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Relationships between Andean Glacier Ice-Core Dust Records and Amazon Basin Riverine Sediments

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Abstract. Dust particle studies in ice cores from the tropical Andes provide important information about climate dynamics. We investigated dust concentrations from a 22.7 m ice-core recovered from the Quelccaya Ice Cap (QIC) in 2018, representing 12 years of snow accumulation. The dust seasonality signal was still preserved with some homogenization of the record due to surface melting and percolation. Using a microparticle counter, we measured the dust concentration from 2–60 µm and divided the annual dust concentration into three distinct groups: fine particle percentage (FPP, 2−10 µm), coarse particle percentage (CPP, 10−20 µm) and giant particle percentage (GPP, 20−60 µm). Increased dust was associated with the warm stage of the Pacific Decadal Oscillation index (PDO) from 2014−2017 with significant increases in FPP and a relative decrease in GPP. There was a positive correlation between PDO and FPP ($r = 0.68$, p-value < 0.02). CPP and GPP were dominant during the PDO cold phase (2005−2013) and were more strongly associated with the Tropical Northern Atlantic index (TNA), which was positive from 2005−2017. The relation between TNA and CPP was $r = 0.60$ (p-value <0.05) and that with GPP was $r = 0.59$ (p-value < 0.05). We also revealed a potential link between QIC dust and Madeira River sediments and runoff. Sediment concentration decreases at Porto Velho station were correlated with %GPP ($r = 0.67$, $p < 0.02$) from 2005–2017. This relationship contributes to a better understanding of the effects of PDO oscillations on both parameters. The %GPP and sediment decreases were potentially linked with the PDO phase change from negative to positive. We also noted a strong negative correlation between FPP and runoff ($r = -0.80$, $p < 0.002$) from 2005−2016, which was understandable due to the relationship of FPP to wetter conditions while runoff decreases were associated with increasing dryness in the southern part of the Madeira Basin. Assessing dust record variability by distinct size groups can help to improve our knowledge of how the Pacific and Atlantic oceans influence atmospheric oscillations in the QIC. In addition, the association of dust variability with dynamic changes in sediments and runoff in the Madeira River system demonstrates the potential for future investigation of linkages between QIC dust and Amazon basin rivers.

1.Introduction

Dust particles, the most abundant aerosol type in the atmosphere, significantly influence climate. This can occur both directly, through scattering and absorption of solar radiation (Di Biagio et al., 2020; Kok et al., 2017), and indirectly, as cloud condensation nuclei and ice nuclei along with biogeochemical cycling of nutrients to marine

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phytoplankton (Ansmann, 2005; Carslaw et al., 2010; Jickells, 2005; Stevens and Feingold, 2009).

Particles archived in Peruvian ice cores preserve the region's climate history, but insufficient knowledge of their size distribution hinders a better understanding of climate dynamics, which can be retrieved by measuring the absolute levels (*i.e.,* total number), size distribution, and composition. Variability in the particle concentration and size distributions is usually directly correlated with changes in climate dynamics along the ice-core record (Delmonte et al., 2002, 2017; Li et al., 2019; Ruth, 2002; Wegner et al., 2015). While absolute concentration depends on many factors (e.g., snow accumulation rate, dust source, and transport processes), the size distribution and relative proportion of particles within a given grain size depends primarily on transport conditions (Delmonte et al., 2004, 2017). Atmospheric dust transport occurs through advection, convection, and turbulent diffusion, while removal occurs through dry and wet deposition (Li et al., 2008; Tegen and Fung, 1994).

South American mountain glaciers function as a buffer for freshwater resources, especially during low-precipitation seasons in countries such as Bolivia and Peru(Vuille et al., 2008). The Andes host > 99% of all tropical glaciers on Earth (Kaser, 1999), providing dust archives that reveal seasonality, allow dry/wet season differentiation, and enable annual layer counting (Kutuzov et al., 2019; Ramirez et al., 2003). South America encompasses many temperature and precipitation zones, with the central Andes being affected by both Atlantic and Pacific atmospheric circulation patterns in the north and south, respectively (Sagredo and Lowell, 2012).

Over the last 50 years, evidence for rapid tropical glacier retreat in the Andean region suggests their disappearance by the end of the 21st century due to warming triggered by anthropogenic and natural forcing (Rabatel et al., 2013). Recent warming in the latter half of the 20th century has impacted the preservation of δ^{18}O-derived seasonality data in Quelccaya Ice Cap (QIC, 13º56' S, 70º50' W, 5670 meters above sea level) ice cores, while dust records remain well preserved (Vuille et al., 2015; Yarleque et al., 2018) and offer more reliable data on climate dynamics.

Recent changes have also been observed over the Madeira River basin in the Amazon-Andean region (Espinoza Villar et al., 2009; Molina-Carpio et al., 2017), which is the largest contributor of sediments to the Amazon River (Ayes Rivera et al., 2019; Vauchel et al., 2017). Erosion of the Andean Cordillera (Ayes Rivera et al., 2019) means that sediment transport from the Amazon basin to the Atlantic Ocean is mainly driven by rivers (Filizola and Guyot, 2011). The junction of the Beni and Mamoré rivers forms the Madeira River (Figure 1) and connects it to the main sediment source in the Andes (Vauchel et al., 2017). As the Madeira River has a significant impact on Amazonian sediment balance (Ayes Rivera et al., 2019), understanding potential connections between dust variability from the QIC and sediment fluxes could help improve our understanding of this complex climate region.

In September 2018, an expedition led by researchers from the Climate and Polar Center at the Federal University of Rio Grande do Sul (CPC-UFRGS) and the Climate Change Institute at the University of Maine (CCI-Maine) recovered a 22.7 m ice-core from the QIC (Figure 1) using an electro-mechanical Stampli drill.

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Frozen ice-core sections were transported to CCI for ICP-MS and ion chromatographic analysis as well as to the Eurocold laboratory (Milan, Italy) for dust concentration analysis.

In this study, we present total dust and density data derived from that expedition and use this to investigate (1) the relationship between large-scale influences such as the Tropical Northern Atlantic (TNA) and Pacific Decadal Oscillation (PDO) indexes, and QIC dust groupings, and (2) the relationship between QIC dust and the Amazon region using sediment and runoff data from the Madeira River at the Porto Velho gage station, which has a complete data series for recent years.

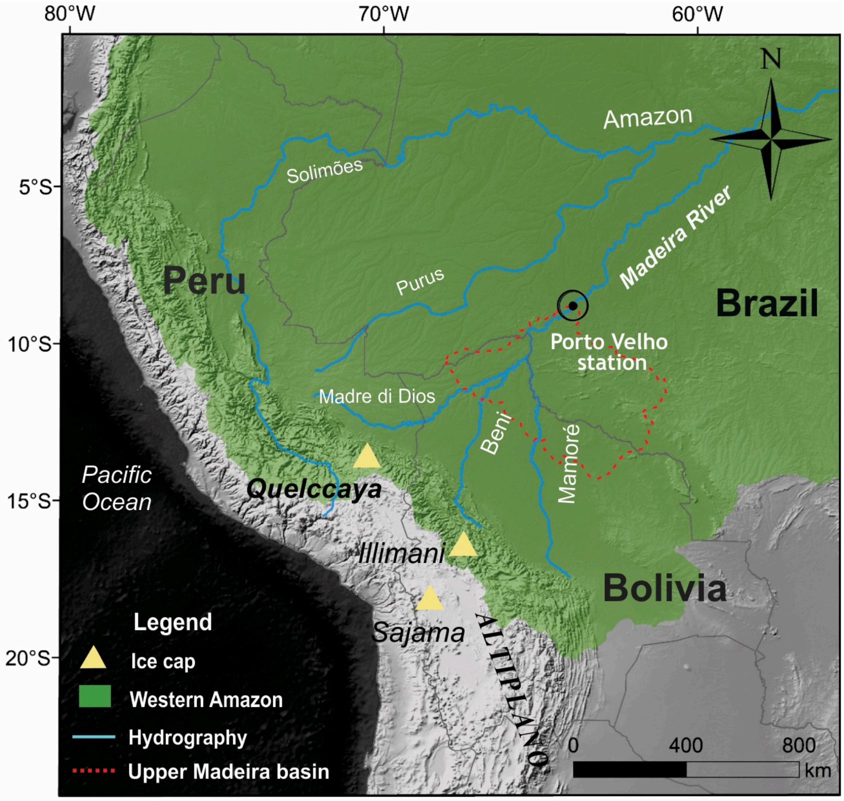

Figure 1: Ice-core sites and main rivers from Upper Madeira Basin in the western Amazon region; map layers were extracted from www.naturalearthdata.com and http://terrabrasilis.dpi.inpe.br.

2.Geographic and climatic setting

Tropical Andean glaciers belong to two distinct continental climate zones (Kaser, 2001) with clear differences in temperature, precipitation, and humidity (Kozhikkodan Veettil et al., 2016; Sagredo and Lowell, 2012; Veettil et al., 2017). The outer tropics (Peru, Bolivia, and northern Chile) are characterized by a tropical climate during the austral summer (high precipitation) and subtropical conditions during the austral winter (little to no precipitation).

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The QIC is located at the northern edge of the Altiplano in the Cordillera Vilcanota of southern Peru (Figure 1). This is the world's largest tropical ice cap (median area of 50.2 km^2 (Hanshaw and Bookhagen, 2014)), from which a previous deep core campaign recovered 1800 years of climate information (Thompson et al., 2013). Located between the Pacific Ocean and the Amazon Basin, during the wet season (austral summer) it is influenced by the South American summer monsoon, when most precipitation occurs (Garreaud, 2009). The Bolivian High and the northward extension of the low-level jet are associated with precipitation over the Andes between 20º S and 8º S from December-March. Extreme wet monthly events on interannual time scales are related to convection over the western Amazon during this period (Segura et al., 2019). In the dry season (austral winter), westerly flow predominates (Garreaud and Aceituno, 2001; Vuille et al., 2000) and higher dust concentrations are attributed to dominant higher wind speeds from the west and northwest, which facilitate entrainment and transport of dust from the high, dry Altiplano (Thompson et al., 1986).

The PDO, a pattern of climatic variability over the North Pacific, has warm and cold phases. During the former, the eastern Pacific exhibits above average temperatures that coincide with wet periods in south-central South America. Two types of pressure anomalies occur during this phase: low pressure over the North Pacific causes wind to flow counterclockwise, and high pressure in the northern subtropical Pacific causes winds to flow clockwise (Guevara-Guillén et al., 2015; Mantua and Hare, 2002).

Atmospheric circulation over the Amazon basin comes from the tropical Atlantic Ocean and is the main source of precipitation (snow) for tropical Andean glaciers. TNA is an indicator of surface temperatures in the eastern tropical North Atlantic Ocean (Enfield et al., 1999). Rainfall increases in the Amazon basin are related to increased water vapor transport from the Atlantic. In addition, droughts in this basin are associated with El Niño or northern tropical Atlantic warming (da Rocha Ribeiro et al., 2018). Severe droughts in 2005 and 2010 over the Amazon basin were associated with warmer TNA conditions, under which an anomalously northward displacement of the Intertropical Convergence Zone leads to weaker northeasterly Atlantic trade winds and rainfall reduction over the Amazon basin (Marengo and Espinoza, 2016), suggesting a reduction in moisture advection from the Amazon basin to Bolivian glaciers (Lindau et al., 2020).

The El Niño Southern Oscillation (ENSO) has environmental and economic impacts on a global scale (McPhaden et al., 2006). Very strong El Niño events (Oceanic Niño Index > +2.0) occurred in 1982–1983, 1997–1998, and 2015–2016, during which QIC margin retreat was greatly enhanced (Thompson et al., 2017). The QIC experiences an increase in westerly wind strength under El Niño conditions and easterly enhancement during La-Niña (Garreaud and Aceituno, 2001; Vuille et al., 2000).

3.Methods

We selected 183 samples, representing 13.4 m water equivalent, for dust particle analysis. Measurements were performed in random order using a microparticle counter (Coulter Counter Multisizer IV, 400-channels) set up in a class 100 clean room at the Eurocold laboratory (Milan, Italy). The instrument was calibrated with 2.07 µm latex and set to detect particles with equivalent spherical diameters from 2–60 µm. Each concentration and size distribution value represented the average of at least three independent measurements in the same sample. The

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total mass of insoluble dust was calculated from the volume size distribution, assuming an average density of 2.5 g/cm^3. A standard was set using ultrapure water and checked after five sample analyses with an average value of ~1 ppb.

We smoothed the dust concentration profile with a moving average calculated using three samples for the total dust concentration to characterize seasonality. We defined the dry season onset for each period as having at least a two-fold increase in the mass dust concentration from the previous sample in the profile. Annual dating was defined from the start of the dry season until the end of the wet season for each year (Figure 2a). For statistical correlations, we used the mean dust concentration for each year. All correlations given here were significant at the 95% level. We defined three groups with distinct ranges: fine particle percentage (FPP, 2–10 µm), coarse particle percentage (CPP, 10–20 µm), and giant particle percentage (GPP, 20–60 µm). We defined a year as the period from April to the following March for PDO and TNA, following the wet season in the QIC (October to March) (Rabatel et al., 2013).

4.Results and discussion

We assessed 12 years of dust accumulation concentrations in the QIC. The profile clearly delineated dry and wet seasons, represented by high and low concentrations, respectively (Figure 2a). The dust concentration measured in the samples ranged from 617–23,176 ppb/mL. The mean seasonal value of dust concentrations during dry and wet seasons was 7247 (± 1458) ppb/mL and 2217 (± 320) ppb/mL, respectively. From 2015 to 2016, there was a 35% increase above average during the wet season.

Recent atmospheric warming in the QIC has resulted in changing depth of the firn/ice transition (Thompson et al., 2017). Comparing with two previous ice cores recovered from QIC, we observed a density alteration in the first 10 m between ice cores over time (Figure 2b). For the 1983 and 2003 cores, the firn/ice transition occurred at ~21–22 and ~18–19 m depth, respectively, compared with our core at ~17–18 m.

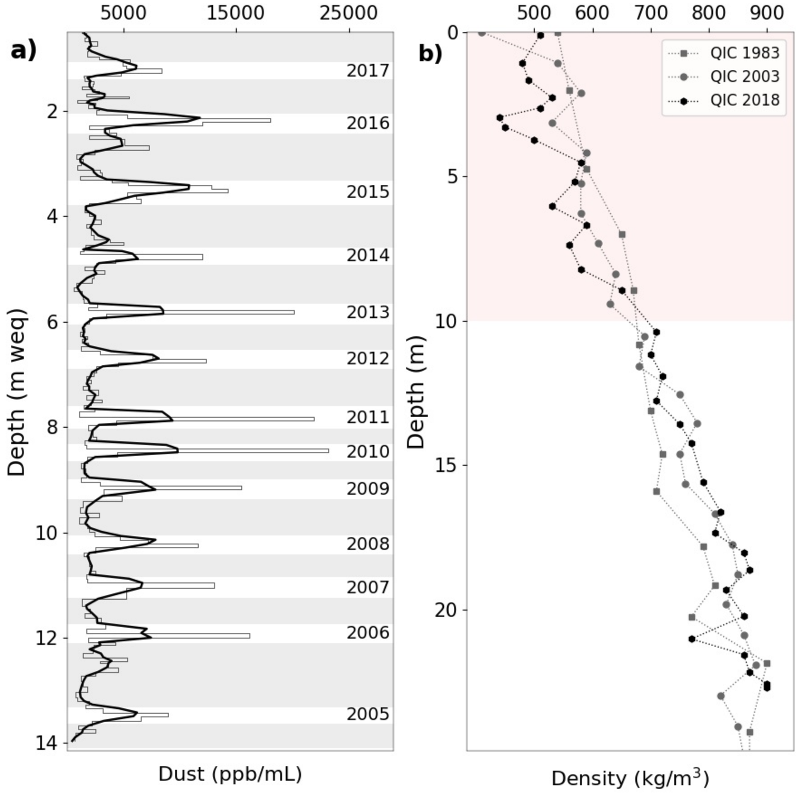

Figure 2: 22.7 m ice-core profile recovered in September 2018 from the Quelccaya Ice Cap, Peru. a) 13.96 m ice-core dust profile (in water equivalent); gray and white shading marking wet and dry seasonality, respectively. b) 2018 density profile compared with 1983 and 2003 ice cores (Thompson et al., 2017); red shading marks the first 10 m with observable density alterations between the three cores.

4.1.Large-scale atmospheric circulation patterns over the central Andes

During recent decades, the snowline altitude of Bolivian glaciers has fluctuated between the warm and cold PDO phases when combined with the ENSO warm and cold phases, respectively (Veettil et al., 2016). In Ecuador, the strong connection between PDO and ENSO is evident mainly in the warm phase, when rainfall is above average. This influence is also observable during drought periods, with ~70% of droughts developing in the negative PDO phase (Oñate-Valdivieso et al., 2020).

The PDO and TNA indices influence precipitation in the Amazon region and the accumulation rate of tropical Andean glaciers during warm and cold phases (da Rocha Ribeiro et al., 2018). In Peru, ENSO and PDO influence precipitation. The country has at least three climatic regions: the west coast, the Andes Cordillera, and the east, with the Cordillera acting as a natural barrier that greatly affects precipitation patterns (Mohammadi et al., 2020; Tapley and Waylen, 1990). When ENSO occurs in phase with PDO, the influence on glacial snowline is stronger and more visible than ENSO events during neutral periods or opposite PDO phases. Due to geography, the Pacific influence primarily determines most of the climate in the Cordillera Blanca (western Peru), which influences the surface energy balance and surface mass balance. However, during El Niño, these events do not significantly affect air temperature trends in the eastern cordilleras (which include glaciers in the Cordillera Vilcanota) (Salzmann et al., 2013; Veettil et al., 2016).

For the QIC, El Niño often results in arid conditions and low accumulation on the ice cap, as recorded in the ice stratigraphy (Thompson, 2000; Thompson et al., 1985, 2013). In the second half of the 20th century, annual QIC dust grew during the warm PDO phases [32] (Figure 3), but did not change significantly otherwise. The warm and cold TNA phases did not appear to have a significant effect on overall dust concentration.

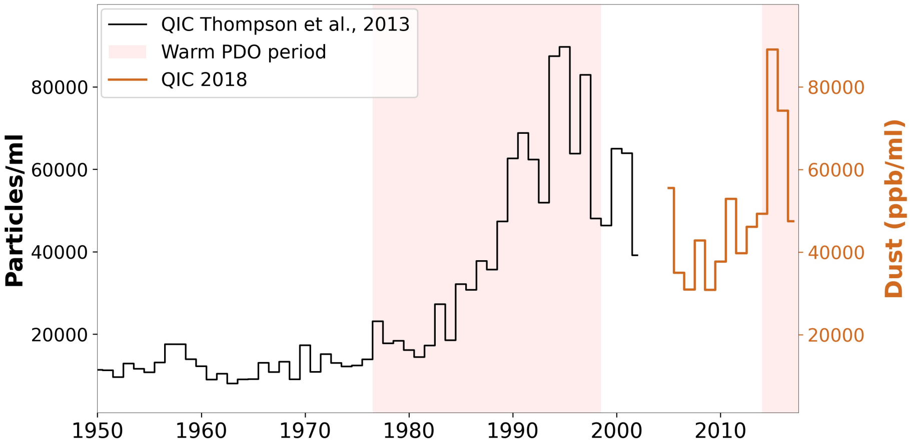

Figure 3: Annual dust concentration profile from the QIC from 1950–2018. Data for 1950–2002 were derived from past study (Thompson et al., 2013) for particles between 0.63−20 µm (black line), extracted from https://www.ncdc.noaa.gov/. Our dust profile includes particles between 2–60 µm (brown line).

In 2018, the annual total dust concentration increase coincided with the recent inversion from the PDO cold phase (2005−2013) to the PDO warm phase (2014−2017). To explore the relationship between total dust concentration in different size ranges (Figure 4). CPP and GPP dominated from 2005−2013 (PDO cold phase) with a significant increase in FPP starting in 2014, when the PDO warm phase began. Up to 2013, the annual mean dust of the FPP group was 965 (±176) ppb/mL., while CPP and GPP had average concentrations of 1265±298 and 1460±259 ppb/mL, respectively. From 2014, FPP became the dominant group with a concentration increase of 49.5%, while CPP and GPP showed decreases of 10.3% and 26.2%, respectively. Therefore, there was a positive trend in the relative FPP group (%FPP, Figure 5a) and a negative trend in the relative GPP group (%GPP, Figure 5b) from 2005–2017 in the core.

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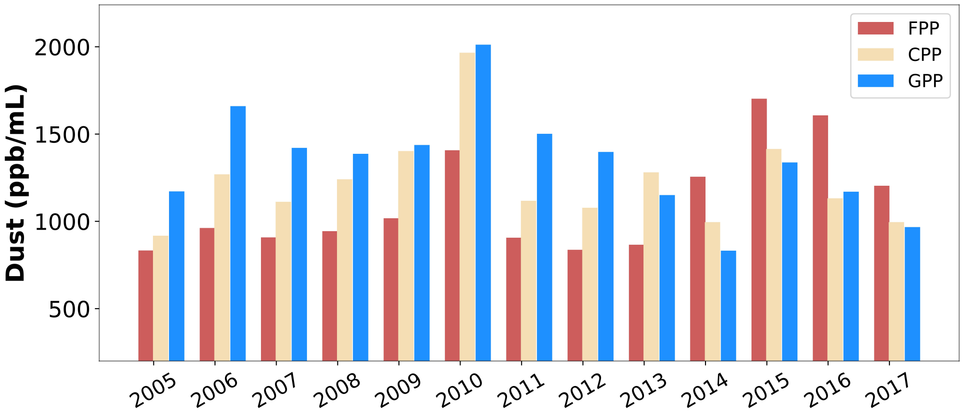


Figure 4: Annual mean concentration of ice-core dust-size groups from 2005–2017 period for FPP (fine, 2−10 µm), CPP (coarse, 10–20 µm), and GPP (giant, 20–60 µm).

The QIC's moisture source is mainly the tropical Atlantic via the Amazon basin (Thompson et al., 2013), but during the positive PDO phase, westerly flow is enhanced (Vuille et al., 2003) over central South America. As dry seasons, this westerly flow can facilitate dust transport from the Altiplano to the QIC region, promoting an increase in the amount of dust during warm PDO periods. In addition, recent studies have documented abnormal precipitation over Peruvian regions caused by Pacific Ocean oscillations when PDO and ENSO are in their positive phases (Mohammadi et al., 2020; Rodríguez-Morata et al., 2019; Vaheddoost, 2020)·(Kayano and Andreoli, 2007), which could favor increases in FPP relative to other groups due to turbulent mixing or wet deposition. The direct association of the PDO index with dust concentration was corroborated by significant correlations at the 95% level, such as %FPP ($r = 0.85$, $p < 0.001$) and %GPP ($r = -0.80$, p-value < 0.002) from 2005–2017. The relationship between PDO and %FPP suggests that the inversion from negative to positive PDO phase could act as a trigger for enhanced FPP levels. This direct relationship is supported by a positive correlation, at the 95% level, between the annual mean dust concentration of FPP and the PDO index ($r = 0.68$, $p < 0.02$) in 2018.

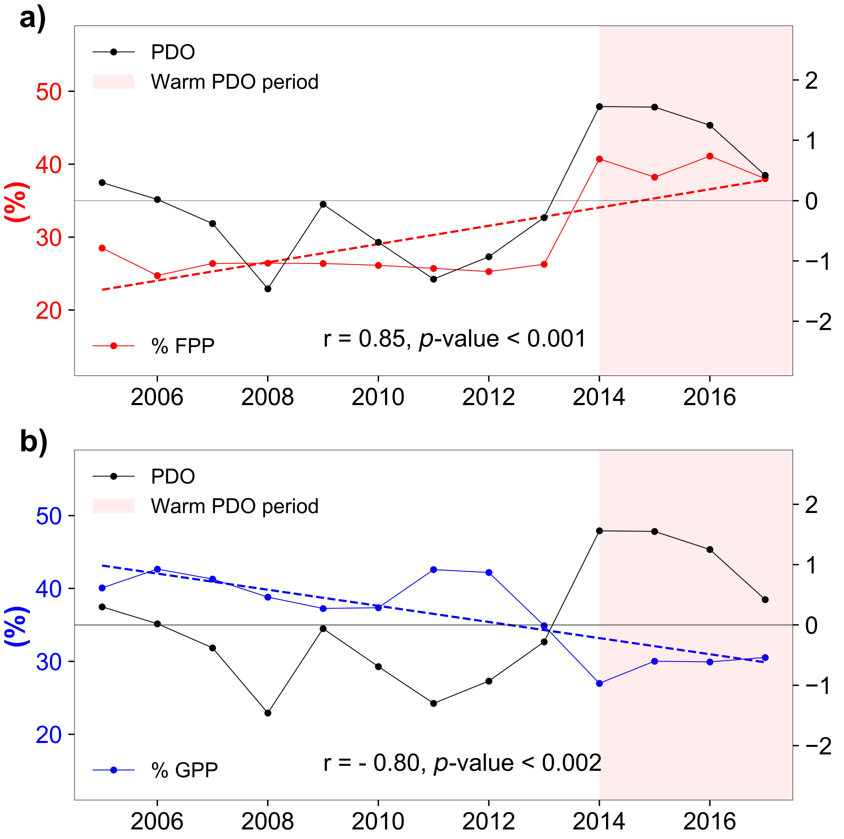


Figure 5: Annual percentage distribution of FPP and GPP with PDO index average from 2005–2017 (derived from https://psl.noaa.gov/data/climateindices). a) Annual %FPP distribution showing a linear positive trend and increases during warm PDO period. b) The relative GPP distribution showing a linear negative trend and decreases during the warm PDO period.

TNA did not show significant phase alterations, remaining largely in the positive phase from 2005–2017. There was a moderate correlation, at the 95% level, between CPP (r = 0.60, $p < 0.05$) and GPP (r = 0.59, p−value < 0.05). Drought conditions during the TNA warm phase (Marengo and Espinoza, 2016) may have led to dry deposition of these dust groups (i.e., by gravitational settling (Tegen and Fung, 1994) from the source area). The association between dust in tropical ice-cores and TNA oscillations is also verified in larger dust of Illimani ice-core. The correlation of these dust groups with TNA in our samples (Figure 6) was very similar to that of dust from the Illimani ice-core (Lindau et al., 2020), which also suggests the possible influence of northern tropical Atlantic warming in relation to QIC dust (> 10 µm). Possibly, as occurs in the Illimani wet seasons, the relative decrease in larger dust particles in the QIC record reflects the less intense convective activity during the wet season, as a consequence of the warm PDO phase and easterly air flow reduction during this period.

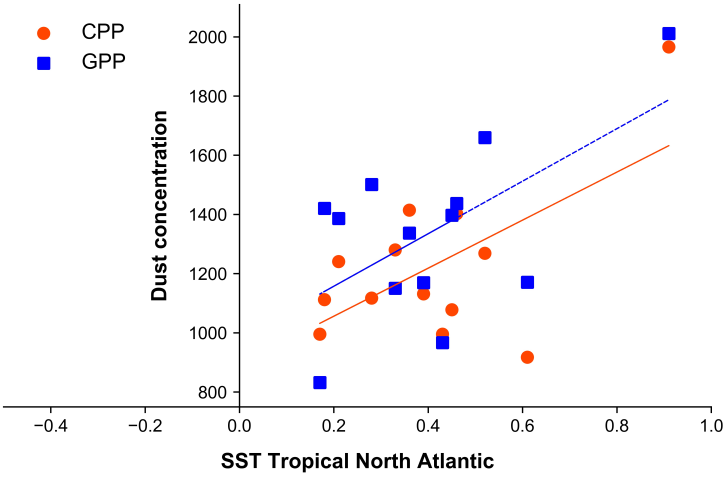


Figure 6: Correlations between annual mean concentrations of CPP and GPP (significant at 95%) from QIC with TNA from 2005–2017, derived from https://psl.noaa.gov/data/climateindices.

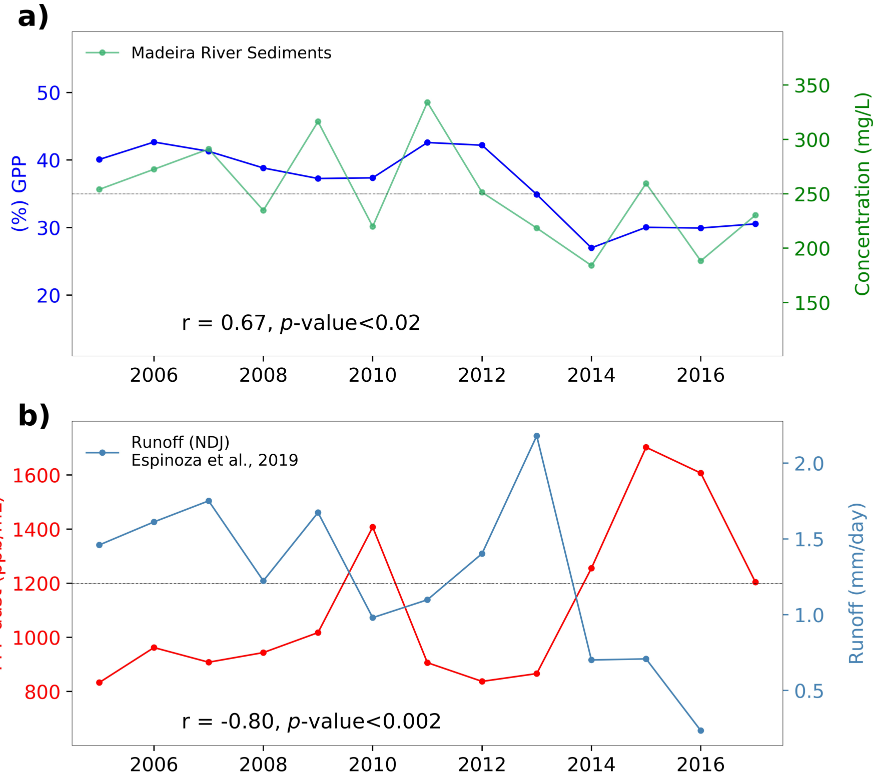
4.2.Madeira River sediments and connections to QIC dust

The Madeira River is the second-largest tributary of the Amazon Basin, with a mean annual discharge at the Porto Velho station of 18,500 m^3/s from 1967–2013 (Molina-Carpio et al., 2017). The Upper Madeira River drainage basin extends over three countries, with 11% in Peru, 73% in Bolivia, and 16% in Brazil (Molina-Carpio et al., 2017). ~50% of its annual precipitation occurs during the wet season from December to February (DJF) (Espinoza Villar et al., 2009). Analyzing the mean annual sediment concentration from 2005–2017 revealed a concentration decrease attributed to the depletion of sediments from the Beni River (Ayes Rivera et al., 2019) (Figure 7a). The sediment yield in Bolivia (the main source of Beni and Madeira river sediments) is directly controlled by climate variability with precipitation seasonality (present in the outer tropics) as the principal factor in high denudation rates (Pepin et al., 2013). The highest sediment concentration (2011) was associated with an abrupt transition into a drought year (2010) and a year of high water discharge during first semester in the Peruvian Amazon (Espinoza et al., 2012). The sediment concentration decreases observed since 2014 still not completely understood and cannot be fully attributed to the dams' construction and operation due to similar reduction observed downstream and upstream of the Porto Velho station (Ayes Rivera et al., 2019).

We investigated the relationship between the annual relative concentration (%) of the dust groups and the mean annual concentration of sediments in the Madeira River from 2005–2017; variability in %GPP coincided with sediment concentration ($r = 0.67$, *p*-value < 0.02 at the 95% level). In addition, there was a similar decrease in %GPP and sediment concentration during the PDO phase inversion (2014–2017). Considering the strong correlation between PDO and %GPP (Figure 5b), this positive relationship observed between %GPP and sediment concentration (Figure 7a) could indicates the effects of multidecadal Pacific oscillations on both parameters.

A recent study in the Upper Madeira Basin revealed a runoff decrease from 1981–2016, associated with an increase in the frequency of dry days and decreased rainfall south of 14º S, compared to a rainfall increase north of 14º S (Espinoza et al., 2019).

275 The relationship between Madeira runoff and FPP over time (Figure 7b) showed a strong negative correlation (r = -0.80, *p*-value < 0.002) from 2005 to 2016, because the link to FPP strengthens with wetter conditions while a decrease in runoff is related to increasing dryness in the southern Madeira Basin.



280 **Figure 7: Comparison of annual records from the Madeira River data at the Porto Velho station (hybam.obs-mip.fr*)* and QIC dust groups. Annual concentrations of Madeira River sediments are averaged from April through March of the following year. a) Annual %GPP and Madeira River sediment concentration with a positive correlation (r = 0.67) from 2005–2017; b) FPP dust concentration from 2005–2017 and runoff (NDJ) values (Espinoza et al., 2019) from 2005–2016, with a negative correlation over this period.**

285 Potentially, the runoff decrease has a direct relationship with drought and rainfall reduction in the southern part of the basin during wet seasons caused by anomalous northward displacement of the Intertropical Convergence Zone during the TNA warm period, but no significant correlations between runoff with TNA or with CPP and GPP groups were found during the same interval (2005−2016).

290 5.Conclusions

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We investigated a shallow ice-core (22.7 m) recovered from the QIC in 2018 and found that seasonal signals were preserved even after seasonal surface melting.

There was an increase in total dust content during the 21st century, coinciding with a warm PDO phase and the dominance of FPP from 2014–2017. The PDO index showed strong correlations with %FPP (r = 0.85, *p* < 0.001) and %GPP (r = -0.80, *p*−value < 0.01) at the 95% level from 2005 to 2017. In the positive phase (2014–2017), the PDO induces strong westerly winds, inhibiting easterly air flow and facilitating dust transport from the high Altiplano, increasing the fine dust content by wet deposition during abnormal precipitation in the Peruvian region. This explains the overall dust increase, more significantly in FPP, as evidenced by a high correlation (r = 0.68, p−value<0.02) at the 95% level.

TNA remained positive from 2005−2017, showing moderate correlations with CPP (r = 0.60, *p*−value < 0.05) and GPP (r = 0.59, *p*−value < 0.05) groups. These dust groups were dominant during the cold PDO phase (2005−2013). Under these two phases (TNA-positive and PDO-negative), dry conditions were dominant, facilitating the deposition of dust particles > 10 µm by gravitational settling.

This study provides a potential link between QIC dust content and the Madeira River via sediment concentration and runoff data. Decreasing sediment concentration at the Porto Velho station had a positive correlation with %GPP (r = 0.67, *p*−value < 0.02) at the 95% level from 2005−2017. In addition, the negative correlation between FPP and runoff (r = -0.80, *p*−value < 0.002) from 2005–2016. This relationship could improve the knowledge of multidecadal Pacific oscillations in this region.

In conclusion, examining distinct particle-size groups in the QIC dust record can improve our understanding of how the Pacific and Atlantic oceans influence dust particle variability in this region. We determined the relationship between dust content variability, sediment concentration, and runoff for the Madeira River, demonstrating the potential for future investigation of the relationship between QIC dust content and Amazon basin rivers.

Acknowledgments

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