Senior Thesis

An Analysis of Microparticle Size Distributions and Relationships with Slope and Particle Coarseness Factors

by

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Approved by:

Dr. Lonnie G. Thompson
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ABSTRACT:

The major focus of this study is to investigate the relationship between the distribution of microparticle size with seasonal fluctuations over short and long term periods in the southern Andes of Peru, as well as to determine if a change in slope and coarseness factors can be associated with the last major change in climate "The Little Ice Age." Microparticle size distribution data, slope and coarseness factors were calculated from microparticle concentration data obtained from ice core samples taken from the summit dome of the Quelccaya Ice Cap, located along the easternmost edge of the Peruvian Andes.

From this study it was concluded that significant changes occur in slope values and coarseness factors associated with the last major climatic change "The Little Ice Age." The size distribution of microparticles indicated by slope values suggests a higher percentages of large particles relative to small particles were deposited during the Little Ice Age. This is most likely due to greater wind speeds during the Little Ice Age period. A direct relationship is established between decadal microparticle size distributions and calculated slope values. Generally, higher negative slope values indicate a steepening of the microparticle size distribution, related to a higher percentage of small particles being deposited. This seasonal fluctuation (wet and dry) in microparticle size distributions can be attributed to seasonal changes in regional circulation, precipitation, and atmospheric radiation levels effecting mass loss.
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INTRODUCTION:

The analysis of microparticle size distributions taken from ice cores of tropical ice fields located in the southern Andes of Peru may be utilized in the reconstruction of the climatic history of tropical South America. The major focus of this study is to investigate the relationships between the distribution in microparticle size with climatic fluctuations over both short and long term periods in the southern Andes of Peru. The area of study is located along the easternmost edge of the Peruvian Andes upon the Quelccaya Ice Cap, (lat. 13°56'S, long. 70°50'W). The Quelccaya Ice Cap is elongated in shape ranging from 3-5 km in width (east to west) and 11 km in length (north to south), covering an area of 55 km², with an elevation of 5,670 m. The Quelccaya Ice Cap is considered a unique tropical glacier primarily due to it's being the highest object in the immediate vicinity as well as local disturbances of both depositional stratigraphy and radiation balance are minimized, (Thompson et al, 1984). This particular tropical ice field provides the in-situ into past climatic conditions of the surrounding tropical region that otherwise may have not been obtainable, due to virtually nonexistents of other climate records. This geographical region of the uplands is divided into two contrasting physical regions. To the west there is the Cordillera Occidental O De La Costa of the western Andes, where the broad peaks rise over 6100 m. On the eastern range of the Andes there is the Cordillera Oriental, where the peaks display slightly lower elevations (5600 m). In between the western and eastern ranges is an extensive highlands referred to as the altiplano, ranging in elevation from 3000 m to 4000 m. From various weather stations around this region we find that the average annual precipitation tends to be rather low. Precipitation records from Cuzco, Peru, at an elevation of 3,312 m, show an annual precipitation average of 750 mm. Records from Huancayo, Peru at an elevation of 3,380 m indicate a yearly average of 724 mm of precipitation, and at La Paz, Bolivia at an
elevation of 4,105 m, the annual average precipitation is 564 mm. (Johnson, 1976). The majority of rainfall occurs during the high sun period (summer season) between November and March. Due to the effects of anabatic winds causing a convergence of warm and cool air, the creation of afternoon showers and thunderstorms are generally very common during the summer season. During the remaining seven months, precipitation drastically declines to only a few millimeters (2-8 mm) in the localities of Cuzco, Huancayo, and La Paz during the driest months of June and July.

In the Southern Peruvian highlands there is a more noticeable seasonal fluctuation in the mean wind speed than is found at lower elevations and in the northern Andes. A change in mean wind direction is also more noticeable from season to season in this region. Wind speeds tend to be greater during the dry season, averaging 4-5 knots in a dominant northwest flow direction. Whereas, during the wet season from November through March, the predominant direction of wind flow is south-southeast at an average speed of 3-4 knots. Channeling of winds due to numerous east-west valleys may play some role in regional wind variations at lower levels, obscuring seasonal windflow patterns from northwest to southeast, indicating a more easterly dominance in annual averages. However, due to the locality of the Quelccaya Ice Cap and its relative elevation to the surrounding topography there is an excellent representation of the regional climatic conditions. Radiosonde data taken from the Lima weather station of the mid-troposphere, indicate very similar seasonal changes in mean wind direction as found upon the Peruvian highlands. An east-southeast air stream flow was observed during the wet season, diverging towards a northwest air stream flow in the dry season.

From previous studies, interpretations of wet and dry seasonal fluctuations have been established through the analysis of shallow pit and ice core samples, (Thompson, 1980). It has been determined that there is a much higher concentration of
microparticles being deposited upon the Quelccaya Ice Cap during the dryer winter months (May - August), whereas generally there is a much lower concentration of microparticles deposited during the wet summer months (November - March).

The initial objective in this study was to determine if a fluctuation in microparticle size distribution could be affiliated with the short term seasonal variation in precipitation between wet and dry periods in the Peruvian highlands. The second objective is to determine if there is a change in microparticle size distributions, or changes in slope values and coarseness factors associated with El Niño events. The final objective was to determine if there is a change in slope and coarseness factors associated with the last major change in climate, "The Little Ice Age."
METHODS OF ANALYSIS:

The microparticle data used in this study was obtained from firn and ice core samples retrieved from a 154m ice core drilled on the Summit (5670m) of the Quelccaya Ice Cap in 1983 by L.G. Thompson. This particular ice core which was analyzed in this study was drilled during the final year of a multi-year glaciological investigation of the Quelccaya Ice Cap. The main objective of this program was to obtain a long ice core, from which the reconstruction of a past climatic record for tropical South America could be interpreted from analysis of microparticles, oxygen isotopes, and total Beta radioactivity. The summit core was chosen in this study primarily due to its location. Weather conditions on the summit dome are similar to those on the plateau above 5400 m. Insignificant amounts of ablation occur on the summit with a net balance approximately equaling accumulation (Thompson and others 1979).

The examination of the ice core was conducted in a class 100 Clean Room microparticle laboratory at the Ohio State University and the Geophysical Isotope Laboratory in Denmark. The microparticle concentration data used to calculate microparticle size distribution profiles, were analyzed from melted ice core samples which were processed using a Coulter counter TAII, with an aperture of 30µm. For each 50ml sample, particles were counted over fifteen intervally spaced channels, ranging from 0.50µm - 16.00µm in diameter. From the fifteen channels only thirteen were actually used for calculating microparticle size distributions. The particle diameter across the thirteen channels range from 0.63µm - 12.60µm diameter.

The method of choosing particular samples to represent seasonal periods of wet and dry within a given year relies on the total particle count of a single sample from the microparticle concentration data previously discussed. From each set of samples representing a year, only one sample is chosen to represent the wet season, and only one sample is chosen to represent the dry.
season of that particular year. The samples representing the wet season are chosen due to their low particle counts relative to the other samples in the year. Where as samples representing the dry season are chosen generally by the highest particle count relative to other samples in the year. These samples are chosen in this manner because of higher depositional rates that occur on the ice field during the dry winter months. A total of ten samples were chosen for each wet and dry season over the course of a decade.

There is a certain percentage of error in this method the deeper one goes in the core. Close to the surface there are many more samples in a one year period. The deeper in the ice core, the more compact the annual record becomes, due to compaction and thinning due to ice flow. Near the surface there are 88 samples in a period of one year, where as at a depth of 100m there may only be one or two samples in a one year period (Figure 9).

From the microparticle concentration data, microparticle size distribution profiles were averaged for both wet and dry seasons over eight separate decadal periods. Over each decade averaged, at least one strong to very strong El Niño event has been recorded and wet and dry particle distribution profiles were plotted. Out of the eight decades averaged, four represent wet and dry seasonal fluctuations of Post-Little Ice Age conditions, and four represent the wet and dry seasonal fluctuations during the Little Ice Age (Table 1).
<table>
<thead>
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<th>Time periods from which wet and dry decadal averages were calculated:</th>
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<td>Post Little Ice Age</td>
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In order to determine differences in microparticle size distributions between seasonal fluctuations of wet and dry periods slope values and particle coarseness factors were calculated. Slope is used as a means of interpreting size distributions of wind blown microparticles. Microparticle size distribution in this study is based on the distribution of microparticles between 0.63\(\mu\)m and 12.60\(\mu\)m diameter. This distribution can be described in slope by the use of the Junge Distribution (Junge, 1963):

\[
\frac{dN(r)}{d\log r} = \alpha \times r^{-\delta}
\]

where \(N(r)\) equals the number of particles with radii greater than \(r\) per ml of water (Steffensen, 1985). Units of \(r\) are in \(\mu\)m and natural logarithms are used. Particle coarseness factors can be explained in terms of a percentage representing the ratio of particles coarser than 1.65\(\mu\)m diameter, divided by the number of particles finer than 1.65\(\mu\)m diameter, (Equation # 1).

\[
c = \frac{1.65\mu m}{0.63\mu m} - \frac{12.60\mu m}{1.65\mu m} \times 100\%
\]

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**Table 1: Decadal Periods**

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<th>Time periods from which wet and dry decadal averages were calculated:</th>
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The use of this equation enables one to determine the depositional periods in which the greater percentage of coarse particles are deposited (Thompson, 1977).
RESULTS:

Eight decadal averages of microparticle size concentrations during wet and dry seasons, were plotted in Figures 1a-8a from the decades in Table 1. There are thirteen different size ranges plotted with a range of 0.63µm to 12.60µm diameter. Also plotted in Figure 1b-8b are microparticle size distribution profiles of wet and dry seasons during a major El Niño event, which fell during each of the 8 decades. The size distribution profiles during each El Niño events are also plotted for wet and dry seasons. In order to determine whether an affiliation can be established between microparticle size distributions and short term variations in climate between wet and dry seasonal fluctuations in the southern Andes, a relationship between microparticle size distribution profiles, slope values, and coarseness factors must be characterized. It has been determined from previous studies that there is a higher concentration of particles deposited upon the Quelccaya Ice Cap during the dryer winter months of May through August (Thompson, 1980). This is illustrated in the distribution profiles (Figure 1a-8a). In general, decadal dry season microparticle size distribution profiles have a higher concentration of particles across the size distribution scale than does the decadal wet season profiles. This difference in distribution profiles between wet and dry seasons can be attributed mainly to seasonal fluctuations in snowfall distribution and general atmospheric accumulation change from wet to dry season. In the southern Peruvian Highlands, precipitation tends to be much less and winds are generally stronger during the dry winter months (April through September) (Johnson, 1976). During this time conditions are more favorable for a higher dust particle transport and deposition. During the wet summer months, November to March, conditions become less favorable for transport of high concentrations of dust particles, due to increasing precipitation, diminishing regional wind speeds and a more easterly wind component.
A comparison of mean slope values from wet and dry seasons during the Post-Little Ice Age (wet mean slope of -3.92, dry mean slope of -3.80) with mean slope values from the wet and dry seasons during the Little Ice Age (wet mean slope of -3.13, dry mean slope of -3.12) from Table 2 a,b, yields a negative mean slope calculated during the dry seasons for both periods. However, the difference in the mean slope values between wet and dry seasons during the Little Ice Age is not as great as the difference found between mean slope values from wet and dry seasons during the Post-Little Ice Age. Mean slope values are considerably less negative in both wet and dry seasons during the Little Ice Age, compared to those of the Post-Little Ice Age (Table 2 a,b). There is a distinct difference between mean slope values in El Niño years during the Post-Little Ice Age and El Niño years during the Little Ice Age. The mean slope value for the dry seasons is more negative during the Post-Little Ice Age (wet mean slope -4.37, dry mean slope -3.47) and less negative during the Little Ice Age (wet mean slope -1.89, dry mean slope -3.27) seen in Table 2 a,b. Comparison of decadal wet and dry slope values from the Post-Little Ice Age with those from the Little Ice Age, indicates a slight difference. Three out of the 4 decadal slope values from the Post-Little Ice Age have less negative values during the dry season (Table 2 a). Only 2 out of the 4 decadal slope values from the Little Ice Age have less negative slope values during the dry season (Table 2 b). Decadal slope values for both wet and dry seasons are generally less negative during the Little Ice Age El Niño years. This suggests that circulation patterns during the Little Ice Age may have been quite different than those during the Post-Little Ice Age El Niño events. Stronger circulation patterns could account for the increase in dust during the Little Ice Age (Thompson et al 1986) and more coarse particles and hence the less negative slope.

Mean coarseness factor values in Table 3 a,b were calculated for the same decades as slope values in Table 2 a,b. In both the
Post-Little Ice Age (wet mean percentage of 4.86, dry mean percentage of 1.36) and Little Ice Age (wet mean percentage of 1.67, dry mean percentage of 1.24) periods, mean coarseness factors are higher during the wet season (Table 3 a, b). During the Post-Little Ice Age there is a large variation between the wet and dry seasonal mean percentages (Table 3 a). The dry season mean coarseness factor is 3.6 times as great as the mean coarseness factor value calculated for the wet season. Mean percentages for wet and dry coarseness factors during the Little Ice Age do not illustrate as great a difference between wet and dry percentages (Table 3 b). The dry season mean is only 1.3 times as great as the mean wet season percentage.

Mean coarseness factors calculated for El Niño years during the Post-Little Ice Age (wet mean percentage of 6.91, dry mean percentage of .70) and Little Ice Age (wet mean percentage of 1.55, dry mean percentage of .72) periods show higher percentages of coarseness during the wet seasons. There is much greater difference between mean wet and dry coarseness factors calculated for El Niño events in the Post-Little Ice Age (Table 3 a) than is found between mean wet and dry coarseness factors in the Little Ice Age (Table 3 b).

Distinct differences in coarseness factors occur between wet and dry decadal values in the Post-Little Ice Age and the wet and dry decadal values in the Little Ice Age (Table 3 a, b). Generally there are lower coarseness factors during the wet season of the Little Ice Age than there are during the wet season of the Post-Little Ice Age. Dry season coarseness factors seem to be rather constant in both periods. This is also reflected in mean dry seasonal coarseness factors previously discussed.

In this study a direct relationship can be established between decadal slope values in Table 4a with decadal wet and dry seasonal microparticle size distribution profiles (Figure 1a-8a). Higher negative slope values should indicate a much higher concentration of small particles relative to large particles.
resulting in steeper particle size distribution profiles. From the 8 decadal wet and dry seasonal slope values in Table 4 a, 5 out of 8 decadal slope values have less negative values during the dry season. This suggests that the 5 corresponding microparticle size distribution profiles (Figure 1a, 3a-5a) should have generally steeper size distributions during the wet season, than does the dry season, and in fact this is the case. Figure 2a, 7a-8a reflects steeper particle size distribution profiles during the dry season rather than the wet, corresponding to higher slope values during the dry season (Table 4a).

Coarseness factors in Table 5a were calculated over the same decadal periods as slope values in Table 4a. Coarseness factors were calculated in order to determine if a relationship could be established between calculated slope values with a comparison of small particles (0.63 µm-1.65 µm) to coarse particles (1.65 µm-12.60 µm). In studying decadal coarseness factors of wet and dry seasons from Table 5a, there are 6 out of 8 decadal values that show higher percentages of coarseness during the wet season. These calculations of coarseness factors do not coincide with slope values from Table 4a. Higher percentages of coarseness calculated for the wet seasonal period indicate that there is a higher percentage of large particles deposited during the wet season, relative to small particles. While during the dry season there is relatively lower percentages of larger particles. When comparing decadal wet and dry coarseness factors from Table 5a, with size distribution profiles in Figure 1a-8a, no direct relationship is evident in the decadal wet and dry distribution profiles.

In determining what effects major El Niño events may have on wet and dry seasonal size distributions of microparticles, a comparison of slope values and coarseness factors were studied. In a study of slope for wet and dry seasons during major El Niño events, 5 out of 8 El Niño years show less negative slope values during the dry season (Table 4b). Slope values calculated for El
Niño years in Table 4b have a distinct relationship with microparticle size distribution profiles in Figure 1b-8b. Slope values for wet seasons are generally more negative than dry season values in Figures 1b-5b, resulting in steeper particle size distribution profiles for the wet season, due to the relative greater increase in the number of small particles. In Figure 6b-8b particle size distribution profiles are steeper during dry seasons and less steep during wet. Slope values in Table 4b for these El Niño years have higher negative values occurring in Figure 1b-5b in the wet season and less negative values for wet seasons in Figure 6b-8b.

Coarseness factors calculated for the eight El Niño events in Table 5b show that 5 out of the 8 El Niño events have higher coarseness factors during the wet season. Higher percentages of coarseness calculated for the wet seasonal periods indicates that there is a higher percentage of large particles deposited during the wet season, relative to small particles. While during the dry season there is relatively lower percentages of large particles relative to the number of small particles. There are exceptions to this as seen in the El Niño years of 1926-1925 (Figure 2b), 1761 (Figure 6b), and 1634 (Figure 8b). A comparison of coarseness factors of wet and dry seasons from Table 5b with slope values of wet and dry seasons, does not reveal any distinct correlation. In a comparison of wet and dry seasonal El Niño coarseness factors in Table 5b with microparticle size distribution in Figure 1b-8b, a direct relationship is also not revealed. However, there must be an indirect relationship which is not as apparent, based on the premise that coarseness factors are dependent upon size distributions.
DISCUSSION:

Before discussing the main results of this study, a short overview of regional geographic location and climatic conditions of the Quelccaya Ice Cap is necessary. The Quelccaya Ice Cap is considered to be an unique tropical glacier, due to it's being the highest object in the immediate vicinity as well as having minimal local disturbances of both depositional stratigraphy and radiation balance (Thompson et al, 1984). The Quelccaya Ice Cap is located (lat, 13°56'S, long. 70°50'W) along the easternmost Peruvian Andes, at a height of 5,670m in the Cordillera Oriental. Due to the location of the Quelccaya Ice Cap and it's relative elevation to the surrounding topography it is an excellent representation of regional climatic conditions in the highlands of tropical South America. In the Peruvian Highlands regional wind speeds tend to be greater during the dry season (May-October) predominantly from the northwest with average wind speeds of 4-5 knots. During the wet season (November-March) winds are generally from the south-southeast with an average wind speed of 3-4 knots (Johnson, 1976). Fluctuations of precipitation occurs in the Peruvian Highlands with seasonal wind changes. The majority of precipitation (>80%) occurs during the high sun period (summer season) between November and March. During the remaining seven months precipitation drastically declines with the increase of stronger northwesterly winds.

This study has demonstrated for those decades considered significant changes occur in slope values and coarseness factors associated with the last major climatic change, "The Little Ice Age." Slope values from Table 2a, calculated for the decades of the Post-Little Ice Age, have an average slope value of -3.86, while the decades for the Little Ice Age have an average slope value of -3.12 (significantly less negative). The less negative slope value calculated from the Little Ice Age suggests a greater number of large particles during the Little Ice Age. This is most likely due to the occurrence of greater wind speeds during these
decades of the Little Ice Age, in fact this is strongly supported by the large concentrations of both soluble and insoluble particles.

Slope values from Table 2a calculated for the decades of the Post-Little Ice Age indicate a general trend of less negative slope values during the dry season. Mean slope values for the Post-Little Ice Age illustrate this dominance of less negative values occurring in the dry season. Slope values from the Little Ice Age do not show as great a difference between wet and dry seasonal slope values as in the Post-Little Ice Age (Table 2a, b). The mean slope values in the Little Ice Age also illustrate less negative values for the dry season, but only a slight difference occurs between wet and dry season values (wet mean slope -3.13, dry mean slope -3.12). This small variation in slope between the wet and dry seasons suggest that seasonal variation in wind speeds and seasonal changes in dominant wind directions may not have been as pronounced during the period of the Little Ice Age. Thus allowing for a more even size distribution in microparticles. On the other hand it may turn out with additional decadal data that this apparent difference may not remain significant.

Differences found in slope values calculated from El Niño events occurring in the Post-Little Ice Age and the Little Ice Age, indicate possible changes in regional circulation patterns over the Peruvian Highlands. There is a distinct change in slope values from the Little Ice Age into Post-Little Ice Age. Slope values for El Niño years from the Little Ice Age are generally less negative during the wet season shown by decadal and mean slope values in Table 2b. Slope values from the Post-Little Ice Age El Niño events in Table 2a have less negative slope values during the dry season. This difference in seasonal slope values suggests that a higher percentage of small particles relative to large particles, were deposited generally in the dry season during the Little Ice Age, and in the wet season during the
Post-Little Ice Age.

In studying coarseness factors between the Post-Little Ice Age and the Little Ice Age there are distinct differences found between the two periods. Although coarseness factors calculated over the same time period do not correlate with calculated slope values. Coarseness factors calculated in Table 3ab for decadal wet and dry seasons illustrate a distinct change in coarseness percentages between the Post-Little Ice Age wet season period and the Little Ice Age wet season period. Over both climatic periods, decadal coarseness factors and mean coarseness factors show a general trend of higher coarseness factors occurring in the wet season (Table 3a). This data indicates a greater increase during the wet season in the number of particles within a range from 1.65μm to 12.60μm diameter. This may be due to greater wind speeds associated with the greater frequency of thunderstorms that arise during the wet season, both during the Little Ice Age and the Post-Little Ice Age periods. Dry seasonal coarseness factors remain relatively constant throughout the Little Ice Age and Post-Little Ice Age periods. However, coarseness factors during the wet seasons in the Post-Little Ice Age are about 3 times as great as wet seasonal coarseness factors during the Little Ice Age. Higher percentages of coarseness occurring in the wet seasons indicates a higher percentage of large particles being deposited during the wet season, relative to the deposition of small particles.

The coarseness factor values during El Niño years in the Post-Little Ice Age and Little Ice Age periods, show a similar relationship to the one between decades of the Post-Little Ice Age and the Little Ice Age periods. However, there is a greater range in coarseness factor values during El Niño years, due to the small sample set being considered.

Microparticle size distribution profiles in Figure 1a-8a illustrate wet and dry seasonal variations in deposition of microparticles. Decadal differences between wet and dry
distribution profiles can be attributed mainly to seasonal snowfall distribution and general atmospheric accumulation change from wet to dry seasons. There tends to be much less precipitation during the dry season (April-September) in the southern Peruvian Highlands, with stronger regional winds from a westerly direction across the altiplano. This in addition to greater atmospheric radiation levels contributing to a greater mass loss, increases particle concentration during the dry winter seasons. There is a seasonal wind shift from westerly winds that occurs in the dry seasons to a predominant easterly wind from the Amazon Basin during the wet season (November-March). This contributes moist air that influences an increase in precipitation. Due to the dilution of microparticle concentration by increased precipitation and the decrease in mass loss, particle concentrations tend to be less in a single sample. This generally explains why there are higher concentrations of particles across the size distribution scale occurring in decadal dry season microparticle size distribution profiles than in wet season microparticle size distribution profiles, in Figure 1a-8a.

In this study a direct relationship is established between microparticle size distribution profiles and calculated slope values during wet and dry seasons. Higher negative slope values indicate that there is higher concentrations of small particles being deposited, relative to large particles. This implies that for a higher negative slope value during the wet season and a less negative slope value for the dry season, the particle size distribution profiles for each should show a steeper distribution profile occurring during the wet season and a less steep distribution profile during the dry season. And in fact this is the case as seen in a comparison made between decadal slope values from Table 4a and decadal distribution profiles in Figures 1a-8a. Consistently higher negative decadal slope values were found to be represented by steeper microparticle size distribution profiles.
From this study there is no conclusive evidence that would suggest there is a distinct change in slope values between wet and dry seasonal periods of an El Niño year (Table 4b). Although El Niño year slope values generally are characterized by less negative slope occurring during the dry season (5 out of 8 El Niño years show less negative slope values during the dry season) there is not a significant difference the dry season values and the wet season values.

In a comparison of wet and dry seasonal coarseness factor values with wet and dry decadal and El Niño year slope values and microparticle size distribution profiles, a direct relationship could not be established. However, there must be an indirect relationship due to the fact that coarseness factors are also dependent upon size distributions. The difference can be attributed to the fact that in coarseness factor calculations the particle sizes are divided into only two groups (0.63µm - 1.65µm and 1.65µm - 12.60µm). In this calculation of slope, the particle sizes are divided into thirteen groups over a size range from 0.63µm to 12.60µm. Slope calculations cover a larger distribution of particle ranges, thus producing a more representative value for characterizing change in microparticle size distributions.
SUMMARY:

Based on a comparison of average decadal slope values from the Post-Little Ice Age and the Little Ice Age periods a difference in regional wind speeds is indicated between the two periods. The average decadal slope value of the Little Ice Age is significantly less negative than the average decadal slope of the Post-Little Ice Age. This difference in average slope values suggests greater wind speeds existed during the Little Ice Age.

Calculated mean and decadal slope values from the Post-Little Ice Age and Little Ice Age illustrate a variation in differences between wet and dry seasonal slope values calculated for the two periods. Slope values during the Little Ice Age tend not to show as great a variation between wet and dry slope values. This may suggest that seasonal variations in wind speeds and seasonal changes in dominant wind direction were not as pronounced during the Little Ice Age. However, additional decadal data is needed to be studied in order to verify this relationship.

A direct relationship is established between decadal microparticle size distributions and calculated decadal slope values. Seasonal slope values generally can be correlated with steepness of microparticle size distribution profiles. A higher negative slope value indicates steeper seasonal size distribution profiles, where as less negative slope values indicate less steepness in the size distribution, reflecting higher concentrations of small particles relative to large particles.

Coarseness factors calculated in this study proved not to be beneficial in establishing direct relationship in seasonal variation (wet and dry) in microparticle size distributions. Coarseness factor values do not correlate with slope values calculated for the same decades. This difference in conflicting seasonal concentrations of small particles relative to large particles, between coarseness factor and slope values can be attributed to the size ranges for which the calculations are made. Coarseness factors are divided into only two groups of
particle size, where as slope is divided into thirteen groups of particle sizes. Thus slope is a better representation of the actual particle size distribution.
Figure 1 (a) QUELLCATA B3 SUMMIT 1944-1935 Decadal Avg. dry --- wet ---

Particle Concentration (log) vs. Diameter (µm)

Figure 1 (b) QUELLCATA B3 SUMMIT 1944-1935 El Niño 1941-1940 dry --- wet ---

Particle Concentration (log) vs. Diameter (µm)

Figure 1 a: Microparticle Size Distribution for Decadel Wet and Dry Averages.

b: Microparticle Size Distribution for Wet and Dry El Niño Event.

Figure 2 (a) QUELLCATA B3 SUMMIT 1931-1922 Decadal Avg. dry --- wet ---

Particle Concentration (log) vs. Diameter (µm)

Figure 2 (b) QUELLCATA B3 SUMMIT 1931-1922 El Niño 1926-1925 dry --- wet ---

Particle Concentration (log) vs. Diameter (µm)

Figure 2 a: Microparticle Size Distribution for Decadel Wet and Dry Averages.

b: Microparticle Size Distribution for Wet and Dry El Niño Event.
Figure 3(a): Microparticle Size Distribution for Decadel Wet and Dry Averages.

Figure 3(b): Microparticle Size Distribution for Wet and Dry El Nino Event.

Figure 4(a): Microparticle Size Distribution for Decadel Wet and Dry Averages.

Figure 4(b): Microparticle Size Distribution for Wet and Dry El Nino Event.
Figure 5 (a) QUELCCATA 83 SUMMIT
1832-1863
Decadel Avg.
--- dry --- wet

Figure 5 (b) QUELCCATA 83 SUMMIT
1832-1863
El Niño 1826
--- dry --- wet

Figure 5 a: Microparticle Size Distribution for Decadel Wet and Dry Averages.
    b: Microparticle Size Distribution for Wet and Dry El Niño Event.

Figure 6 (a) QUELCCATA 83 SUMMIT
1764-1755
Decadel Avg.
--- dry --- wet

Figure 6 (b) QUELCCATA 83 SUMMIT
1764-1755
El Niño 1761
--- dry --- wet

Figure 6 a: Microparticle Size Distribution for Decadel Wet and Dry Averages.
    b: Microparticle Size Distribution for Wet and Dry El Niño Event.
Figure 7(a) a: Microparticle Size Distribution for Decadel Wet and Dry Averages. b: Microparticle Size Distribution for Wet and Dry El Nino Event.

Figure 8(a) a: Microparticle Size Distribution for Decadel Wet and Dry Averages. b: Microparticle Size Distribution for Wet and Dry El Nino Event.
Figure 9 Total Samples per Decade
TABLE 2 (a) SLOPE VALUES

<table>
<thead>
<tr>
<th>Decadal Periods</th>
<th>Dry Season</th>
<th>Wet Season</th>
<th>El Niño Period</th>
<th>Dry Season</th>
<th>Wet Season</th>
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</thead>
<tbody>
<tr>
<td>1944-1935</td>
<td>-4.41</td>
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</tr>
<tr>
<td>1904-1895</td>
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<td>1900-1899</td>
<td>-4.09</td>
<td>-4.59</td>
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TABLE 2 (b) SLOPE VALUES

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<th>Wet Season</th>
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Less Negative Slope Values [ ]
Less Negative Mean Slope Values [ ]

TABLE 3 (a) COARSENESS FACTOR VALUES

<table>
<thead>
<tr>
<th>Decadal Periods</th>
<th>Dry Season</th>
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<th>El Niño Period</th>
<th>Dry Season</th>
<th>Wet Season</th>
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<tbody>
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TABLE 3 (b) COARSENESS FACTOR VALUES

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<th>El Niño Period</th>
<th>Dry Season</th>
<th>Wet Season</th>
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<td>[0.52]</td>
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Greatest Coarseness Factor Value [ ]
Greatest Mean Coarseness Factor Value [ ]
Table 4  Slope Values for 8 Decadal Periods and 8 El Nino Years

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<th>Decadal Periods:</th>
<th>Dry Season</th>
<th>Wet Season</th>
<th>El Nino Period</th>
<th>Dry Season</th>
<th>Wet Season</th>
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<tbody>
<tr>
<td>1931-1922</td>
<td>-3.94</td>
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<td>[-3.68]</td>
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<td>[-4.09]</td>
<td>-4.59</td>
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</table>

Less Negative Slope Value [ ]

Table 5 Coarseness Factors for 8 Decadal Periods & 8 El Nino Years

<table>
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<th>Decadal Periods:</th>
<th>Dry Season</th>
<th>Wet Season</th>
<th>El Nino Period</th>
<th>Dry Season</th>
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<tbody>
<tr>
<td>1944-1935</td>
<td>1.45</td>
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<td>1.76</td>
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<tr>
<td>1904-1895</td>
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<td>[5.14]</td>
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<td>1.16</td>
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<td>1828</td>
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<td>0.63</td>
</tr>
<tr>
<td>1764-1755</td>
<td>0.72</td>
<td>[1.52]</td>
<td>1761</td>
<td>0.38</td>
<td>[4.47]</td>
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<tr>
<td>1707-1698</td>
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<td>[1.70]</td>
<td>1701</td>
<td>0.19</td>
<td>[0.52]</td>
</tr>
<tr>
<td>1639-1630</td>
<td>[2.19]</td>
<td>1.66</td>
<td>1634</td>
<td>[1.44]</td>
<td>0.52</td>
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Greatest Coarseness Factor Value [ ]
REFERENCES

Imbrie, John and Katherine Palmer Imbrie, 1979, Ice Ages
Solving the Mystery. Enslow Publishers. Short Hill, N.J.

Climate of Central and South America. p. 147-184.

Junge, C.E. 1963, Air Chemistry and Radioactivity. Academic

Steffensen, J.P., 1985, Microparticles in Snow from the South

Thompson, L.G. 1977, Leader, six-man Glaciological party
on Quelccaya Ice Cap, Peru (NSF) Grant.

Thompson, L.G., S. Hastenrath and B. Morales Arnao. 1979
Climatic Ice Core Records from the Tropical Quelccaya

Thompson, L.G., 1980, Glaciological Investigations of the
Tropical Quelccaya Ice Cap, Peru. Journal of Glaciology,
Vol. 25, No. 91, 1980.

Thompson, L.G., E. Mosley-Thompson, P.M. Groottes, M.
Pourchet and S. Hastenrath, 1984. Tropical glaciers:
potential for ice core paleoclimatic reconstructions.
Journal of Geophysical Research, Vol. 89, No. D3,
4639-4646.