# METEOROLOGICAL, CHEMICAL, AND ISOTOPIC CHARACTERISTICS OF PRECIPITATION EVENTS ON THE QUELCCAYA ICECAP, PERU: 2014-2016

By

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# ABSTRACT

The Quelccaya Icecap, located in the Cordillera Vilcanota of Southern Peru, is the source of ice cores dating back almost 2,000 years. These are a critical paleoclimatic record for the tropics, where a large part of the world's population is located. However, the record is complex, and most now believe that the annual layers of the Quelccaya Icecap reveal more about precipitation variability than temperature. The aim of this research is to improve scientific understanding of current precipitation patterns and their effects on the icecap in order to fully resolve this record. A meteorological station installed at 5,650 m in 2014, near the summit of the Icecap, provides meteorological data including snow depth, liquid equivalent precipitation, precipitation type and intensity, and wind speed and direction. NOAA's HYSPLIT Model was used to run 72-hour backward air trajectories for each precipitation event using GDAS data with half-degree resolution. Isotopic and chemical analysis was performed on the 2016 snowpack yielding stable oxygen isotope ratios and trace element concentrations. The isotopes were used to date the snowpack, and the resulting age model was compared to isotopic measurements from citizen scientists. Trace elements were used make general inferences about regional processes.

Keywords: Andes, Quelccaya Icecap, Climate-Glacier Interactions, Isotopes

## Introduction

The glaciers of the Central Andes of Peru serve as a water resource for rural communities as well as large population centers by providing water for agricultural irrigation, hydropower, economic activities such as mining, as well as acting as a buffer that releases water during the pronounced dry season (Drenkhan *et al.* 2014). In addition, the relatively small area of the glaciers and their respective position near the freezing level make them very sensitive to small changes in climate. The Quelccaya Icecap in southern Peru is the largest glacier in the tropics, provides a well-preserved timeline of annual layers in the ice, and is one of the most important records of past climates in the tropics (Thompson *et al.* 2013). However, considerable uncertainty remains surrounding the interpretation of this record (Seimon *et al.* 2003). Some of this uncertainty stems from an incomplete understanding of precipitation delivery patterns in the region (Perry *et al*. 2014, Hurley *et al*. 2015). There are also questions surrounding the interpretation of the stable oxygen isotope ratios (Birkos 2009, Vimeux *et al.* 2009). The purpose of this paper is to investigate the relationships between the atmospheric circulation associated with precipitation occurrences and the trace element and stable oxygen isotope records preserved in annual snow pits. A combination of model trajectories, in situ measurements from snow pits and a meteorological station on the Quelccaya Icecap, and citizen science observations from the surrounding area are used to gain a better understanding of the connections between the regional synoptic patterns and snowpack composition. A complete understanding of these relationships is critical for the interpretation of the paleoclimatic record contained in the annual layers of the Quelccaya Icecap.

## Literature Synthesis

### Site Significance

The Quelccaya Icecap contains one of the most important climatic records in the tropics due to its high elevation and relatively flat summit that allow for the preservation of annually resolved ice layers dating back approximately 1,800 years (Thompson *et al.* 2013) (Fig. 1). This record has been used to study key climatic events such as abrupt changes in climate and the Little Ice Age through the analysis of layer characteristics such as stable oxygen isotope ratios and dust concentrations (Thompson *et al.* 1986 & 2006). However, there is evidence that such methods could be refined in future studies using historic dust-producing events such as earthquakes that leave a depositional signature on Quelccaya (Seimon 2003).

The distinct wet and dry seasons are the dominant form of intra-annual climate variability in the Central Andes of Peru, which has made precipitation a constant consideration when analyzing the ice core record of Quelccaya (Thompson *et al.* 1985). However, debate remains surrounding the interpretation of the stable oxygen isotope ratios, with some initially suggesting that these values were a record of past temperature as opposed to precipitation (Thompson *et al.* 1985; Melice & Roucou 1998). A review of studies examining these ratios in older ice layers have found it difficult to determine a single dominant control over isotope ratios, and it seems clear that a simple temperature relationship does not fit well (Vimeux *et al.*

2009). The authors suggest that precipitation is likely a more dominant control, but that there is no single, dominant control. It is important to establish a better understanding of the isotope ratio record before using it as an indicator of paleoclimates. The El Niño/Southern Oscillation (ENSO) is a major control of inter-annual variability and glacier behavior in the region (Francou *et al* 2003). As such, it is an ever-present consideration when studying climate in relation to tropical glaciers, and there is evidence to suggest that Quelccaya ice cores contain a valuable record of ENSO events (Thompson *et al*. 1984).

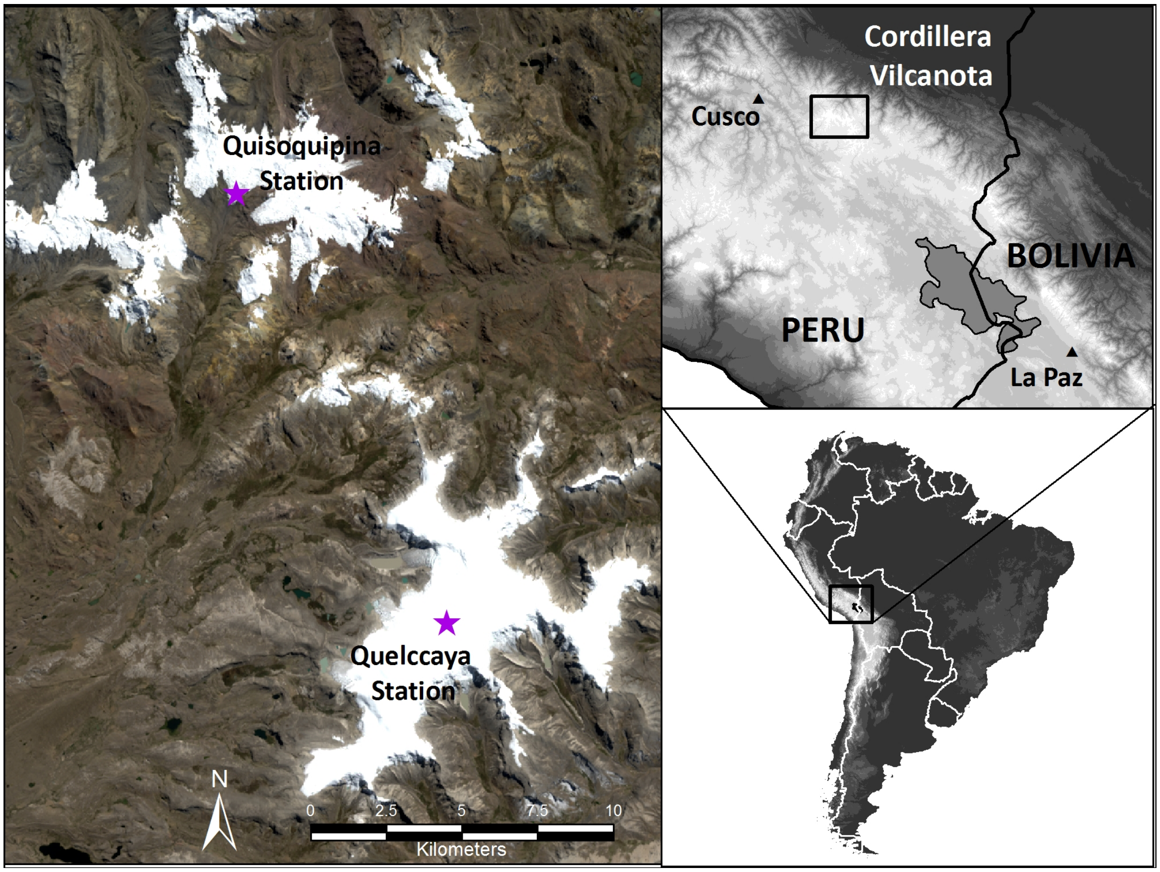


*Figure 1. Study area – Quelccaya Icecap in the Cordillera Vilcanota of Peru*

## Regional Patterns

Despite the promising records contained in the Quelccaya ice cores, there is still a great deal of work to be done before these records are completely understood. Much of this uncertainty stems from an incomplete understanding of the region's meteorology and climatology due to limited study and data scarcity (Perry *et al*. 2017). Many of the climatic studies focus on climate-glacier interactions. Salzmann *et al.* (2013) found that there has been only a moderate increase in temperature and no significant trends in precipitation totals since 1985 when rapid deglaciation began in the Cordillera Vilcanota. Their conclusion was that an increase in specific humidity was a major cause of the observed loss. A similar pattern was observed to the south in Bolivia, where the Chacaltaya glacier retreated rapidly due to increased humidity and a later onset of the wet season, which leaves bare ice exposed to the high tropical sun (Francou *et al*. 2003).

Studies focused on regional atmospheric circulation have shown that easterly winds transport moisture to the region during the wet season in conjunction with the intensification and southward displacement of the Bolivian High, whereas in the dry season, westerly winds prevent moisture transport and inhibit precipitation (Garreaud 1999 & Vuille 1999). An examination of convection patterns in the Central Andes using rain gauge and satellite data showed that precipitation variability in the region is not spatially coherent (Vuille 2004). However, Perry *et al.* (2014) found evidence of regional coherence of precipitation variability in the smaller area of the Cordillera Vilcanota, though this study focused mainly on nighttime stratiform precipitation. In addition, trajectory analysis using NOAA's HYSPLIT model showed that a majority of air masses resulting in precipitation followed a northwesterly trajectory and originated in the Amazon Basin. The regional coherence found in this study would suggest that similar mechanisms result in precipitation at Quelccaya, which is also located in the Cordillera Vilcanota, however Hurley *et al*. (2015) suggest that most snowfall on Quelccaya is associated with convection on the leading edge of cold air incursions originating in southern South America.

## Isotopes and Trace Element Analysis

In Antarctica and other polar regions, there is a strong temperature-isotope relationship (Jouzel *et al.* 2003). However, as noted previously, this relationship weakens considerably in lower latitudes, where a stronger connection can be found between isotopes and precipitation amount (Dansgaard 1964). In addition, the pronounced wet and dry seasons mean that the record contained in the snowpack and ice layers is primarily a representation of wet season conditions and precipitation events (Hardy *et al.* 2003). While Hardy *et al*. (2003) point out the importance of understanding the potential impacts of post-depositional processes on the chemistry of the snowpack due to the long dry season, Bonnaveira (2004) found that the effects of such processes were fairly small at their study site on Illimani to the southeast of Quelccaya. However, Ginot *et* al. (2001) encountered more significant post-depositional effects at Cerro Tapado in northern Chile. Volatile compounds were released from the snow surface, while others that were trapped in the snowpack became enriched. Geographically, Quelccaya is more similar to Illimani, as it is in the tropics and positioned relatively close to the Amazon. Cerro Tapado is significantly further south in the subtropics. Based on the premise that the isotope profile is primarily the result of precipitation during the wet season, Hurley *et al.* (2015) were able to create an age model of the annual snowpack using positive changes in snow height after the seasonal minimum and the isotope profile from a snow pit. This allows the snowpack to be conservatively dated and compared to meteorological observations.

Other types of chemical analysis, such as trace element and ion concentrations, provide evidence of where precipitation originated instead of the amount of precipitation produced. This analysis has been performed in the higher latitudes, where sodium records were used to examine the frequency of marine air mass incursions (Mayewski *et al*. 2017). In central West Antarctica, Reusch *et al*. (1999) used similar analysis methods to assess the spatial variability in chemical compositions. The results provided insights into possible shifts in meteorology at the synoptic-scale as well as finer scales. In the region of interest, chemical analysis was performed on snow pits from the annual accumulation of 1982 on the Quelccaya Icecap (Lyons *et al*. 1985). Based on patterns of coincident iron, silicate, sodium, and microparticles, the authors determined that there was likely a local source of crustal weathering that resulted in higher concentrations during the dry season and lower concentrations in the wet season. In addition, sulfate and nitrate fluctuations were believed to be the result of either seasonal cycles of biological input or seasonal shifts in winds in relation to the Amazon Basin. Sulfate values also indicated that the north and west of the Amazon basin were likely influential source regions for precipitation. However, the authors presented several questions surrounding the proper methods for analyzing glacier water samples for chemistry and pointed out the need for future glaciochemical studies to understand the paleoclimatic record.

## Data and Methods

### Meteorological Station Data

An automated meteorological station installed by a team from Appalachian State University in October of 2014 near the summit of the Quelccaya Icecap at 5,650 m records hourly variables including temperature, relative humidity, and wind speed and direction (Table 1) (Fig. 2). In addition, a snow height sensor, weighing precipitation gauge, and present weather sensor allow for comprehensive precipitation monitoring. Hourly snow height measurements provide seasonal and event accumulation data in addition to recording the timing of ablation. The weighing precipitation gauge records hourly liquid equivalent precipitation, which provides more detail for precipitation event characteristics and allows for more accurate snow density calculations. In addition, the precipitation gauge is surrounded by a double Alter-shield. The type of wind shield in place has been shown to be the most important factor in solid precipitation measurement accuracy, and the double Alter-shield performs better than single Alter-shields (Rasmussen *et al.* 2012). However, these data are not available for the entire 2014-2015 period. The present weather sensor makes hourly observations of precipitation type, phase and intensity. This data gives both overall characteristics of precipitation at Quelccaya as well as temporal changes in precipitation characteristics within events.

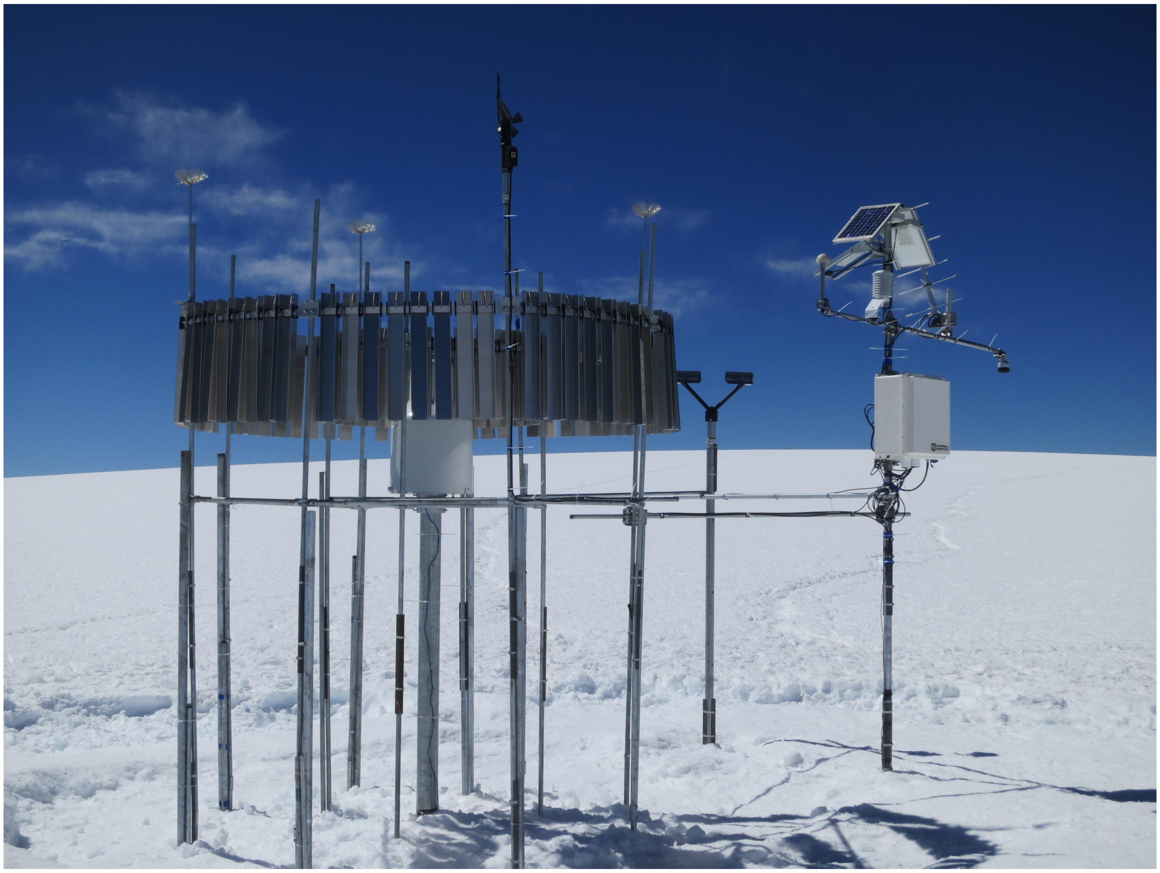


*Figure 2. Meteorological station near the summit of Quelccaya at 5,650 m*

## Snow Pit Sampling

In July of 2016, a team from Appalachian State University dug a snow pit on the Quelccaya Icecap to the bottom of the annual layer, which was found at a depth of 1.26 m. One wall was shaded to prevent melt and scraped clean to remove contamination from shoveling. Snow samples were collected at approximately 2 cm intervals in separate vials and allowed to melt. These samples were analyzed for trace element concentrations at the University of Maine. The same pit was also cored for stable oxygen isotope ratios. The cores were then separated into samples of approximately 12.566 g, which after melting resulted in aliquots of 10 mm liquid water equivalent. Various ablation periods throughout the wet season likely affected the clarity of these signals (Fig. 3). However, the data are potentially valuable, as they represent the 2015-2016 wet season, which was a strong El Niño event.

## Citizen Science Observations

Appalachian State University contracts citizen science observers at various sites in the Cordillera Vilcanota, including at the base of Quelccaya. All observation stations are located at over 4,000 m. The observers use a precipitation gauge to take daily precipitation measurements of liquid water equivalent at approximately 1200 UTC. These measurements are taken by a trained observer using citizen science precipitation observation and snowfall measurement protocols (Cifelli *et al*. 2005; Doesken and Judson 1998). In addition, liquid samples from the precipitation events are collected in vials and later analyzed for stable oxygen isotope ratios.

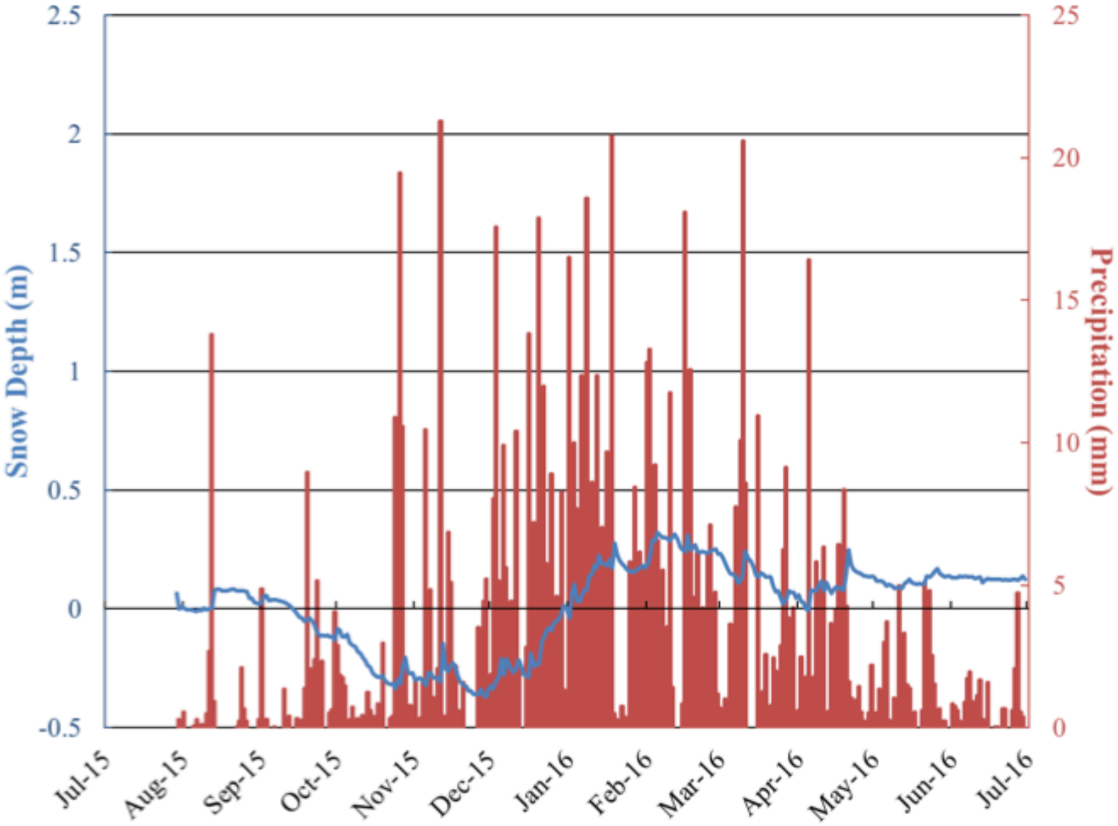


*Figure 3. Snow accumulation and liquid equivalent precipitation for 2015-2016.*

## Age Model

In order to date the snow pit profile, an age model was created using the stable oxygen isotope ratios from the core mentioned previously. The age model method of Hurley *et al.* (2016) was recreated using each positive 24-hour snow height change after the seasonal snow height minimum to assign dates to the isotope profile. The study presented here has the added benefit of liquid equivalent precipitation data from a weighing precipitation gauge. A similar methodology was used to create a separate age model using hourly precipitation, which eliminates the assumption of constant density in age model calculations. Both age models were referenced to the date of minimum snow height (29 November 2015).

### Trajectory Analysis

Backward air trajectories were run with four-dimensional (x, y, z, t) Global Data Assimilation System (GDAS) 0.5° data using the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) Model for each precipitation event (Draxler & Rolph 2015). Events were identified by measurements from the weighing precipitation gauge and present weather sensor and were considered to be over after three hours without precipitation. The next hour of precipitation began a new event. This analysis uses the methods of Perry *et al.* (2014). However, this study uses three hours without precipitation as a break instead of the six hours used by Perry *et al.* Quelccaya experiences more hours of precipitation than Cusco, Peru, which was the site of the previous study. Using six hours as a break resulted in very long precipitation events. The goal of using shorter breaks is to separate long events into shorter ones with more uniform characteristics.

The starting time of each backward trajectory was the hour of the greatest precipitation (maturation hour), which was weighted towards the middle of the event if multiple hours had the same precipitation total. Each trajectory was given an ending height of 6,000 m. The cluster analysis tool from the HYSPLIT Model was used to create average trajectories from individual event trajectories. The number of average trajectories was chosen by selecting the lowest number of average trajectories that minimized the total spatial variance within all of the clusters.

| Data | Resolution | Period | Source |
|---|---|---|---|
| Precipitation Type | 1-hr | 2014-2016 | Parsivel Disdrometer |
| Temperature | 1-hr | 2014-2016 | Precipitation Monitoring Station |
| Relative Humidity | 1-hr | 2014-2016 | Precipitation Monitoring Station |
| Wind Speed & Direction | 1-hr | 2014-2016 | Precipitation Monitoring Station |
| Liquid Equivalent Precipitation | 1-hr | 2014-2016 | Pluvio$^2$ Weighing Gauge |
| Reanalysis Time Series | 6-hr | 2014-2016 | ERA-Interim Reanalysis |
| Backward Air Trajectories | 1-hr | 2014-2016 | GDAS 0.5° Data & HYSPLIT Model |
| Trace Element Samples | ~2 cm | 2015-2016 | Quelccaya Snow pit |
| Oxygen Isotope Ratios | ~10 mm LWE | 2015-2016 | Quelccaya Snow pit |
| Oxygen Isotope Ratios | 1 per event | 2014-2016 | Citizen Science Observers<br>Quelccaya Base (4,950 m)<br>Murmurani Alto (5,050 m) |
| Wind Direction | - | November 2014 | Radiosonde Observations |

*Table 1. Summary of Data Sources*

## Results

### Trajectory Analysis

Trajectory analysis was performed for all precipitation events recorded on Quelccaya during the period of 2014-2016. Average trajectories for both 2014-2015 and 2015-2016 show a dominance of events with moisture coming from the northwest (Fig. 4). However, there are noticeable differences between the two accumulation seasons. The largest average trajectory from 2015-2016, which contains the most individual trajectories, has a more westerly influence and

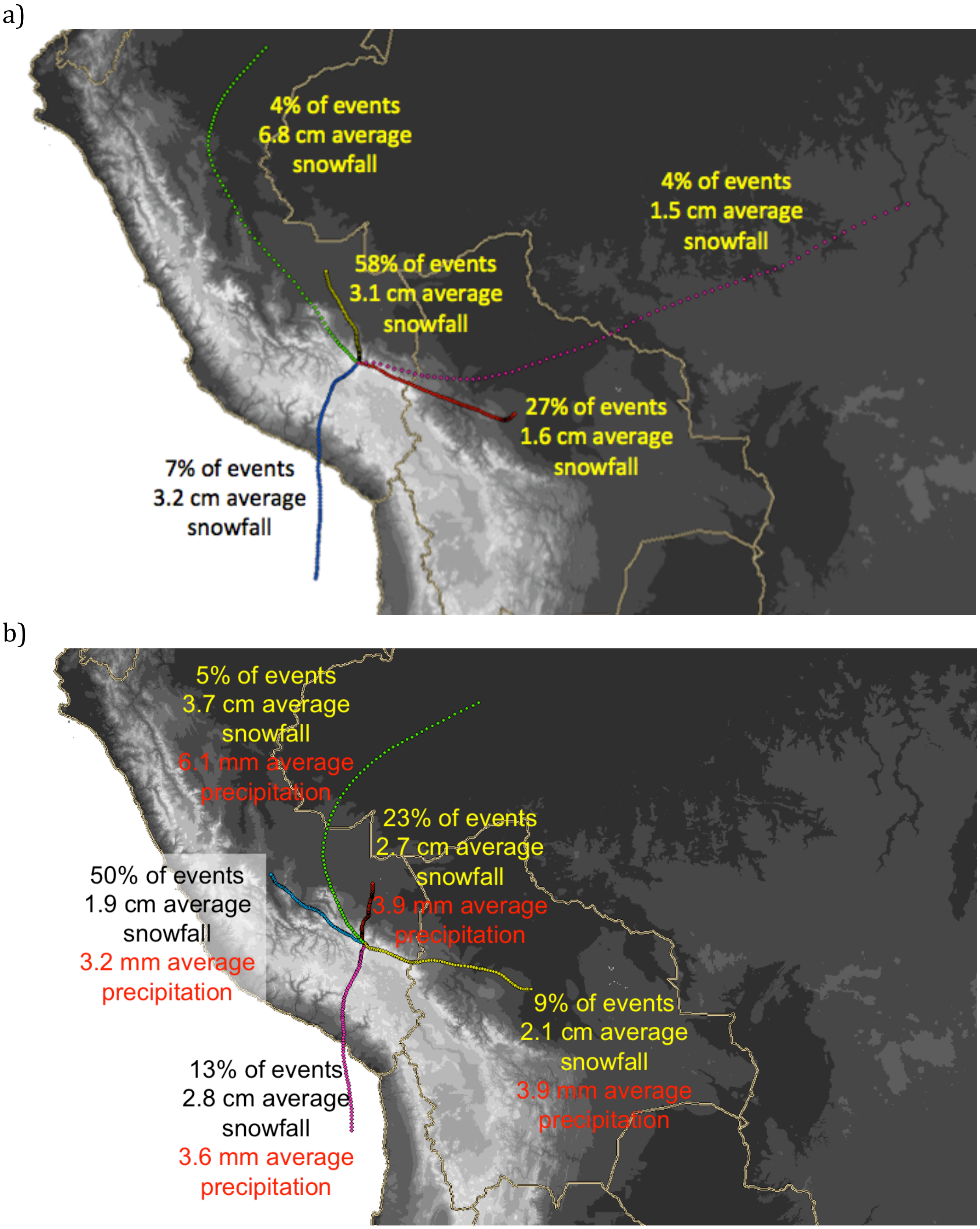


*Figure 4. a) Average trajectories for 2014-2015 with average snowfall. b) Average trajectories for 2015-2016 with average snowfall and liquid equivalent precipitation.*

| Year | Cluster | Number of Events (% of events) | Average Snowfall (cm) | Average Precipitation (mm) |
|---|---|---|---|---|
| 2014-2015 | 1 | 62 (58%) | 3.1 | - |
| 2014-2015 | 2 | 29 (27%) | 1.6 | - |
| 2014-2015 | 3 | 8 (7%) | 3.2 | - |
| 2014-2015 | 4 | 4 (4%) | 6.8 | - |
| 2014-2015 | 5 | 4 (4%) | 1.5 | - |
| 2015-2016 | 1 | 111 (50%) | 1.9 | 3.2 |
| 2015-2016 | 2 | 51 (23%) | 2.7 | 3.9 |
| 2015-2016 | 3 | 29 (13%) | 2.8 | 3.6 |
| 2015-2016 | 4 | 20 (9%) | 2.1 | 3.9 |
| 2015-2016 | 5 | 12 (5%) | 3.7 | 6.1 |

*Table 2. Summary statistics of clustered average trajectories*

travels along the boundary between the Andes and the Amazon Basin, while the dominant average trajectory from 2014-2015 is more northerly and originates from farther into the Amazon Basin. 2014-2015 also has a considerable number of events with moisture originating from the Amazon Basin in the east. The differences in average snow water equivalent between trajectories during 2015-2016 are minimal, however, this relationship is unknown for the 2014-2015 wet season due to the lack of liquid equivalent precipitation measurements.

The average trajectories from 2015-2016 show an increased westerly flow when compared to 2014-2015. In addition to a more westerly influence in the largest average trajectory, there is an absence of the southeasterly trajectories that made up 27% of events in 2014-2015. This is likely associated with the strong El Niño that occurred during 2015-2016, whereas 2014-2015 was a more neutral phase. The enhanced westerly flow associated with these events suppressed moisture transport from the Amazon basin. This is apparent in the lower average snowfall for the largest average trajectory. It is also a possible contributor to the ablation periods during the wet season and relatively low accumulation totals measured at Quelccaya.

## Meteorological Event Characteristics

Analysis of meteorological data from the summit of Quelccaya during precipitation events reveals several important details about the general characteristics of these events. An examination of the timing of precipitation events reveals a clear maximum in the afternoon (Fig. 5b). Again, the pattern is similar for the top decile of the heaviest events, but nighttime events are more common for the heavier events than for all precipitation events combined. It appears that daytime events, which are inferred to be convective in nature, are more common at Quelccaya than in other parts of the Cordillera Vilcanota, where studies have shown that nighttime events, which are inferred to be stratiform, are more important to precipitation totals (Perry *et al.* 2014). This increase in the importance of local convection may be due to the higher elevation of Quelccaya as opposed to lower elevation sites such as Cusco that were analyzed in the study. However, Figure 5a shows that nighttime precipitation is relatively more prominent when examining all hours instead of only maturation hour. This supports the idea that nighttime events are longer-lived and likely stratiform.

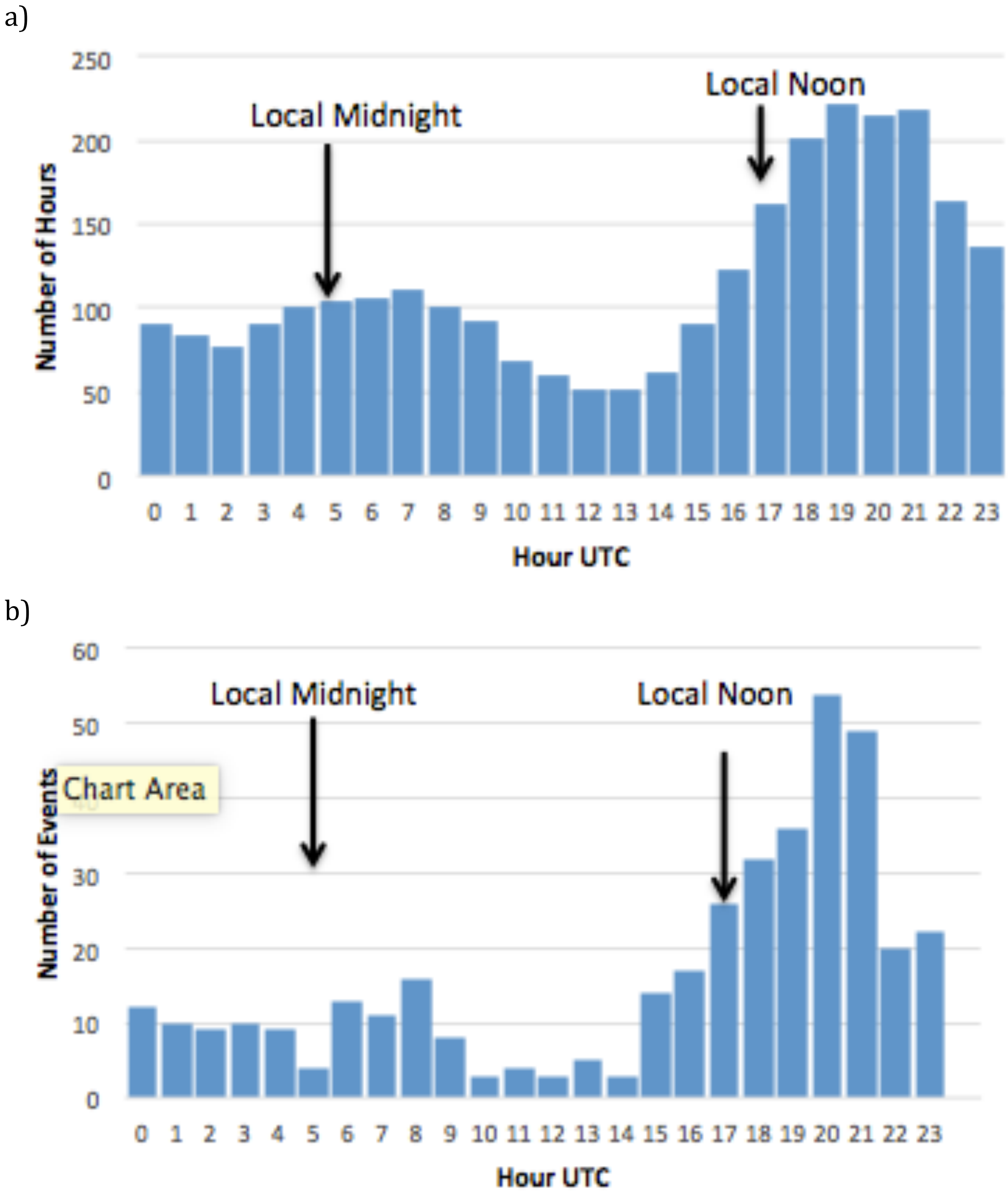


*Figure 5. a) Timing of all hours of precipitation b) Timing of event maturation hour 2014-2016.*

Analysis of wind direction measurements from near the summit of Quelccaya reveals several interesting patterns (Fig. 6). Over the entire study period, there were maxima from the northwest and southeast, with the southeasterly maximum

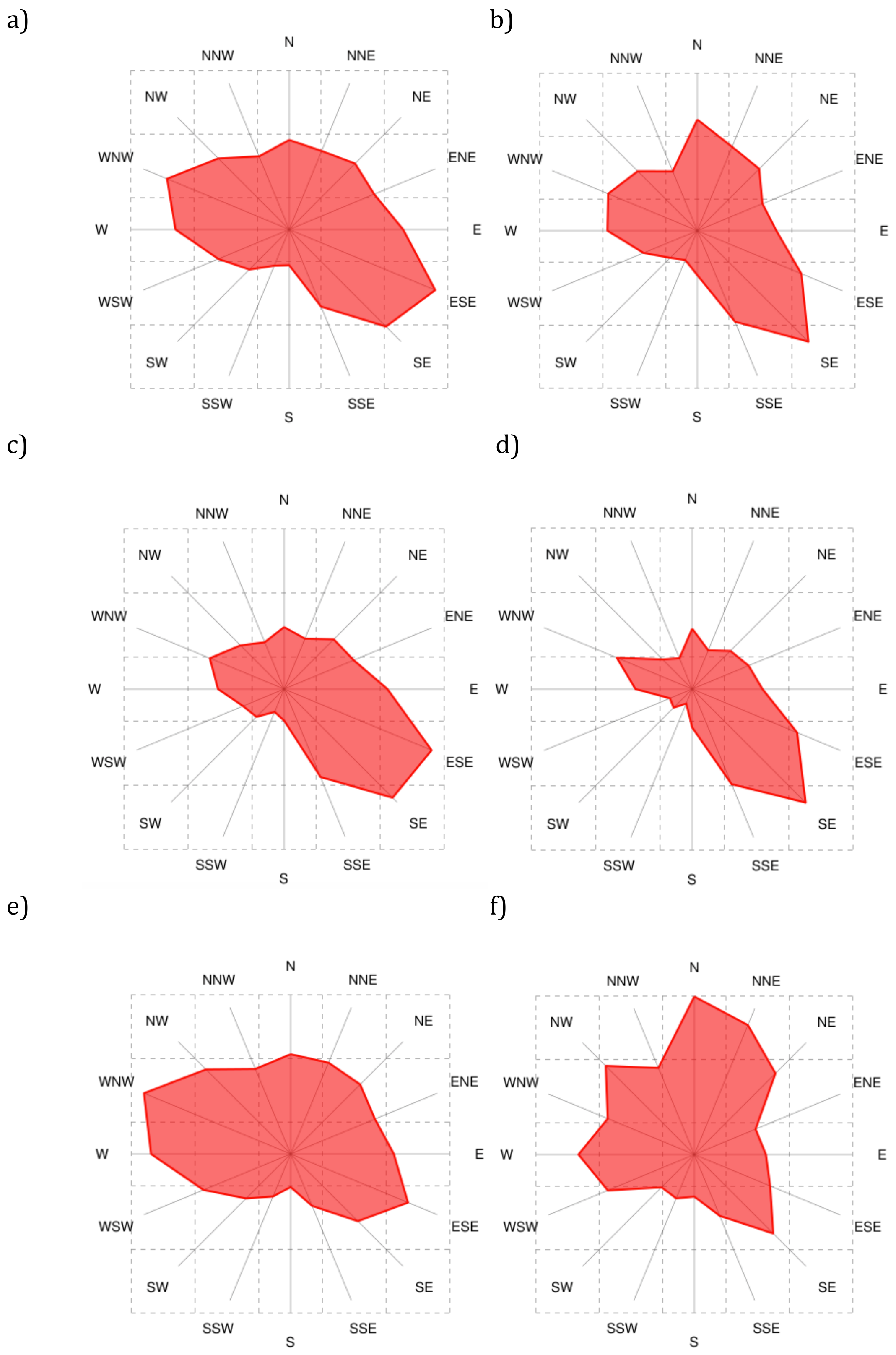


*Figure 6. Wind direction for a) all hours 2014-2016 b) precipitation hours 2014-2016 c) all hours 2014-2015 d) precipitation hours 2014-2015 e) all hours 2015-2016 f) precipitation hours 2015-2016*

more prominent during hours with precipitation. However, when the years are examined individually, it is clear that there are considerable differences between 2014-2015 and 2015-2016. 2014-2015 shows a dominance of southeasterly wind during hours with and without precipitation. The patterns during 2015-2016 show a general dominance of northwesterly wind over the entire study period, but precipitation hours have more evenly distributed wind directions with a maximum from the north-northeast and lesser maxima from the northwest and southeast. These results show that there was indeed an overall shift to more westerly winds during the 2015-2016 El Niño event as has been suggested previously.

Table 3 shows a comparison between wind direction measurements from the summit of Quelccaya (~500 hPa), sounding observations from multiple radiosonde launches, and ERA-Interim Reanalysis data for the Quelccaya grid cell. Overall, reanalysis data are consistent with the sounding data, which show generally good agreement in the region. In addition, the meteorological station data from Quelccaya correspond relatively well with both data sources, which indicates that measurements taken at the summit are generally representative of the wind patterns in the surrounding area.

| Sounding Date and Time (UTC) | Pressure Level (hPa) | ERA Interim Wind Direction (°) | Sounding Wind Direction (°) | Station Wind Direction (°) |
|---|---|---|---|---|
| 04 November 2014 1200 | 200 | 274 | 281 | - |
| | 300 | 149 | 144 | - |
| | 500 | 135 | 110 | 138 |
| 04 November 2014 1800 | 200 | 295 | 263 | - |
| | 300 | 144 | 144 | - |
| | 500 | 147 | 110 | 102 |
| 05 November 2014 0000 | 200 | 319 | 310 | - |
| | 300 | 135 | 123 | - |
| | 500 | 153 | 131 | 139 |
| 06 November 2014 0000 | 200 | 208 | 16 | - |
| | 300 | 122 | 108 | - |
| | 500 | 125 | 108 | 134 |
| 06 November 2014 1200 | 200 | 181 | 66 | - |
| | 300 | 108 | 99 | - |
| | 500 | 89 | 76 | 117 |
| 07 November 2014 2100* | 200 | 149 | 145 | - |
| | 300 | 67 | 87 | - |
| | 500 | 93 | 100 | 85 |

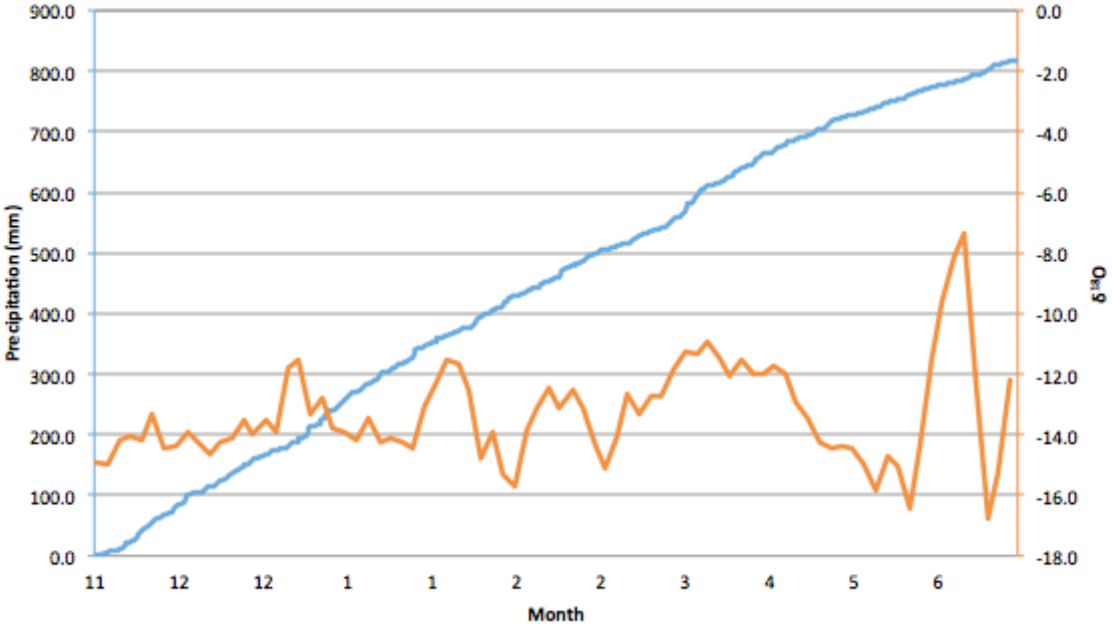
*Table 3. Wind direction measurements from radiosondes, the Quelccaya station, and ERA-Interim Reanalysis data*
**1800 UTC had to be used instead of 2100 UTC*

## Age Model and Isotope Analysis

Using the methods of Hurley *et al.* (2015), an age model of the Quelccaya snowpack from 2015-2016 was created with both snow height change (Fig. 7b) and liquid equivalent precipitation (Fig. 7a). Isotope values were assigned to the period between minimum snow height (29 November 2015) and the date of sampling (17 July 2016).

The later parts of the age model match up well with the idea presented by Birkos (2009) that $\delta^{18}O$ values become increasingly depleted as an event progresses. This is due to the tendency of the heavier oxygen isotopes to precipitate earlier in the event, leaving more depleted precipitation later in the event. This phenomenon is apparent in June in Figure 7b. A sharp increase in snow height, signifying a strong event, coincides with a sharp decline in δ$^{18}$O values that is likely the result of depletion over the course of the event. A similar occurrence can be seen during May and possibly as far back as the beginning of February. However, it seems that such events do not match up as well further back in the age model. As noted previously, there were periods of significant ablation in the time span of the age model. This certainly affected isotope values in the snow pit, and a general smoothing of the data points can be seen progressively deeper in the pit and earlier in the age model. As a result, confidence in the age model is lower for the earlier periods.

a)



b)

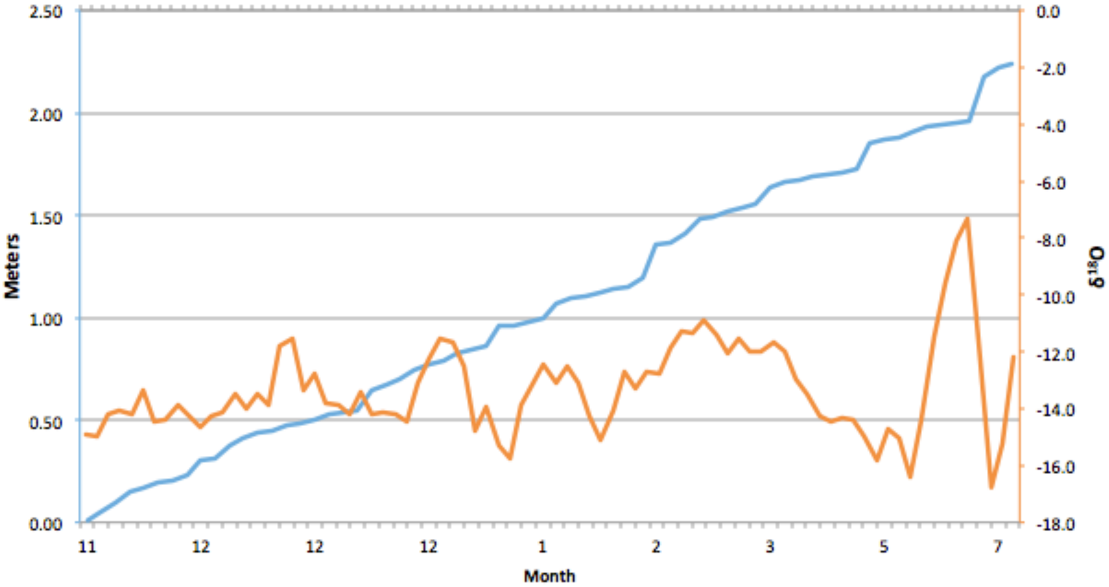
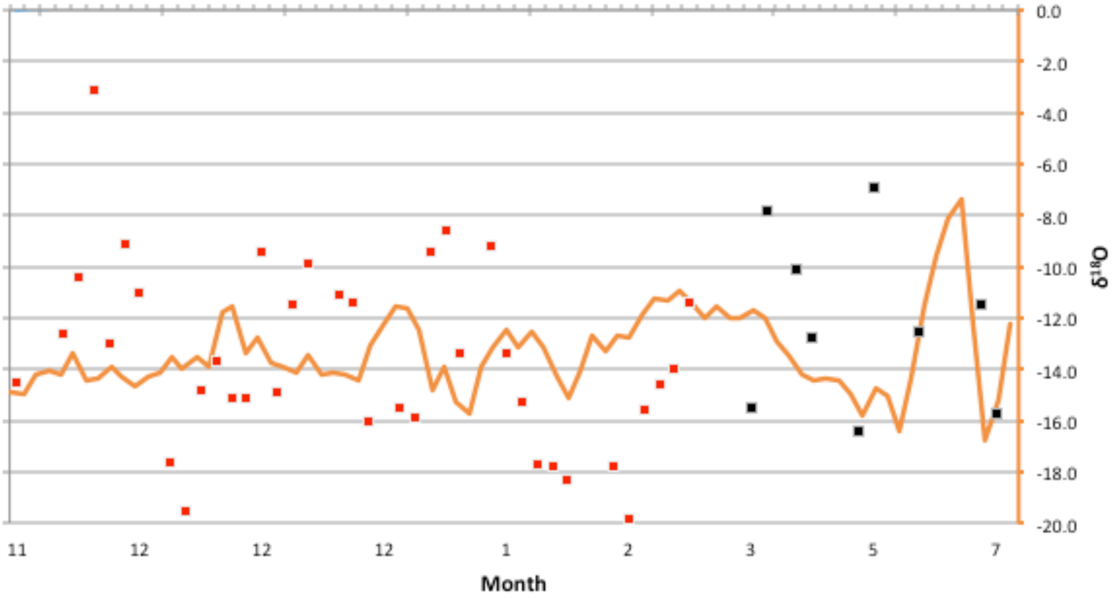


*Figure 7. a) Isotope age model using hourly liquid equivalent precipitation. b) Isotope age model using cumulative snow height change.*

a)



b)

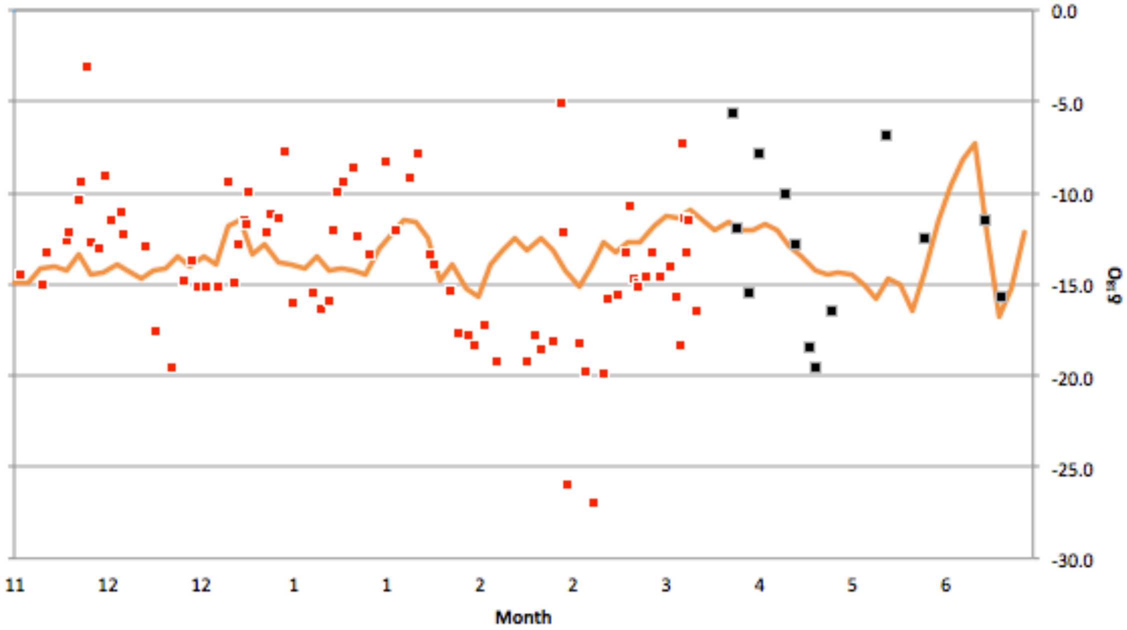


*Figure 8. a) Snow height isotope age model with citizen science observations from Murmurani Alto (red) and the base of Quelccaya (black) b) Liquid equivalent precipitation age model with citizen science observations*

One method of assessing the age model is to compare the isotope values from the snow pit to those measured by citizen science observers on known dates (Fig. 8). Observations from the base of Quelccaya are available from the beginning of April until the collection date. Observations from Murmurani Alto, near Laguna Sibinacocha, are available from the beginning of the age model until the end of March, providing almost complete coverage of the period. The model fits well with the observations closest to the collection date from the base of Quelccaya, though there are a few points of departure that may be the result of ambiguities in the observations. Due to the proximity of the sites, the observed differences are likely caused in large part by the difference in elevation. Orographic effects have considerable influence over precipitation amounts, which could result in some of the observed difference.  The quality of the fit decreases in the earlier parts of the age model.  Though there was almost certainly some smoothing of the isotope data, some of the observed differences in this part of the model may also be due to the larger distance between the snow pit and citizen science observation site.

The liquid equivalent precipitation model allows for more matches with citizen science observations, as there are more dates included in the model. Precipitation occurred on days that did not register a positive snow height change. The increased matching potential is an advantage, though it is unclear if the smaller hourly precipitation signals are recorded in the snowpack or isotope record.

## Trace Element Analysis

The depleted snowpack resulted in low confidence in the age model.  This makes detailed analysis of the chemical record difficult, as dates cannot be confidently assigned to trace element values.  It is also important to note that the same ablation that likely impacted the isotope record would have also affected the trace element record.  However, empirical orthogonal function (EOF) analysis reveals a peak in crustal elements at around 20 cm deep in the snowpack (Fig. 9). This is interpreted as a classic dust signal and is likely associated with a dry period, similar to the findings of Lyons *et al.* (1985).

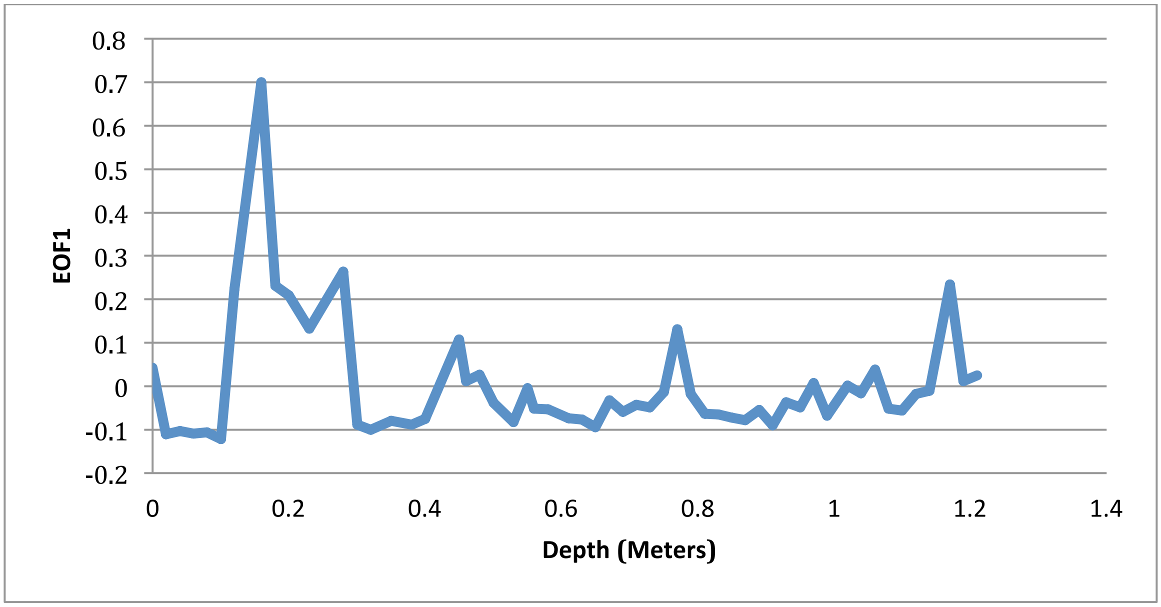


*Figure 9. Percentage of variance explained by EOF1 elements*

## Conclusions

Trajectory analysis reveals a dominance of northwest flow in moisture transport to Quelccaya. This pattern seems to generally remain in place regardless of the ENSO phase. However, the 2015-2016 El Niño event caused small shifts that resulted in significant suppression of moisture transport from the Amazon Basin and. The largest trajectory was farther west, and there was a decrease in the number of events with moisture from farther east in the Amazon Basin. The result was low accumulation during the wet season at the summit.

The general event characteristics measured near the summit of Quelccaya suggest a dominance of daytime convective events. This is a departure from other parts of the region that receive much of their precipitation totals overnight from stratiform events. However, it does appear that nighttime events are relatively more productive. The differences between Quelccaya and other locations in the region may result from the elevation difference between the study sites.

Wind direction measurements show considerable interannual variability between flow patterns at Quelccaya, and it is likely that these differences are due at least in part to the ENSO phase. However, further study is needed to investigate the linkages between winds at Quelccaya, moisture transport to the area, and how this relationship is affected by different ENSO phases.

The age model created for the 2015-2016 snow pit performed well for the later parts of the period, as it matched up well with observed values. However, performance declined farther back in time. This was likely due in part to the ablation that occurred at various times throughout the model period. However, it is possible that future strong El Niño events will produce similar conditions, and past events may have had similar conditions as well. Therefore, it is important to attempt to understand the snowpack during these years, as they will be critical for interpreting the ENSO record contained in the annual layers of the Quelccaya Icecap. In addition, similar studies performed during neutral phase and la Niña years will provide valuable insight into how circulation changes with phase and what impacts this has on the glacier.

A better-preserved snowpack will allow for more detailed trace element analysis, which could be used to compare EOF dust signals to precipitation measurements. By combining chemical and isotopic analysis, it will be possible to interpret the atmospheric patterns that affect Quelccaya during both wet and dry periods.

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