity east of the glacier.

The analysis of Summit Core A (SCA) began in November 2019 and was completed in March 2020. The core was cut into 2051 samples for: (a) oxygen isotopes ($\delta^{18}O$, $\delta^{17}O$) and hydrogen isotopes (δD); (b) mineral dust concentrations and size distributions between 0.63 and 16 µm diameter; (c) major anion concentrations (methylsulfonate, fluoride, chloride, nitrate, and sulfate);

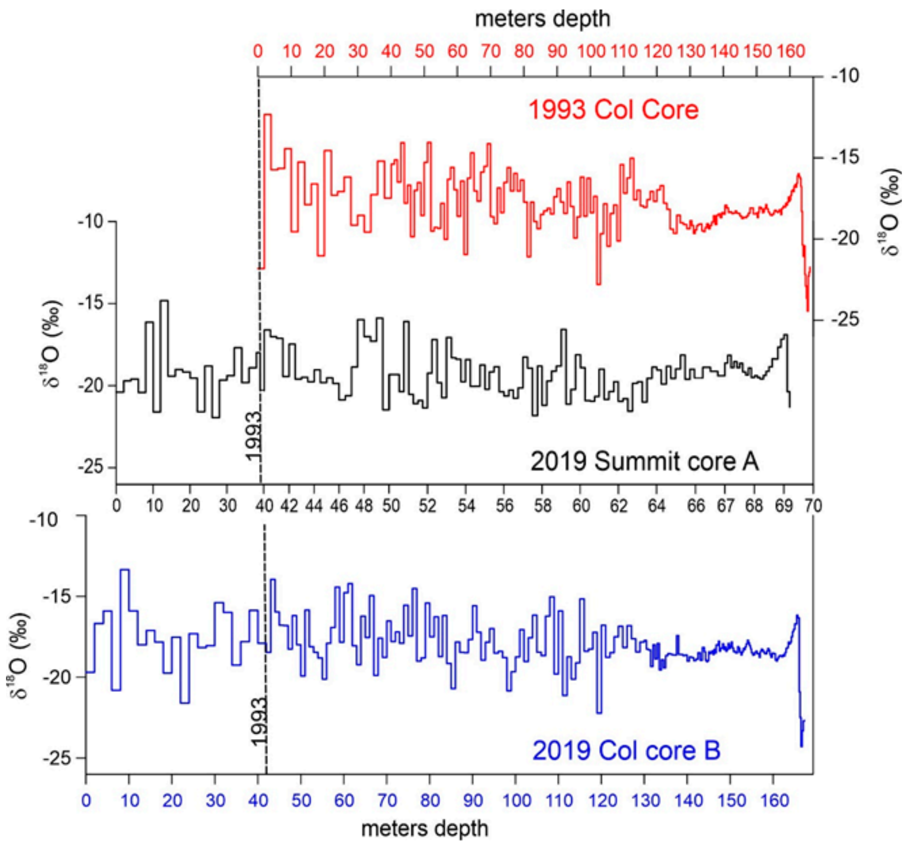

Figure 8. Comparisons between the depth averages of $\delta^{18}O$ profiles from the 1993 col core and the 2019 SCA and CCB. Dashed lines in SCA and CCB mark the year 1993.

and (d) major cation concentrations (sodium, ammonium, potassium, magnesium, and calcium). Since the $\delta^{18}O$ profile for SCA resembles that from the Huascarán col core drilled in 1993 (Thompson et al., 1995) (Figure 8), a preliminary timescale was created by matching the two profiles. Although SCA is only 41% of the length of the 1993 col core and the two col cores drilled in 2019, it appears to extend back to ~13.2 ka BP, or 6000 years younger than the 1993 col core. Annual layers in $\delta^{18}O$, nitrate, and dust concentrations are discernible to 55 m, which corresponds to 1920 CE. The most recent ~1000 years of the SCA record is contained in the top 66 meters, while 12,000 years is contained in the bottom 3 meters. This rate of increase of the time to depth ratio is similar to that observed in the 1993 col core, in which 9000 years of the ~19,000 record occur in the bottom 3 meters. The temperature measured at the base of the borehole at the summit (-9 °C) indicates that no melting is occurring that would remove ice from the bottom.

Toward the end of March 2020, most operations OSU-BPCRC were shut down due to state mandates regarding the COVID-19 pandemic. After the laboratory personnel received permission from the university to return to work in mid-June 2020, the analysis of Col core B (CCB) began. Over the following year the core was cut into 5138 samples for each of the parameters listed above for SCA. Because the ice in the col is almost 100 meters thicker than on the summit, annual layer thinning occurs at a greater depth and individual years can be discerned to ~123 meters. As expected, the $\delta^{18}O$ profiles from the 1993 and 2019 col cores strongly resemble each other, especially the isotopic enrichment just above the sudden depletion of ~8‰ toward the bottom of the records (Figure 8).

Comparison of the 1993 and 2019 col records shows that ~42 meters of ice and firn accumulated over 26 years (Figure 8). Likewise, comparison of the $\delta^{18}O$ profiles from the 1993 col core and the much shorter SCA indicates that ~39 meters of ice and firn accumulated at the higher elevation site over 26 years.

The laboratory analyses of the bottom 19 meters of Summit core B (SCB) and the top 142 meters of Col core A (CCA) have been completed. Future plans include the completion of the CCA analyses. Along with these routine measurements of the chemical species and dust in the OSU-BPCRC labs, additional high-resolution measurements of methane (CH_4) concentrations and $\delta^{18}O_{atm}$ are underway. The CH_4 analyses are being conducted by Prof. Edward Brook at Oregon State University. To date, three samples from SCA and three samples from CCB have been measured for CH_4 concentrations. The preliminary results look promising and suggest that the ice at both the summit and the col is sufficiently cold to preserve unaltered methane histories directly above the Amazon Basin. Additional methane measurements are currently underway on both the summit and col ice cores. Measurements of $\delta^{18}O_{atm}$ will be conducted by Dr. Jeffrey Severinghaus at Scripps Oceanographic Institution. It is anticipated that the data from both these gas analyses will help refine the time scales of the cores at depth.

The field team excavated a 3-meter snow pit at the col drill site and a 2-meter pit at the summit site and collected 10-cm long samples for $\delta^{18}O$, $\delta^{17}O$, δD, dust and major ion concentrations, trace elements, and black carbon (BC) analyses. One of the objectives of the Huascarán program is to assess the seasonal variability of BC deposition at the col and summit and evaluate its potential to develop a high-resolution, long-term Amazon fire history.

Development of a Huascarán Methane Record

While the Huascarán analysis is still underway and much work remains to be done, our first assessment indicates that these new cores have much to tell us about the tropical climatic, environmental, ecological, biological, and anthropologic history of the Andes and the Amazon Basin over the last ~19 to 20 ka. In addition to the data obtained from the 1993 cores ($\delta^{18}O$, dust and major anion concentrations), we anticipate that the new cores will provide valuable data on major cation and black carbon concentrations, microorganisms (viruses and bacteria), pollen and atmospheric gases.

Measurements of methane concentrations are underway in both the 2019 col and summit cores. Although there are several multi-millennial records of CH_4 from polar ice cores, very few exist from glaciers in the lower-latitudes and none exist from the tropical Andes. This data gap limits our understanding of how CH_4 has varied in the tropics before and during the Anthropocene. The central Andes, including Huascarán, lie above and downwind of the Amazon Basin, one of Earth's most significant CH_4 emitters. This is of interest because most estimates indicate that tropical CH_4 sources are the largest component of the global CH_4 source budget. Although the Amazon Basin covers only 4% of Earth's surface area, it is thought to contribute 14 to 20% of the global natural emissions of CH_4 (Wilson et al., 2016). A ~20,000-year time series of CH_4 variations from Huascarán will be integrated with similar records from Antarctica and Greenland to produce a global record of atmospheric CH_4 variability. As a bonus, such a record would provide additional time markers for the Huascarán cores because the timing of abrupt global CH_4 variations is well known from the polar ice core CH_4 records.

Conclusions

Ice cores recovered in 2019 from Nevado Huascarán are providing valuable records of climatic and environmental variations in the central Andes and the Amazon Basin extending back to the Last Glacial Stage. The records are also from the highest glacier in the tropical Andes, and for this reason their climate records have remained intact while all the others from lower elevation glaciers and ice caps in Peru have been altered by melt due to rising temperatures and its percolation through the upper porous firn layers (Thompson et al., 2017; and 2021). Unfortunately, the 2019 field program was also a salvage mission, since the rising 0 °C isotherm in the Andes ensures that the ice on Huascarán will eventually suffer the same fate as that on lower elevation tropical glaciers. The very cold temperatures throughout the Huascarán ice are essential for the recovery of what may be the only records of methane concentrations, microbes, and organic species since the Last Glacial Stage from a tropical ice core. These data may also provide unique information on the history of environmental conditions in the Amazon Rainforest.

For the scientists, students, technicians, and mountaineers who were involved in the 1993 Huascarán project, the 2019 expedition and especially the drilling of the South Peak was a major step toward the completion of a program that was started a quarter of a century earlier. The challenge going forward that is faced by the next generation of scientists is how to use these ice core data and information from other Andean glaciological and climatological studies to help assess the future security and livelihoods of villages and towns that are located in mountain regions and exist on the front lines of climate change and its effects on mountain hazards and water resources. Also, current and future generations of scientists need to build long-term productive relationships not only with local institutions but also with local communities, and to find accessible ways to disseminate useful information with them.

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References

Brienen, R. J. W., Phillips, O. L., Feldpausch, T. R., Gloor, E., Baker, T. R., Lloyd, J., Lopez-Gonzalez, G., Monteagudo-Mendoza, A., Malhi, Y., Lewis, S. L. . . . Zagt, R.J. (2015). Long-term decline of the Amazon carbon sink. *Nature*, 519, 344–348.

Clapperton, C. M. (1993). *Quaternary geology and geomorphology of South America.* New York, Elsevier Science.

CLIMAP. (1976). The surface of the ice-age earth: Quantitative geologic evidence is used to reconstruct boundary conditions for the climate 18,000 years ago. *Science*, 191(4232), 1131–1137.

CLIMAP. (1981). *Seasonal reconstructions of the Earth's surface at the Last Glacial Maximum.* Map and Chart Series MC–36. Geological Society of America.

de Oliveira, G., Brunsell, N. A., Moraes, E. C., Shimabukuro, Y. E., dos Santos, T. V., von Randow, C., de Aguiar, R. G. and Aragao, L. E. O. C. (2019). Effects of land-cover changes on the partitioning of surface energy and water fluxes in Amazonia using high-resolution satellite imagery. *Ecohydrology,* 12(6), e2126.

Gomes da Rocha, D. and Kaefer, I. L. (2019). What has become of the refugia hypothesis to explain biological diversity in Amazonia? *Ecology and Evolution,* 9(7), 4302-4309.

Guilderson, T. P., Fairbanks, R. G. and Rubenstone, J. L. (1994). Tropical temperature variations since 20,000 years ago: Modulating interhemispheric climate change. *Science,* 263(5147), 663-665.

Haffer, J. (1969). Speciation in Amazonian forest birds: Most species probably originated in forest refuges during dry climatic periods. *Science,* 165(3889), 131-137.

Häggi, C., Chiessi, C. M., Merkel, U., Mulitza, S., Prange, M., Schulz, M. and Schefuß, E. (2017). Response of the Amazon rainforest to late Pleistocene climate variability. *Earth and Planetary Science Letters,* 479, 50–59.

Harding, S. M., McComiskie, M., Wolff, M., Trewin, D., and Hunter, S. (2014). *State of the tropics.* Cairns, Australia, James Cook University.

Lovejoy, T. E. and Nobre, C. (2018). Amazon tipping point. *Science Advances,* 4(2), aat2340.

Nobre, C. A., Sampaio, G., Borma, L. S., Castilla-Rubio, J. C., Silva, J. S. and Cardoso, M. (2016). Land-use and climate change risks in the Amazon and the need of a novel sustainable development paradigm. *Proceedings of the National Academy of Sciences,* 113(39), 10759–10768.

Olson, D. M., Dinerstein, E., Wikramanayake, E. D., Burgess, N. D., Powell, G. V. N., Underwood, E. C., D'amico, J. A., Itoua, I., Strand, H. E., Morrison, J. C., Loucks, C. J., Allnutt, T. F., Ricketts, T. H., Kura, Y., Lamoreux, J. F., Wettengel, W. W., Hedao, P. and Kassem, K. R. (2001). Terrestrial ecoregions of the world: A new global map of life on Earth: A new map of terrestrial ecoregions provides an innovative tool for conserving biodiversity. *Bioscience*, 51(11), 933-938.

Robertson, G. P. and Tiedje, J. M. (1988). Deforestation alters denitrification in a lowland tropical rain forest. *Nature,* 336, 756–759.

Salazar, L. F. and Nobre, C. A. (2010). Climate change and thresholds of biome shifts in Amazonia. *Geophysical Research Letters,* 37(17), L17706.

Seltzer, A. M., Ng, J., Aeschbach, W., Kipfer, R., Kulongoski, J. T., Severinghaus, J. P. and Stute, M. (2021). Widespread six degrees Celsius cooling on land during the Last Glacial Maximum. *Nature,* 593, 228-232.

Stark, S. C., Breshears, D. D., Garcia, E. S., Law, D. J., Minor, D. M., Saleska, S. R., Swann, A. L. S., Villegas, J. C., Aragão, L. E. O. C., Bella, E. M., Borma, L. S., Cobb, N. S., Litvak, M. E., Magnusson, W. E., Morton, J. M. and Redmond, M. D. (2016). Toward accounting for ecoclimate teleconnections: Intra- and inter-continental consequences of altered energy balance after vegetation change. *Landscape Ecology,* 31, 181–194.

Stute, M., Forster, M., Frischkorn, H., Serejo, A., Clark, J. F., Schlosser, P., Broecker, W. S. and Bonani, G. (1995). Cooling of tropical Brazil [5 degrees C] during the last glacial maximum. *Science,* 269(5222), 379-383.

Thompson, L. G., Mosley-Thompson, E., Davis, M. E., Lin, P.-N., Henderson, K. A., Cole-Dai, J., Bolzan, J. F. and Liu, K.-B. (1995). Late glacial stage and Holocene tropical ice core records from Huascarán, Peru. *Science,* 269(5220), 46–50.

Thompson, L. G., Mosley-Thompson, E. and Henderson, K. A. (2000). Ice-core palaeoclimate records in tropical South America since the Last Glacial Maximum. Journal of Quaternary *Science,* 15(4), 377–394.

Thompson, L. G., Mosley-Thompson, E., Davis, M. E., Zagorodnov, V. S., Howat, I. M., Mikhalenko, V. N. and Lin, P.-N. (2013). Annually resolved ice core records of tropical climate variability over the past ~1800 years. *Science,* 340(6135), 945–950.

Thompson, L. G., Davis, M. E., Mosley-Thompson, E., Beaudon, E., Porter, S. E., Kutuzov, S., Lin, P.-N., Mikhalenko V. N., Mountain, K. R. (2017). Impacts of recent warming and the 2015/16 El Niño on tropical Peruvian ice fields. Journal of G*eophysical Research: Atmospheres,* 122(23), 12688-12701.

Thompson, L. G., Davis, M. E., Mosley-Thompson, E., Porter, S. E., Valdivia Corrales, G., Shuman, C. A. and Tucker, C. J. (2021). The impacts of warming on rapidly retreating high-altitude, low-latitude glaciers and ice core-derived climate records. *Global and Planetary Change*, 203, 103538.

Werth, D. and Avissar, R. (2002). The local and global effects of Amazon deforestation. J*ournal of Geophysical Research: Atmospheres*, 107(D20), LBA 55-1 - LBA 55-8.

Wilson, C., Gloor, M., Gatti, L. V., Miller, J. B., Monks, S. A., McNorton, J., Bloom, A. A., Basso, L. S. and Chipperfield, M. P. (2016). Contribution of regional sources to atmospheric methane over the Amazon Basin in 2010 and 2011. *Global Biogeochemical Cycles*, 30(3), 400-420.