Chapter 3

The Amazon Glaciers

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Abstract

In this chapter, we will examine the relationship between the Andean tropical glaciers and the Amazon rainforest, presenting a comprehensive overview on those ice masses that are the headwaters of the Amazon River and examining changes in environmental processes that may affect their mass balance and how they may feedback into the Amazon lowlands environmental processes. The first part of this chapter describes the present glaciological knowledge on these Andean ice masses that flow towards the Amazon drainage basin, about 1666 km^2 (of which 68% are in Peru, 24% in Bolivia and the remaining 8% in Ecuador). The mass balance of these glaciers is strongly dependent on the Amazon hydrological cycle, as water coming from the Atlantic Ocean and recycled though the rainforest is the main source of their precipitation. A second part of the chapter explores how two environmental systems are interconnected and interacted. The third part of chapter examines the present (last 50 years) human-made changes in the Amazon basin and how they may affect the Andean ice masses. These glaciers also hold the best proxy for the Amazon Holocene changes, the record left in the snow and ice chemistry. So, as a complement to this chapter, we review the information on the paleoenvironmental changes found in ice cores in Bolivia and Peru and what they may point about the future of the Andean tropical glaciers.

Keywords: Amazon basin, tropical glaciers, South America

1. Introduction

This chapter examines the relationship between the Andean tropical glaciers and the Amazon rainforest, presenting a comprehensive overview on those ice masses that are the headwaters of the Amazon River and examining changes in environmental processes that may affect their mass balance and how they may feedback into the Amazon lowlands environmental processes.

The first part of this chapter describes the present glaciological knowledge on these Andean ice masses that flow towards the Amazon drainage basin, about 1666 km^2 (of which 68% are in Peru, 24% in Bolivia and the remaining 8% in Ecuador). The mass balance of these glaciers is strongly dependent on the Amazon hydrological cycle because the main source of their snow precipitation are air masses bringing water from the Atlantic Ocean, this water is recycled through the rainforest several times. So, this part of the text also discusses the present atmospheric circulation and how it controls precipitation over the eastern tropical Andean mountains (characterised by a wet and a dry season in Bolivia and Peru) and how signals of changes in the Amazon atmosphere (e.g., pollutants such as black carbon due to biomass burning and trace elements [1]) may be transported to these glaciers. Another important point to consider is how the El Niño-Southern Oscillation (ENSO) phenomenon controls the yearly precipitation variability on these glacier sites.

A second part of the chapter explores how two environmental systems are interconnected and interacted. Not only the existent ice masses are strongly controlled by environmental processes in the rainforest, but the glaciers self-affect their lowlands as providers of sediments [2]. Here, we consider these glaciers as sources of sediments (the Andes tributaries contribute to 90–95% of the Amazon River load [3]), organic matter and nutrients to Amazon basin and how they affect the biochemical, ecological and geomorphological processes. An important point examined is how the melt water variability affects the drainage in the headwaters of the basin (in Bolivia and Peru), and what they represent as water storage and hydric resources for the mountain communities.

The third part of chapter examines the present (last 50 years) human-made changes in the Amazon basin and how they affect the Andean ice masses. The Amazon environment has undergone major changes due to immigration (and the consequent increase of the population in major cities), and intense deforestation (mainly for soy and cattle-culture expansions), affecting the characteristics of the lower atmosphere, changes in land use and land cover also alter and transform the dynamics and formation of clouds [4]. These processes may decrease the precipitation over the Eastern Andes [5], reducing further ice cover already under fast retreat due to climatic warming [6]. One of the main points here to consider is how the loss of mass of these glaciers will affect the water resources of Bolivia and Peru, the former one already under strong hydric stress.

These glaciers also hold the best proxy for the Amazon Holocene changes, the record left in the snow and ice chemistry. So, as a complement to this chapter, we review the information on the paleoenvironmental changes found in ice cores in Bolivia and Peru [1, 7] and what they may point about the future of the Andean tropical glaciers.

2. The present glaciological knowledge on the Andean ice masses that flow towards the Amazon drainage basin

The tropics can be defined as a region where the atmospheric circulation dynamics and the energy conditions present high thermal homogeneity (**Figure 1**). For this reason, the annual

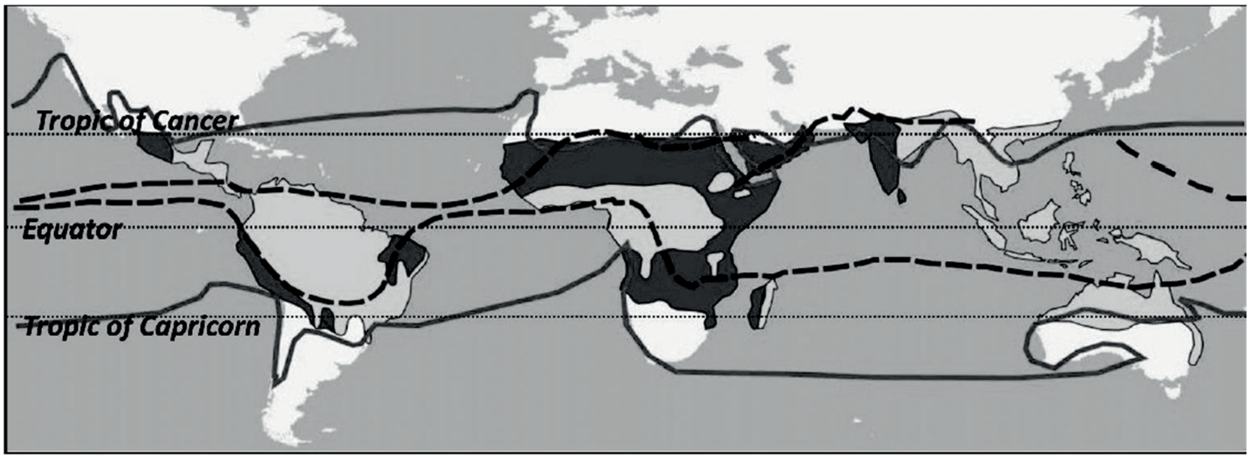

Figure 1. The tropics: in light gray, are the areas that present high precipitation throughout the year; and in dark grey, are the areas with a wet and dry season during the year. The dashed lines identify the seasonal oscillation of the intertropical convergence zone and the continuous lines delimit the tropical zone from the thermal point of view, adapted from Kaser and Osmaston [9].

thermal amplitude is lower than the diurnal temperature variation [8]. In the tropics, unlike the temperate regions, the linear behaviour of the temperature causes the 0.1°C atmospheric isotherm to remain practically at the same altitude, allowing the occurrence of ablation in the glacier terminus throughout the year. At these latitudes, all ice masses are at the pressure melting point and they are classified from the thermal point of view as warm glaciers [9].

In the tropical regions, the conditions of humidity and precipitation (responsible for accumulation) are directly related to the oscillation of the Sun position throughout the year. With a delay of a few weeks in relation to this solar variation, the intertropical convergence zone (ITCZ) position reaches once a year its maximum latitude in a hemisphere, causing a wet season and a very different dry season between these two points of change [9].

In the tropics, glaciers exist in South America (from Bolivia to Venezuela), Africa (Kilimanjaro, Mount Kenya and Rwenzori) and Oceania (West Papua). The Andes have approximately 99% of the ice masses located in the tropics [9]. Tropical South America has an ice cover of 2500 km^2, in which 70% are in Peru, 20% in Bolivia and 10% in Ecuador, Colombia and Venezuela.

The morphology of these sub-equatorial ice masses caused perplexity to the first European travellers. Unlike Alps glaciers, tropical glaciers do not form extensive tongues that flow down the valley walls; they are small in size, like small ice caps, which only cover the mountain peaks [10]. According to Kaser et al. [11], this morphology of the terminal part of the glaciers is due to the continuous annual ablation, unlike what is found in the middle latitudes. Another difference pointed out by the same authors [11] is the glaciers response time to the climatic conditions. In the tropics, the proportion of glaciers that have their area entirely within the ablation sector (glaciers with less than 1 km^2) is higher than in the middle latitudes. Consequently, tropical ice masses respond faster to climate changes than the middle latitude ones.

The distribution of these tropical glaciers is controlled, fundamentally, by two factors: altitude and precipitation. In the former one, the high mountains 'block' the humidity driven by the air masses, providing conditions for the formation of glaciers. The second one is determinant for the equilibrium line altitude (ELA), because the glaciers will only exist where ELA is below the ridges of the mountains [8].

In the Andean mountains, the precipitation is regulated, mainly, by winds coming from the east, which originates on the Atlantic Ocean and mixes to the air masses of the Amazonian origin. The glaciers are distributed predominantly from 12°N to 23°S, in an area tectonically lifted above 5000 m, which 'intercepts' air masses coming from the Amazon forest. This results in a negative precipitation gradient from NE to SW. For example, in northern Bolivia, the ELA is between 5300 and 5800 m a.s.l. Further to the south in this country, even areas 6000 m a.s.l. can be free of ice due to aridity [12].

Figure 2 shows the Amazon River basin and the glaciers that flow to it. For the year 2015, we determined that the 'Amazonian' glaciers covered 1666 km^2 (we obtained this result using the global land ice measurements from space: (GLIMS) database [13]). Of these ice masses,

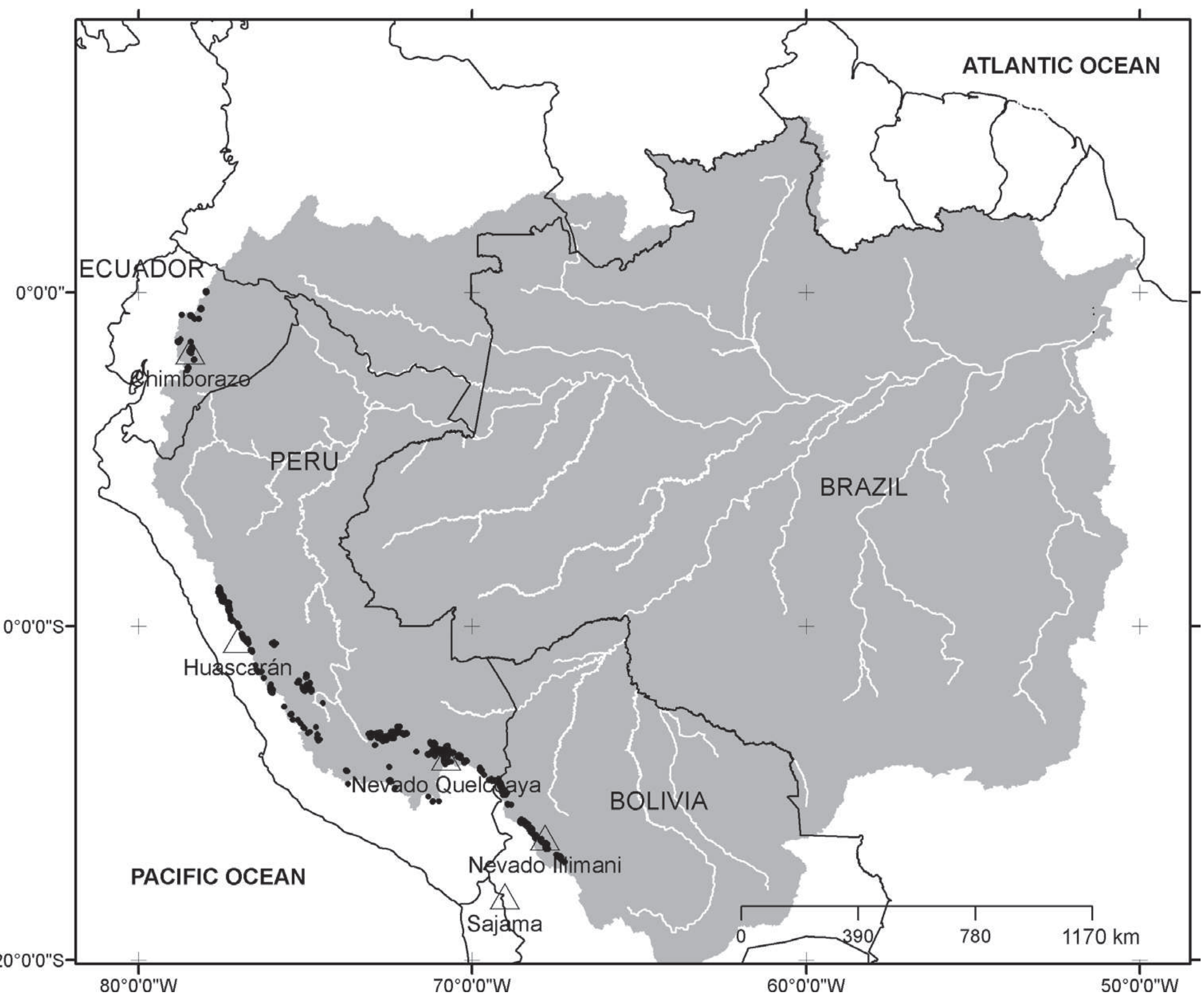

Figure 2. The Amazon glaciers (Andean ice masses flowing towards the Amazon River drainage basin) are shown as black spots. The main ice core sites extracted from the tropical Andes are shown as triangles. The gray area delimits the watershed of the Amazon River.

68% (1129 km^2) are in Peru, 24% (397 km^2) are in Bolivia and the remaining 8% (139 km^2) is in Ecuador. The glacial regime of these ice masses shows yearly humid and dry seasons (Peru and Bolivia) or precipitation throughout the year (Ecuador).

Changes in the Amazonian climate, due to deforestation, indicate that the river sources in the Andes mountains may suffer a significant decrease in their water supply (precipitation) as a result of the reduction of atmospheric humidity [6]. Consequently, the Andean countries may suffer significantly from the rainfall reduction in the Amazon forest [15], as it is already observed, in a similar process, in mountains in western Costa Rica due to deforestation to the east [14]. The Amazonian basin and its forests (by evapotranspiration) affect, therefore, the rainfall in the Andes. This decrease in precipitation, combined with the increase in global temperature, directly influences the behaviour of tropical glaciers [6].

However, the relationship between the hydrological cycle and the climate in South America, especially in the Amazon, still lack further studies. In this region, the weather station networks are very sparse and the lack of high-quality precipitation and river flows data make it difficult to study climate change and climate variability. Thus, it is important to obtain indirect indicators that provide regional environmental information; this point is discussed below when examining the Andean ice cores record.

In the Andean tropical glaciers, the accumulation measured above the 5500 m altitude varies from 0.70 to 1.20 m water equivalent per year. No higher accumulation is observed, which may be related to the low amount of water vapour transported by air masses above 6000 m or to strong winds that do not allow greater accumulations on the summits [16]. On the other hand, larger glaciers can take between 5 and 10 years to respond to changes in the environment. This means that a glacier front movement in a given year depends both on the mass balance in the ablation zone during the same year and on the entire surface of the glacier during previous years. This explains the importance of a long-term analysis on the variations in the glacier front position when studying trends of climate change [10].

The warming rate more than tripled from 1973 to 1998 (from 0.11°C to 0.32–0.34°C/decade); the hottest years were 1997 and 1998, El Niño years [17]. The retraction of several glaciers in the Peruvian Andes [18, 19] was concomitant to this warming. Although it is difficult to pinpoint cause and effect, it seems that climatic warming is the main driver of the rapid retraction and the disappearance of high-altitude ice fields and glaciers in the tropics. These high-altitude tropical ice masses are very close to their melting point [20]; therefore, they respond fast to any change in air temperature. Unlike glaciers in temperate regions in the southern hemisphere, where precipitation on the glacier occurs during the austral winter at low temperatures, in the tropics it happens during the warmer austral summer months. This causes the processes of ablation and accumulation to occur simultaneously, unlike the middle latitude glaciers. This makes your study an excellent indicator of changes in climatic patterns.

The recent glacier retreat in the tropical Andes is the greatest since their maximum extent in the Little Ice Age (LIA, mid-seventeenth to early eighteenth century) [21]. For the past 50 years, the mean mass balance for the Andean glaciers has been more negative at a global scale. This behaviour is attributed, at least partially, to a higher frequency of El Niño events and a warming of the regional troposphere. Several authors project that the smallest glaciers located below 5400 m a.s.l. may disappear before the end of the twenty-first century, given the present climate-warming trend [21, 22].

3. Interconnected and interacted environmental systems

Although greatly reduced in area today when compared to the last glacial maximum (LGM, about 18,000 years before the present), glaciers are important agents of erosion, carving and shaping the high Andean valleys. In addition, in periods when rainfall is scarce, ice melting maintains a minimum water flow and so supplies hydroelectric generation plants, urban centres, etc. Thus, glaciers act as regulators of the hydrological regime in many Andean regions [10].

The tropical Andes includes the headwaters of the Amazon River, which strongly affects its geomorphology, biochemistry and ecology [2]. This can be interpreted in terms of source of sediments, organic matter and nutrients for the lower basin sectors (**Figure 3**) and foreseeable alterations (such as ones due to the construction of dams) can cause major environmental changes [2]. These include the capture of large volumes of sediments and difficulties for the

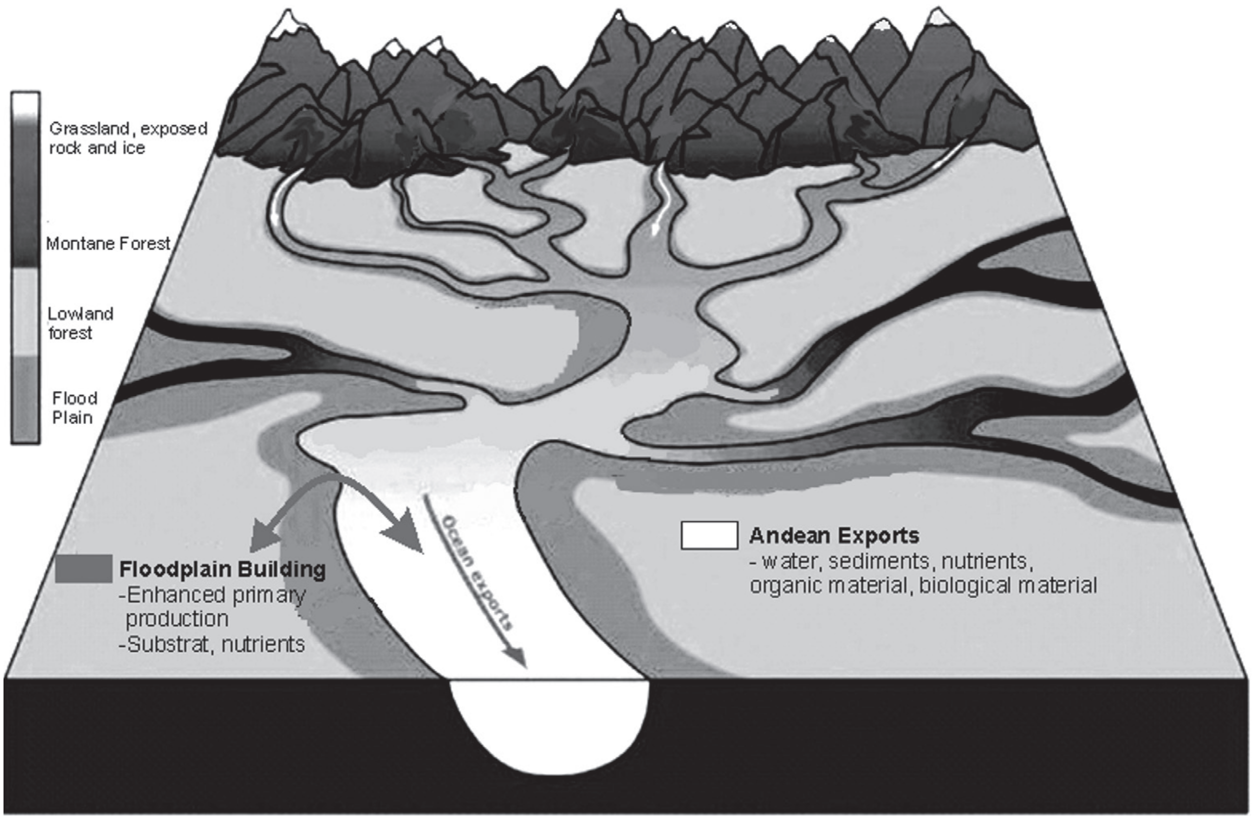

Figure 3. The influence of the Andes on the ecology and biochemistry of the Amazonian forest, adapted from McClain and Naiman [2].

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migrating fishes moving from and to the lowlands. It is estimated that less than a quarter of waters of the Amazon basin originate in the Andes, but a greater proportion of the suspended sediments may originate in the mountainous areas. The tributary rivers coming from the Andes provide 90–95% of the suspended sediments of the Amazon River [3]. Taking as an example the Madeira River, which has its headwaters in the high Andes in Bolivia, the total dissolved solids for the Bolivian lowlands at 7 mega grams (Mg) per km^2 per year and the contribution of the Andean basin at 80 Mg per km^2 per year [23]. As for the total sediment load exported from the basin to this river, more than 50% are deposited in the Amazonian plain [24].

There are few regional studies on the sediments flow and the variability of the processes that mobilise them in the Andes. From the transformation of fields to agriculture to the development of hydroelectric plants, this landscape is modified daily. These themes are of great importance, after all, are the most productive components of the Amazon system that are being altered.

The Andean rivers, due to their favourable topography and climate, have a considerable potential for hydroelectric power generation. Practically, half of the regional electricity comes from this power source and small power plants are quite common. Hydroelectricity generation supplies 80, 45, 70 and 40% of the Colombian, Ecuadorian, Peruvian and Bolivian needs, respectively [25]. Studies are developed to identify future demands for energy and to increase the utilisation of the hydroelectric potential in the region with the construction of several small power plants, mainly in Peru and Ecuador [26, 27].

4. Human-made changes in the Amazon basin and how they may affect the Andean ice masses

In the last decades, the Amazonian environment has undergone great changes due to immigration (and the consequent increase in big cities population), and the intense expansion of the soybean cultivation and cattle raising, resulting in an intense deforestation. This is very serious because the forest recycles around 50% of its rainfall, and even an area deforestation of about 30% will not generate sufficient precipitation to maintain itself, generating a negative feedback where ‘the greater the forest loss, the less precipitation’ [28].

Studies show that many of the South American tropical glaciers have suffered drastic reductions in their areas. To illustrate this, according to the Working Group on Snow and Ice of the International Hydrological Program of the United Nations Educational, Scientific and Cultural Organization (GTHN-PHI-UNESCO), the Cordillera Blanca in Peru have lost 26% of this glacial surface (from 1970 to 2003); for Bolivia, it is estimated a reduction in the order of 50% from the 1970s to the present day; in Ecuador, the glacier inventories points to a 27% area loss from 1997 to 2006 [29].

One of the factors responsible for the disappearance of these ice masses could be the increase in the mean annual temperature in the tropical Andes by approximately +0.8°C from 1970 to

2000 [30]. This is due to the increase in rainfall (in lieu of snow) in the lower sectors of the glaciers. Thus, ice is more exposed (<albedo), increasing the amount of energy absorbed by the glacier surface and intensifying its melting [31]. This situation means that small glaciers (<1 km^2), located at low altitudes, do not recover their deficit, even during the colder years. Therefore, they are in serious danger of disappearing [16].

The Amazonian climate is regular, being exceptionally modified during El Niño events, which changes the rain regime bringing dry periods in the rainy season (December/January/February) [32]. During this climatic event, the intertropical convergence zone (ITCZ) moves farther north than its normal position on the tropical Atlantic Ocean. As a consequence, we have weaker trade winds from the northeast that reduce the moisture that penetrates into the interior of the Amazon region, and so, inhibiting the formation of convective activity. Another consequence is the increase in temperature and carbon dioxide levels. As successive dry years (due to El Niño) reduce the vegetation, primary photosynthesis increases by human intervention, fires in the forests, mainly in Brazil and Bolivia [33].

For precipitation, however, no trend is evident and its variability may be associated with regional particularities, marked by its relation to ENSO phenomenon. El Niño events are associated with temperatures 1–3°C above the average in the Central Andes, which causes an increase in the melting of glaciers and decrease in cloudiness, which end up keeping albedo values low [34]. In hydrographic basins that have essentially a glacial regime, melting flows dominate during El Niños events. On the other hand, in the hydrological basins with few glacierized areas, the water runoff increase by melting is not enough to compensate for the deficits produced by precipitation scarcity (i.e. Bolivia and southern Peru). The greater frequency of El Niño events, since the 1970s, associated with the increase in the mean annual temperature, explains part of the retreat of the tropical Andean glaciers [21, 29].

The irregular behaviour of the El Niño–La Niña events is one of the main uncertainties in the climate projections for the Andes. Thus, a reliable prediction for this region is difficult, since the runoff depends heavily on the occurrence of these events. El Niño accelerates the retreat of the glaciers by rising temperatures (in Bolivia, Peru and Ecuador) or by the decrease of precipitation (in Bolivia and southern Peru). Therefore, the models for this region should be treated with great care [35].

Current projections suggest that the mean temperatures in the Andes can increase by 4.5–5°C in the twenty-first century [36]. As for the disappearance of the glaciers, there will initially be an increase in the flows of the rivers in the basins supplied by melting water, followed by a drastic decrease in the volume and in the regularity of the water resources, and finally, the hydrological regime will become more and more nival-pluvial.

The flow volume of the rivers in the Cordillera Blanca (Peru) drainage basin may disappear between 2175 and 2250 [37]. In Colombia, the retraction of the glaciers will result in water availability problems between 2015 and 2025 [38]. In Ecuador, the reduction of melting water will not only affect headwater areas, but also especially the production of water in the páramos (moorlands) and existing aquifers [31]. The issue becomes even more complex when we take into account the domestic water use, countries like Ecuador and Colombia depend fundamentally on the flow of páramos water (this is a mountain ecosystem, which has great potential for water storage) of the Andes [36, 39, 40]. In addition, in Bolivia and southern Peru, the water source predominantly comes from the high Andean rivers.

As most tropical glaciers are less than 200 m thick and have a small ice volume, their total melting would cause an insignificant increase in sea level (±0.1 mm). If we consider the melting of all mountain glaciers in the world, this increase would be of only 24 cm [16]. If the entire ice sheets of Antarctica and Greenland melted, it would produce an increase of approximately 72 m in the sea level. Thus, the study of tropical glaciers as regulators of regional water availability, as well as 'production' of sediments and nutrients for the Amazon basin, is of great importance, but the impact on the sea level is negligible.

In future scenarios of climate change, it is anticipated that many of the small mountain glaciers located in low-lying areas of the tropics will disappear in few decades. In addition to the decline in water resource, shrinkage of tropical ice masses will also create hazards, such as instability in mountain slopes, glacier detachment, avalanches and lagoon overflow, as well as changes in ecosystems [36, 39, 41]. An increase in the frequency of extreme events (e.g. storms) may have implications for slope stability, with risks for cities in areas at lower elevations. The effects on the nutrient cycle are still uncertain [2].

The expected environmental changes will cause profound modifications in the flow patterns of many rivers. These modifications will reduce the rivers capacity to provide ecosystem services (sources of water and food, recreation, assimilation of the páramos and flow control) [39, 42]. An alternative to this scenario would be the creation of water regulations and policies that recognise the need to maintain specific flow regimes to sustain ecosystems [43].

We highlighted the importance of the South American tropical glaciers for the Amazon basin at a regional scale. Although these glaciers cover a small area (about 2500 km^2), the impact of the environmental changes on them will have consequences for the Amazonian rivers. However, more studies are needed to determine the processes and scales of these modifications and develop mechanisms to protect the ecosystems associated with the Andean glaciers.

5. Andean glaciers also hold the best proxy for the Amazon Holocene changes, the record left in the snow and ice chemistry

Reliable climatic data from the Amazon are still deficient; a detailed monitoring of large areas of the Amazon basin requires a dense network of rain gauges, which in some cases is not feasible by topography and forest [44]. Therefore, any analysis in this region should be taken with caution [45, 46]. On the other hand, ice cores provide archives of the past climate record, on the climatic forcing at the time of its deposition (as changes in solar activity) and volcanic eruptions.

Several ice cores were extracted and analysed in the Andes for information on the environmental conditions of the tropics (**Figure 2**): in southern Peru (Quelccaya ice cap, 13°56′ S, 70°50′ W, 5670 m a.s.l.); in the Cordillera Branca, Peru (Huascarán mountain, 9°07′ S, 77°37′ W, 6048 m a.s.l.); in western Bolivia (Sajama ice cap, 18°06′ S, 68°53′ W, 6542 m a.s.l.) and in the central sector of the Andes (Nevado Illimani, 16°37′ S, 67°46′ W, 6350 m a.s.l.) [11, 47–51]. The Nevado Illimani record is particularly interesting for this chapter, as it is less than 500 km of the Amazon rainforest (receiving by advection the humid masses from this region), providing information on the composition and evolution of the atmospheric chemistry of the Amazon region [11, 51].

The annual climate over the tropics is dominated by two well-defined seasons (summer/wet and winter/dry) and the glaciers of the central Andes are fed during the wet season by precipitation coming from the Amazon basin. Therefore, we can consider the snow and ice layers of these glaciers as indirect indicators (proxies) of the environmental conditions of the South America.

The snowfall of the Illimani Nevado shows traces of biomass emission (e.g. ammonia, acetate, potassium) as a dominant contribution coming from the Amazon basin [52]. It is important to notice that water vapour recycles several times along its path from the Atlantic through the Amazon basin before precipitating in the Andes glaciers.

An alternative technique for the study of the climatic variables of a region can be based on the ratio in the stable isotope ratios (δD and δ^{18}O) in rainwater and snow [53, 54]. It is known that the present proportion of these elements is controlled by meteorological parameters (temperature, precipitation volume, etc.), which allows reconstructing/estimate the climatic conditions in the past. This technique also allows the identification of the air masses that undergo precipitation [47, 51, 53, 55, 56].

The analysis of the four ice cores extracted from the Andean tropics (Huascarán, Quelccaya, Illimani and Sajama) was based (mostly) on the information deduced from the content of hydrogen and oxygen isotopes. The results showed good consistency among the records, suggesting a similar climatic history for the twentieth century [51]. Initially, Lonnie Thompson from the Ohio State University used the isotopic oxygen content record to analyse temperature changes based on similar records for high latitudes [48, 49]. Notwithstanding, when comparing the meteorological records with the isotopic records for the tropical Andes, other authors [55, 57] identified a strong correlation between changes in precipitation and changes in oxygen values. These authors come to the conclusion that changes in precipitation origin and amount are more important than temperature (as originally proposed by for high latitudes [53]) as controller of the isotopic ratios in the tropics.

A study of the Huascarán mountain ice cores identified that zonal wind variations over South America at 500 hPa are closely related to the interannual variations in the δ^{18}O values [48]. This suggests that the sea surface temperature (SST) in the western tropical Atlantic influences the circulation at 500 hPa, the moisture isotopic fractionation process along its Amazon pathway and so, the δ^{18}O precipitation at the ice core site.

It is not known whether the temperature effect or the amount effect predominates in the isotopic signal in tropical glaciers [58]. The authors determined the correlation of δ^{18}O with the ENSO variability in the Illimani Nevado ice core, and identified that more negative values

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of this isotope ratio coincide with Pacific SST (sea surface temperature) below average. But this interpretation on stable oxygen isotopic ratios should be taken with caution, though it is assumed that the lowlands to the east of the Andes and the Atlantic Ocean are the sources of moisture for precipitation in the glaciers, the local conditions such as condensation and water recycling should not be overlooked.

The Atlantic Ocean, by the trade winds circulation, 'feeds' moisture into the Andean snow-fields, so the SST variability in the Andes precipitation is first 'filtered' across the Atlantic sector. When the Pacific is hot/cold, surface temperature anomalies are redistributed to the tropical Atlantic basin, so the moisture flow responsible for the precipitation in the Andes can be remotely controlled by tropical Pacific conditions [59].

Briefly, we can say that the primary moisture source for precipitation in the tropical glaciers of the Amazon basin is the Atlantic Ocean. So, the record of an Andean ice cores is a link between the meteorological processes of the Amazon basin, Andes and the Atlantic Ocean. Although the $\delta^{18}O$ variations in the tropical Peru are strongly controlled to ENSO variability [7, 60] on an interannual scale, the Amazon source has remained consistent since the late glacial stage (LGS) [61] and all Peruvian-Bolivian high-altitude ice core records reflect the Amazonian source.

The low nitrate record from the Huascarán and Sajama ice cores point to a less extensive Amazon Basin forest [20] during the LGS. This reduction of forest cover and expansion of savannahs are consistent with greater abundance of eolian particles at the Huascarán core site [20, 48].

For the little ice age (LIA, generally accept as a cool period from 1200 to 1800 C.E.), elevated concentrations of nitrate (NO_3^-) and relative low ^{18}O at the Quelccaya site are observed [7], interpreting these observations as a consequence of more moist condition to the south over the Amazon Basin. Furthermore, they observed that the LIA is a marked feature in three ice core records (Huascarán, Quelccaya and Illimani). During the past 200 years, $\delta^{18}O$ have increased, reaching the highest values for the past 6000 years [7].

Finally, the Illimani ice core records positive trends in trace species of anthropogenic origin (Cu, As, Zn, Cd, Co, Ni and Cr) from the beginning of twentieth century [1], high amounts of biomass emission tracers (ammonium, formate, acetate, oxalate, potassium) are found at the same core [62].

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