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CLIMATE CHANGE AND THE ANDEAN CRYOSPHERE

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KEY MESSAGES

The cryosphere is a major component of the Andes mountains.
Glaciers, snow-covered surfaces and permafrost represent a critical source of freshwater contributing to the sustainability of Andean populations' socioeconomic activities. Likewise, glaciers play a key role in the hydrological cycle acting as freshwater reservoirs and buffers for human settlements and natural ecosystems.

Climate change is already strongly affecting the Andean mountains, and will continue to do so in the future.
Temperature rise and changes in precipitation patterns in the Andes are leading to the decline of ice accumulation, accelerating glacier and snow cover retreat.

Andean glaciers are some of the fastest retreating and largest contributors to sea level rise on Earth.
Mass loss rate was found to be highest in the Southern Andes than in any other mountainous region of the world. Lowest altitude glaciers in the Tropical Andes are also retreating fast and at risk of vanishing due to their small size.

Glacier and snow cover retreat will have serious consequences for the region.
The Andean populations are already facing consequences such as changes in hydrological regimes, water scarcity, landslides, sea level rise, biodiversity and ecosystem services loss; and these are only expected to intensify along the century unless appropriate measures are taken.

It is crucial to enhance mitigation ambition globally to safeguard the future of glaciers and to avoid rapid and large scale deglaciation.
The magnitude and rate of snow and ice loss depends on how much greenhouse gas emissions are reduced in the next decades.

Andean countries will have to adapt to changes derived from a melting cryosphere.
There is a serious need for more effective adaptation planning and implementation, involving several actors at the international, national and subnational levels, and integrating scientific, ancestral and local knowledge. It is also urgent and necessary that Andean countries move forward in carrying out glacier inventories and discussing public policies and regulations to protect glaciers from other threats such as mining activities.

CONTENTS

INTRODUCTION

The cryosphere has unique functions and influences the physical, biological and social systems over a large part of our planet's surface. Glaciers and frozen grounds play a crucial role in feed back and regulation of the Earth's climate, simultaneously influencing the hydrological cycle and the sea level.

As all its components are inherently sensitive to temperature and precipitation changes, the cryosphere is a natural integrator of climate variability and provides some of the most visible consequences of anthropogenic climate change.

Almost all glaciers monitored worldwide are retreating due to human-induced atmospheric temperature rise. Because of human activities, many glaciers are in disequilimbrium with the current climate and, therefore, are projected to decline considerably in the future, even under the least warming scenarios. If adequate measures are not taken, the impacts triggered by the changes the cryosphere is experimenting today may become irreversible at relevant time scales for human societies.

Glacier loss and changes in seasonal snow cover have direct impacts on the availability of water resources affecting many communities and ecosystems. As a result of widespread melting, high mountains of the world are undergoing unprecedented large-scale environmental transformations, which imply deep and far-reaching impacts and even involve processes that further enhance global warming.

The Andean mountains are not an exception, and their glaciers are retreating at one of the fastest rates in the world. In some areas, they have already completely disappeared. The still remaining ice masses will continue retreating throughout the century, and their survival is at stake, threatening the ecosystems and societies depending on them.

The recent Intergovernmental Panel on Climate Change (IPCC) Special Report on the Ocean and the Cryosphere in a Changing Climate Change (SROCC) compiles the best available science on the widespread shrinking of the cryosphere over our planet[1]. This report seeks to expand this information at the regional level, reflecting the importance and status of the Andean cryosphere in a changing climate.

Scientific evidence has never been so sound regarding the impacts of our actions on the environment. As the landscape responds to climate change, we are running out of time to act. We hope this brief report will draw the attention of decision-makers, private sector representatives, civil society and the inhabitants of the Andean countries to the importance of taking immediate and collective measures to guarantee the safeguard and protection of their cryosphere.

THE ANDES

Snow-capped peaks, Cordillera Real, La Paz, Bolivia.

01.

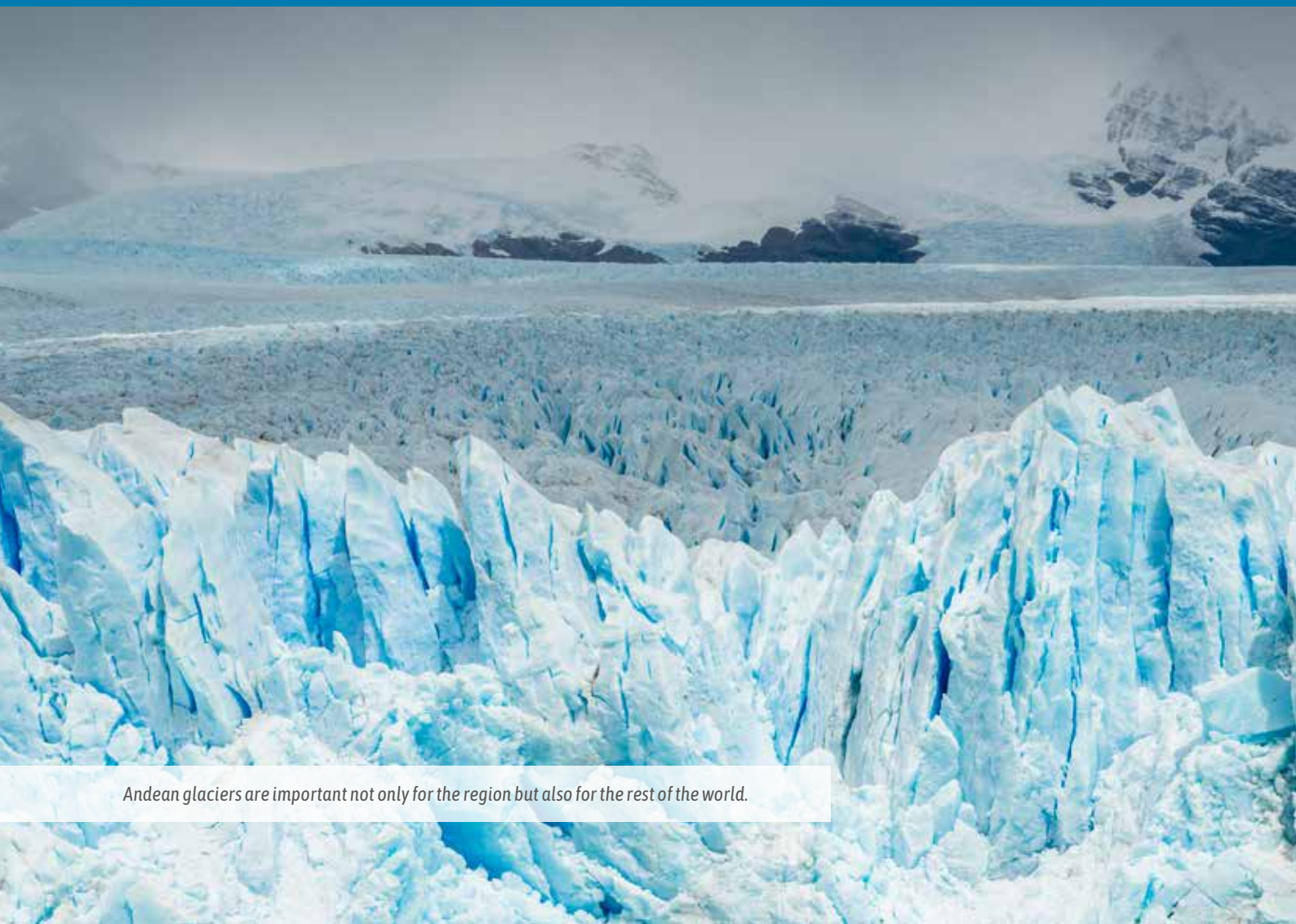
The Andes is the most important mountain range in South America, covering the contiguous region from eastern Venezuela to southern Argentina and Chile, extending through the territories of Colombia, Ecuador, Peru and Bolivia. Occupying more than 2,500,000 km^2, they are home to a population of about 85 million (45% of the total country populations), being the northern Andes one of the most densely populated mountain regions in the world[2]. A further 20 million people downstream, along the Pacific coast of South America, are also dependent on the resources and services the Andes provide.

Most cities across this mountain range are located along river banks dominated by seasonal meltwater from snow accumulated during the winter and mountain glaciers. Urban consumption, industries and agriculture are highly dependent on the water supplied by these rivers.

A large number of inhabitants live below the poverty threshold, and factors such as unsustainable land-use and management, increasing urbanization and climate change seriously threaten the sustainability of this region's development[2].

Mountain glaciers and seasonal snowmelt are critical freshwater sources representing a crucial contribution to the sustainability of the Andean populations' socioeconomic activities. Their disappearance would have serious ecological and social implications for these countries, affecting not only their landscapes and ecosystems but also their communities, regional infrastructure and development.

THE ROLE AND IMPORTANCE OF THE CRYOSPHERE IN THE ANDES AND WORLDWIDE



Andean glaciers are important not only for the region but also for the rest of the world.

02.

The cryosphere encompasses all regions of Earth's surface where water is in solid form. It comprises several components: snow-covered areas, river ice, lake ice, snow cover and ice shelves, sea ice, glaciers and polar icecaps, and frozen ground found not only on the surface (such as permafrost) but also beneath the oceans[3].

Glaciers and polar icecaps represent the main strategic freshwater reserves on the planet, acting as recharge sources for rivers, lakes and groundwater in arid regions and during drought periods. Besides being important for the hydrological cycle, they play a critical role in the global climate system and sea level through complex feedback mechanisms.

WHAT IS A GLACIER? WHAT IS AN ICE FIELD?

Glaciers are perennial ice masses that form on the Earth's surface by the accumulation and compression of snow, in a process lasting many years. They are dynamic bodies, slowly flowing downstream as frozen rivers. Glacial ice can range in age from hundred or thousand years, such as Patagonian glaciers, to millions of years as in Antarctica and Greenland[3].

On the other hand, ice fields are large areas of interconnected glaciers, usually found in a mountainous region, and their topography is determined by the shape of the surrounding landforms. They are larger than alpine glaciers, but smaller than icecaps and ice sheets[4].

GLOBAL CLIMATE REGULATION

The cryosphere plays a major role in the global climate. Snow and ice have a high albedo (reflectivity), that is, they reflect up to 90% of the incident solar radiation (as compared to 31% of the global average) thus regulating atmospheric temperature. Dark surfaces have a low albedo (they absorb energy and heat up), while white surfaces have a high albedo, reflecting a large part of the solar energy back into space. As atmospheric temperature rises, glaciers reduce in size and snow layers disappear making the surrounding dark soil absorb more radiation, producing more warming which in turn increases melting (positive feedback). At a larger scale, this feedback process accelerates global warming.

> The cryosphere plays a major role in the Earth's climate, helping to maintain an appropriate temperature range on our planet.

WATER REGULATION

According to temperature and precipitation variations throughout the year, glaciers accumulate water through heavy snowfalls during the wet and cold season, and lose mass through melting during warmer and drier periods, thus providing a buffer against drought and seasonal variability of precipitation.

In other words, glaciers act as "sponges", playing a major role in the regulation of water basins: these ice bodies accumulate water in humid periods, while in dry periods when water is scarce their melting ensures supply to river basins, lakes and other land water systems.

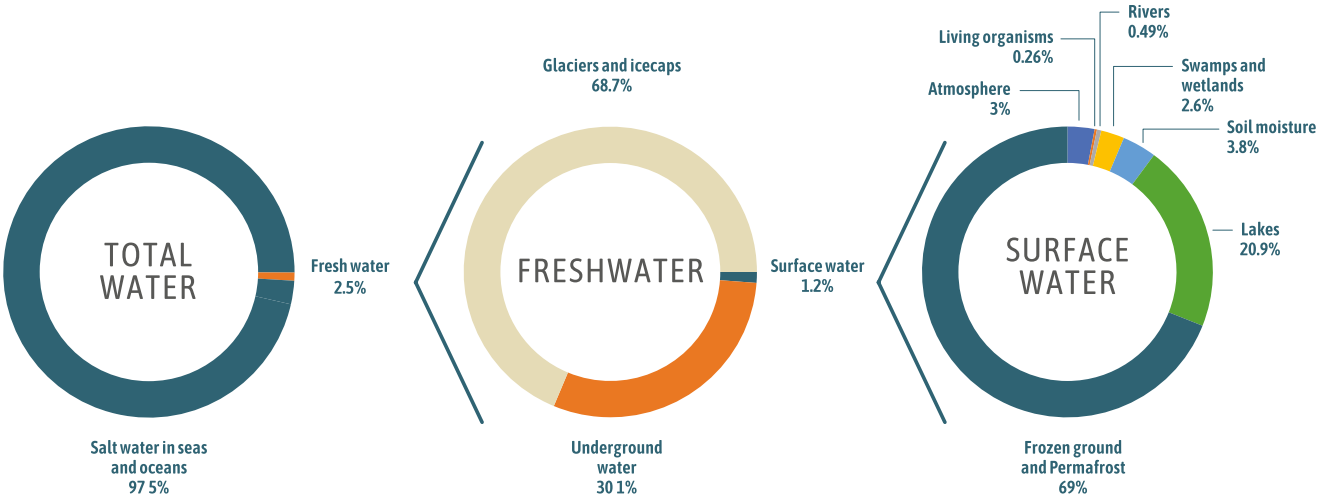
In the Andes and in many coastal plains of the region, glacial meltwater is the most important source for irrigation, hydroelectric power and drinking water supply for populations, especially during the dry season and drought periods. They also play a vital role for the ecology of many wetlands [5–7].

FRESHWATER RESERVOIRS

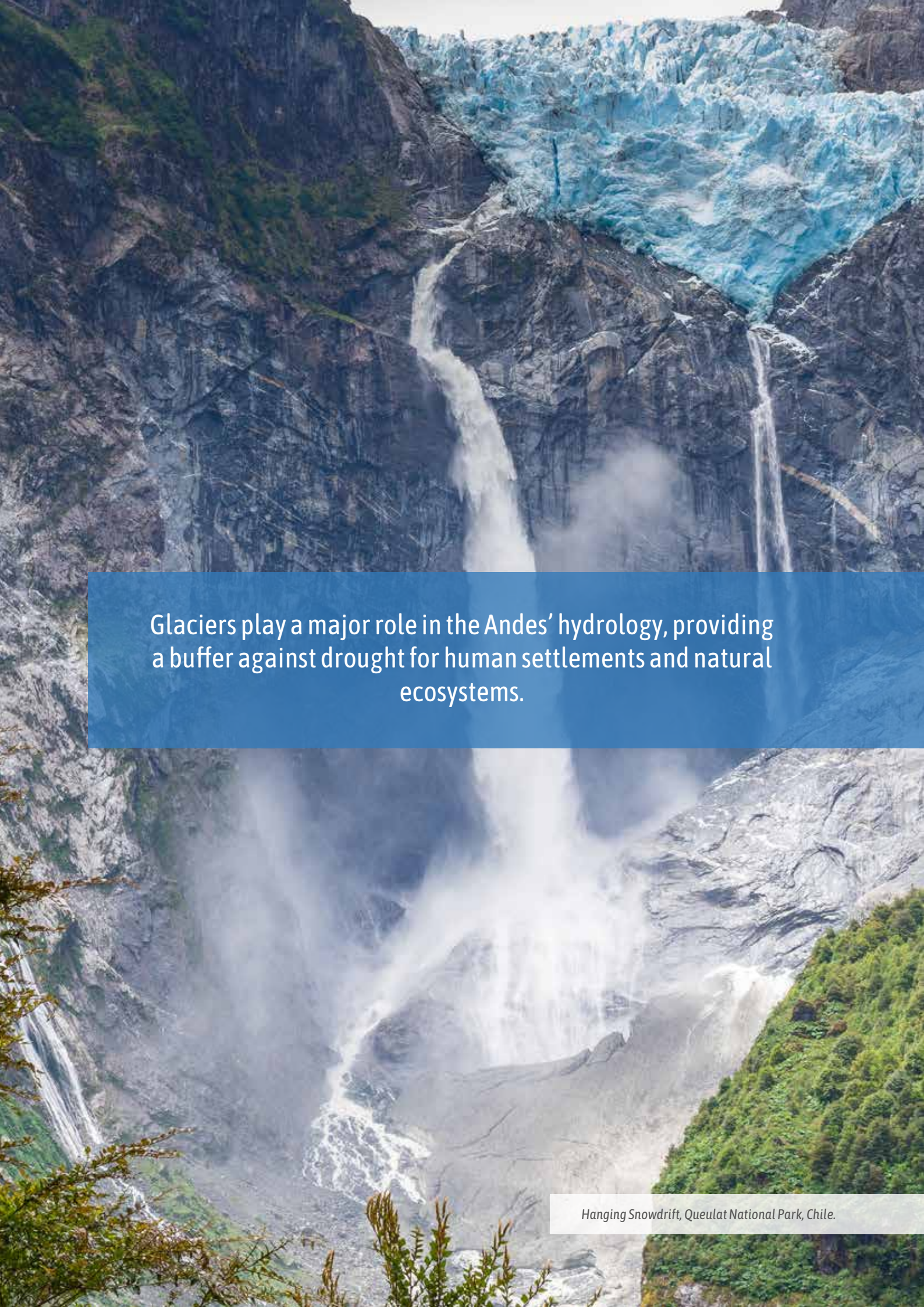
Freshwater is probably the most important ecosystem service provided by the cryosphere in this mountain range. Glaciers and rock glaciers practically store all of the strategic freshwater reserves in the Andes mountain range.

Meltwater plays a crucial role in freshwater supply for 75 million people living in the Andean region, and for other 20 million people living downstream. About 2.2% of the water supply in Quito (Ecuador) and 15% in La Paz (Bolivia) originate from glacial runoff[7, 8]. In the Peruvian region of Ancash, glaciers provide up to 67% of the water supply during the dry season, and up to 91% during severe droughts. The glacier-fed rivers in the Maipo river basin, the main water supply for the city of Santiago de Chile, provide 67% of the water by the end of dry summers[9]. Mendoza is the Argentine province with the largest irrigated area in the Central Andes of Argentina. The climate is dry and hydric resources depend mainly on snowmelt and glacier runoff.

To highlight the importance of glaciers as freshwater reservoirs, it is worth noting that less than 3% of the water on our planet is freshwater. Even more, most of this 3% is inaccessible for human consumption as 68% is frozen in polar ice layers, and just over 30% is found in underground reservoirs. Only 0.3% of the freshwater is accessible on the surface of our planet forming lakes, rivers and swamps [10].



Water distribution in the planet[10].



Glaciers play a major role in the Andes' hydrology, providing a buffer against drought for human settlements and natural ecosystems.

Hanging Snowdrift, Queulat National Park, Chile.

These figures indicate that the actual amount of freshwater accessible for humans and ecosystems is extremely limited.

Meltwater decrease, climate projections, population growth, urbanization, the expansion of productive and extractive sectors (large-scale agriculture, mining) and the increasing power and electricity demands show that the competition for water supply will continue to intensify in the Andean countries [11].

> Glacier runoff and seasonal snowmelt are critical water sources, representing a crucial contribution to the sustainability of Andean communities and their socioeconomic activities.

GLACIERS AND HUMAN ACTIVITIES

Agriculture

Glacier meltwater ensures not only freshwater supply but also hydrological stability for agriculture in many Andean valleys throughout the year. A good example of this is Del Santa valley in Peru, where the wide waters of the Cordillera Blanca supply the peoples and agriculture of mountain valleys along the adjacent coastal plain. The Longitudinal Valley of Chile (Intermediate Depression), with its Mediterranean climate, subsists thanks to meltwater originating the in Andean glaciers throughout the year. In this region, meltwater is the basis for its export-oriented and intensive irrigation agriculture [12].

Energy

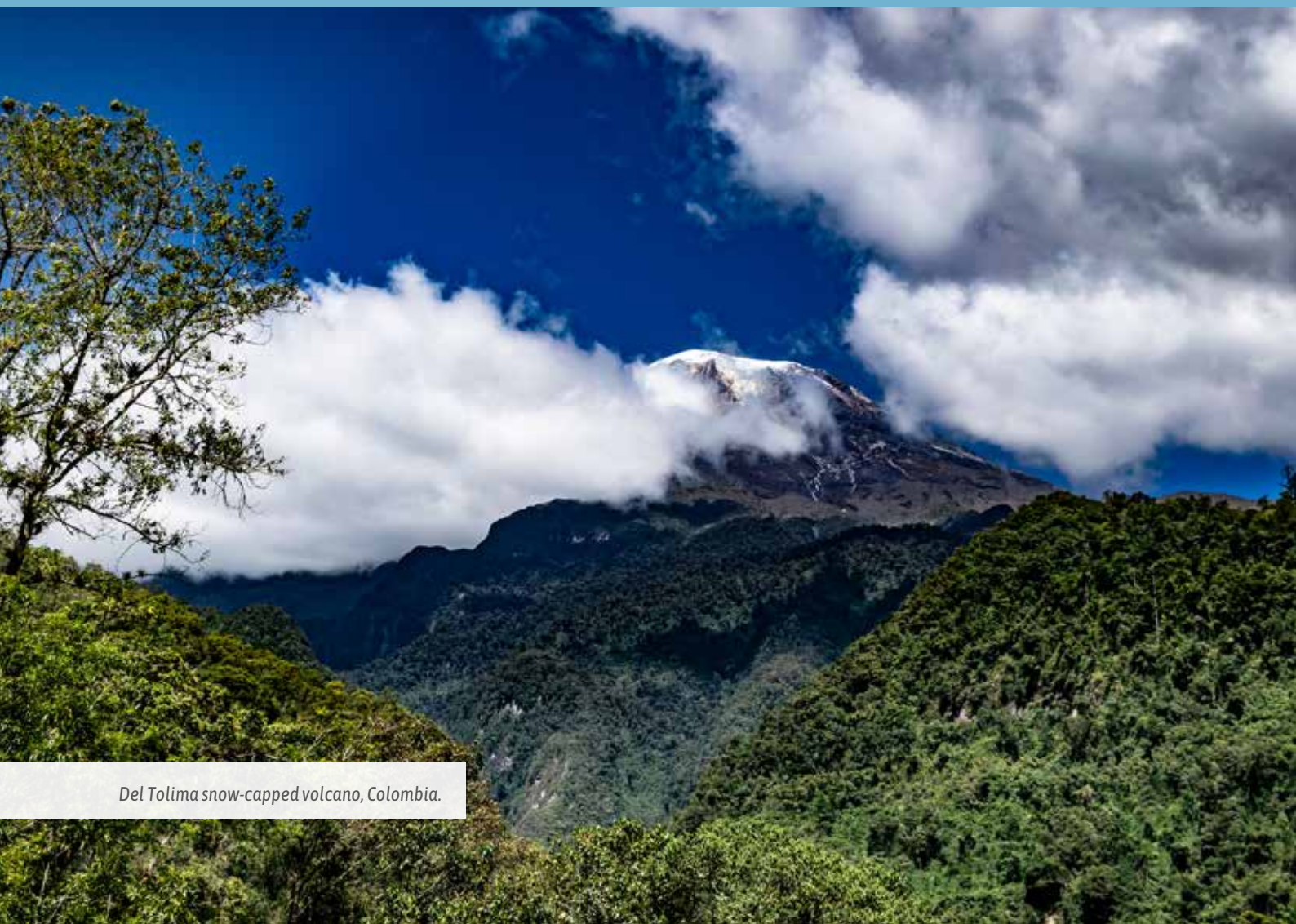
The Andean region has become highly dependent on hydropower, which represents 30% of total energy in Argentina and Bolivia, over 50% in Ecuador, and about 70% in Peru and Colombia. Current streamflow of many of these basins includes a substantial contribution of high mountain glaciers [13,14].

Tourism

Andean glaciers represent a great attraction for national and international tourists, providing economic benefits for mountain communities. For example, Los Glaciares National Park, in the Argentine Patagonia, receives about 450 thousand tourists per year, and Pastoruri Glacier, in Peru, used to receive 100 thousand tourists per year in the ‘90s, providing livelihood opportunities to thousands of inhabitants in the Cordillera Blanca.

Tourists walking on a Patagonian glacier.

ANDEAN GLACIERS



Del Tolima snow-capped volcano, Colombia.

03.

With an estimated number of about 18,990 glaciers (Randolph's Glacier Inventory, 2017), the Andes contain the largest glacierized area in the Southern hemisphere, outside of Antarctica.

The wide variety of topographic and climate conditions of this mountain range results in a great diversity of ice masses. Andean glaciers cover an ample range of altitudes, from the highest peaks and volcanoes of over 6,000 meters above sea level in the Tropical and Ecuadorian Andes, to sea level in Patagonia and Tierra del Fuego. Most of them are located along the border between Argentina and Chile, and only a small number can be found in the Tropical Andes (from Venezuela to Bolivia). The latter constitute more than 95% of the world's tropical glaciers[15].

TROPICAL ANDES

Venezuela

In 1952, 10 glaciers could be found in Venezuela's mountains. A recent inventory showed that today, only one of them remains: the Humboldt glacier[16]. This glacier is located on the northeast flank of Humboldt Peak, the second highest peak in Venezuela (4,942 MAMSL).

Colombia

In Colombia, the still existing small glaciers or nevados are located on the mountain peaks above 4,850 MAMSL, covering approximately 37 km2. There are currently only 6 glaciers, 4 of which cover the peaks of active volcanoes: Sierra Nevada of Santa Marta, Sierra Nevada El Cocuy or Güicán, Del Ruiz snow-capped Volcano, Santa Isabel snow-capped Volcano, Del Tolima snow-capped Volcano and Del Huila snow-capped Volcano [17].

Ecuador

The glaciers in this country are located closer to the equator than any other Andean glacier. They are confined to the highest summits of two mountain ranges: Cordillera Occidental (western range), where four glaciers are located, and Cordillera Oriental (eastern range), which contains three glaciers. It is more likely to find glaciers in the Cordillera Oriental because the Amazon's humid air favours snowfall in this region[18]. The glaciers located in Antisana and Cotopaxi volcanoes are particularly interesting because they contribute to water supply for the capital of Ecuador, Quito, where over 2 million people live [14,19,20].

Perú

Peru concentrates the vast majority of the world's tropical glaciers21 ranging from a minimum average altitude of 4,800 MAMSL to a maximum of 6,768 MAMSL.

Glaciated areas are found in 20 different mountain ranges, extending from the centre-north to the southern frontier of Peru. There are two main glacier systems: The first and the largest of them, Cordillera Blanca, begins at the Cordillera Occidental or western range, stretching along 200 km in the north-central part of Peru. Eight of the largest glaciers of this country are located on the Cordillera Blanca, the tropical mountain range with more glaciers in the world22. The second of them, the Quelccaya Ice Cap, located on Vilcanota Mountain Range, is the largest ice mass in this country.

Crater of Cotopaxi volcano, one of Ecuador's most active volcanoes, located 50 km away from Quito.

Glacier on Vilcanota Mountain Range, Peru.

Bolivia

Bolivian glaciers represent 20% of the world's tropical glaciers and are distributed along the Cordillera Occidental and the Cordillera Oriental. In turn, the latter is divided into four smaller mountain chains: Apolobamba, Real, Tres Cruces and Santa Vera Cruz Nevado. Eastern mountain ranges contain the majority of the glaciers consisting of icecaps, valley and mountain glaciers. The Cordillera Occidental preserves only a few small glaciers: the Sajama and others on nearby volcanoes. Due to reduced precipitation, glaciers are currently inexistent in the south of Bolivia [23].

> Over 95% of the world's tropical glaciers are located in the Tropical Andes.

Huayna Potosi, a glacierized mountain in Bolivia.

SOUTHERN ANDES

The Southern Andes (or extratropical Andes) run along the border between Chile and Argentina, and are home to most ice masses in this continent.

Chile

Chilean glaciers represent almost 80% of the total glacierized area of the Southern Andes. They extend from the Tacora volcano in the southern Altiplano to Hoste Island in Cape Horn. The first complete satellite inventory of Chilean glaciers identified 24,005 ice masses, larger than 0.01 km2, covering an area of de 23 708 ± 1185 km2 and corresponding to about 3.1% of the Chilean territory.

Argentina

Argentina's territory has 8,484 km2 covered with ice: 5,769 km2 in the Andes Mountain Range and 2,715 km2 in the islands of the South Atlantic [25].

In the Desert Andes, northwest of Argentina, glaciers are scarce but cover an ample area including the Puna and the Cordillera Oriental. In the rest of the inventoried regions, glaciers mostly concentrate in the eastern and most elevated portions of hydric basins, following the main Cordillera chains [25].

Area covered by glaciers in the Argentine and Chilean Andes, by climate region. Data obtained from Chile and Argentina's inventories [24,25].

Río Blanco Glacier (left), De los Tres Glacier (right) and Mount Fitz Roy, Argentine Patagonia

Balmaceda Glacier, Chilean Patagonia.

Patagonian Ice Fields

The Northern Patagonian Ice Field, located in Chile, and the Southern Patagonian Ice Field, shared by Chile and Argentina, represent the largest ice mass on the planet, excluding the polar icecaps in Antarctica and the Artic[26]. These Patagonian ice fields are the only remains of a much larger Patagonian Ice Sheet, which reached its maximum size about 18,000 years ago.

Currently, they cover a surface of 4,200 and 13,000 km2, respectively, discharging meltwater and ice into the ocean on the west and into the lakes on the east[26,27]. From these ice fields 49 calving glaciers run off, among which are: the Viedma (978 km^2), Upsala (902 km^2) and Perito Moreno (258 km^2) glaciers, in Argentina; and the Pio XI (the largest glacier in the Southern hemisphere, 1,265 km^2), Balmaceda, Serrano and Grey, in Chile.

Aerial view of Leones glacier and Leones Lake in Northern Patagonian Ice Field, Chile.

> The Patagonian Andes concentrate most of the glaciers in the continent and host the world's third largest ice field: The Patagonian Ice Fields.

THE IMPACTS OF CLIMATE CHANGE ON THE ANDEAN CRYOSPHERE

Perito Moreno Glacier calving in Argentina.

04.

CLIMATE CHANGE

The acceleration of climate change in the last decades exceeds both in magnitude and speed any other temperature variation in the past two millennia.

Scientific evidence for human influence on the global climate is overwhelming and many of the changes observed since the '50s are taking place at an unprecedented speed[28]. Global mean temperature rise observed since the mid-20th century is unequivocally being driven by increased anthropogenic emissions of greenhouse gases (GHG) into the atmosphere. Human-induced global warming has reached 1°C above preindustrial levels, and this increase has already had severe impacts on human and natural systems all over the world[29]. These impacts are evidenced in the increase of global atmospheric and ocean mean temperatures, cryosphere melting worldwide and sea level rise.

The recent IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC) points out that, under all climate scenarios considered for the 21st century, surface air temperature rise in high mountain regions will surpass the average rates of global warming[1]. It is very likely that the Andes will experience increasingly warmer years and that this warming will continue accelerating the retreat of glaciers and snowed surfaces.

This report also concludes that the vast majority of glaciers monitored in the world's high mountain regions have been retreating and losing mass at increasing rates in the last two decades. Alarmingly, the southern Andes experienced glacier mass loss at one of the largest rates in the world.

THE ANDES IN A CHANGING CLIMATE

Numerous studies confirm that the Andes have undergone significant warming in the last century. However, the degree of warming in different locations differs significantly, mostly because of the topographic variations and elevation dependent warming.

In the Northern Andes (Venezuela, Colombia, Ecuador and Peru), annual mean temperature has increased by about 0.8°C during the 20th century[30]. In the Andean mountains of Chile and Argentina, the temperatures have increased between 0.2°C y 0.3°C per decade since the middle '70s and they are still rising [31, 32].

The rate of surface air warming intensifies with elevation, a phenomenon referred to as elevation dependent warming (EDW). Thus, higher altitudes experience much faster temperature changes than less elevated surroundings[33]. During the last 50 years, surface warming in the highest areas of the tropical Andes has increased by about 0.1°C per decade[32].

Precipitation trends are difficult to estimate in the Andes since it varies substantially with time and location and reliable long-term observational records lack. Besides, annual precipitation is subject to considerable variability as it depends on location and is under the influence of El Niño events.

However, the overall tendency during the last two decades was a generalized reduction of snow-cover, associated with temperature increase. The snow line is moving upwards as a consequence of the freezing level altitude increase (0°C isotherm). This tendency was particularly significant in the Central Andes and in the eastern flanks [34].

CLIMATE PROJECTIONS FOR THE ANDES

Climate projections indicate that temperatures in the Tropical Andes could increase between 2°C y 5°C by the end of the 21st century, while in the Southern Andes an increase between 1°C y 7°C is estimated[28, 35].

Most climate models predict precipitation increases during the wet season and decreases during the dry season in the Tropical Andes. Under a high emission scenario for 2100 (RCP 8.5), precipitation is projected to increase across the coastal regions of Colombia and Ecuador, in some areas across the Eastern Andes and south to the equator. However, precipitation decreases are projected for the Southern Tropical Andes region, including the Altiplano, which would lead to stronger droughts. Regarding the Southern Andes (Chile and Argentina), significant precipitation decreases are expected for the next century [28].

The fractures on Grey Glacier, Chile, evidence the impacts of climate change on Patagonian glaciers.

OBSERVED CLIMATE CHANGE IMPACTS ON THE ANDEAN CRYOSPHERE

In the Andean mountains, progressive warming and changes in precipitation patterns are leading to a reduction of ice accumulation and accelerating glacier and snow cover decline at an alarming rate[36, 37].

Between 2000 and 2018, the total ice mass loss rate in the Andes was 22.9 Gt per year. This means that, in the whole region, glaciers lost in average about 0.70 meters of water equivalent per year, that is, above 12.5 meters of water equivalent in 18 years[37].

Glaciers in the southern Patagonian Andes and Tropical Andes suffered more severe mass reductions compared to the relatively moderate losses evidenced in the Dry Andes. This mass loss has maintained a high and constant rate for the last 20 years[37].

In the Southern Andes, the average glacier mass loss was one of the highest in the world during the last three decades, likely surpassing the loss in any other mountainous region of the planet[1, 37].

Tropical Andean glaciers are particularly vulnerable to climate change because they maintain a close to melting point temperature throughout the year, especially those smaller glaciers located at lower altitudes[38]. Slight temperature changes have important consequences for glacier mass balance in these regions.

Glacier decline due to climate change is being evidenced in every Andean country:

Venezuela has lost all but one of its glaciers: the Humboldt glacier. However, it is foreseen that this glacier will also disappear by 2021[16].

In Colombia, rapid ice retreat has taken place throughout the century and it has only accelerated in the past decades. Eight tropical glaciers in Colombia have disappeared during the 20th century[39] and this trend will likely persist during the 21st century[40]. Only the largest glaciers located on the highest peaks are predicted to continue existing until the second half of this century.

Ecuador's glaciers have suffered a dramatic retreat in the last 50 to 60 years, and this retreat is expected to continue along the century. Glacier mass loss in the region near Quito has been substantial in the past decades, and this trend is expected to continue under different climate change scenarios[15, 41]. For instance, Cotopaxi volcano has lost about 52% of its ice cover between 1976 and 2016[18, 42, 43].

In the last 50 years, Peruvian glaciers lost between 40 and 98% of their area. This country is home of the largest number of tropical glaciers in the world and its glaciers have experienced a huge retreat in all mountain ranges, the Chila Cordillera being the most affected[44]. Vilcanota Cordillera lost half of its glacierized area between the end of the 1970s and the beginning of the 2010s[45–47]. It is estimated that the Quelccaya glacier, an important water resource for the city of Lima, lost 42% of its size during the 1990s and 2000s[48].

In Bolivia, as from the 1960s, Cordillera Real glaciers have lost about half of their mass[49]. Many of these glaciers, with an area below 0.5 km2, are so small that they are extremely vulnerable to further retreat. Chacaltaya glacier, located in the Cordillera Real, used to be a small ski resort for the urban population of La Paz. By 2009, this glacier had completely disappeared.

In the Andes of Chile and Argentina, most glaciers are also retreating at rates that have been increasing in the last few decades[37, 50, 51]. In consequence, glacial lakes have increased in number (43%) and in extension (7%) between 1986 and 2016[52]. The great glaciers of southern Patagonia have experienced the most staggering retreat.

Pastoruri glacier, in the Cordillera Blanca, Peru, has lost a large part of its original size due to climate change.

Glaciers are retreating in all Andean countries: estimated glacier mass loss rates are highest in the Southern Andes, placing them among the fastest retreating in the world. Tropical Andes glaciers are also seriously affected and especially vulnerable to further decline.

This sub-region contains the Patagonian Ice Fields, and is characterized by a large number of outlet glaciers calving into lakes and the ocean. In the past two decades, the Southern Patagonian Andes exhibited one of the most negative mass balance rate of the world's mountainous regions[1, 37]. The melting rate and the contribution to sea level rise of Patagonian Ice Fields significantly increased during the 20th century[37, 53, 54]. Some estimates indicate that meltwater from these ice fields represents almost 10% of the total increase of the sea level in the planet attributable to mountain glaciers during the past 50 years[37, 54]. Northern Patagonia and Tierra del Fuego glaciers also show negative mass balances. Between 2000 and 2009, glacier mass balances in the Desert Andes, Central Andes and Northern Patagonia stayed relatively stable, in contrast with what was being evidenced in other regions. However, in 2009, this shifted and glaciers in these areas started retreating drastically[37]. Moreover, some glaciers located at higher altitudes are also retreating, though at a lower speed, and a few of them are still advancing due to the local climate dynamics.

WHAT WILL HAPPEN TO ANDEAN GLACIERS IN THE FUTURE?

As pointed out before, temperature increase and changes in the precipitation regime associated to anthropogenic climate change are directly affecting glacier behaviour and balance, accelerating melting. Glaciers are complex systems, meaning their regimes and balances are affected by multiple non-linear interactions between different processes and factors. Therefore, their behaviour is mostly determined by particular local conditions.

The first global study on glaciers of the International Union for Conservation of Nature (IUCN) used combined data from an inventory documenting 19,000 glaciers as World Human Heritage sites, and predicts that almost 50% of them could completely disappear by 2100 if GHG as-usual emissions continue[55]. These sites include Los Glaciares National Park in Argentina, which contains some of the largest glaciers on Earth. According to this study, the Park could lose about 60% of its current glacier ice by 2100[55].

The IPCC SROCC concludes that glaciers in almost all mountain regions will continue to decline throughout the century, but highlights that the projected average mass reductions for 2015-2100 vary between different emission scenarios: 18% reductions are estimated for a low-emission scenario (RCP2.6) increasing to 36% under a high-emission scenario (RCP8.5)[1].

For low altitude regions, this effect will become even more drastic: in the Tropical Andes, glaciological models for all emission scenarios suggest that glaciers will dramatically reduce in size in the future. Again, the magnitude of this loss depends on the emission scenarios: volume losses of 78-97% are predicted under a moderate warming scenario, while losses rise to 93-100% under a high-emission scenario [56].

> All climate projections indicate that Andean glaciers will continue shrinking throughout the century. The magnitude and, thus, the impact of this retreat depends on how much GHG emissions are reduced in the next decades.

EACH DEGREE MATTERS: THE IMPORTANCE OF REDUCING GLOBAL EMISSIONS

Even though the most optimistic scenarios foresee that many glaciers will disappear and others will retreat substantially, the magnitude of this decline varies under different emission reduction scenarios.

New studies show that the differences of glacier retreat under low and in high emission scenarios during the 21st century and the associated impacts are significant[57–61]. While some studies suggest that reducing emissions would have a rather limited effect on glacier mass loss in the 21st century, mitigation will exert strong control in the long-term. Preventing the total disappearance of these ice masses implies an enormous benefit for future generations[61].

Between now and the end of the century, glacier melting under a 1.5°C scenario would contribute 7.6 cm to sea level rise. This figure rises to 8.9 cm under a 2°C temperature increase scenario, and up to 14.2 under a high-emission scenario [61].

In the Peruvian Andes, ambitious emissions reduction could safeguard 40% of current glacier areas. On the contrary, a high-emission pathway would result in the almost complete disappearance of tropical glaciers by the end of this century, entailing serious consequences[60,62].

These findings highlight the tremendous importance of strengthening climate commitments and action at the global level, enhancing mitigation ambition and implementing strong GHG emission reduction policies.

> Enhancing mitigation ambition and climate action at global level is crucial to safeguard the future of the cryosphere, and to prevent large-scale deglaciation.

OTHER THREATS: MINING

Mining activities in the Andes have been highly destructive for these mountain's ecosystems, including páramos, salt pans, High Andean Wetlands and glaciers[63]. National and international mining enterprises have contributed to the direct destruction of many glaciers in numerous countries of the region, and particularly in Chile. Some mischievous activities that affect glaciers locally are: road construction during the exploration stage, where glaciers are covered with sand, salt and rocks; excavation extraction and the use of explosives; spillage of oil, petrol and toxics; massive ice removal with machinery; and burying glaciers under sterile dumps, thus accelerating their sliding speed due to the increased weight.

To date, mining industry has covered, removed and put at risk millions of cubic metres of glacial ice in the Mapocho and Aconcagua basins in the Chilean Andes[64]. Some national and sub-national governments have strong interests in maintaining and promoting mining whatever the environmental cost, because this activity represents an important sector of their economies.

Water use in the mining industry is not a minor issue either, as numerous mining concessions and operations are located in areas with water shortage, such as in the Atacama Desert, in the far north of Chile. Moreover, the chemicals and waste materials from these activities usually pollute and acidify freshwater.

> In a context of climate change and increasing water shortage in many Andean countries, the expansion of mining activities becomes incompatible with glacier preservation and, therefore, with guaranteeing access to water as a fundamental human right.

CONSEQUENCES

Peruvian woman sowing in a field close to Maras, in the Sacred Valley, Peru. Local farmers from surrounding areas still follow traditional agricultural practices.

05.

Glacier decline has and will have unprecedented systemic and synergic effects. Their retreat is already changing runoff contribution in many mountain basins in the world[65].

It is predicted that snow line changes and glacier retreat will keep causing natural hazards and risks for biodiversity, terrestrial and freshwater ecosystems, agriculture, hydropower, recreational activities and infrastructure. In turn, this melting reduces the global albedo effect and further increases global warming in a positive feedback process.

These changes will pose great challenges for livelihoods and other economic activities within and beyond the mountain regions of the Andean countries. Adequate adaptation measures must be adopted to mitigate these impacts.

It is worth noting that consequences derived from glacier loss are particularly severe when people have limited adaptation capacity to changes in water availability due to a lack of financial resources and knowledge, or when water demand is increasingly intensified [66].

Dangers and impacts observed in ecosystems and human systems during the last three decades attributable, at least partially, to cryospheric changes in the Andean region. Adapted from: IPCC, 2019[1].

FRESHWATER SUPPLY

Accelerated glacier loss leads to great changes in seasonal hydrological regimes, affecting glacier meltwater contribution to the available water supply, and maximum runoff timing [67].

Although glacier retreat causes an increase in water availability in the short term, their disappearance will cause very abrupt changes on seasonal flows due to the lack of a buffer during the dry season[67,68]. Peak water, is the tipping point of glacier melt supply, when runoff in glacier-fed rivers reaches the maximum, and starts steadily decreasing thereafter. Annual runoff will gradually shift from continuously supplying water to concentrating its largest contribution in the rainy season while providing scarce or zero supply in the dry season[69]. This situation has severe impacts on water availability for human consumption, agriculture and hydropower generation.

Many Andean highland rural areas are particularly vulnerable to water scarcity, especially in arid and semi-arid regions. Greater river runoff changes are expected in regions where rivers flow through seasonally arid areas, such as Perú[70]. Water stress is further exacerbated in these regions as they are typically rural communities at poverty risk and limited adaptation capacities [71–74].

> Glacier water storage and supply reduction as result of climate change has significantly affected Andean hydrological regimes, and this trend will continue in coming years.

In the arid Andes of Chile and Argentina fluvial discharge of the San Juan, Mendoza, Aconcagua and Maipo rivers decreased drastically after 2009, with reductions oscillating between 28 and 46% [37]. This worrying runoff reduction in populated semi-arid basins concurs with a substantial glacial mass loss after 2009. These changes reflect the very dry conditions this region has been experiencing since 2010 (collectively known as "Mega-drought") and which have yet not ended. Since 2009, glacier meltwater contribution to these basins helped mitigating the effects of this widespread dry period by supplying between 3 and 8% of river discharg [37]. This evidences the importance of glaciers as water reserves and buffers in these semi-arid regions.

Mountain glacier decline can also directly affect water quality. In the Tropical Andes, this has strongly impaired water quality in areas such as the Cordillera Blanca, Peru, were sulfide-rich rock outcrops are left exposed after ice retreats [75].

SEA LEVEL RISE

Greenland and Antarctica melting ice sheets, as well as glaciers retreating all over the world are causing Sea Level Rise (SLR) [76, 77]. Likewise, this meltwater can also disrupt global ocean circulation[78] and marine ecosystems[79].

Global glacier mass loss has significantly increased in the past few decades. Between 1961 and 2016, the world's glaciers have lost over 9 billion tons of ice, contributing 27 mm to SLR. Ice loss rate is currently estimated in 335,000 million tons per year, which is equivalent to almost 1 mm/year of SLR[80]. This represents between 25 and 30% of the observed SLR equaling the contribution of Greenland's ice sheet melt and surpassing that of Antarctica.

Excluding the polar ice caps and Greenland, the largest contribution to SLR comes from glaciers in Alaska, followed by those in Patagonia [80].

ANDEAN CONTRIBUTION TO THE SEA LEVEL RISE

The total Andes glacier mass loss in the last two decades corresponds to 10% of the total global glacier contribution to SLR. Although covering an area three times smaller, Andean contribution doubles that of all High Mountain Asia glaciers [37].

In particular, Patagonian Ice Fields melt has greatly contributed to SLR per unit area. The glaciers in this region cover an extension five times smaller than that of their counterparts in Alaska (90,000 km2), which are responsible for 30% of the total contribution of mountain glaciers [82].

Therefore, Patagonia's contribution to the SLR is disproportionately larger than what would be expected for its glacierized area.

Andean glacier melt contributes significantly to Sea Level Rise. Much of this freshwater loss into the oceans is irreversible.

LOSS OF ECOSYSTEM SERVICES AND BIODIVERSITY

Our understanding of the processes involved in glacier retreat has greatly improved over the last few years, yet the consequences of this changes on Andean natural ecosystems remain little known. There is evidence that cryosphere shrinkage leads to biodiversity loss and even to the extinction of some endemic species in glacier-fed basins[83].

Glacier retreat could seriously affect Andean ecosystems, such as the northern tropical Andes páramos. These ecosystems contain unique endemic flora and provide a myriad of ecosystem resources and services to society[84]. In Ecuador, meltwater contribution decline will not only affect tlower-elevation basins and river regulation capacity (particularly during the dry season), but will also interrupt water production capacity of the páramos and existing aquifers, as these are partially fed by glacier meltwater[85–87].

Wetlands, particularly along river banks and springs in the grasslands and deserts of the High Andes, are archipelagos of biodiversity where cryosphere degradation can lead to less water availability, salinization and, in turn, an increase in GHG emissions [88].

The páramos, one of the most important ecosystems in the Andes, could be severely affected by glacier retreat.

FLOODS, LANDSLIDES AND AVALANCHES

The acceleration of snow and glacier melting leads to new glacial lake formations that could amplify natural hazards for downstream populations.

In some cases, these moraine-dammed lakes, or lakes contained by material deposits transported by glaciers, can be highly unstable. With time, dam failures could cause a glacier lake outburst flood or GLOF. GLOFs are sudden, fast flowing releases of water retained in glacial lakes, and can result in floods and alter the course and quality of water, posing an important threat for downstream communities and infrastracture[89].

Some examples of these events in the Andes include a 1941 GLOF in Palcacocha Lake, Peru, killing 5,000 people; and more recently, a big GLOF caused by Lake 513 which destroyed part of the Peruvian city of Carhuaz in 2010[90].

Another relevant associated hazard, comes from rapid permafrost thaw in high-elevation areas and mountain flanks, increasing hillslope susceptibility to land-sliding and the risk for rock avalanches. Since the 1940's, these types of events have already killed thousands of people[91, 92] in the Cordillera Blanca, Peru, and they are still a threat[93].

ECONOMIC ACTIVITIES AND ENERGY

Andean glacier retreat will have negative impacts on the economy of mountain communities subsisting on them for being tourist attractions. Some glacier landscapes are losing their aesthetics or appeal, while others face sustained decline or even complete disappearance. Pastoruri glacier is one of the most accessible Peruvian Andes glaciers, and receives thousands of tourists every year. By the end of 2007, access to this area was closed due to "adverse climate conditions". This glacier has lost 22% of its extension and 15.5% of its ice mass in the last 30-35 years. During the period 1991-2006, the Chacaltaya glacier area, the highest ski resort of Bolivia lost 80% of its size. By 2009, the glacier had completely disappeared, losing its function as summer ski resort [94].

The recently exposed landscapes left behind by retreating glaciers contain large quantities of loose material, which is washed away to downstream rivers and impacts freshwater quality. Increased water sedimentation also represents a problem for hydropower plants, as this may erode turbines.

For most Andean countries, hydroelectric energy is the main power source for electricity. Hydropower production strongly relies on water resources, which are increasingly being affected by seasonal runoff reduction as the cryosphere melts. Therefore, many of these countries will probably have to turn to other energy sources, which translates into large capital disbursements, greater operative and maintenance costs and, most probably, a higher dependence on fossil fuels and installation of hydropower plants in the Amazon basin. Both latter alternatives have enormous environmental and ecological impacts.

Payachata's nevados, located in the border between Bolivia and Chile. Unloading as ice and snowmelt may trigger increased volcanic activity.

Chacaltaya used to be the highest ski resort in the world and the only one in Bolivia.

POLICIES AND PROTECTION: ARE THEY ENOUGH?

06.

There is a clear need to strengthen glacier protection policies as strategic water reserves in Andean countries, as this resource becomes particularly important in a climate change context.

With the exception of Argentina, no Andean country has adopted an official law for protecting glaciers. The adoption and consideration of national laws for regulating or protecting glaciers is quite recent, and this issue has only begun to appear in political agendas in the last two decades. In some Andean countries, glaciers are probably only safeguarded within the context of protected areas.

Notwithstanding the fact that Chile's territory concentrates the largest glacierized area in the continent, this country has not yet adopted a glacier protection law (GPL). A first draft law was proposed in 2006, and this original proposal has been reviewed three times, and some claim weakened, since [95]. However, these initiatives were unsuccessful due to strong pressures from the mining industry on the authorities to curb this type of legislation that would ban mining activities in glacial and periglacial environments. In 2019, the Commission on Environment and National Assets of the Senate unanimously approved a proposal to legislate the Draft GPL in order to preserve them as strategic water reserves, sources of scientific information and sustainable tourism.

ARGENTINA'S GLACIER PROTECTION LAW

Argentina was the first country in the world to enact an official law for glacier protection all over its territory. However, its enactment went along a winding path. In 2008, it was approved by the two chambers of the National Congress, to later become vetoed by the then President, Cristina Fernández de Kirchner, who argued that this legislation would have adverse economic impacts for the country as it would hinder mining activities[96].

However, this veto drew attention to this debate, that up to that moment had taken place among specialists and actors directly involved, triggering an awareness and socialization campaign that brought public discussion into the conflict of interests between mining enterprises (with their political allies) and the collective (environmental) rights movement. Finally, the Congress passed the GPL on September 30th 2010.

Obstacles for its effective implementation

Even though the enactment of the GPL meant a great step in terms of environmental protection, its implementation has faced and still faces serious challenges and pressures from mining lobbies and some provincial governments [97]:

• The very first budget allocation for the implementation of the law was identified in 2018, 8 years after its enactment.

• Soon after its enactment, the Federal Justice of the province of San Juan granted injunction reliefs as requested by Barrick Gold Corp. and the Argentine Mining Workers Union (AOMA for its acronym in Spanish), and proper implementation of the Glacier Law was hampered in San Juan until 2012.

The impressive Perito Moreno glacier stems from the Southern Patagonian Ice Field and flows into the Argentino Lake.

• In 2014, the Supreme Court rejected a request submitted by the Mining Chamber of the province of Jujuy to have it declared unconstitutional, and repealed another injunction relief given by the Federal Court of that province that was suspending the effectiveness of the Law.

• In 2017, the Executive Power intended to reform the Glacier Law's regulatory decree in order to flexibilize the criteria used to establish which areas would be banned from harmful activities such as mining.

• In 2019, the National Supreme Court of Justice ratified the constitutionality of this Law, rejecting an effort by mining giant Barrick Gold Corp. and the province of San Juan.

The importance of the inventory

The development of the National Glacier Inventory (as mandated by Article 3 of the law) was carried out under the responsibility of the Ministry of Environment and the Argentinean Institute of Nivology, Glaciology and Environmental Sciences (IANIGLA). This process had a strong political backlash after the institute established, based on satellite images and international scientific criteria, that only ice masses with surfaces greater than 1 hectare would be inventoried. By setting a criterion that did not correspond to that established in the law (which protects all ice bodies "whatever their shape, size and state of conservation"), it was considered that this methodology violated the law and the case was brought to trial. Likewise, many NGOs stated delays in its publication, also due to a lack of cooperation from some provinces, allowed the continuity of mining activities and contamination in areas that should have been protected [97].

Climate Change and the Glacier Protection Law

Article 10(b) of this law requires the formulation of climate policies that guarantee the preservation of glacier and periglacial environment, both at national level and within the framework of the international climate change agreements. By virtue of this, the Argentine government should adopt climate change mitigation measures that contribute to the said objective.

Articles of Law N° 26,639 on the Regime of Minimum Budgets for Glacier and Periglacial Environment Protection (Argentina)

1. Aims: establishment of minimum budgets for the protection of glacier and periglacial environment as water reservoirs.
2. Definition of glaciers and periglacial environment.
3. Creation of a National Glacier Inventory (NGI)
4. Data included in the NGI.
5. Institution responsible for carrying out the Inventory.
6. Banned activities.
7. Description of activities requiring Environmental Impact Evaluation.
8. Competent authorities: National Park Administration (APN for its acronym in Spanish)
9. National implementation authority.
10. Role of the national implementation authority.
11. Infringements and sanctions.
12. Penalties for recidivism.
13. Infringer's responsibilities.
14. Destination of funds collected through fines.
15. Deadlines to develop the inventory.
16. Antarctic Sector: Law Implementation under the Antarctic Treaty.
17. Deadlines to law Implementation.
18. Be it communicated to the executive.

THE ROAD AHEAD: CHALLENGES AND OPPORTUNITIES

"Ice and stone" by mause_1960, licensed under CC BY 2.0.

07.

Undoubtedly, the gradual disappearance of many Andean glaciers due to climate change can become irreversible if urgent mitigation measures are not taken. Many glaciers will continue retreating along the century and, therefore, Andean communities will have to face the challenges that come with it such as water scarcity, hazards and loss of ecosystem services.

Glacier retreat, precipitation decrease and continuous demographic growth will further increase pressure on local hydrological systems, and this should receive proper attention. It will be essential to maximise water storage opportunities and to avoid frozen freshwater reservoirs from running off into the ocean and contributing to sea level rise.

To do so, decision-making processes need to be constructed collectively, through the articulation of numerous actors at the national and international level in order to achieve the implementation of consensus-based, effective and no-regret policies.

RAISING THE ODDS: ENHANCING CLIMATE AMBITION

Adopting urgent mitigation measures at the global level is of the outmost importance to stop global warming. Limiting cryosphere changes mainly depends on the ambition to rapidly reduce GHG emissions, which will require the decarbonisation of energy and the economy as well as rapid and unprecedented changes in all aspects of society.

The objective of the Paris Agreement is to keep global warming well below 2°C above pre-industrial levels and, to pursue additional efforts to limit temperature increase even further to 1.5°C. To reach this target, the world should cut carbon emissions by at least 49% (as compared to 2017 levels) by 2030, and achieve carbon neutrality by the year 2050[29].

Currently, climate pledges are far from being enough to achieve this objective, as we are heading for a 3.2°C world.

Countries must urgently show a greater commitment to tackle climate change in their National Determined Contributions (NDCs) and Long-Term Strategies for 2050 (LTS), not only to safeguard the Andean cryosphere, but also avoid severe impacts on ecosystems, human health and the well-being of people worldwide. In turn, this would also facilitate compliance with the United Nations Sustainable Development Goals (SDGs).

ADAPTING

Adaptation measures aim to moderate climate risk at an acceptable level, and to take advantage of opportunities resulting from climate change effects[73]. In particular, it is necessary to implement and plan adaptation measures to replace the roles snow and ice play in areas where a substantial cryosphere reduction is projected[14].

Some of these measures include implementing different knowledges and infrastructure for water harvesting, efficient water usage and supply, and enhancing natural water storage in Andean ecosystems (Ecosystem based Adaptation) [22,98].

ECOSYSTEM-BASED ADAPTATION (EBA)

Ecosystem based Adaptation is the use of biodiversity and ecosystem services in an overall strategy to help people adapt to climate change impacts[99].

Andean wet páramos ecosystems, located in the highlands of western Venezuela, Colombia, Ecuador and northern Peru, have proved crucial as water sources and reservoirs[4]. Therefore, it is important to find ways for supporting and improving natural storage and water regulation capacity of these ecosystems through conservation and restoration. Technical expertise and traditional knowledge is critical for achieving successful EbA meassures[100], and its implications must be carefully considered[101].

As it promotes ecosystem sustainable management, conservation and restoration, EbA approaches are aligned with the Convention on Biological Diversity (CBD), the United Nations Convention to Combat Desertification (UNCCD), the Convention on Wetlands (Ramsar Convention), the United Nations Declaration on the Rights of Indigenous Peoples (UNDRIP) and the United Nations Forum on Forests (UNFF). This entails synergies and complementarities between EbA activities and strategies and other actions aimed at ecosystem management, conservation and recovery for a variety of purposes [102].

As previously stated, glacier lake outburst floods (GLOFs) also represent a great hazard for many Andean communities. Engineering techniques, such as installing pumps to reduce water levels can reduce hazards from moraine dam failures[90]. Besides, it is essential to establish wider and more effective monitoring systems to improve risk management[22].

Before implementing this type of strategies, it is important to carry out a thorough analysis of the socio-economic factors underlying vulnerability to climate change. An inclusive and careful approach reduces maladaptation risk, that is, the risk of implementing measures that foster adaptation in the short-term but insidiously affect systems' long-term vulnerability and/or adaptive capacity to climate change. It is then important to avoid taking actions that respond to short-term economic interests, but compromise ecosystems resilience and reduce adaptation capacity in the long-term.

While available resources are scarce and still many Andean countries have to undertake countless actions, it is necessary to invest in adaptation as soon as possible, because otherwise climate change impacts will soon become an unmanageable burden for the regions' development agendas [103].

PROTECTING

To protect glaciers from the impacts of mining, dams and other economic activities in Andean countries', it is urgent and necessary to advance the debate on public policies and regulations at a national and regional level.

Creating glacier protection laws is worthless if not accompanied by strong federal commitments, budget allocation and tools to guarantee its proper implementation. Therefore, it is crucial to:

• Facilitate and accelerate the completion of glacier inventories in all the countries of the region, including all glaciers and their periglacial environment, as far as methodologically possible.

• Audit ongoing activities and projects representing a threat for the glaciers and the periglacial environment. Moreover, auditing should be in charge of institutions not related to the promotion of harmful activities.

• Enforce the banning of projects or activities trying to settle in glacier areas or periglacial environments.

• Order the cessation or transfer of ongoing projects in glacier of periglacial areas, conducting proper clean up and restoration.

It is also imperative to also safeguard the delicate Andean ecosystems and its biodiversity by creating protected areas.

STRENGTHENING THE ROLE OF LOCAL COMMUNITIES

Local communities' participation, together with Andean local and regional authorities, is essential for identifying the most adequate adaptation measures. This participation not only uses the experience of the communities themselves to implement and design effective strategies, but also strengthens their sense of land ownership and awareness on the value of the ecosystems and their valuable services [22].

RECOGNISING AND INCORPORATING ANCESTRAL KNOWLEDGE

The recognition of indigenous and local knowledge and its integration with scientific knowledge enhances resilience and adaptation to climate change effects[28]. In the Andes, many of these ancestral practices are related to agricultural water management, for example, the use of terraces and rows, and irrigation and water storing techniques by means of aquifer recharge (qochas or "water sowing").

FACILITATING AND STRENGTHENING THE ROLE OF SCIENCE IN DECISION-MAKING

Incorporating scientific knowledge into decision making and strengthening technical capacities of public institutions are the cornerstones for sound policy making regarding climate change. Science-policy interactions are often weak, and is often frequently hampered by failing to identify common targets and objectives. The best available science is central to an effective and impactful decision making.

Potential action lines could be articulating networks of experts and strengthening relevant ongoing research projects on cryospheric changes and its impacts on communities. It is also necessary to strengthen regional professional skills and to develop networks with research groups at the international level. Finally, it could prove advantageous to promote a regional free-access scientific journal or platform on this subject, in Spanish, to facilitate and centralize knowledge exchange.

EDUCATING

Fostering population awareness regarding climate change impacts on glaciers and hydric resources is crucial. It is necessary to support the creation of a regional critical mass of experts, specialised in education and climate change, as well as to generate alliances for building and spreading knowledge for the benefit of people.

COOPERATING

Cryosphere changes interconnect along a broad range of socio-ecologic contexts, legal frameworks, governments and institutions1. Promoting interregional and international cooperation, knowledge and experience sharing will be necessary to face the impacts of cryosphere disappearance.

Financing, education, research, training and technology transfer programs are just a few examples of the types of links that can be and are being created between the Andean countries and also with the rest of the world.
United Nations Framework Convention on Climate Change (UNFCCC) recognises the potential benefits of regional synergies and promoting cooperation for developing and implementing adaptation measures. Some of them are knowledge exchange, duplicated efforts avoidance, economies of scale, cost sharing, and conflict minimisation [22].

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